Detectors

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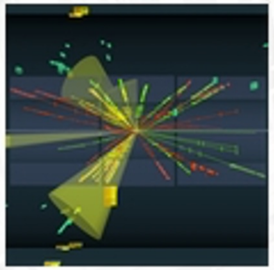
CIEMAT



TAE 2024 - International Workshop on High Energy Physics
Benasque Science Center, Sep 01 - Sep 14, 2024)

Contents

- ✓ General principles and interactions
- ✓ Ionization detectors
  - Gaseous
  - Solid state
- ✓ Light detectors
  - Scintillators
    - Organic
    - Inorganic
    - Gas/liquid Noble
  - Cherenkov
- ✓ Photodetectors
- ✓ Calorimeters

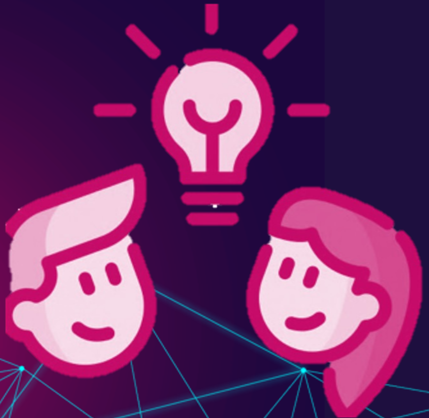
Detection objectives

Produce a measurable signal when they are crossing by the particles so that it can provide:

- Identify all the particles passing through (μ, e, p, π…)
- Measure the particles properties (charge, momentum, energy, mass…)
- Reconstruct the generation process (particles - as bosons W, Z, H - only can be detected through their decay products)

Each experiment is designed according to

- ○ The physics process to be studied
  (A collider general purpose experiment, neutrino experiments, dark matter searches…)
- ○ The “environmental” condition of the experiment
  (Rate of particles, timing, backgrounds induced by beams or materials (radiopurity)….)
  - Big differences for example in colliders depending on energy and the type of particles, lepton vs hadron colliders



Each new experiment is a new challenge and usually goes hand in hand with detector advances.
The design of an experiment requires important R&D on detectors and electronics

General principle

The particles can interact with matter

The “footprint” depends on:

- the particle characteristics

&

- the material type

The footprints allow to distinguish the particle type, energy, charge, track

When many particles interact simultaneously, disentangling the different footprints and associate them to each individual particle can be a quite a challenge.

Interaction of particles with matter

CHARGED PARTICLES

Excitation and ionization	Loss of energy & emission of e- from the atom
Multiple Scattering	Change of trajectory
Bremsstrahlung	Change of trajectory, loss of energy & photon emission (relevant only for electrons and positrons)
Čerenkov radiation	Photon emission, very low energy loss (crossing a dielectric medium faster than the light speed in this medium)

PHOTONS

Photoelectric effect	Photon absorbed & emission of e- from the atom
Compton effect	Change of trajectory, loss of energy & emission of e- from the atom (relevant only 0.5-10 MeV)
Pair production	Photon disappears & emission of a pair e-e+ (Cutoff: $E_\gamma > 2m_ec^2$)

HADRONS

Nuclear interaction	Loss of energy, production of charged and neutral mesons & nucleons (intranuclear cascade & nuclear des-excitation - evaporation)

NEUTRINOS

Only interacts via *gravity and weak interaction.*

Extremely weakly interaction: (solar/reactor: E~ MeV, $\sigma \sim 10^{-44}$ cm^2, $\lambda_{lead} \sim 10^{16}$ m; accelerators: E~ GeV $\sigma \sim 10^{-40}$ cm^2 , $\lambda_{lead} \sim 10^{12}$ m)

Detected through their products after being absorbed in neutrino experiments and looking to missing E_T in colliders

Two main ways (complementary) for identifying & measuring particle properties

Detectors to reconstruct the trajectory of the particle (trakers/muon)

Do not destroy the particle

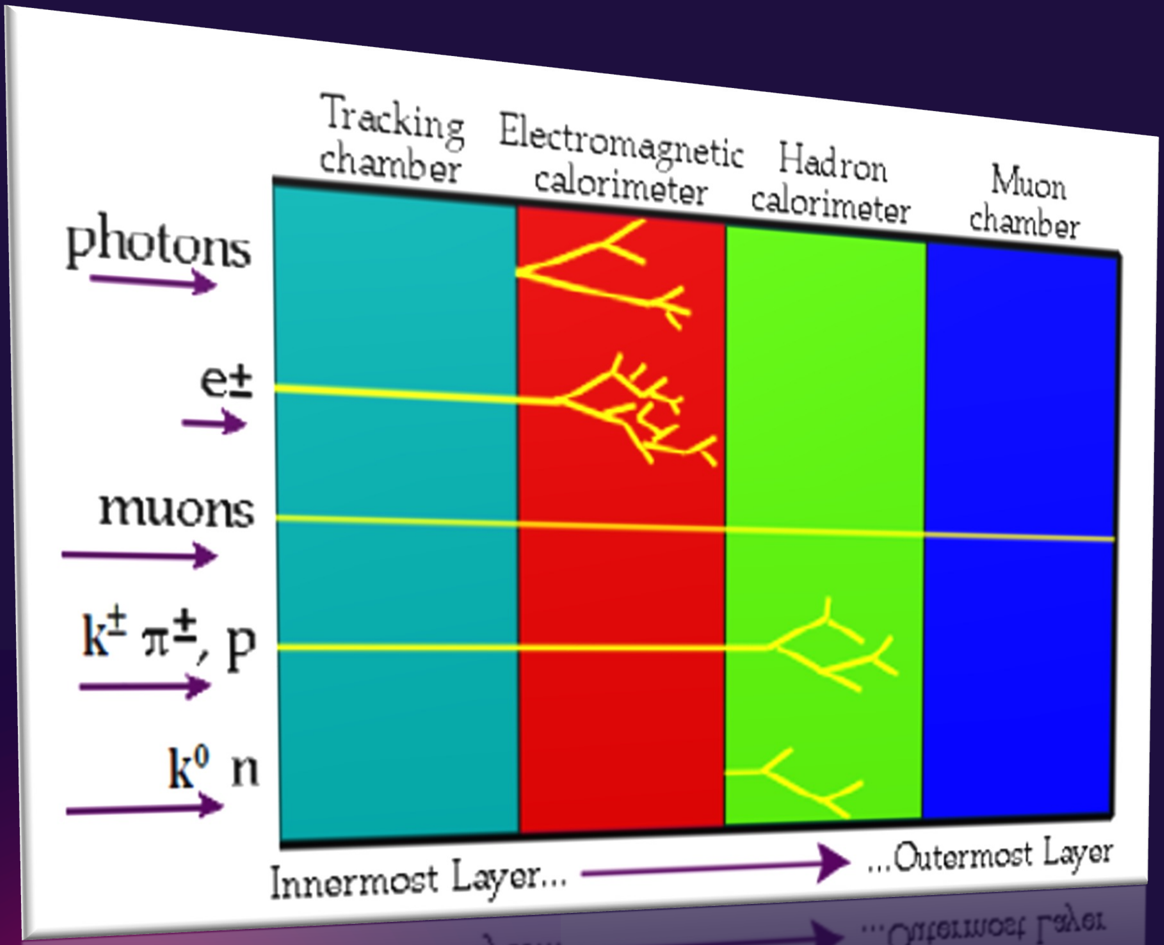
Further measurements with other/more detectors are possible

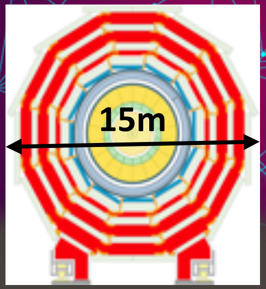
Detectors which stops the particle and measure its energy (Calorimeters)

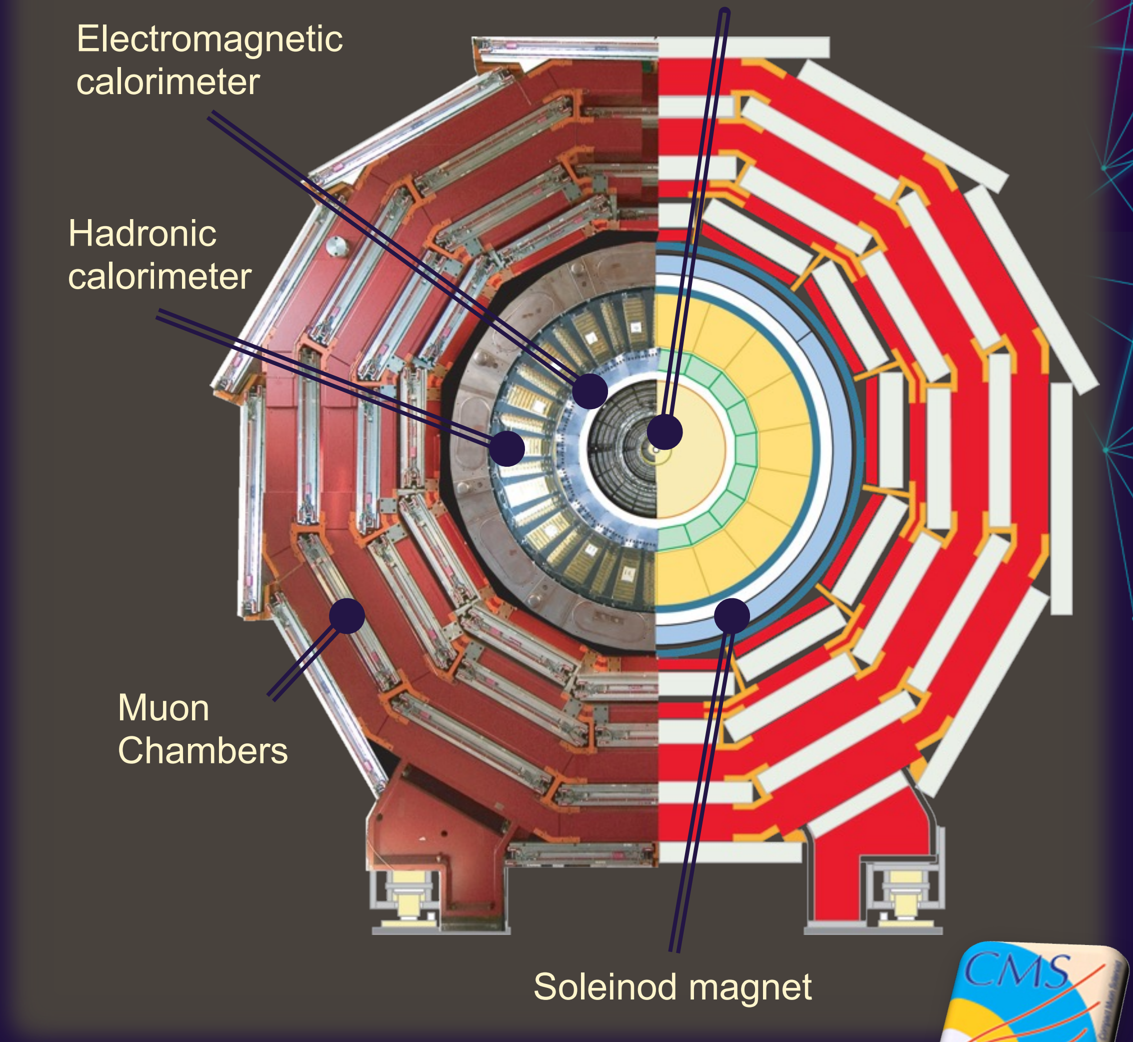
Particle is destroyed

Experiments uses several subdetectors and combine different detector types depending on the physic processes to be studied
They are combined or not with magnets

Detectors specialization







Tracking and muon detectors

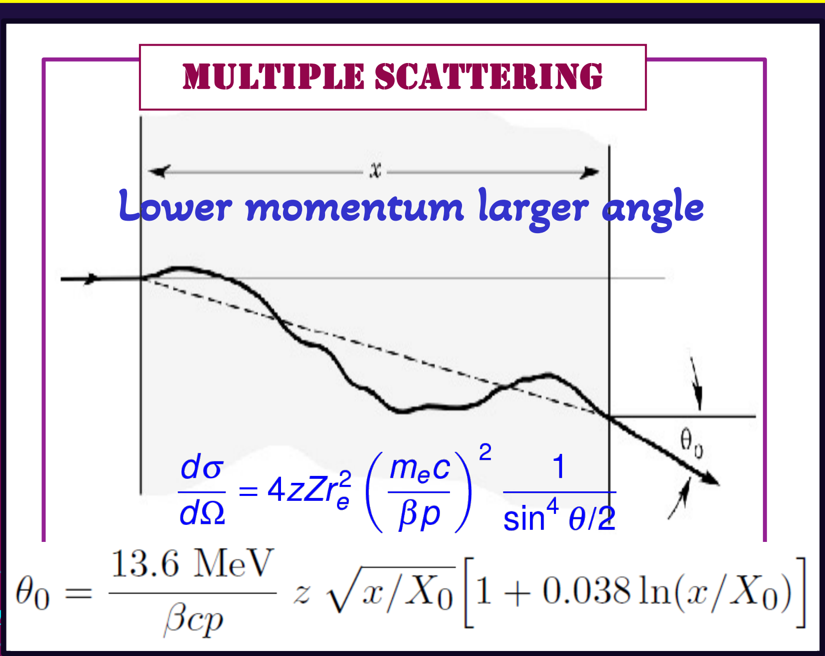
They use **several layer of detectors** (same or different technologies)

Particles pass trough producing signals **loosing very few energy**

From the signals **is possible to reconstruct the trajectory**

SOME REQUIREMENTS

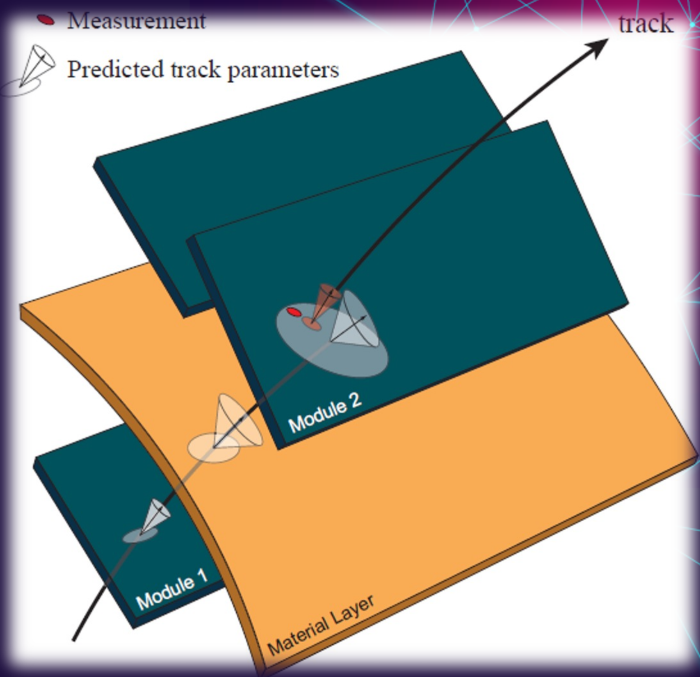
- ✓ Position precision Tens of microns
- ✓ Time precision few nanoseconds or less
- ✓ Small material budged to avoid too much energy loses or multiple scattering



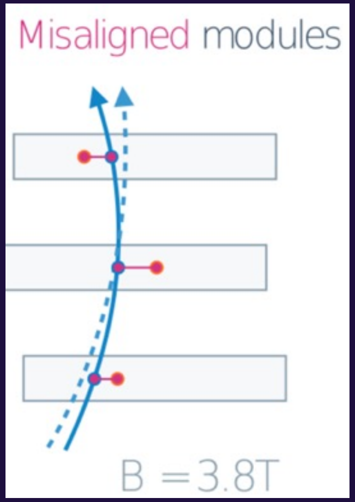
$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2\frac{1}{\sin^4\theta/2}$$

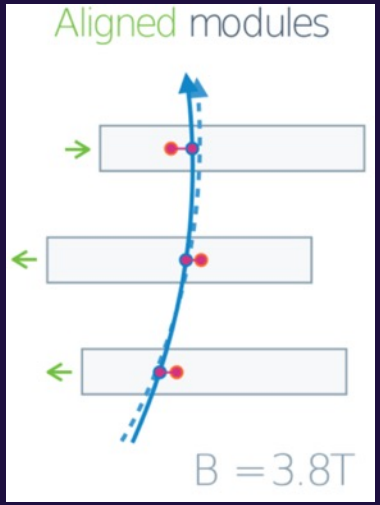
$$\theta_0 = \frac{13.6\text{ MeV}}{\beta c p}\, z\sqrt{x/X_0}\left[1+0.038\ln(x/X_0)\right]$$

Only meassures **charged particles**



Position precision
=> Good alignment is mandatory





Tracking and muon detectors

They use several layer of detectors (same or different technologies)

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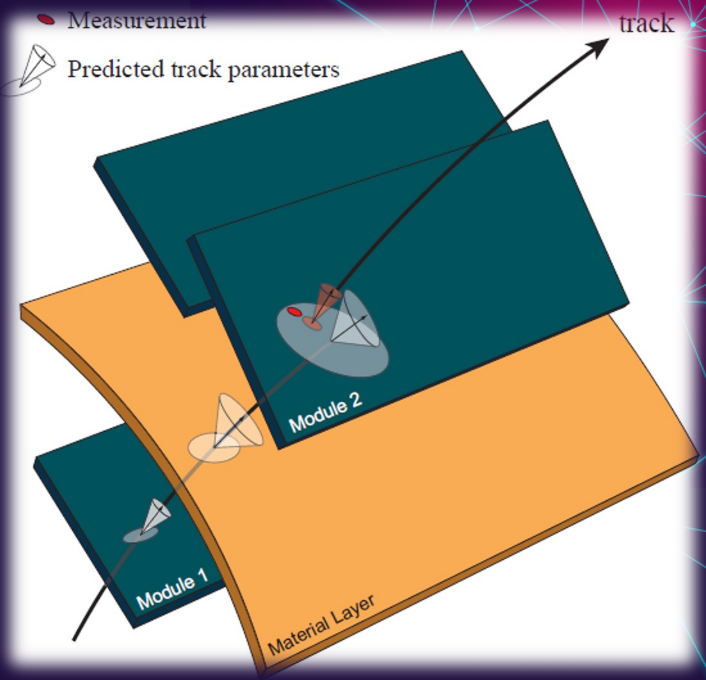
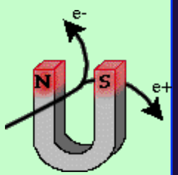


FROM THEM DIFFERENT MEASUREMENTS ARE POSSIBLE

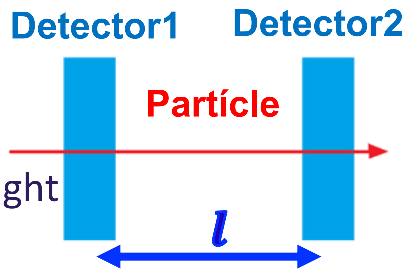
Measure the charge

Using a magnet and measuring the trajectory curvature



Particle velocity

Time Of Flight (TOF)

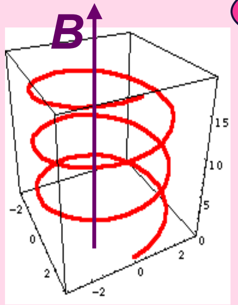


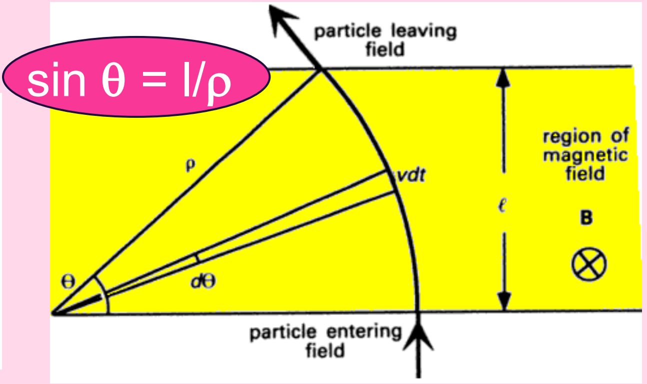
The momentum

$$\frac{d\mathbf{p}}{dt} = \frac{q}{c}\mathbf{v}\times\mathbf{B}$$

$p = qB\rho$

$\sin\theta = l/\rho$





Particle physics detectors clasification based on the physics process and produced signal

Ionization detectors

- Gaseous
- Liquid
- Semiconductors

Light detectors

- Scintillator light
  - Organics (e.g. plastics)
  - Inorganics (e.g. cristals)
  - Gas/liquid noble (Ar, Xe...)
- Cherenkov Light

Photodetectors

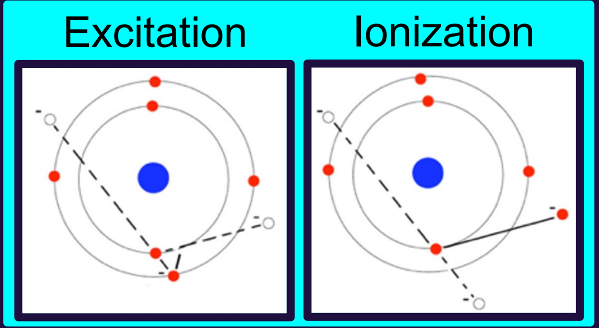
- Photodomultiplier tubes
- Semiconductors
- Hibrids

+ Calorimeters

IONIZATION DETECTORS

Gaseous (& Liquid)
Solid state – semiconductors (silicon detectors)

Ionization detectors – basic principles



A charged particle crossing a material interacts with its atoms and loss energy.

Is this energy lost is high enough can excite or ionize the atom creating pairs electron/ion (gas and liquid) or electron/hole (solid)

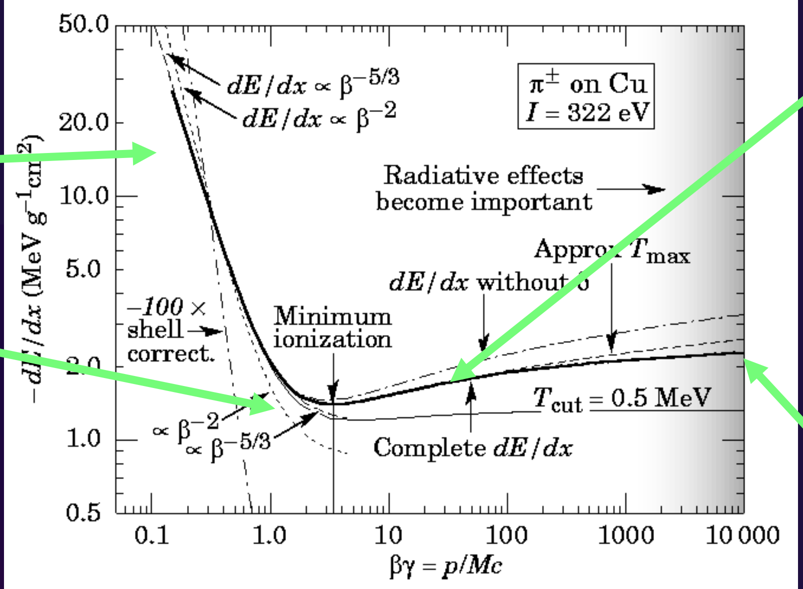
dE/dx depends on the charge and velocity of the particle Independent of its mass

Bethe-Bloch formula

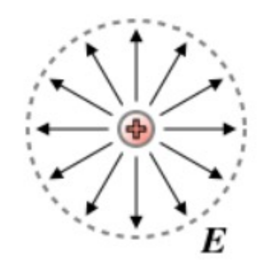
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln\left(\frac{2 m_e c^2 \gamma^2 \beta^2}{I} \right) - \beta^2 - \frac{\delta}{2} \right]$$

At low energy ($\beta\gamma < 3$)
$1/\beta$ dominates

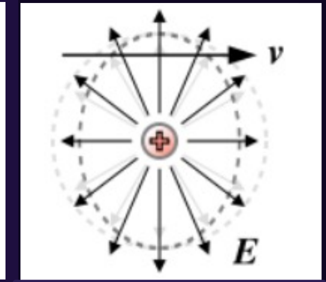
At $\beta\gamma \sim$ 3-4
A minimum is reached



At relativistic energies small increase (“*relativistic rise*”)
due to the logarithmic term.
(expansion of the E field allowing farthest interaction)



Field at rest (spheric)



Field moving at constant v (oblate spheroid)

Higher v, larger transverse E
Negligible effect for low v

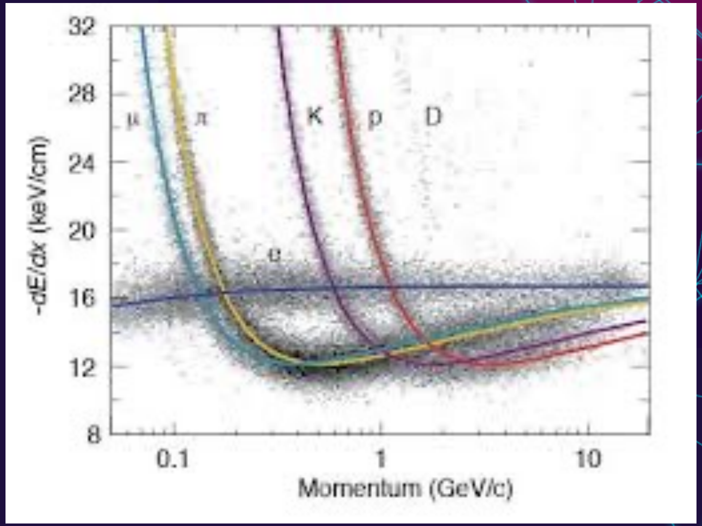
Fermi Plateau
Atoms polarization screening the E field
Density effect – δ in the formula

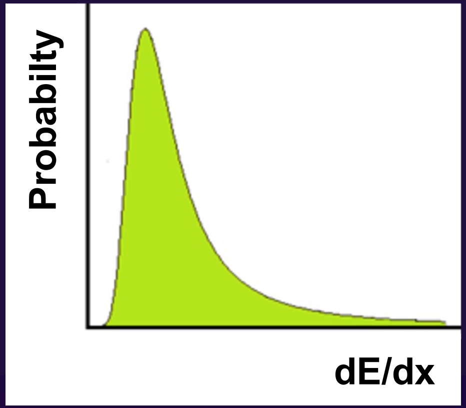
MIP: Minimum Ionization Particle
Definition of a particle which loses energy only due to ionization and the lost energy is equal to the minimum of the dE/dx distribution

Ionization detectors - basic principles (II)

For a particular material dE/dx is a function of the velocity β

Particles with the same velocity and different mass dE/dx vs p ⇒ Displaced curves





Landau fluctuations

Large variations from interaction to interaction

To measure dE/dx, large volumes where many interactions happens are needed
Average over lower values (truncated mean)

The emitted electrons by ionization can produce new ionizations if the energy is high enough (secondary electrons)

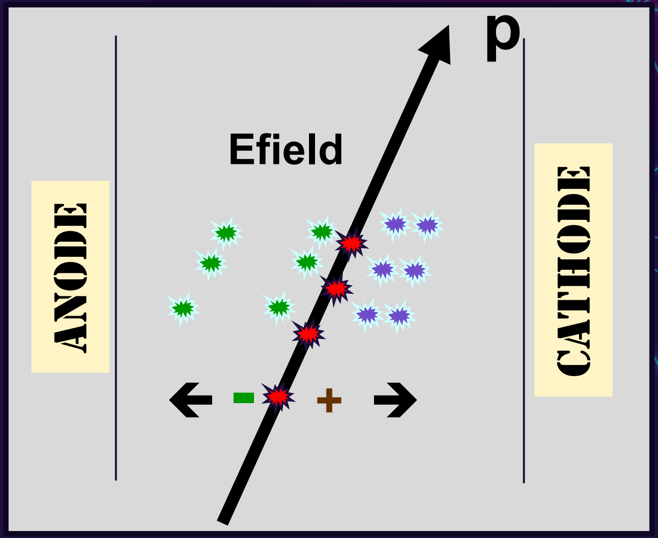
In case of very large dE/dx ➔ Delta ray production
It can scape and produce a secondary track

Ionization detectors – basic principles (III)

A charged particle can excite or ionize the atom creating pairs electron/ion (gas and liquid) or electron/hole (solid), These electrons (primary electrons) have enough energy to produce some other ionizations (secondary)

The electrons and ions move in any direction loosing energy and finalize are neutralized

By applying an electric field electrons and ions/holes will move following the field lines towards the anode and the cathode respectively. If the field is sufficiently high they will arrive to the anode/cathode and can produce an electric pulse which can be recorded with the appropriate electronic setup



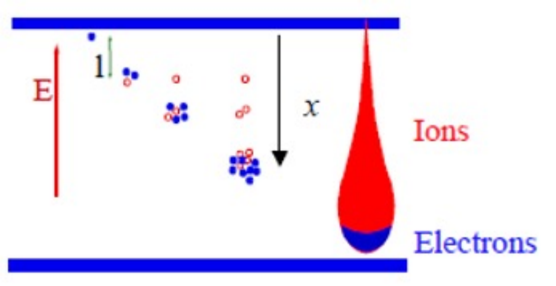
The motion of electrons and ions is called drift velocity.
Ions move a factor 1000 slower due to its masses.

Ionization detectors - Amplification, avalanche development

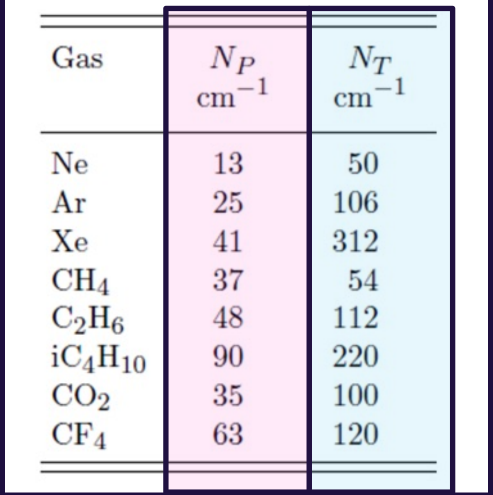
If the E field is high, the electrons liberated in the ionization, will be accelerate acquiring energy enough to produce new ionizations, and the new electrons liberated can, in turn, produce again new ionizations and so on.
The result is an avalanche of electrons

$$G = n/n_o$$

G= Gain/amplification
n= total number of e-
n_0=number of e- produced by ionization without multiplication



AMPLIFICATION ON GASEOUS DETECTORS



Gas	N_P cm^{-1}	N_T cm^{-1}
Ne	13	50
Ar	25	106
Xe	41	312
CH_4	37	54
C_2H_6	48	112
iC_4H_{10}	90	220
CO_2	35	100
CF_4	63	120

N_P= Number primary e- produced
N_T = Total number of e- (no gain)
(primary and secondary)

The number of ionizations in a gas is low, producing in total $\mathcal{O}$ (100) pairs electron/ion per cm, difficult to detect because the typical noise in amplifications is $\mathcal{O}$ (1000) e-

The relative grown of e- in the avalanche is:

$$dn/n = \alpha\, dx$$

α = First Townsend coefficient

Constant E field

$$G = n/n_o = e^{\alpha x}$$

Non constant E field

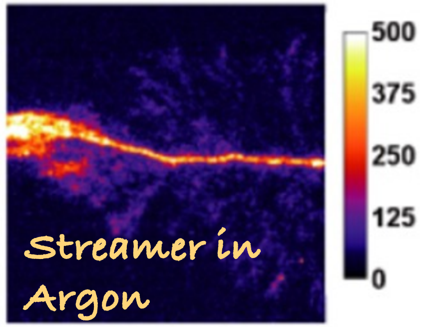
$$G = n/n_o = e^{\int \alpha(x)\, dx}$$

$$\boxed{\alpha = PAe^{-BP/E}}$$

P = Gas pressure
E = E field
A and **B** = constants for a gas and a range of E and P

Gain cannot become infinite by increasing the external E field.
Large gains ➔ Presence of many e- and ions will distort the field.
There will be recombination of e- + ions producing photons: Avalanche saturation
Or, producing and streamer between cathode and anode: Sparks

Gain Limit ~10^6-10^8



Streamer in Argon

Gaseous detectors: Operation modes

Depending on the voltage applied

I. Recombination

Electrons doesn´t arrive to the anode

II. Ionization mode

Electrons arrive to the anode and there are not avalanches

III. Proportional region (Gain$\sim 10^3$-10^5)

The number of electrons in the avalanche is proportional to the initial ionization

IV. Region of limited proportionality (Gain$\sim 10^5$-10^8)

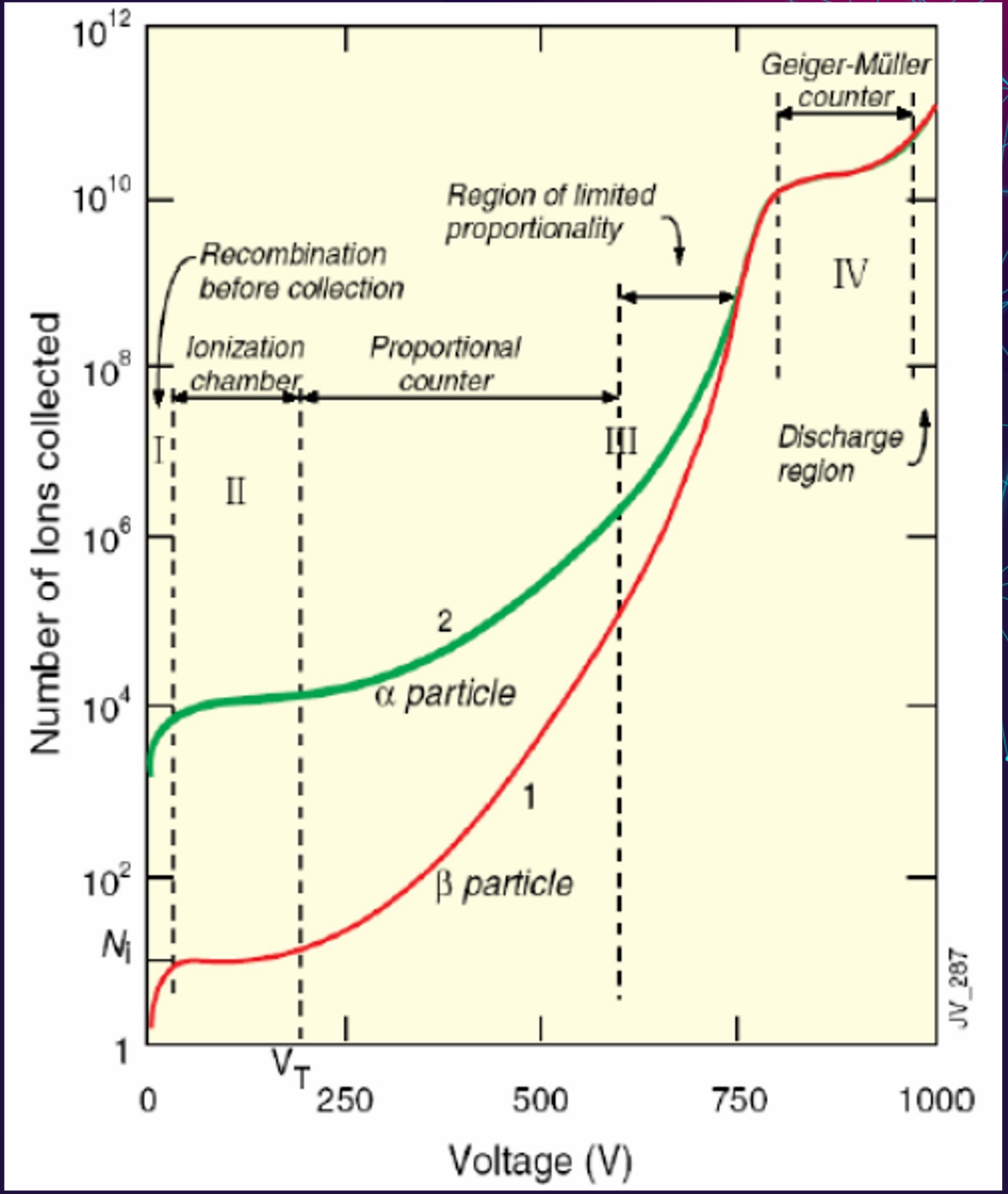
Saturation, large photo emission (which will produce more electrons), secondary avalanches

V. Geiger – Müeller region (Gain $\geq 10^3$-10^5)

Massive photo emission

Full length of anode affected.

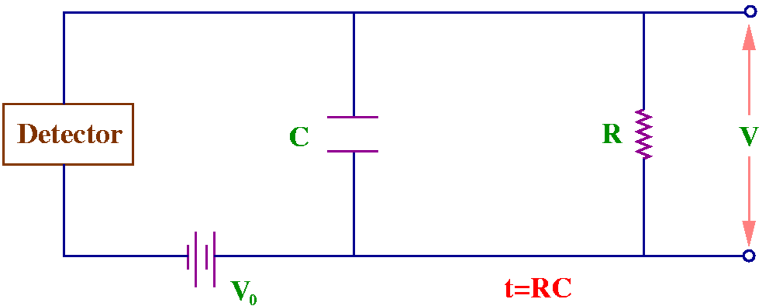
VI. Continuous discharge



Ionization detectors – basic readout

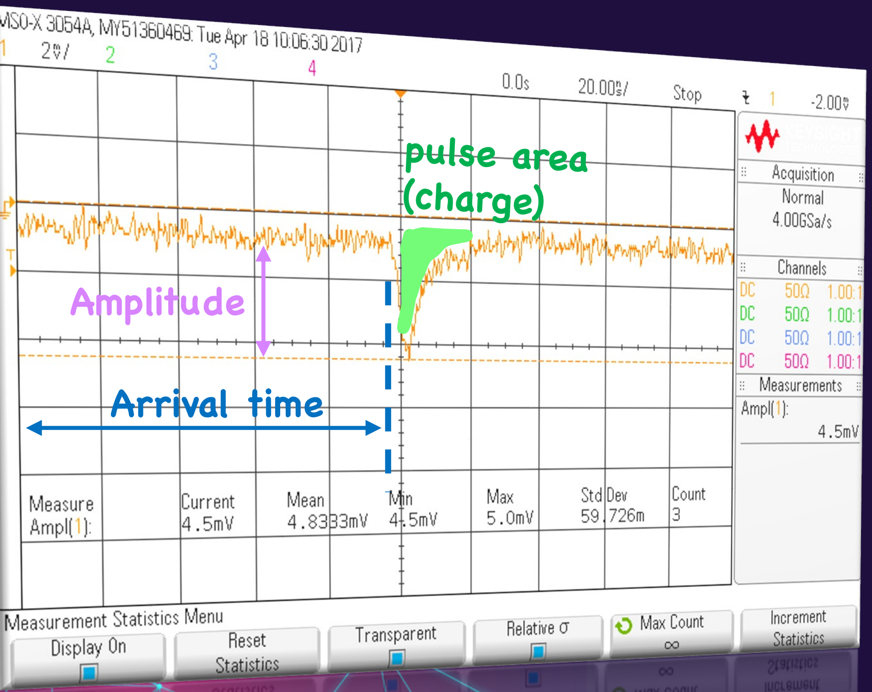
The charge produced by the ionization generates an electrical current which can be read with the appropriate electronics

$$i(t) = \frac{dq(t)}{dt}$$



Capacitor becomes charged momentarily and is discharged after through the resistor, creating a current pulse which can be processed

From the generated pulse it is possible to extract:



Measure	Current	Mean	Min	Max	Std Dev	Count
Ampl(1):	4.5mV	4.8333mV	4.5mV	5.0mV	59.726m	3

- ○ **Charge** → Information of **the particle energy.**
  It is given by the **pulse area**
  Some electronics allows to provide this information also from the **amplitude**
- ○ **Time** → It is important that **rising edge is not degraded**

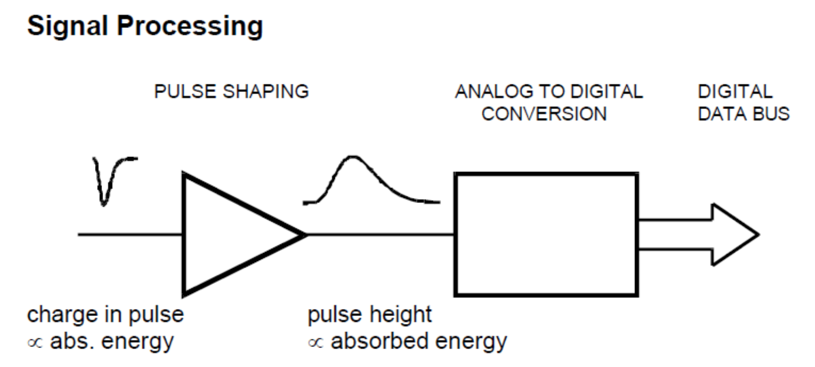
Analogic signal is sent to a digital converted to read:

- **Charge** : ADC (Analogical Digital Converter)

or

- **Arrival time**: TDC (Time Digital Converter)

Preamplifiers and pulse shaping are often used. Discriminators are also used to filter electronic noise requiring signal is bigger than a threshold



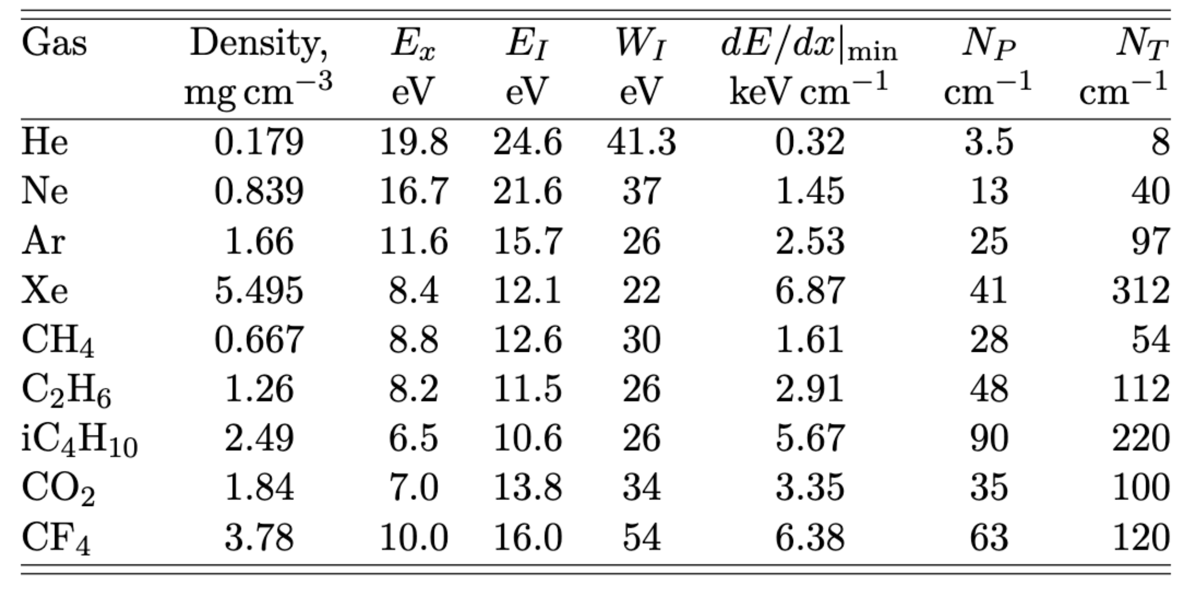
Gaseous Detectors. Which gas?

The main component use to be a noble gas, they produces high gains with lower voltages.
The most used is the Argon because is cheaper

Those gases have a problem.

The excited states produce photons that cannot be absorbed by the gas

Photons can ionize the cathode and produce new avalanches.
The detector can enter in a continuous discharge



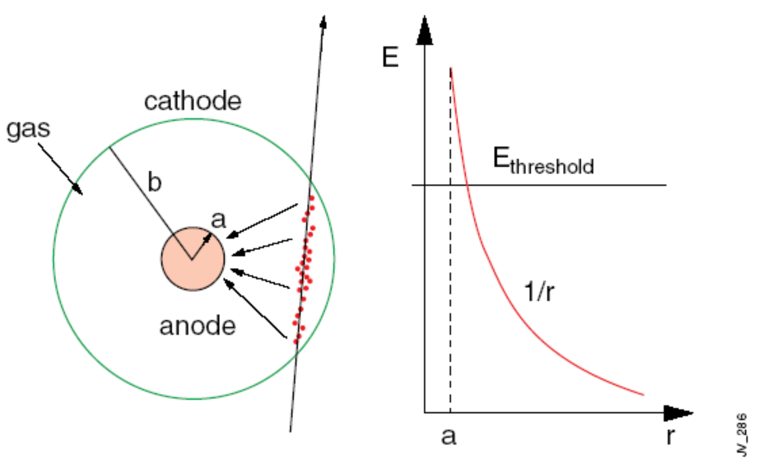
Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx\|_{\min}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
He	0.179	19.8	24.6	41.3	0.32	3.5	8
Ne	0.839	16.7	21.6	37	1.45	13	40
Ar	1.66	11.6	15.7	26	2.53	25	97
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	28	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	54	6.38	63	120

To solve the problem

polyatomic gases (as CO_2 or iC_4H_{10}) are added (Quenchers).
They can neutralize photon emission because they have different excited states which don´t irradiate allowing to work at High gains ($\sim 10^5$)

Gaseous detectors – Basic designs

Cylindrical detector with a wire in the center



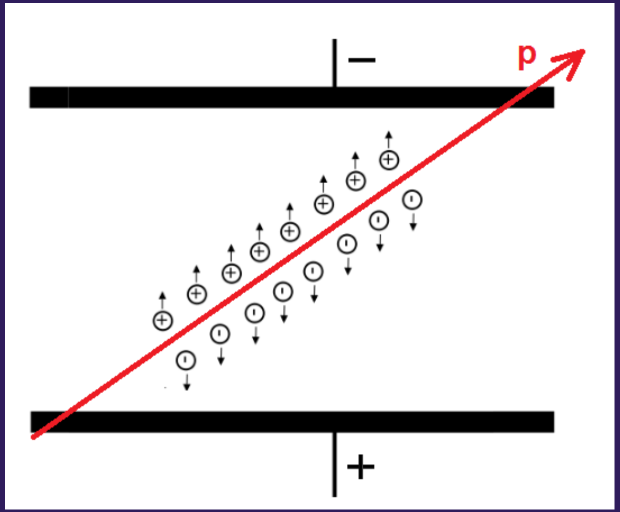
2a = wire diameter = ~ 30-60 μm

By applying a voltage V_0 to the wire

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

E field increases close to the wire
Avalanche is produced only near to the wire

Parallel Plate Chambers



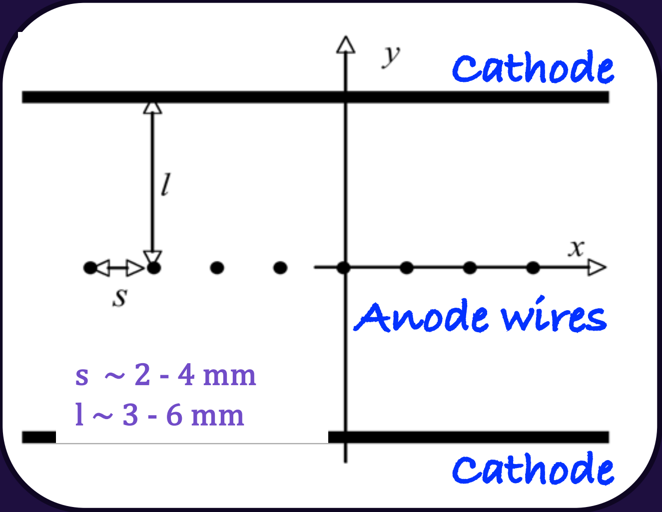
By applying a different voltage at the plates

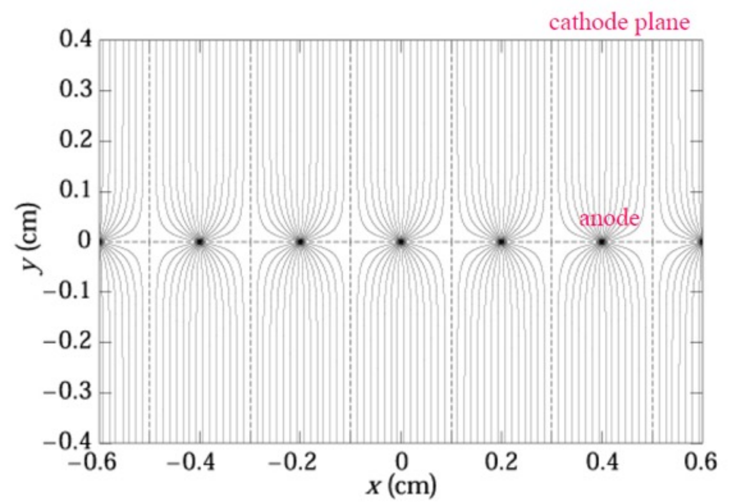
$$E = \frac{\Delta V}{d}$$

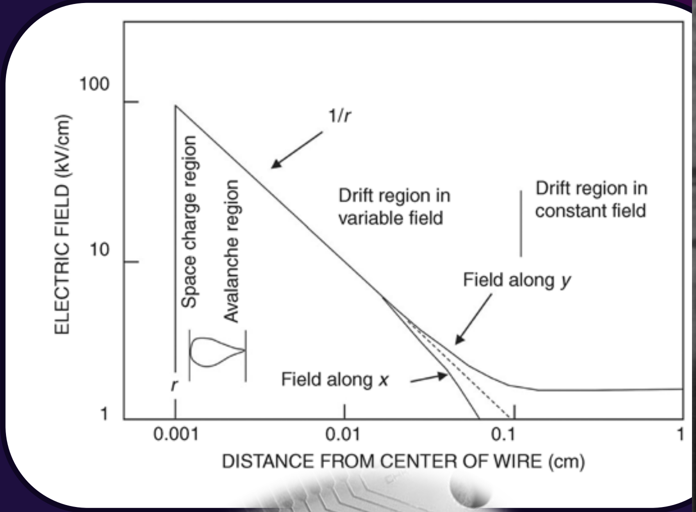
E field is homogeneous along the gas volume
Avalanche is produced anywhere

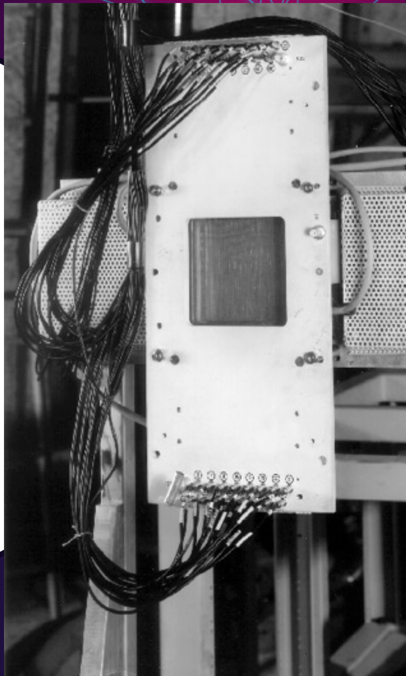
Gaseous detectors: Multiwire chambers – MWPC

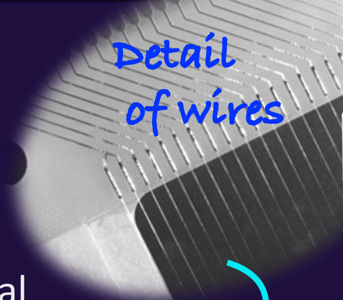
G. Charpak, NIM 62(1968)262
Nobel prize 1992









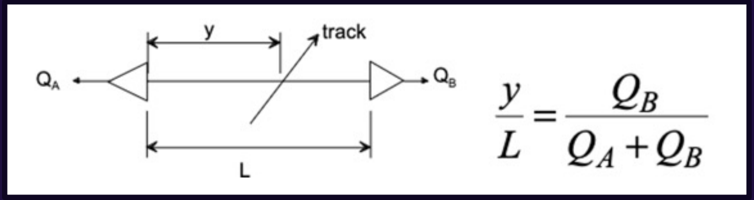


Wires must be positioned with a very high precision

Each wire acts as an independent detector

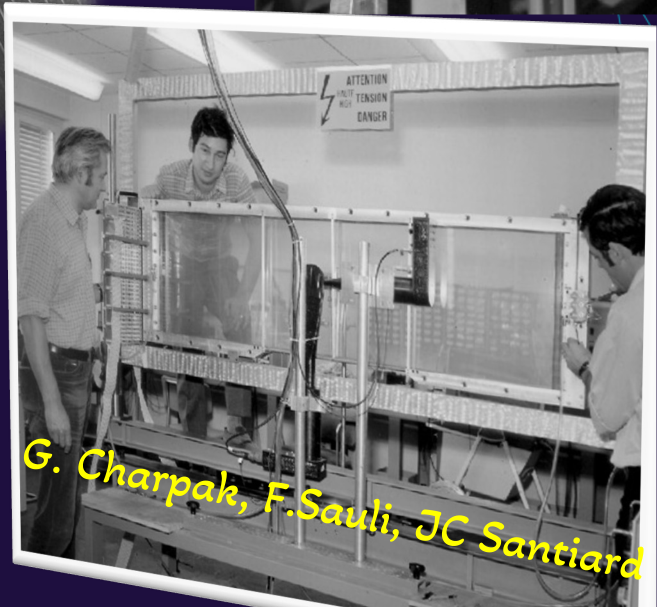
- X coordinate is given by the wire position
- The orthogonal coordinated (z in the sketch) can be obtained from:

a) Charge division of the wire signal

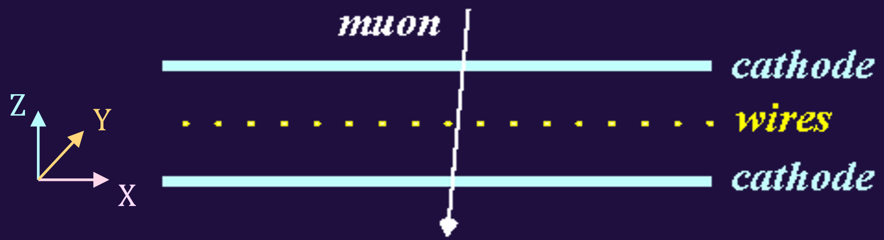


$$\frac{y}{L} = \frac{Q_B}{Q_A + Q_B}$$

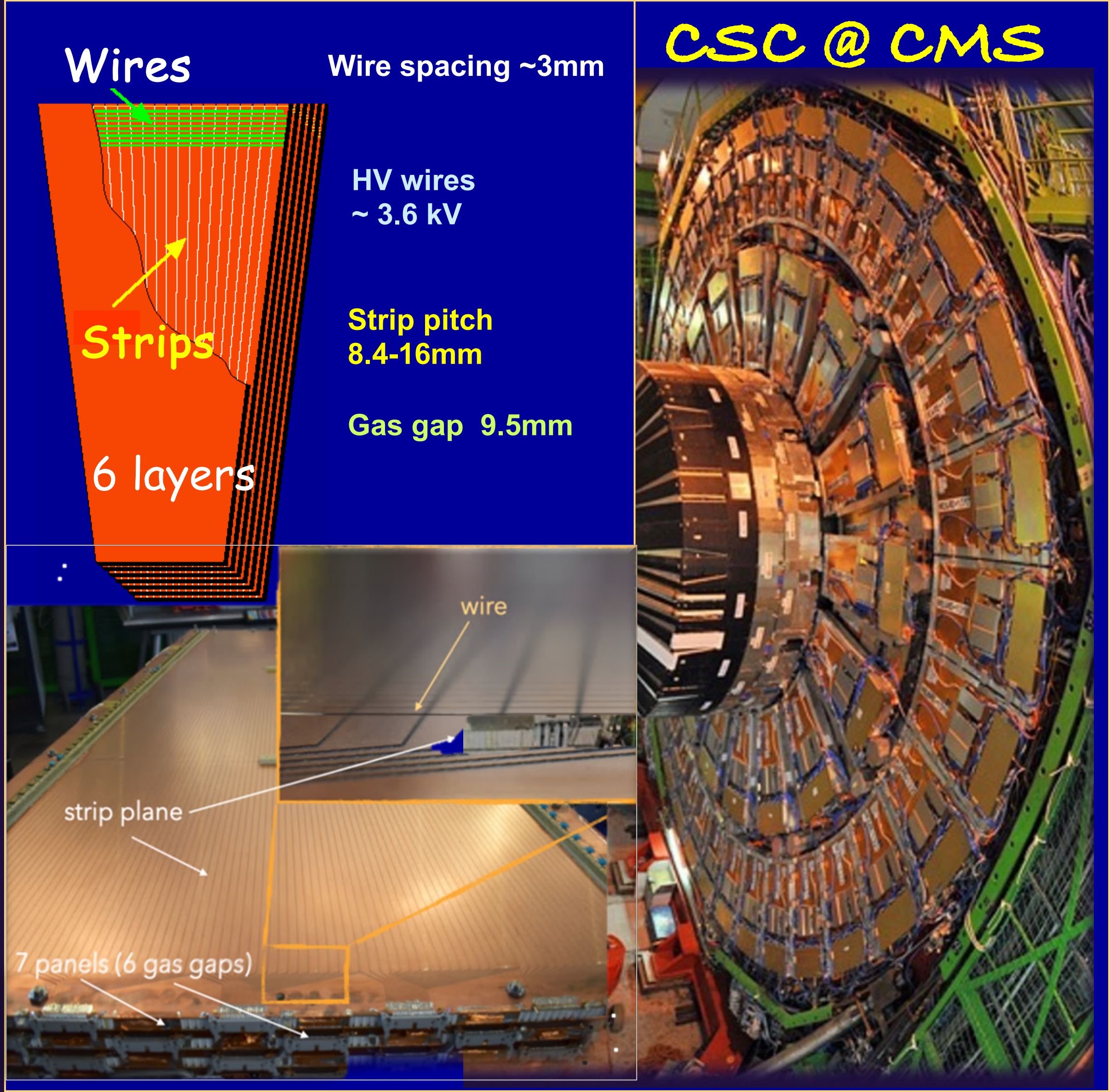
b) Timing difference of the wire signal arrival
c) A second detector rotated 90 degrees
d) Segmenting the cathodes


G. Charpak, F.Sauli, JC Santiard

Gaseous detectors: Cathode Strip Chamber (CSC)



wire distance ~ wire-cathode distance ~2.5 cm

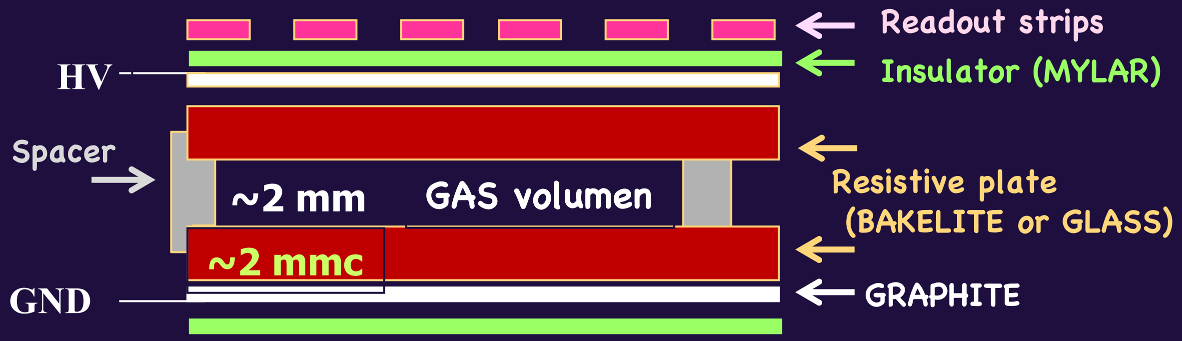


The avalanche induces a signal in the cathode

- **X coordinate** is given by the **wire position**
- **Y coordinate** can be obtained calculating the **gravity center** of the **charge distribution in the strips**

Y (Strip) resolution
< 100 microns

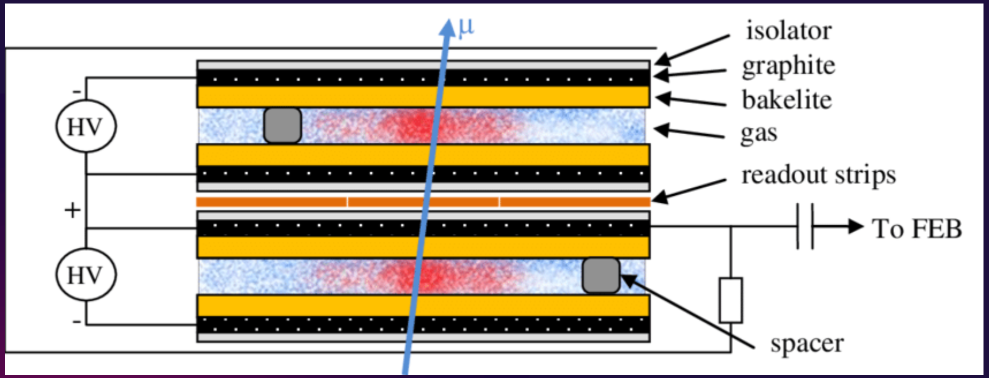
Gaseous Detectors: Resistive plate chambers



Two operation modes
- ➢ Streamer: ~100pC. Low rate capabilities (<100Hz/cm2)
- ➢ Proportional: ~pC. High rate (used at LHC experiments)

Fast detector, time resolution ~ns

Double gas gap RPC @ CMS

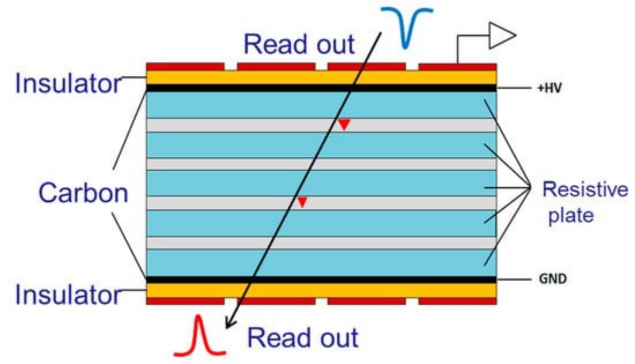


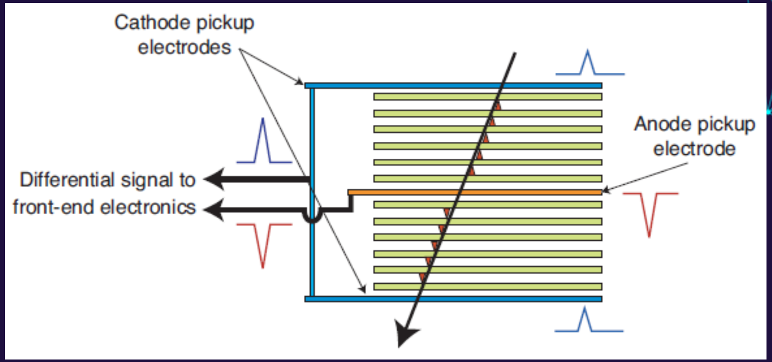
2 gaps with a common readout strip

Half HV for each gap, but same charge collected

Multi-gap RPCs

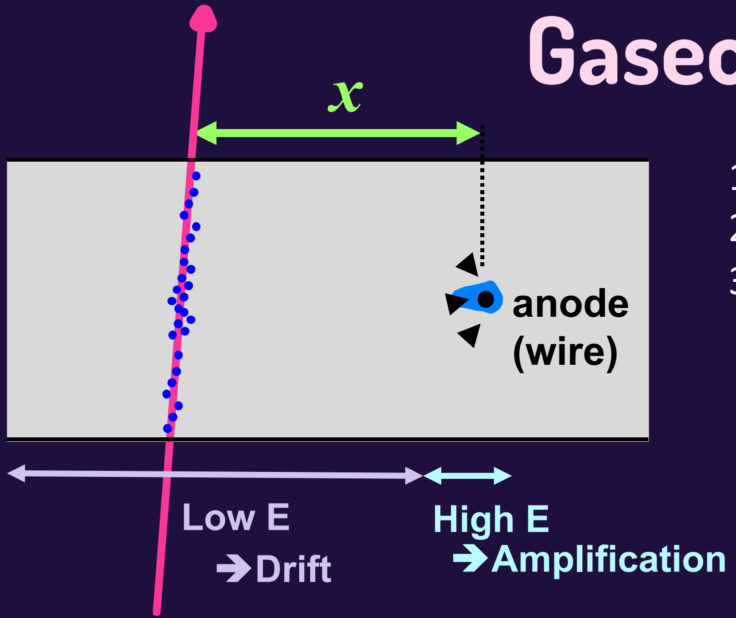
Different possible designs
Readout at the external or internal plane





Smaller gas gap → Higher E field →Faster drift velocity
Avalanche limited to a small space
Better time resolution (<100 ps) *Timing detector*
Several gas gaps to maintain the efficiency

Gaseous Detectors: Drift Chambers



1. The particle ionize the gas
2. The electrons/ions drift to the anode/cathode
3. Close to the anode E is very high given rise to an avalanche

The arrival time **t** is register using an external signal t_0 (trigger) , given usually by another detector

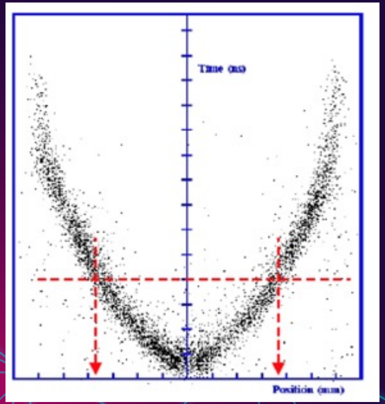
The position (x) of the particle is measured $x = \int v_D(t)dt$

v_D = Drift velocity (~50 microns/ns)

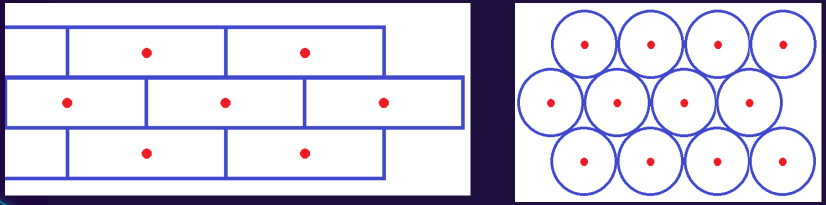
Lower number of channels with respect to MWPC and CSC

Design must optimize the homogeneity of v_D along the full volume

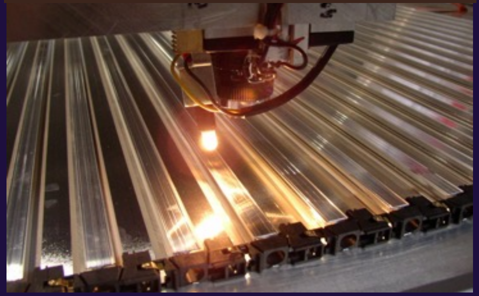
RIGHT – LEFT AMBIGUITY



Solution: Use of at least 3 staggered layers

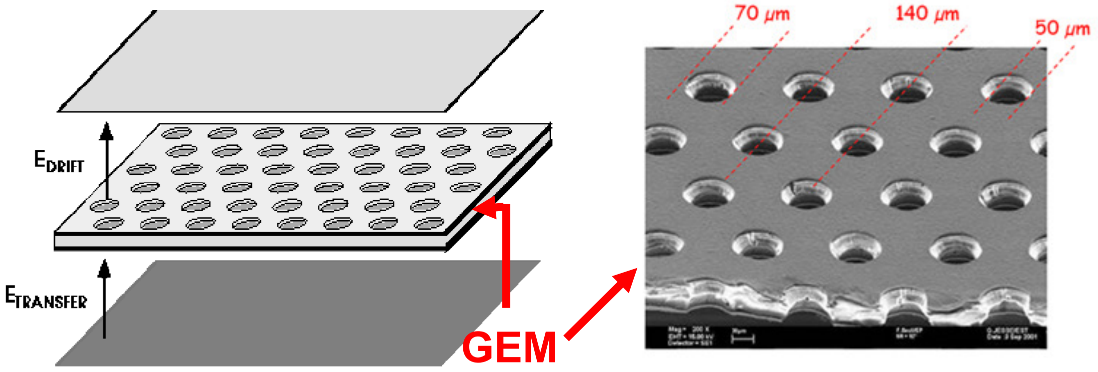


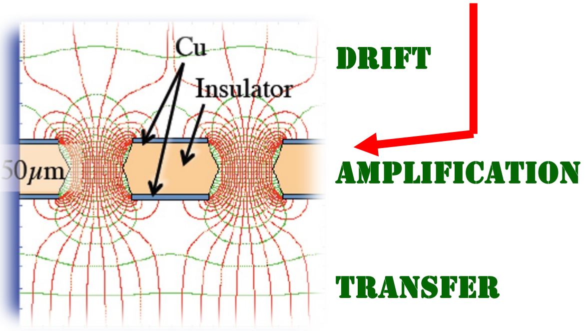
Layer of CMS DT during QC of wire possition



Micropattern Gaseous Detectors (MPGDs)

GAS ELECTRON MULTIPLIER





GEM foil

holes (~30-200 μm)

pitch ~50-300 μm

GEM foil metalized in both sides

High voltages applied on the two faces of the foil → High E ~100kV/cm

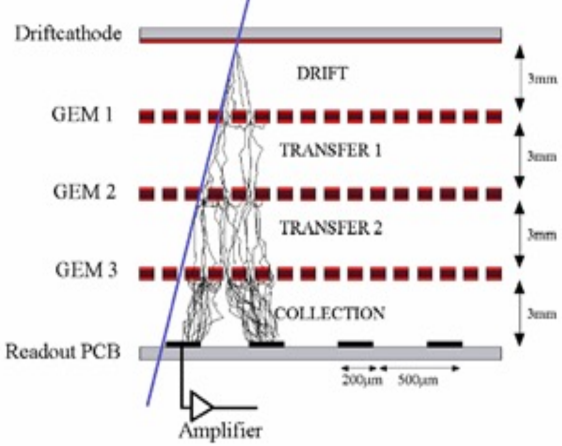
Amplification produced in the holes

Ions collected on the holes

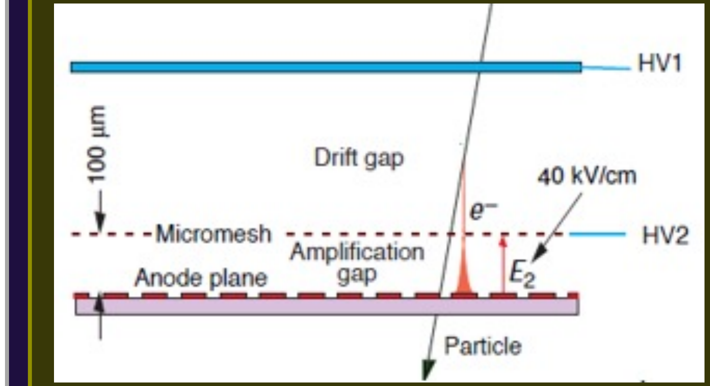
→ High rate capability ~MHz/mm^2

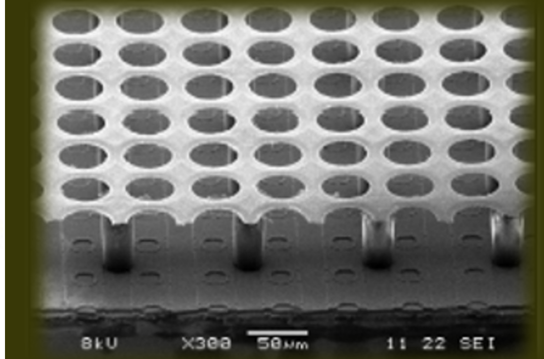
Electrons collected on the bottom using strips or pads

Multi-GEM



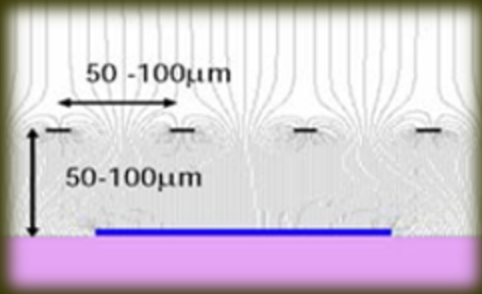
MICROMEGAS
MICROMesh GASeous structure





- A drift region few mm (~1kV/cm)
- A narrow multiplication region (25 -150 μm (50-70 kV/cm)

Between a metallic grid (micromesh) and readout electrode (pads/strips)



narrow multiplication region ➔ allow resolutions ~12 μm

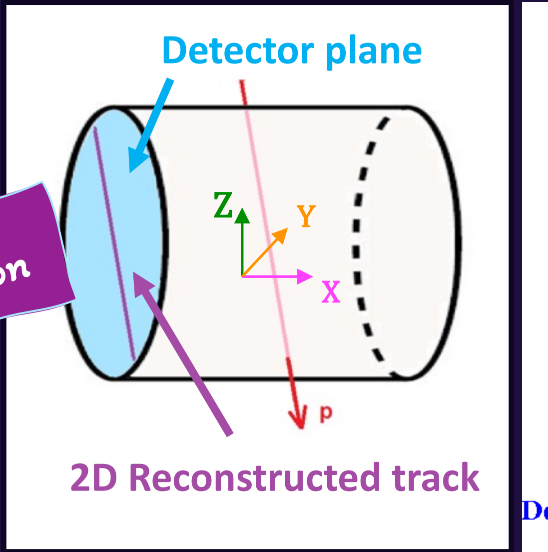
Gaseous/liquid Detectors: Time Projection Chamber - TPC

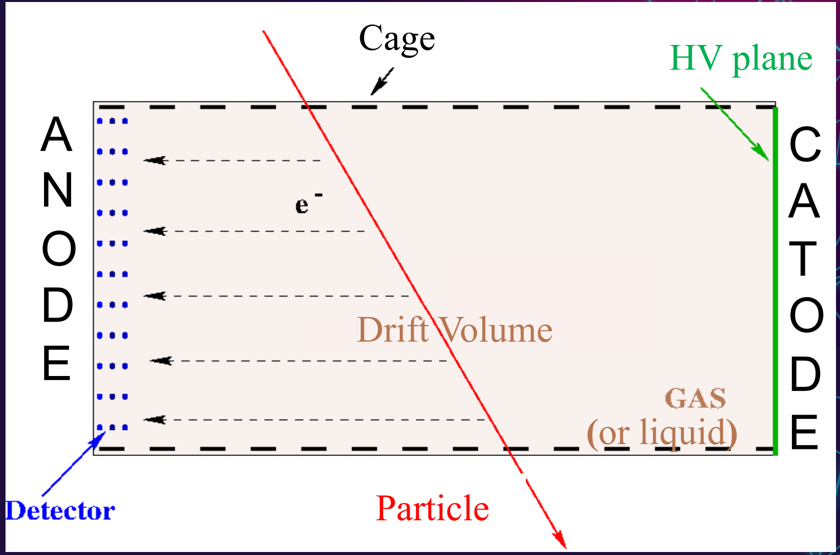
Similar príncipe as Drift Chambers
Very big cylinder (m) filled with gas (some times liquid)

The individual channels of the detector plane allow reconstruct the track in 2D (Y, Z in the sketch), and the arrival time the other coordinate (X)

3D Reconstruction

Allows dE/dx measurements
and, if a B field is applied, measure the momentum

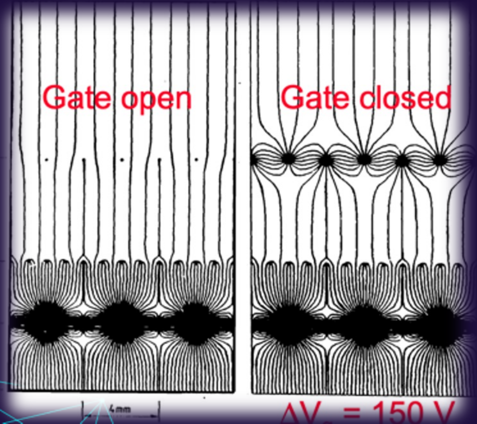


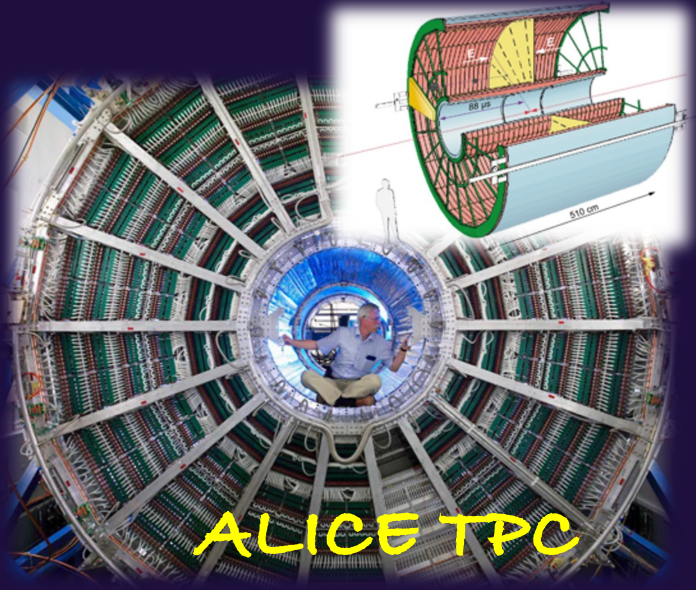


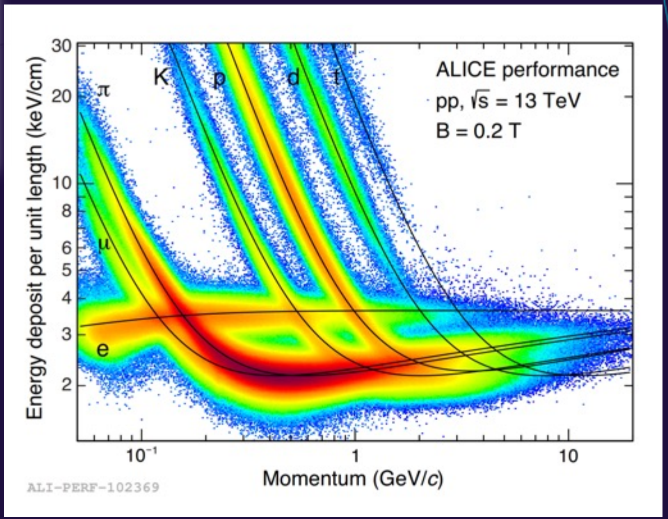
The first, and more common detectors plane used are the MWPC but can be used others as e.g GEM

Large drift volume
- E field and Vdrift must be very homogeneous
- Drift back (very slow) of ions from the avalanche can distort the field

➔ gating





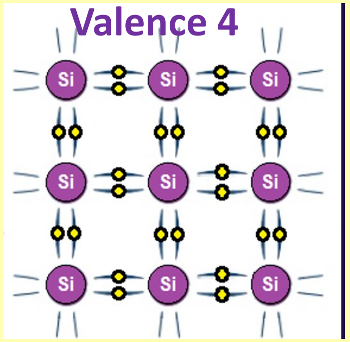


Solid State ionization detectors – Basic principles

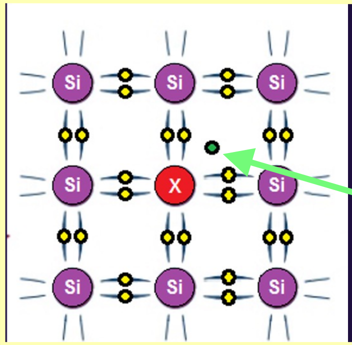
They use a semiconductor – Group IV (Si, Ge, diamante) doped (to increase the conductivity). Silicon is the most used(lower price)

T=0K

Silicon



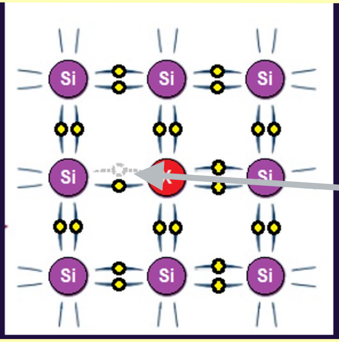
Dopped Silicon



X= Group V (Valence 5):
As, Pb, Sb (donor)

Excess of electrons

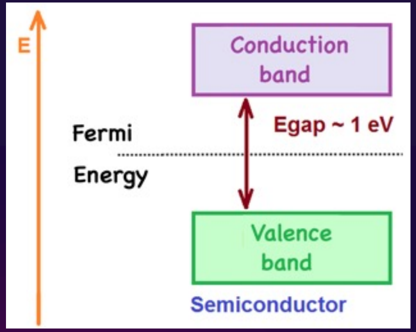
Semiconductor type-n

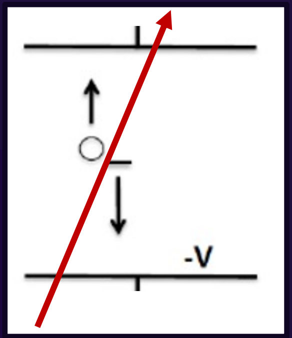


X= Group III (Valence 3):
B, Al, Ga, In (acceptor)

Excess of holes

Semiconductor type-p





The charged particle transfer energy to electrons and pass them from the valence band to the conduction band.

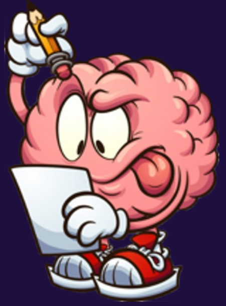
➔ Two charge carriers electrons and holes

By applying a E field (as in gaseous detectors) it can be detected

BUT When T>0 electrons can pass to the conduction band)
Those free electrons will also move due to the E field. ➔ NOISE

At room temperature the number of free electrons is orders of magnitude bigger than those produced by ionization

➔ PARTICLE CANNOT BE DETECTED

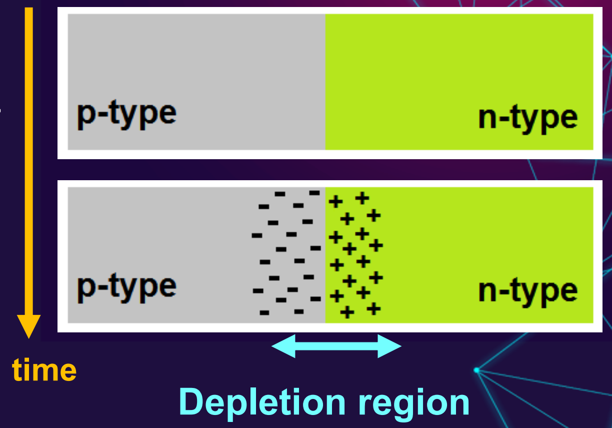


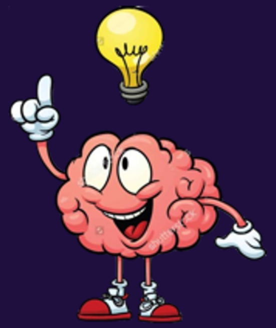
Solid State ionization detectors – Basic principles (II)

By putting together **a** **type-p semiconductor** (excess of holes) and other of **type-n** (excess of electrons) the difference of concentration of holes and electrons produces a diffusion from one material to the other

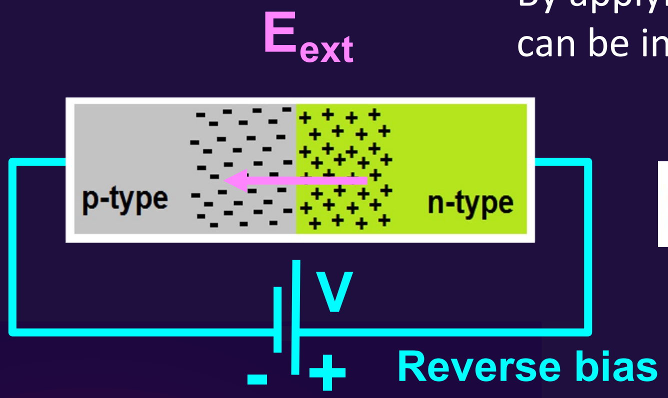
→ This creates an E field that will stop the diffusion.

→ A depletion region without free charges is created





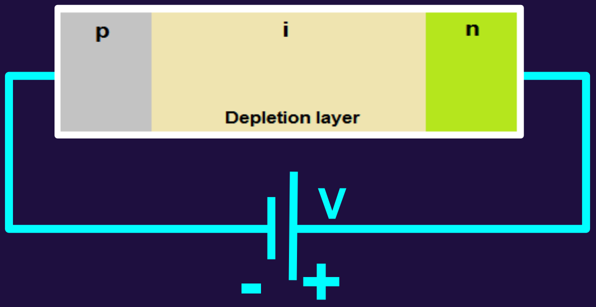
By applying an external voltage the depletion region width (W) can be increased



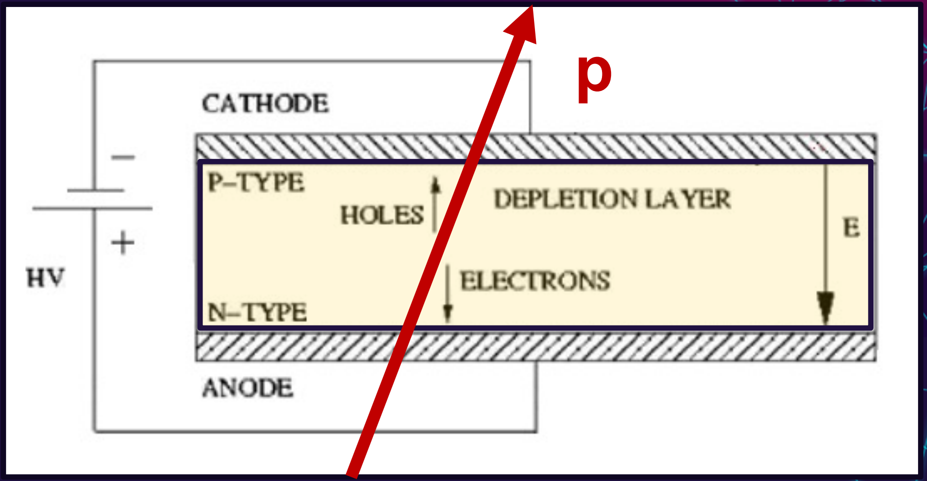
$$W = \sqrt{2\epsilon\,(V + V_{bi})/Ne}$$

ε= Dielectric constant
V = External applied voltage
V_{bi} = Voltage created by the p-n junction (~0.5V)
N = Dopant density

Same can be done by putting together 3 materials a p-i-n (i=intrinsic semiconductor – no dopped)



Solid State vs gas ionization detectors



Semiconductors have higher density and low ionization energy

$(dE/dx)_{\text{Silicon}} = 3.87$ MeV /cm

➔ $3.2\ 10^4$ e-h pairs en 300μm ~106 pairs/μm

versus ~100 pairs/cm in gas

3 orders of magnitude higher ➔ Amplification is not required

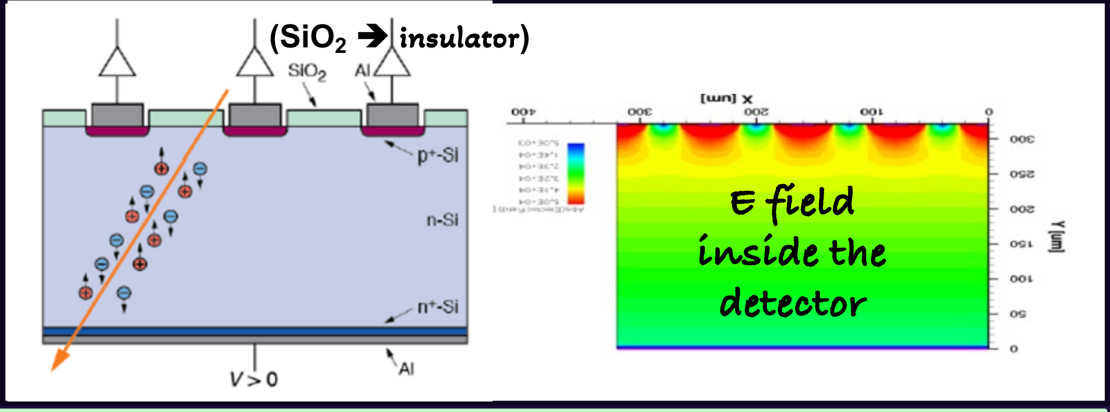
Silicon at 300K $4.35\ 10^8$ e-h free pairs en 300μm per 1x1 cm^2

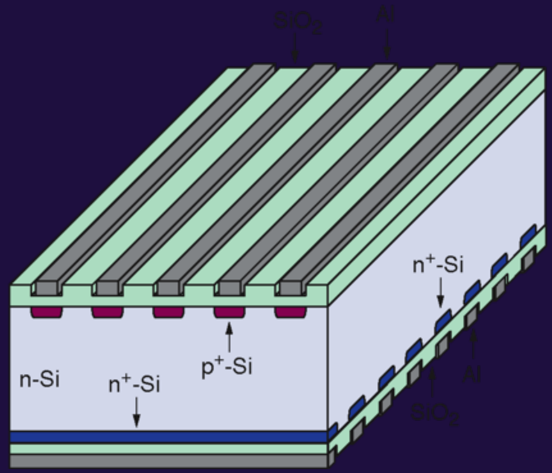
Depletion layer is mandatory

Drift velocity of holes is similar to electrons (compared with ions that is 1000 times slower)

Operation voltage <200 V
Thickness ~300mm.
Strip pitch 20-150mm

Microstrip Silicon detectors

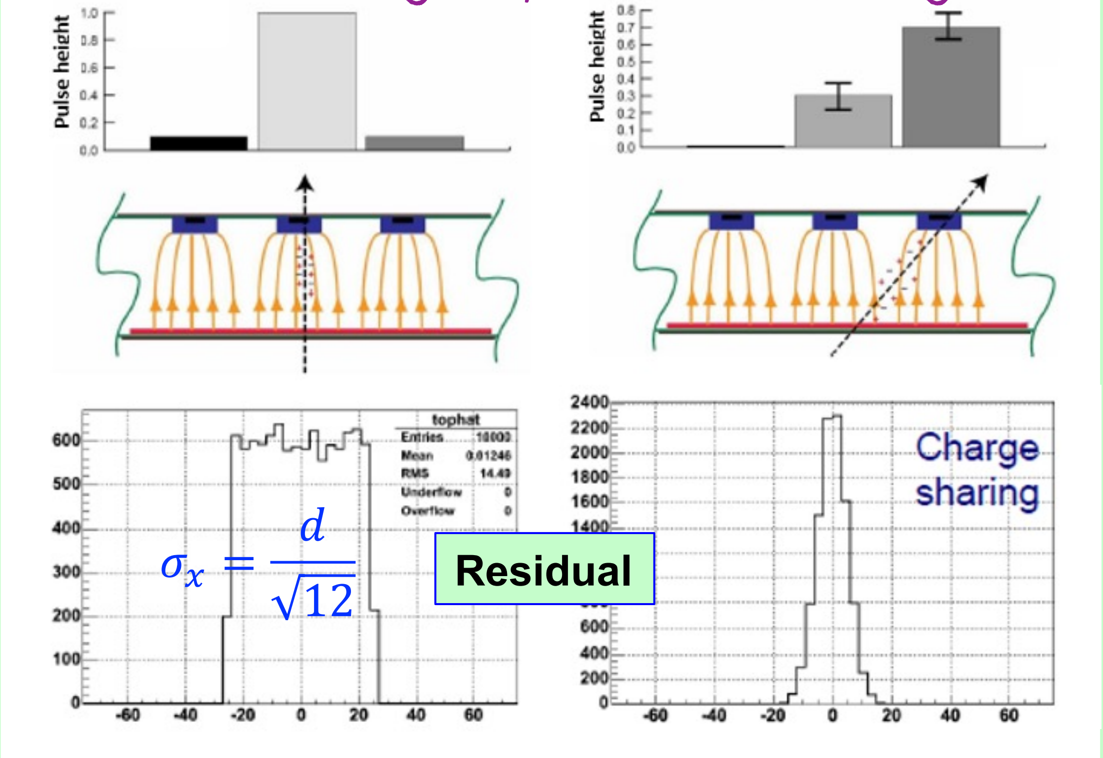




Double-sided microstrip detector

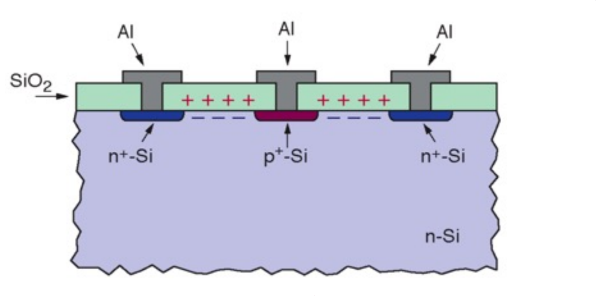
Static positive oxide charges at the Si-SiO2 interface, catch electrons and electrons form an accumulation layer underneath the oxide
→ strips interconnection

Position measured by computing charge gravity center

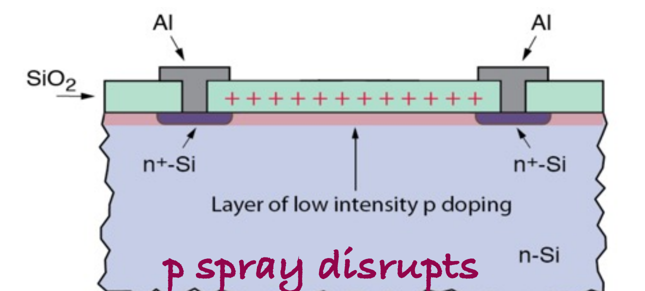


$$\sigma_x = \frac{d}{\sqrt{12}}$$

Several solutions adding new components

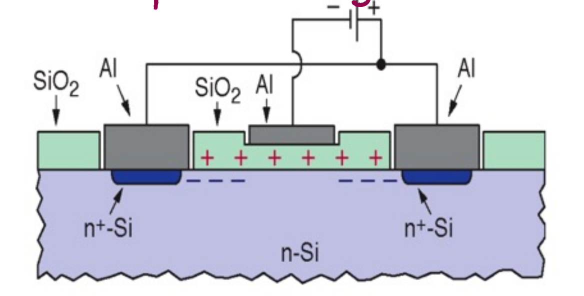


p+ stops, blocking electrodes

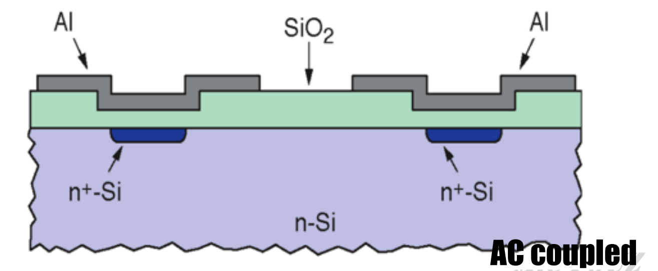


p spray disrupts e- accumulation layer

Field plate at negative V



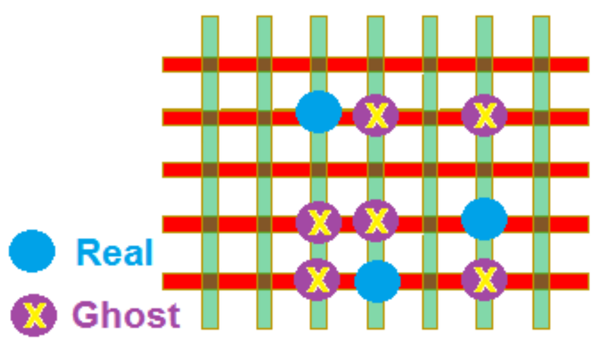
Al strips act as field plates



AC coupled

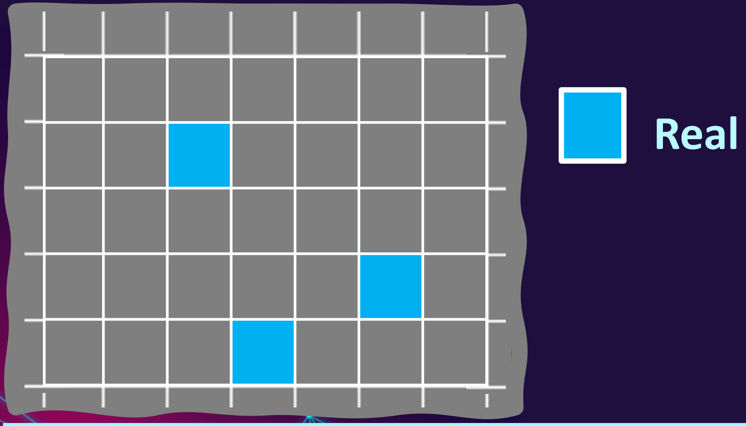
Pixel detectors

In case of simultaneous particle tracks double sided microstrips are non unambiguous



n particles → n^2 combinations
→ n^2-n false

Pixel detector produces unambiguous signals



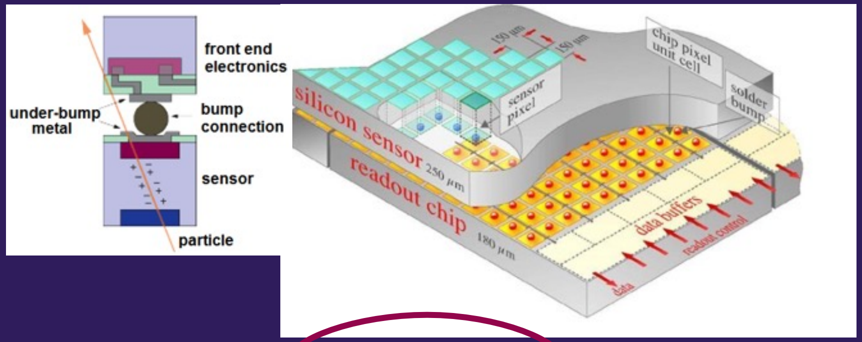
Large number of readout channels
Large power consumption of electronics

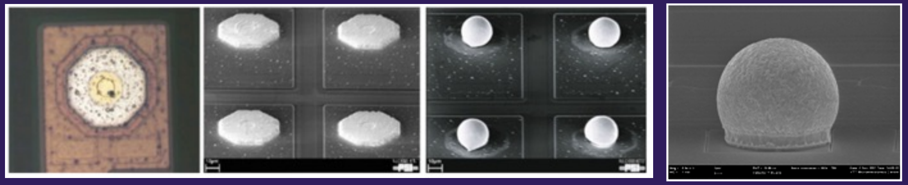
HYBRID PIXEL DETECTORS

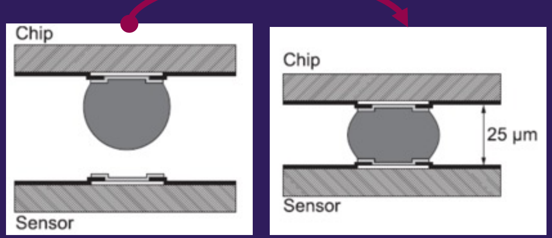
Planar and 3D sensors

Sensor and readout electronics in **two** separate chips

Connected by "bump bonding"







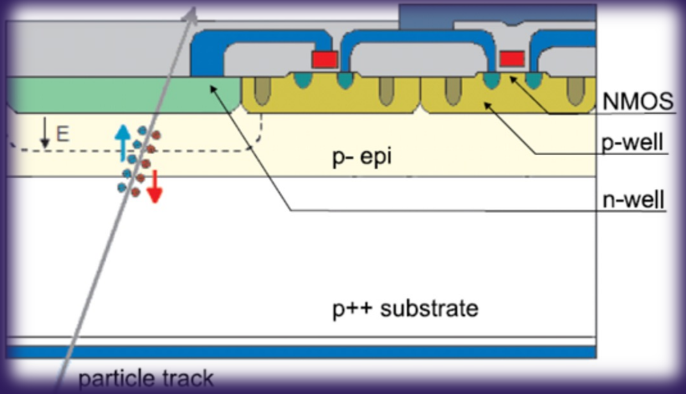
Large material budget and complex assembly

MONOLITHIC PIXEL DETECTORS

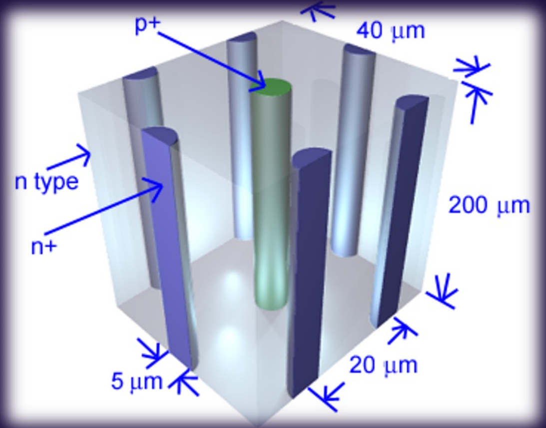
Sensor and readout electronics in the **same** chip

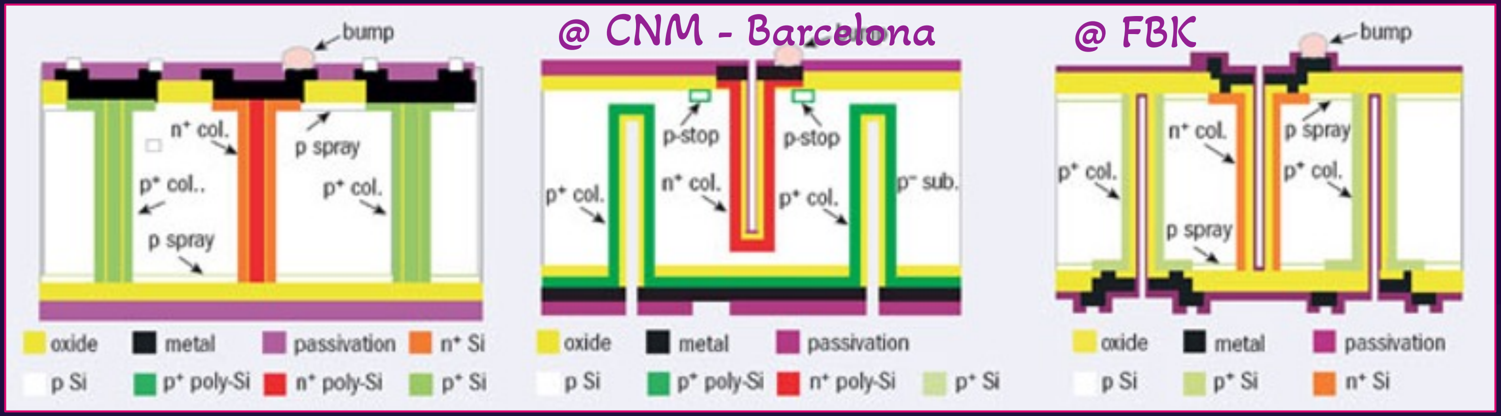
Many flavors

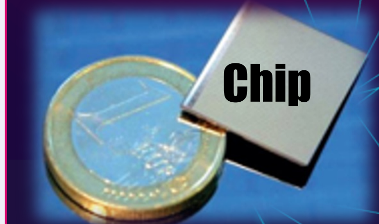
- *MAPS (Monolithic Active Pixel Sensor)*
- *DMAPS (Depleted Monolithic Active Pixel Sensor)*
- *SOI (Silicon On Insulator)*
- *DEPFET (Depleted p channel Field Efect Transistor)*
- *....*



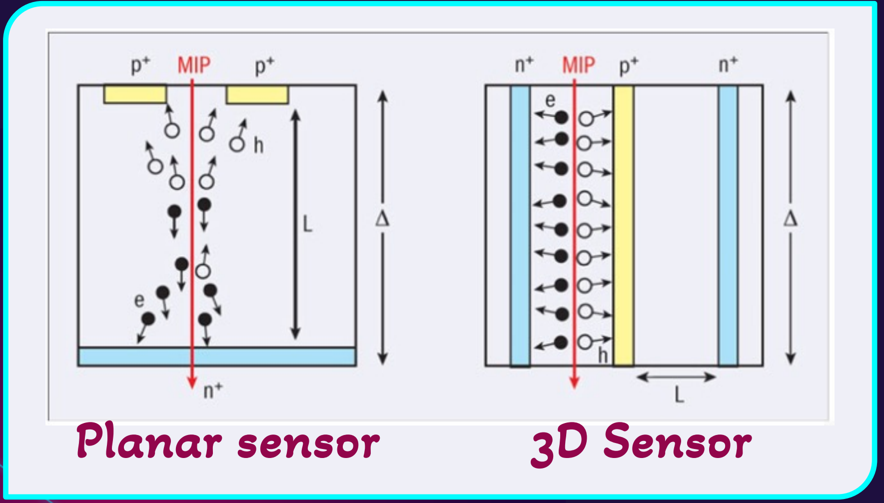
3D silicon detectors







(*) FBK: Fondazione Bruno Kessler, Trento Italy



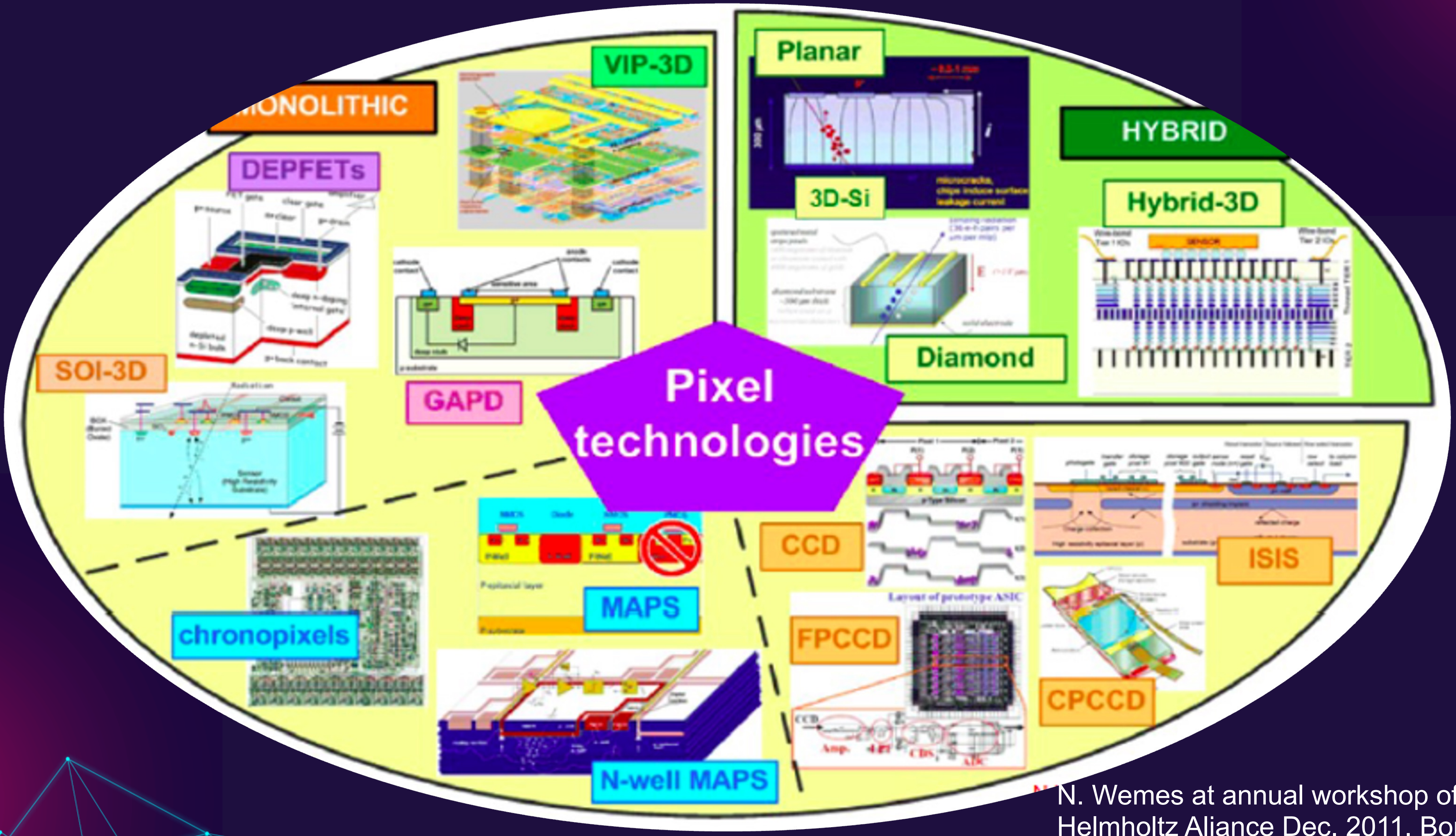
Deep holes are etched into the silicon bulk and filled with n+ and p+ material

Substrate thickness and distance between electrodes are independent

Lower voltage (<10-20V)
Faster charge collection
➔ Higher rate capability

The electrodes introduce dead spaces

Solid State pixel ionization detectors “zoo”

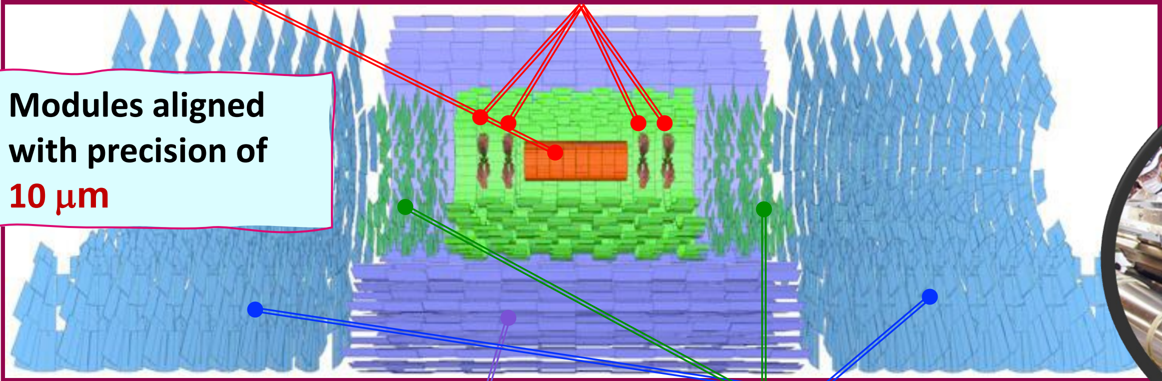


N. Wemes at annual workshop of the Helmholtz Aliance Dec. 2011. Bonn

Silicon Tracking detectors

CMS tracking

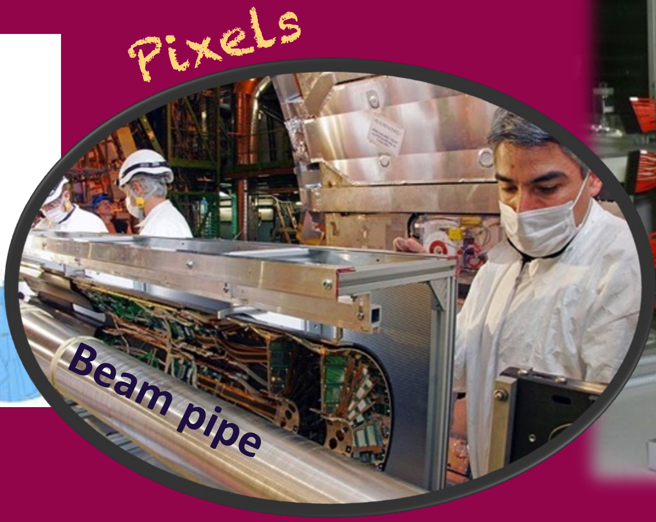
Pixel: 100 μm x 150 μm, 66x10^6 channels
3 layers in the barrel, 2 disks in each endcap

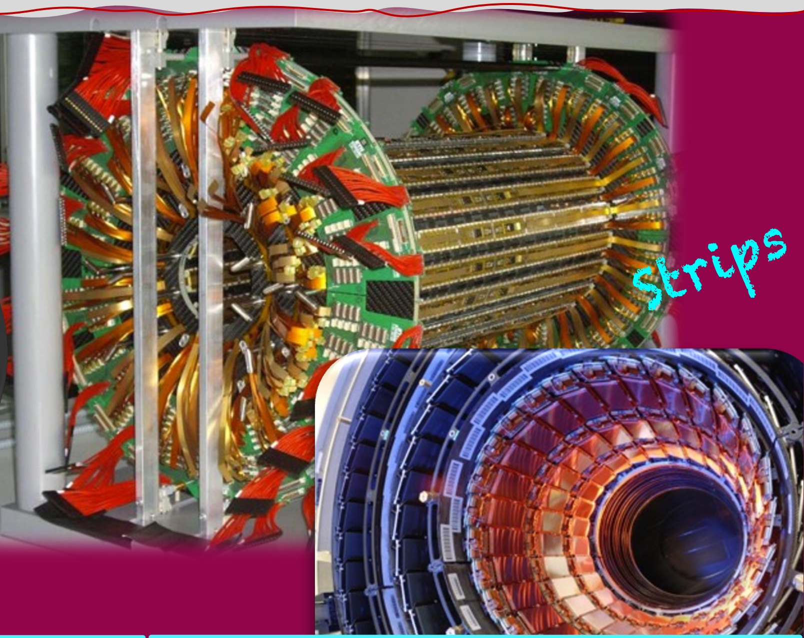


Modules aligned with precision of 10 μm

Strips: **10** layers barrel, 12 (**3**+**9**) endcaps
80-205 μm, 9.6x10^6 channels

First experiment with an inner tracking made 100% silicon detectors. Bigest up to now



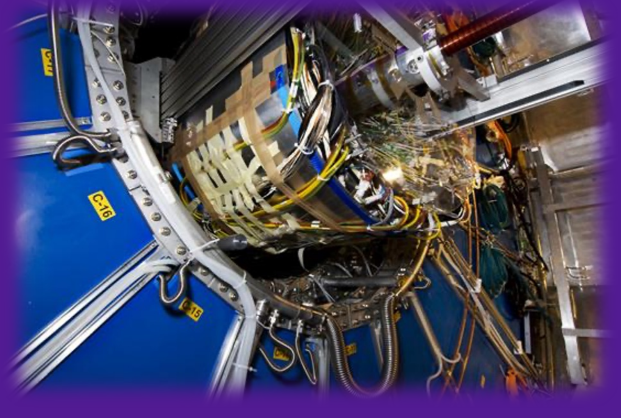


First LHCb Vertex Locator (VELO)

ATLAS pixel detector

ATLAS Insertable B-Layer (IBL)

ALICE pixel detector



LIGHT DETECTORS

- Scintillators
  - Organic
  - Inorganic
  - Gas/liquid Noble

- Cherenkov

Scintillator detectors – Basic principles and types

Charged particles can excite the atoms or molecules.
Some excited states can decay producing light
This light sometimes is re-absorbed sometimes not

The process of production of this light is different depending on the material type

Classification of scintillator detectors depending on the light production process

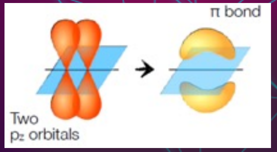
Organic e.g plastics
Inorganic e.g crystals
Gas/Liquid Noble (Ar, Xe…)

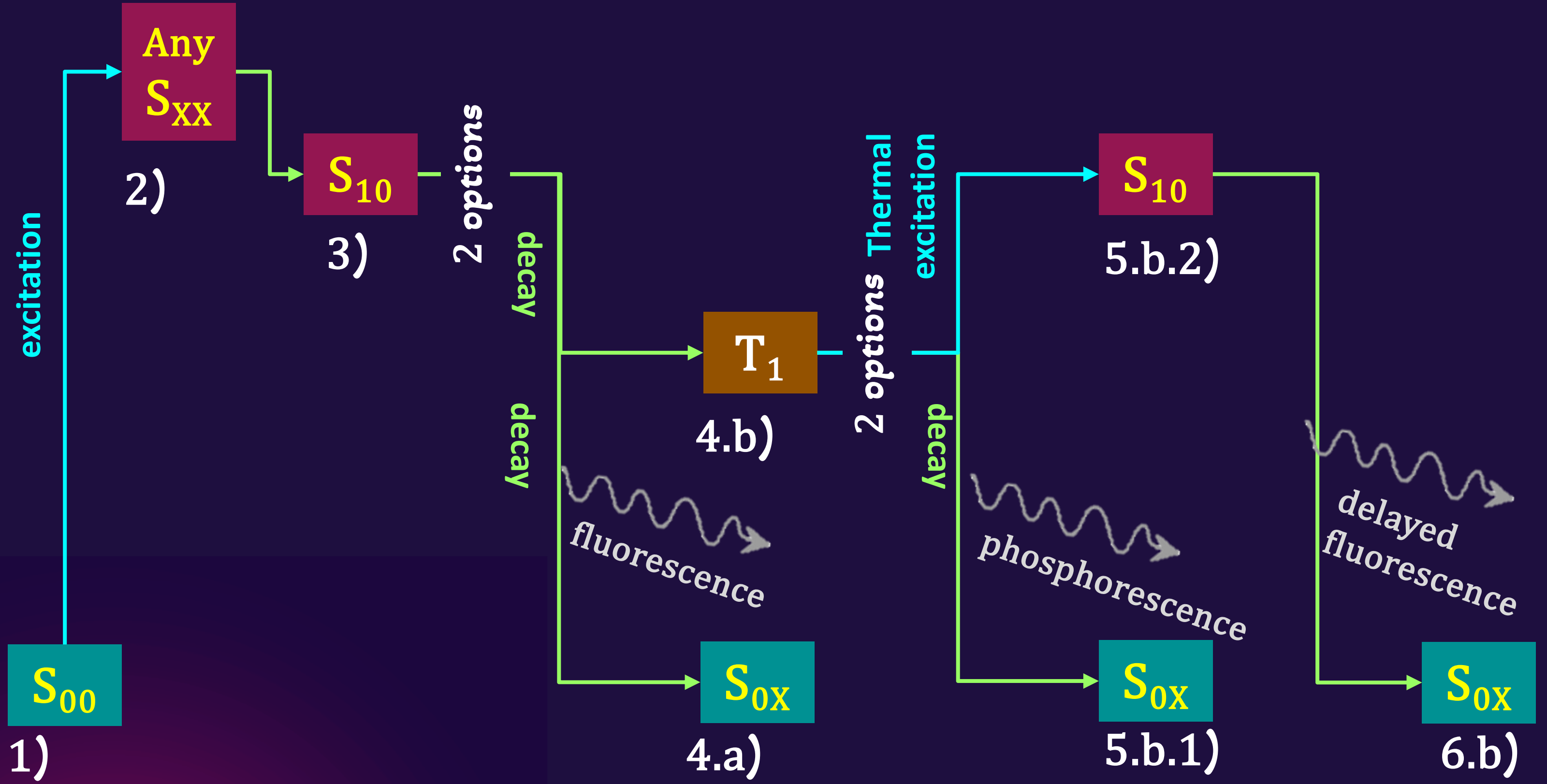
The produced light must be transformed in an electric signal
➔ A external photo detector is needed

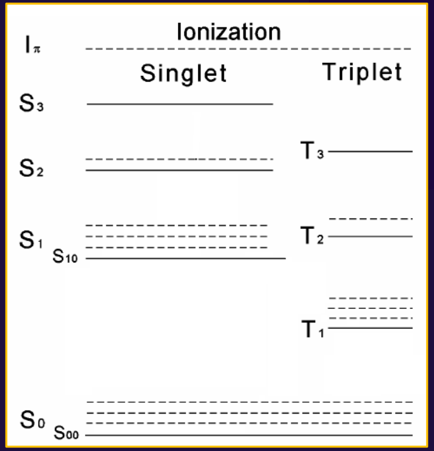
Organic scintillators – Basic principles

Light is produced in transitions in individual molecules. It is a molecular property
It can happens on solid, liquid and gas, or in molecules embedded in other material

The light is originated by electrons on π orbitals







Electronic states
- Singlets (spin 0)
- Triplets (spin 1)

Each is subdivided in several rotational states

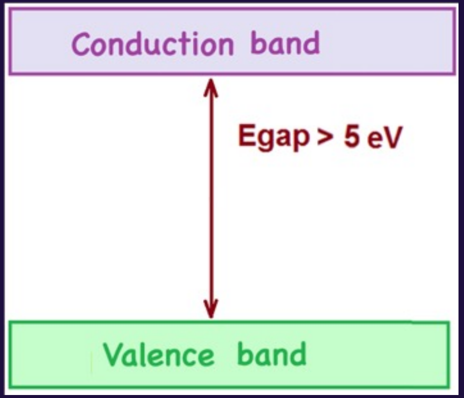
Phosphorescence
- arrives later 10^{-6} s vs 10^{-8} s
- Larger wave length (T_1 lower energy than S_{10})

In case of having different components, energy can be transferred to a different molecule
Adding small concentration of another scintillator material with higher efficiency (named "fluor") , energy is transferred to the fluor, fluor excites to S_{1x} and decay emitting light (fluorescence)

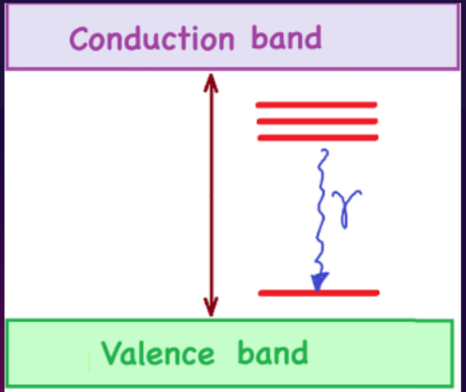
Fluor increases light yield because emit more light and with a larger wave length ➔ Energy cannot be reabsorbed by the solvent

A third component can be added to act as WLS (Wave Length Shifter)
Absorb light and emit in a different wave length more appropriate for photodetectors

Inorganic Scintillators



The energy levels are determined by the crystalline lattice. It is NOT a molecular process
The insulator gas gap is too large, inefficient emission of light and too large energy to emit around the visible range



It is needed to add impurities (activators) which in certain points of the crystalline lattice modify the energy band, creating energy states in the forbidden band from which the light emission is appropriate
This zones are called luminescence centers
Some materials have themselves variations on the lattice which act as activators

Sometimes the excited state cannot come back directly to the ground state, but can be thermally excited and decay after ==> phosphorescence

The electron can be also absorbed without further light emission => Quenching

Nobel gases (gaseous or liquid state) Ar, Xe, Kr

The atoms can be ionized or excited

The excited states can combinate with a an atom in ground state creating an excimer

$$X^{*} + X \rightarrow X_2^{*}$$

Excimers decay emitting light as for the organic scintillators

- Decay from single state is faster (~6ns en Ar)
- Decay from triplet state μs

The produced light cannot be reabsorbed by the atoms

Organic vs inorganic scintillators

ORGANICS

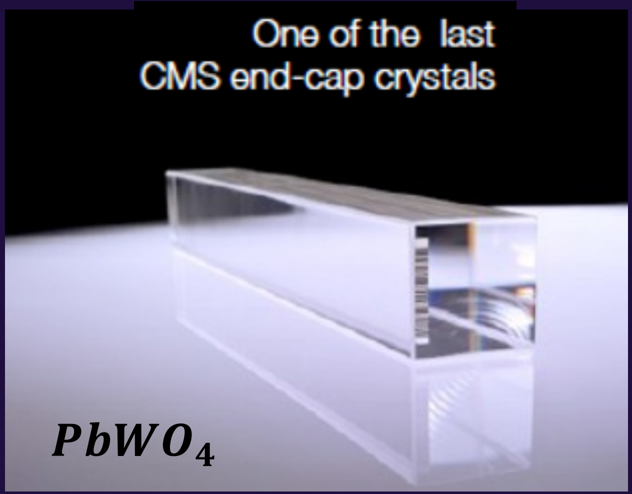
Lower signal
Fast (<ns)
Low density
Independent of T (between -20^0C and 60^0C)
Cheaper
Easier manufacturing on different sizes and shapes

INORGANICS

High signal
Slower (till μs)
High Density
Dependence on T
Expensive
Difficult manufacturing (crystal growing)

Inorganics are used in calorimeters due to its high density
Are slower but produce much light ➔ better energy resolution


Plastic Scintillator BC412


One of the last CMS end-cap crystals

$PbWO_4$

Cherenkov Detectors – basic principles

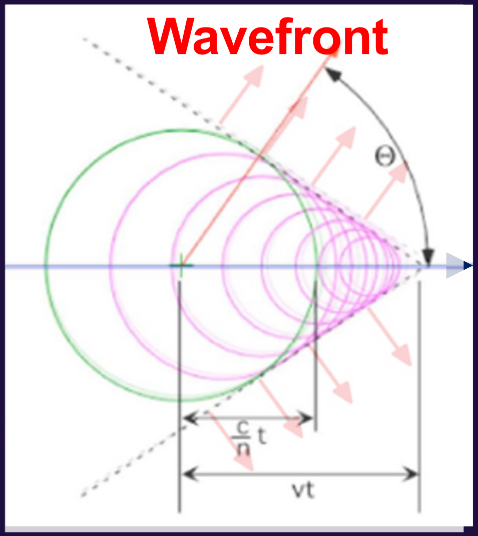
Cherenkov light happens when a charged particle travel faster than light in a material

The E field given off by the particle is propagated by photons, the photons are non canceled and light is produced

Light is emitted with and angle (θ) which depends on particle velocity and the medium refractive index (n)

Very small energy loss (<1%)

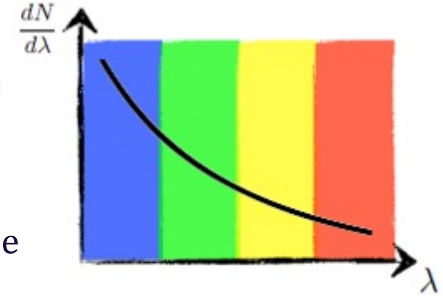
$$\cos\theta = \frac{1}{n\beta}$$



Particle velocity can be computed by measuring the light angle and the particle trajectory

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta$$

λ = wavelength
z = charge of particle



Number of photons *increases with* ***charge of particle***

UV light dominates

Cherenkov detectors are used for

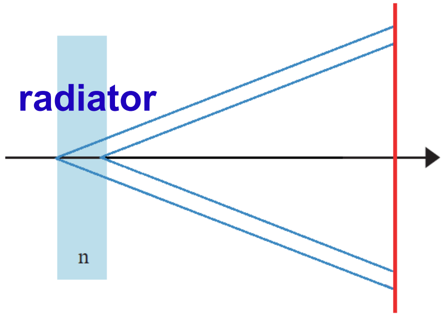
- *Particle identification*
  - Threshold çherenkov counters.
    Select particles above a certain threshold on number of detected photons
  - Imaging Cherenkov
- *Energy measurement*

Ring Cherenkov detectors

The Cherenkov light is emitted in a cone.
Looking the light in the perpendicular plane to the particle direction:

- Light emitted in a time **t** will form a **circumference**
- Light emitted in a time **t+δ** will form another **circumference** with smaller radius

The space between both circumferences defines a ring



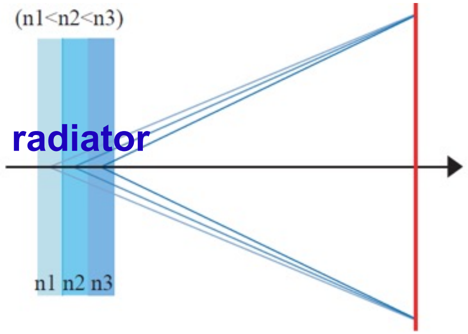
If the light is produced in a thin medium (radiator) a ring is produced

Resolution is given by the ring thickness
Thickness depends on the medium

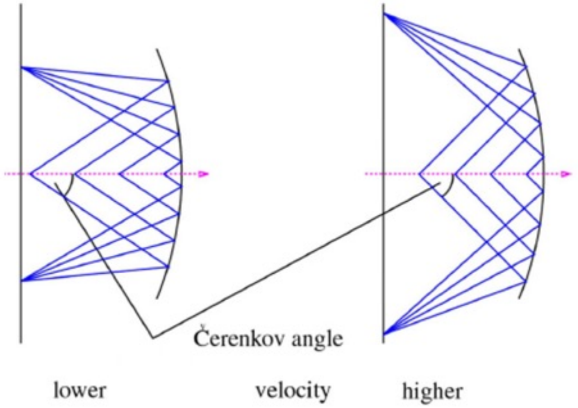
Using a radiator made with different refractive index:

Increase the light (more thickness) without degrading the resolution

Proximity focusing RICH

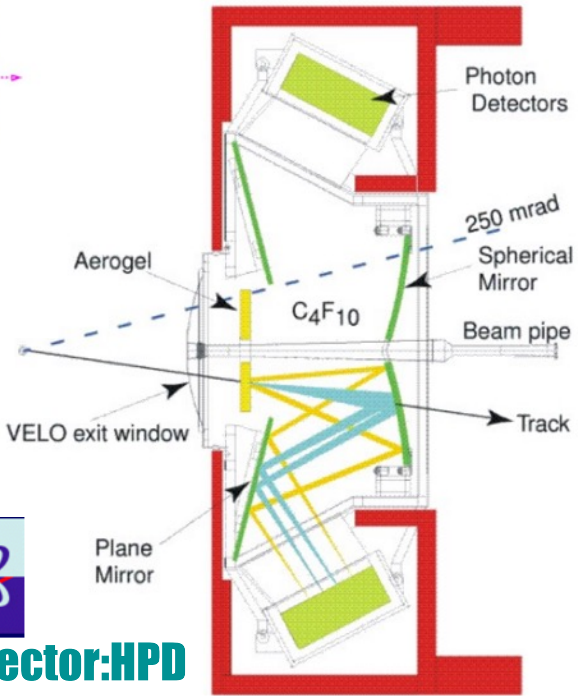


Aerogel (Si_xO_y) allows regulate n between 1.01 y 1.13



An mirror can be also used for focusing the light

Focusing RICH



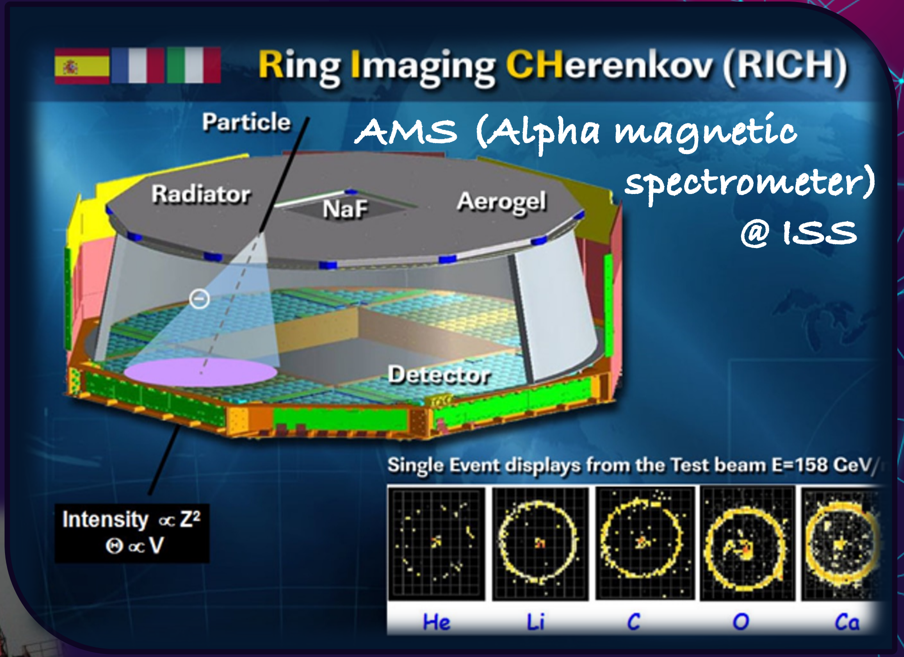
LHCb

Fotodetector:HPD

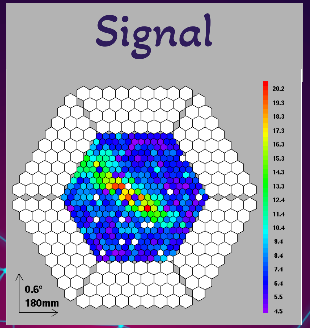
Cherenkov Detectors – Some applications

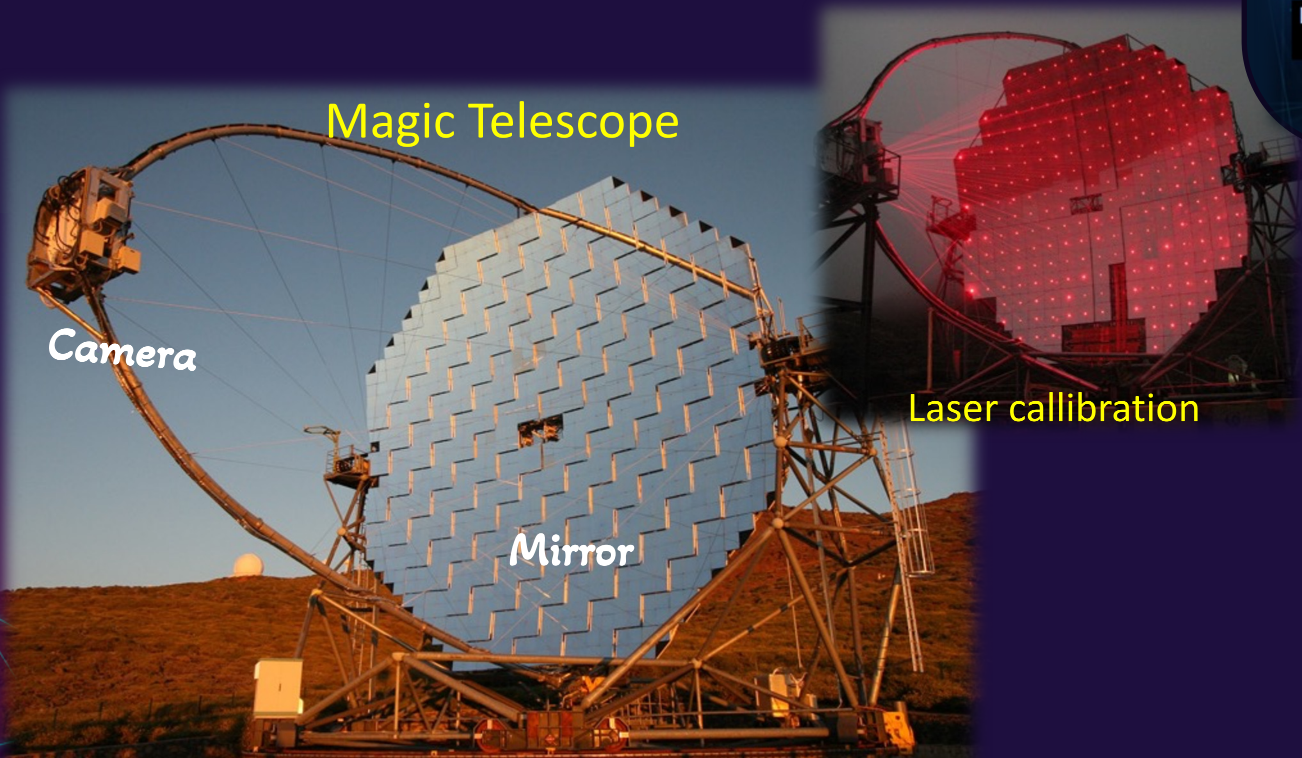
Used in many type of experiments as e.g

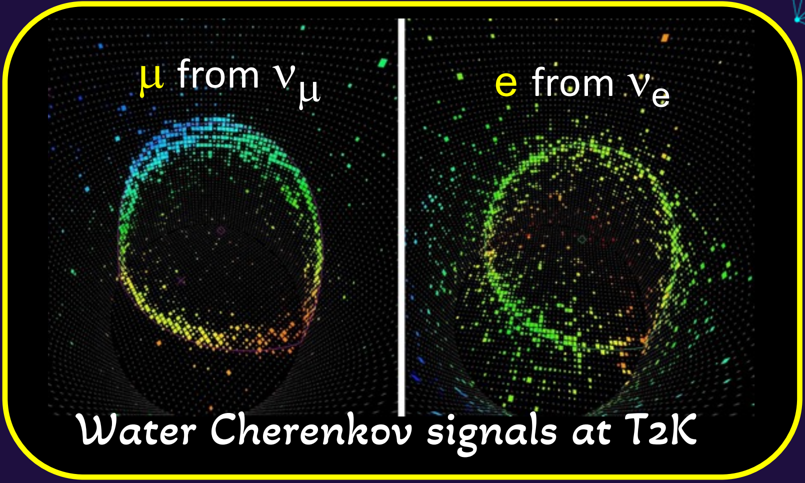
- Neutrino using water Cherenkov (IceCube, T2K, Super-K , JUNO)
- High energetic gamma rays & Dark matter with water Cherenkov detector as (HAWC - Water Cherenkov Observatory at Puebla-México) or Cherenkov telescopes (as MAGIC and CTA in Spain)
- Antimatter & dark matter AMS experiment using a RICH
- Calorimeters (as CMS forward calorimeter with quartz fibers)



AMS (Alpha magnetic spectrometer) @ ISS

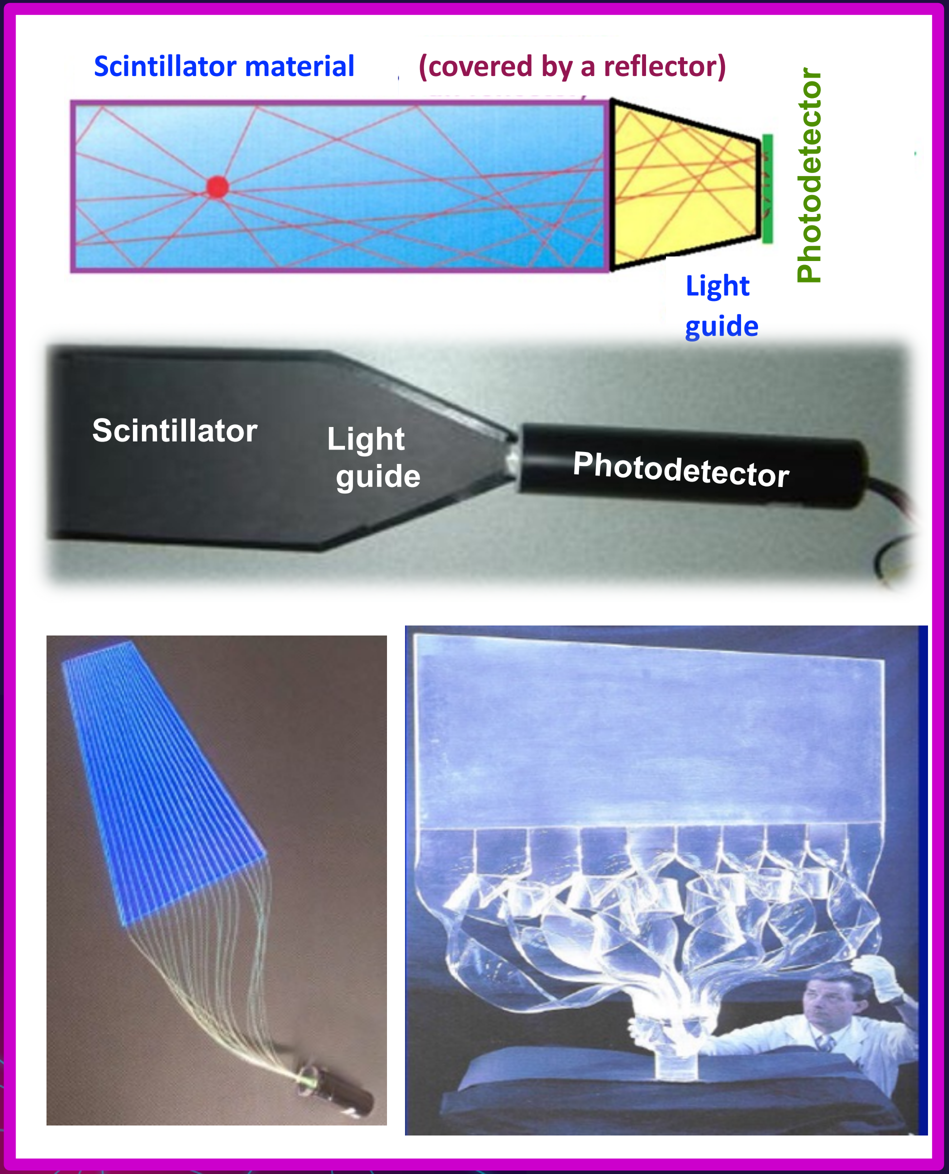






Water Cherenkov signals at T2K

Readout of scintillator and cherenkov detectors

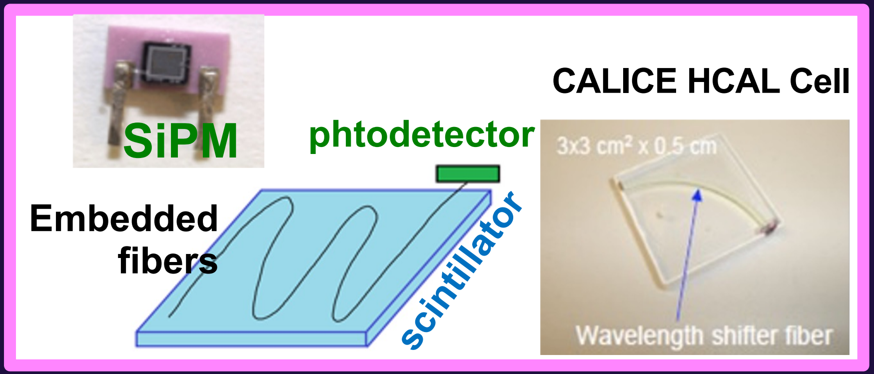


The light must be converted in an electrical signal.

A photodetector is used to convert light to electrical signal
The light must be guide to the photodetector

By using scintillator or quartz (Cherenkov light) fibers, the signal is produced on the fiber and the fiber itself guide the light to the photodetector

Wave Length Shifter fibers absorbs the light and emit it again in a different wave length

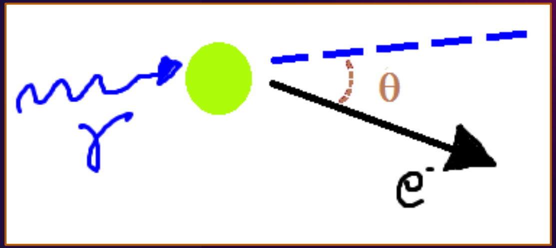


PHOTODETECTORS

Photomultiplier tubes
Solid state photodetectors
Hybrids

Photodetectors – Conversion photons to electrons

The first step is to convert the photon in an **electron**.



This is achieved by the **photoelectric effect**

$$E_e = h\nu_0 - E_b$$

E_b = binding energy (or work function) of the electron to the particular material.

Material must be thin enough to allow electrons to arrive to the surface

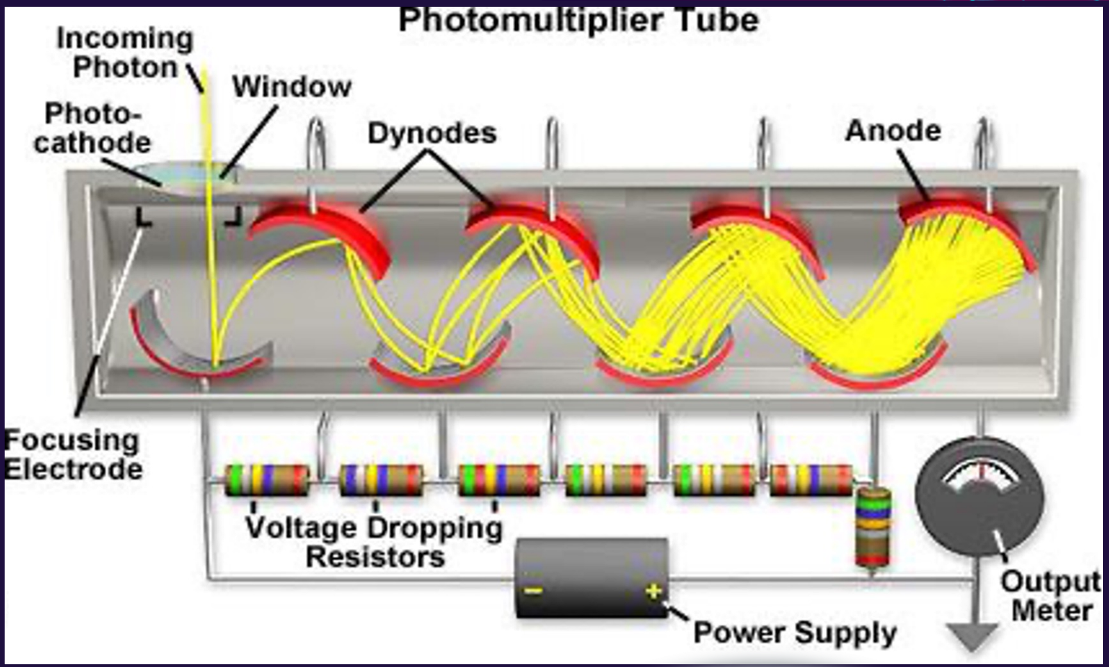
QE (Quantum Efficiency)

$$QE = \frac{Ne^{-}emitted}{N\gamma}$$

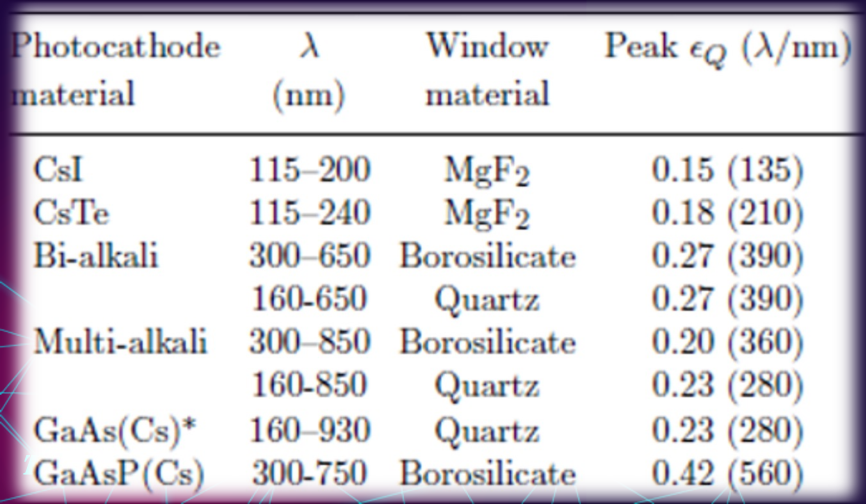
Photomultiplier Tubes (PMT)

1934 Harly Iams & Bernand Salzberg (RCA)

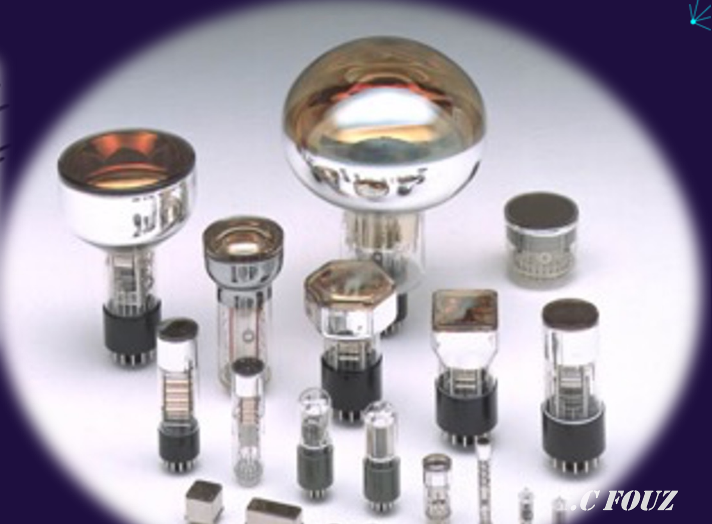
1. Photon is converted in an electron on the photocathode
2. Once the electron enters on the vacuum tube will be accelerated by the E field and will travel to the electrode (dynode)
3. The electron will produce secondary electrons on the dynode
4. All the electrons will travel to the next dynode producing new electrons and so on ➔ Avalanche process
5. The last dynode is an anode where electrons are collected and a signal will be produced



PMTs are affected by Bfield, including sometimes the earth´s magnetic field (could need mu-metal shielding).
PMTs cannot work inside a magnet



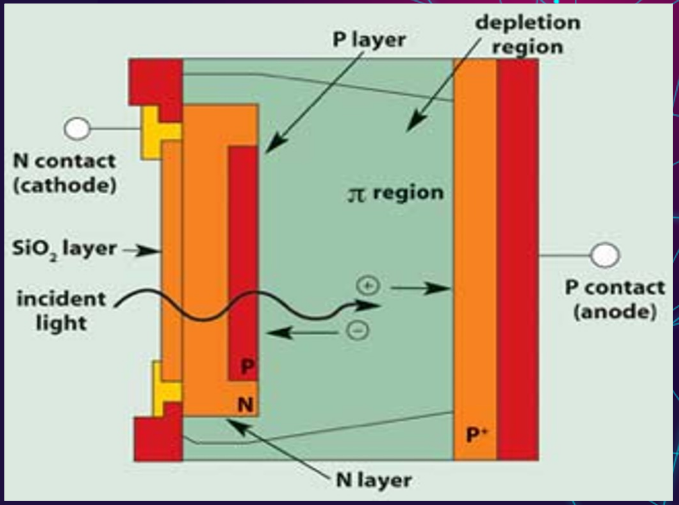
Photocathode material	λ (nm)	Window material	Peak ϵ_Q (λ/nm)
CsI	115–200	MgF_2	0.15 (135)
CsTe	115–240	MgF_2	0.18 (210)
Bi-alkali	300–650	Borosilicate	0.27 (390)
	160-650	Quartz	0.27 (390)
Multi-alkali	300–850	Borosilicate	0.20 (360)
	160-850	Quartz	0.23 (280)
GaAs(Cs)*	160–930	Quartz	0.23 (280)
GaAsP(Cs)	300-750	Borosilicate	0.42 (560)



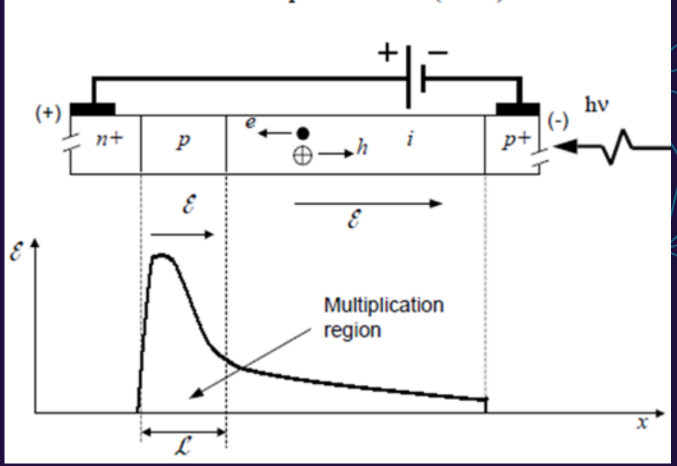
Solid state photodetectors

APD – Avalanche PhotoDiode

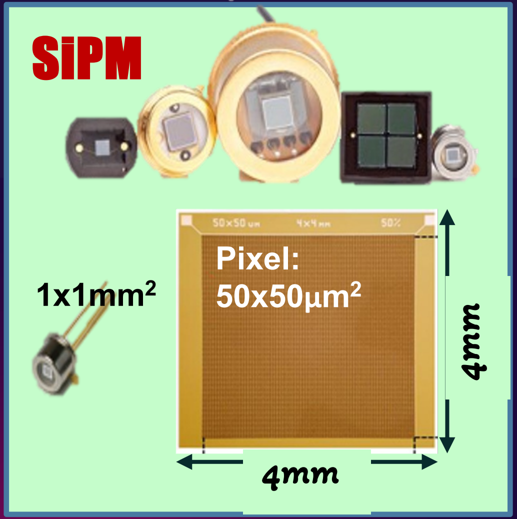
This detector use a high voltage which produce an electron avalanche
It has an extra layer of type p between the depletion region and and n+
Amplification happens between p-n+



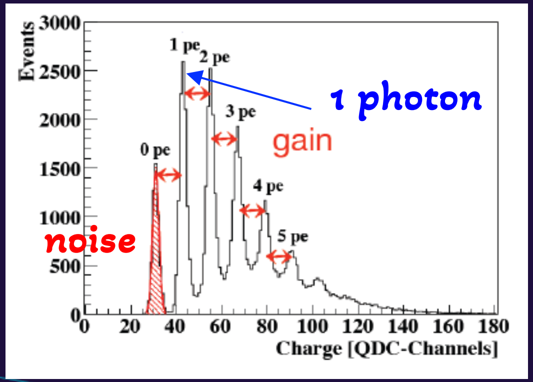
Avalanche photodiodes (APD)



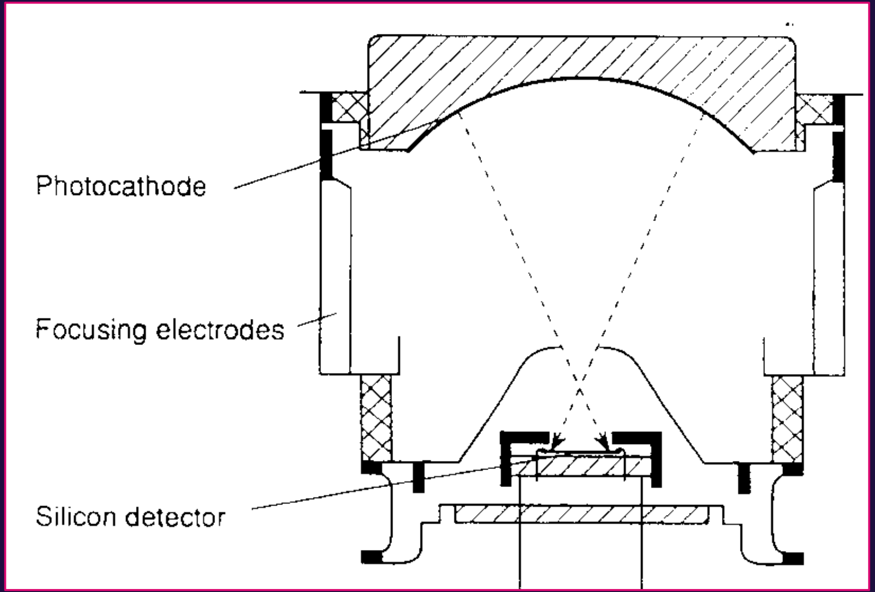
SiPM – Silicon PhotoDiode



It is and array of APD cells (~1000 pixels/mm^2) operating in Geiger-mode
Single photon device
Small pixels-> no more than 1 photon per pixel
Adding number of pixels with signal = total number of photons



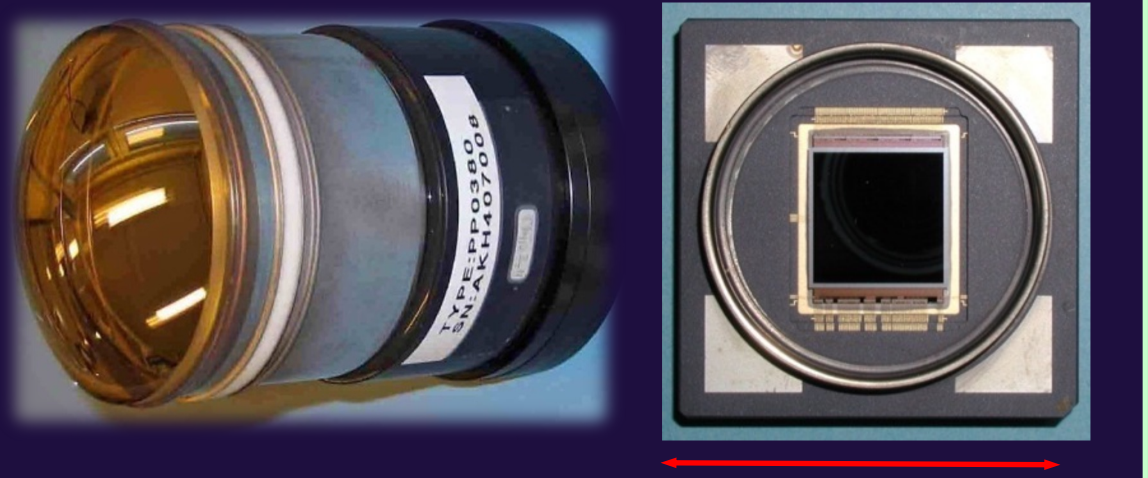
Hybrid Photodetectors - HPD



Take advantage of the excellent space and energy resolution of silicon detectors

1. Photons produce electrons in the photocathode
2. Electrons are accelerated on the vacuum tube (ΔV ~20-20kV) and focused towards the detector
3. Multiplication is produced in a single step at the silicon detector (less fluctuations than in PMTs)

Pixel-HPD anode



8192 pixels of 50 × 400 μm.

10-inch prototype HPD (CERN) for Air Shower Telescope CLUE.

Summary of detectors tecnologies

Ionization detectors

Gaseous

Liquids

Semiconductors

Detect the ionization electrons produced by a charge particle by applying an electric field wich forces them to travel to the anode. The induced difference of voltage can be "seen" as an **electric signal**, coupling a capacitor and a resistance (real implementations is more complex)

Photodetectors

Photomultiplier tubes

Semiconductors

Hibrids

Convert photons in electrons by the photoelectric effect producing an **electric signal**
They are use to produce the signal of scintillators/Cherenkov detectors. They **ARE NOT USED** to detect photons produced in a collider

Light detectors

Scintillator light

Organics (e.g. plastics)

Inorganics (e.g. crystals)

Gases/liquids nobles (Ar, Xe…)

Organics: Single molecules are excited on π orbitals, light is produced when decay to the ground state (S_{00})

Inorganics: In a material electrons are excited to the conduction band emitting ligt coming back to the valence band.

Gases/liquids nobles: The excited **atomos** combine with the non excited forming **excimers** which come back to the ground state as the organics

Cherenkov light

Light is produced by a charged particle when its velocity is bigger than the light velocity in that material. (Depends on the refractive index of the material

They need to be coupled to a *photodetector* to produce an electric signal

CALORIMETERS

Electromagnetic

Hadronic

Calorimetry Principles

Destructive process

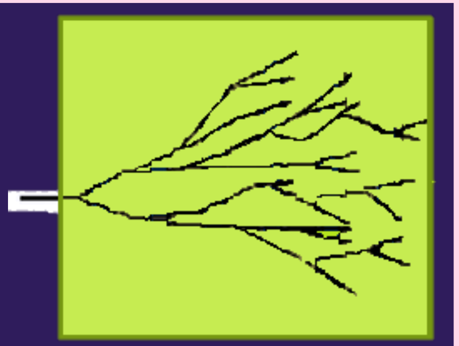
A calorimeter is a detector made of a high-density material in which most of particles can lost their energy by interacting with the matter through different processes generating a particle shower.

The signal measuring the energy can be produced and recorded either on the high-density material either using detectors interleaved with the dense material

Detects **charged** and **neutral** particles

Homogeneous calorimeter

It uses **a high-density material** where the shower is generated **and produces the signal**



Some typical materials

BGO, PbWO… → Scintillation
Lead Glass → Cherenkov light

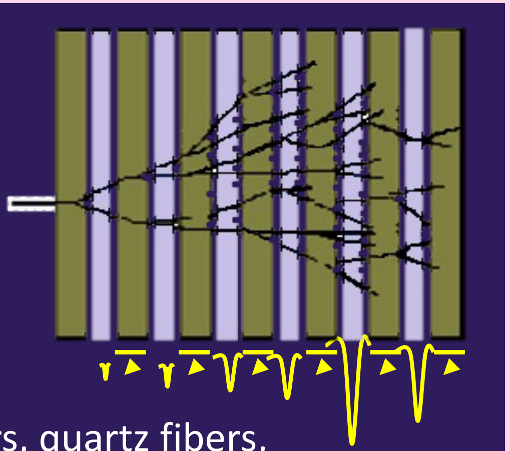
Advantages: Best energy resolution

Disadvantages: Expensive

Used only for electromagnetic calorimeters

Sampling calorimeter

It alternates **layers of high-densitity material (passive absorber)** where the shower is generated **and detectors (active planes) to produce the signal**



Typical absorbers Fe, Pb, U

Typical detectors

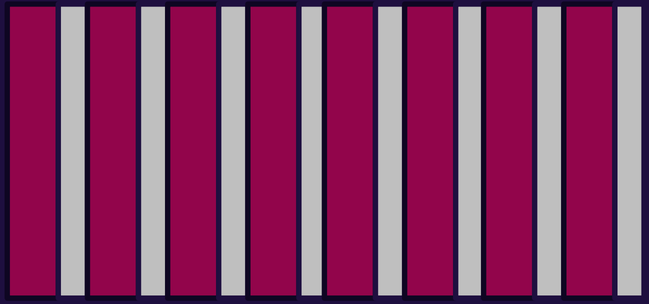
Gaseous detectors, plastic scintillators, quartz fibers, silicon detectors noble liquid ionization chambers…

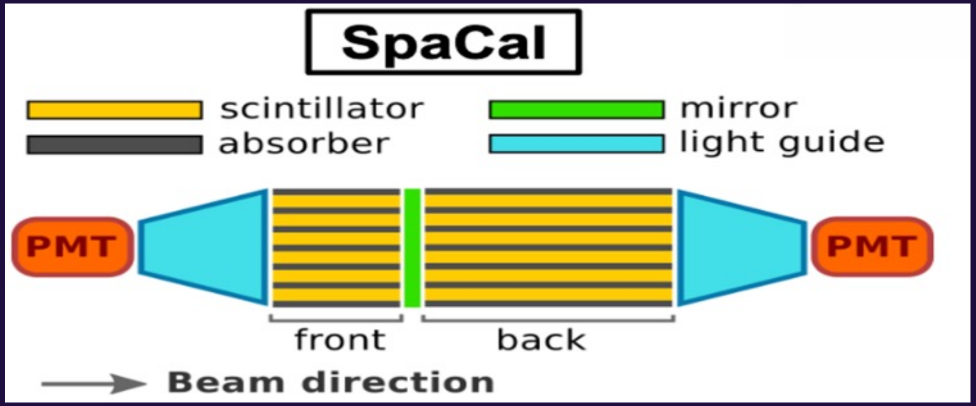
Advantages: Cheap absorber
Optimization of absorber/sensor
Compactness

Disadvantages: Worse energy resolution due to lower energy deposition and sampling fluctuations

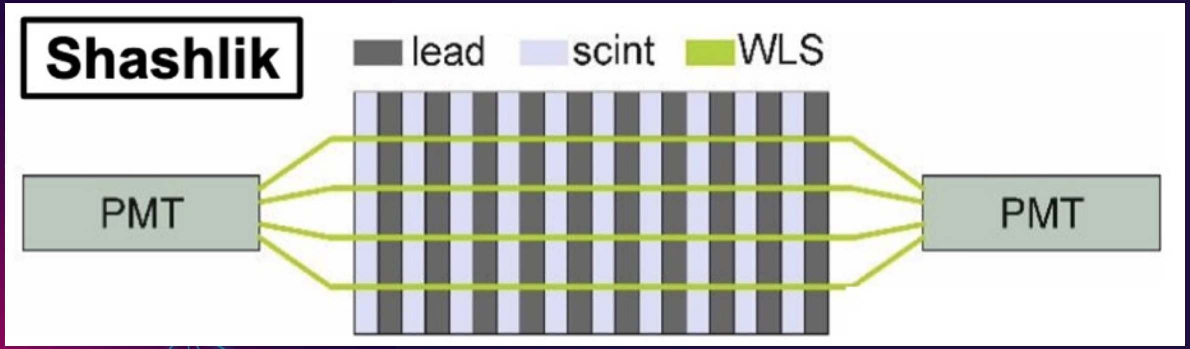
Sampling calorimeter geometries

Sandwich





Scintillating fibers inserted in a dense absorber
They convert deposited energy in light and transport it to the photodetectors



The conversion in light is done in another material and the fibers only transport it to the photodetectors

Processes involved on the lost of energy on calorimeters

Different particles ➔ Different interactions in the calorimeters

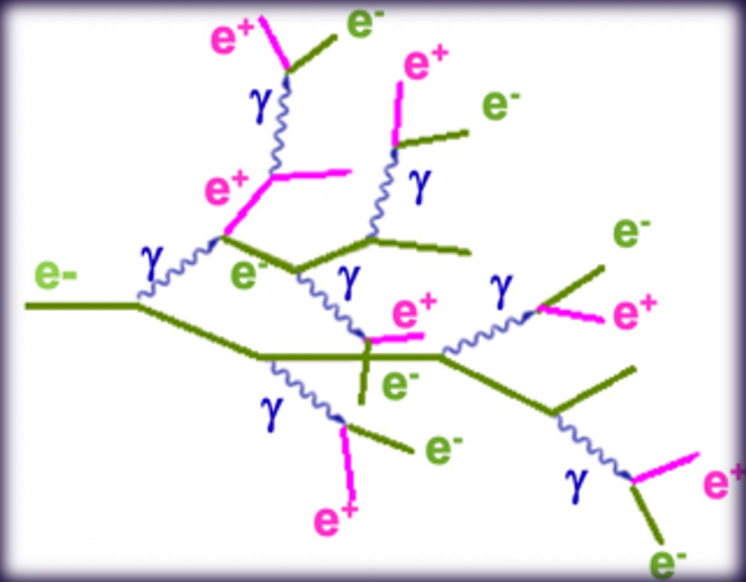
Main process involved on the lost of energy in calorimeters

Ionization.	Charged particles	Electromagnetic
Bremsstrhahlung	Electrons, positrons (and muons with very high energy)	
Photoelectric effect	Photons	
Compton effect	Photons	
Pair production	Photons	
Nuclear interactions	Hadrons	

Two different types of showers: Electromagnetic and hadronic

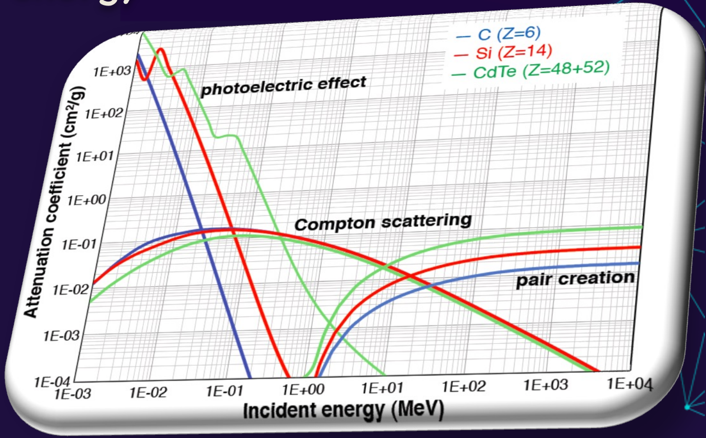
➔ Two types of calorimeters

Electromagnetic shower processes



1. An electron or positron produces photons due to bremsstrahlung
2. The photons converts on e+e-
3. The new e+e- produces more photons
4. And so on… ➔ A shower is produced

at each stage the new particles have less energy

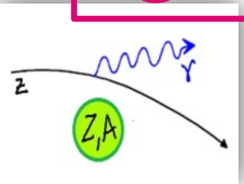


Bremsstrahlung

$$\frac{dE}{dx} = \boxed{4\alpha N_A \frac{Z^2}{A} r_e^2} \cdot E \boxed{\ln \frac{183}{Z^{\frac{1}{3}}}} = \frac{E}{\boxed{X_0}}$$

Radiation Length

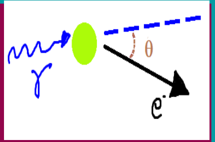
$$\frac{dE}{dx} \propto \frac{E}{m^2}$$



Only relevant for e+, e- or high energetic μ

X_0 = distance after which an electron reduces its energy a factor e (~ 63.2%) due to bremsstrahlung

Photoelectric effect



For $h\nu \ll m_e c^2$

$$\sigma = 4\alpha^4 \sqrt{2} Z^5 \frac{8\pi r_e^2}{3} \left(\frac{m_e c^2}{h\nu}\right)^{7/2}$$

In general

$$\sigma \propto \frac{Z^n}{h\nu^m}$$

n between 4-5
m between 3,5-1

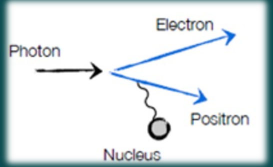
Decreases when E_γ increases
Increases with Z of material
Larger E_γ lower angle

e-e+ pair production

For $E_\gamma \gg m_e c^2$

$$\sigma_{pair} = 4Z^5 \alpha r_e^2 \left(\frac{7}{9} ln \frac{183}{Z^{1/3}} - \frac{7}{54}\right)$$

$$\boxed{\sigma_{pair} = \frac{7}{9} \frac{N_A}{A} \frac{1}{X_0}}$$



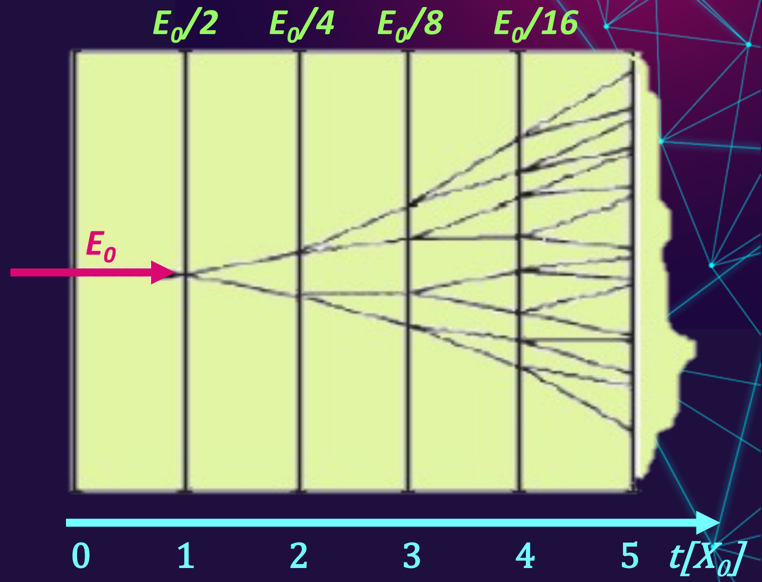
Dominates for high E_γ

Electromagnetic shower – Simple model

Facts

In a length X_0 electron loses $\sim 2/3$ of energy due to bremssthralung
In al length X_0 photon has a probability of 7/9 of producing an e+e- pair

On a simplistic approach, and assuming there are not more involved processes, after a length X_0 an energetic electron will originate a pair e+e-



After a thickness $n = tX_0$

$$N(t) = 2^t \quad \text{Number of particles}$$

$$E(t) = \frac{E_0}{2^t} \quad \text{Energy per particle}$$

At some moment:

- Photon energy is too low to produce more pairs
- The energy loss by ionization becomes more important than the bremsstrahlung

The number of particles in the shower starts to decrease

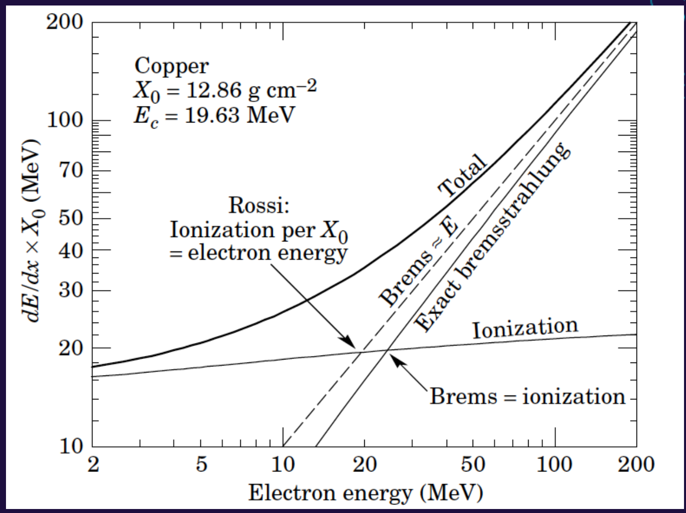
Maximum of the shower

$$N(t_{\max}) = \frac{E_0}{E_c} \qquad t_{\max} = 1.44 \ln\left(\frac{E_0}{E_c}\right)$$

Critical Energy (E_c)

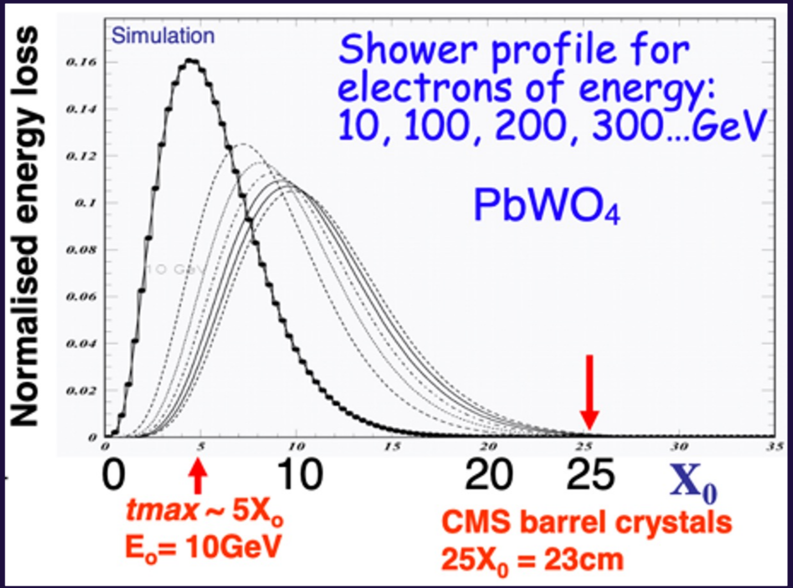
The energy for which the loss by ionization and bremsstrahlung are equal

$$\boxed{\varepsilon_c \approx \frac{550MeV}{Z}}$$



Electromagnetic shower profile

Longitudinal development



Parametrization

$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 \frac{b^{\alpha+1}}{\Gamma(\alpha+1)} t^{\alpha} e^{-bt}$$

t = absorber thickness in unities of X_0 ($t=x/X_0$)

α ,**b** depends on the particle energy

Transversal development

- The photons and the e-e+ pairs are produced with an angle
- Electrons experiment multiple scattering
  Dominates first stages of the shower
- Low energetic photons can travel far away from the shower axis
  Form and halo of lower energy, dominates after the shower maximum

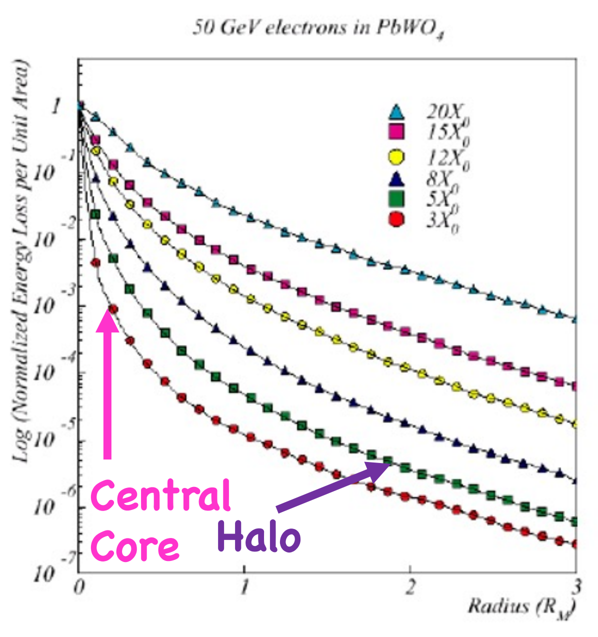
Profile can be described by the sum of 2 gaussian

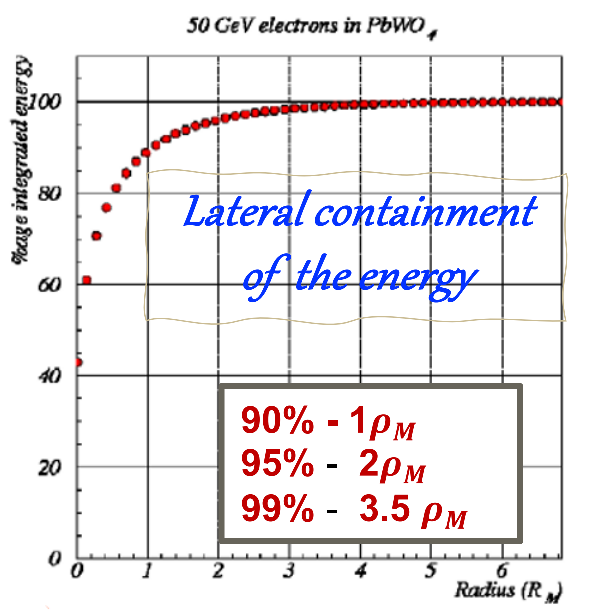
ρ_M = Molière radius

Average of the shower transversal width after 1 X_0

$$\rho_M = \frac{21.2MeV}{E_c} \cdot X_0$$

Calorimeter size to contain the shower
~25 X_0 x 3.45 ρ_M



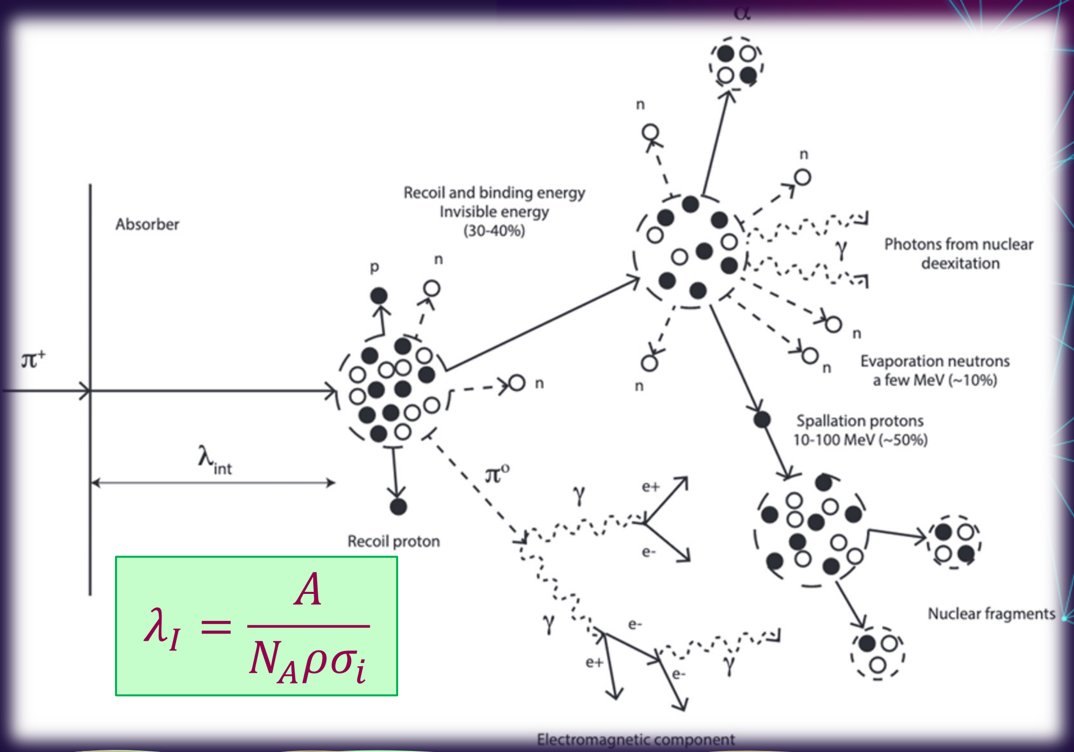


90% - 1ρ_M
95% - 2ρ_M
99% - 3.5 ρ_M

Hadronic shower. Nuclear interaction

The processes involved on hadronic shower are much complex than for the electromagnetic one

1. The hadron penetrates the material till it suffers a strong interaction with some nucleus
    - If the hadron has electric charge it produces ionizations along the path, in other case not signal is produced
2. Spallation is the most likely process due to this strong interaction
    1. The hadron interacts with the nucleons producing an intranuclear cascade of particles. Some of them scape from the nucleus
    2. After the nucleus des-excite emitting lower energetic particles (evaporation). Most of them are neutrons. Photons are also produced mainly if the remanent nucleus is radioactive.
    3. In case of very heavy materials fission can be also produced instead of evaporation
3. The new particles will interact again



$$\lambda_I = \frac{A}{N_A \rho \sigma_i}$$

λ_{int} = Interaction length = mean free path of a particle before undergoing an inelastic nuclear interaction

λ_{int} is the equivalent to X_o in the e.m shower

Hadronic shower – Basic principles

- The particles produced in the nuclear interaction can interact again, originating aº shower

The new hadronic particles interact as the initial one
Other particles will only interact electromagnetically

At the first stages of the shower the particles are very energetic and can produce pions

$$N_\pi = 2\left(\frac{E_0}{m_n c^3}\right)^{1/4}$$

In average $\sim 1/3$ are π^0 , which decay in photons
But this fraction fluctuates a lot from event to event

Two shower components, a pure hadronic and a electromagnetic.
(fraction fluctuates from event to event)

- Part of the energy lost by the particle during the nuclear interaction is "invisible"
  - Neutrinos don´t interacts
  - Muons very few energy by ionization (behave as a MIP)
  - Slow neutrons can scape from the detector
  - Binding and atomic recoil energies (the most important contribution)

Degrades
energy resolution

A large fraction of energy mainly recoil and binding energy (30-40%) and slow neutrons cannot be detected
Large fluctuations

Hadronic shower profile

Longitudinal development

Can be parametrized with a phenomenological function

$$\mathrm{d}E = K\left\{wS^{a-1}\mathrm{e}^{bs} + (1-w)t^{c-1}\mathrm{e}^{-dt}\right\}\mathrm{d}s$$

K = Normalization factor

w and $1-w$ = Relative weights of both curves

s = Depth from the origin of the shower in X_0 units

t = Depth from the origin of the shower in λ_I units

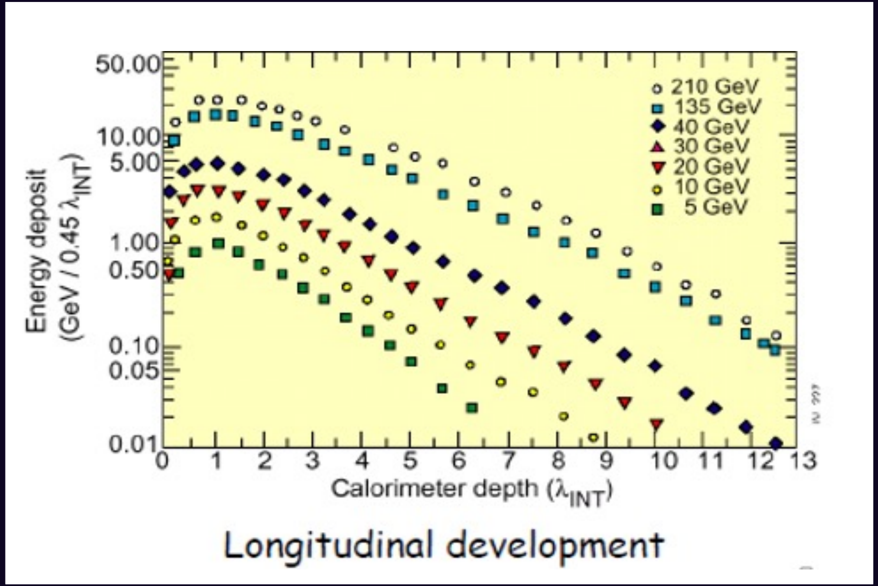
a , b , c, d = Parameters from data fit

Describes e.m component
Closes to shower vertex

Describes the exponential dependence at large distances of the hadronic part

$$t_{max} \approx 0.2 \ln E(GeV) + 0.7$$

$$L(95\%) = t_{\max} + 2.5\lambda_I$$

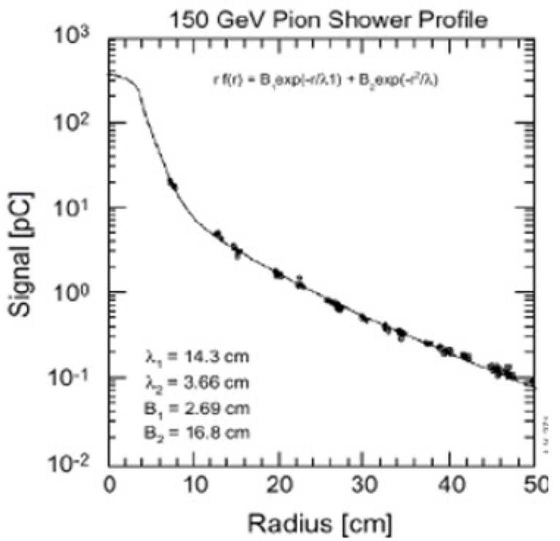


Longitudinal development

Transversal development

Two components

1. A high energetic central part with the e.m component
2. A peripheric part with low energy neutrons



95% hadronic shower contained within
9 λ_I longitudinal and 1λ_I lateral

Electromagnetic vs hadronic showers

Electromagnetic shower

Size related to X_0 (longitudinal) and ρ_M (transverse)

Longitudinal size: 95% length = ~20-22 X_0

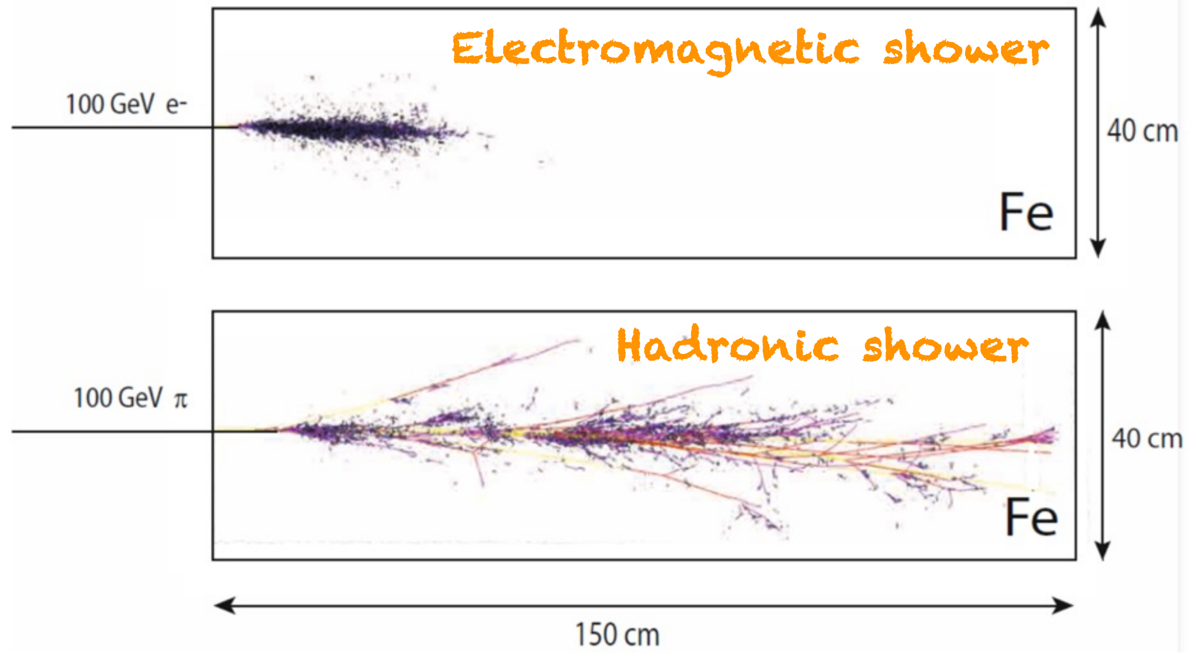
Transverse size: 90% in a cylinder of radius of ρ_M
95% in a cylinder of radius of $2\rho_M$

Hadronic shower

Size related to λ_I (longitudinal and transverse)

Longitudinal size: 95% length = 6-9 λ_i

Transverse size: 95% in a cylinder of radius = λ_I



	Fe	Pb	W	BGO	Al	Cu	$PbWO_4$
X_0 [cm]	1.76	0.56	0.35	1.12	8.90	1.44	8.90
ρ_M [cm]	1.72	1.60	0.93	2.26	4.42	1.57	4.42
λ_I [cm]	16.77	17.69	9.95	26.74	39.7	15.32	39.7

Hadronic showers are larger than electromagnetic

Material election impacts the design

Calorimeters - Energy resolution and compensation

The measurement of the energy is influenced by the fluctuations in the shower process and the signal

$$\frac{\sigma(N)}{N} = \frac{1}{\sqrt{N}} \quad \text{as } N \propto E_0 \quad \Rightarrow \quad \frac{\sigma(E)}{E} = \frac{a_\mathrm{i}}{\sqrt{E}}$$

a_i = intrinsic resolution. Constant for each calorimeter and the resolution lowest limit

For sampling calorimeters only particles crossing the active medium can be detected (the shower shape fluctuates from event to event but the detectors are at fixed positions)

$$\left.\frac{\sigma(E)}{E}\right|_t = \left.\frac{\sigma(E)}{E}\right|_i \oplus \left.\frac{\sigma(E)}{E}\right|_s = \frac{\sqrt{a_i^2 + a_s^2}}{\sqrt{E}} = \frac{a}{\sqrt{E}}$$

In a **real calorimeter** there are more contributions

$$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}}$$

$a = intrinsic\ term$

$b = constant\ term$ ➡

$c = noise\ term$

Dead spaces

Inhomogeneities

Bad calibration

Non-linearity of readout electronics

….

In a **hadronic calorimeter** there are two components

$$\boxed{Signal = S_{em} + S_{had} = \boldsymbol{e} f_{em} E + \boldsymbol{h} f_{had} E}$$

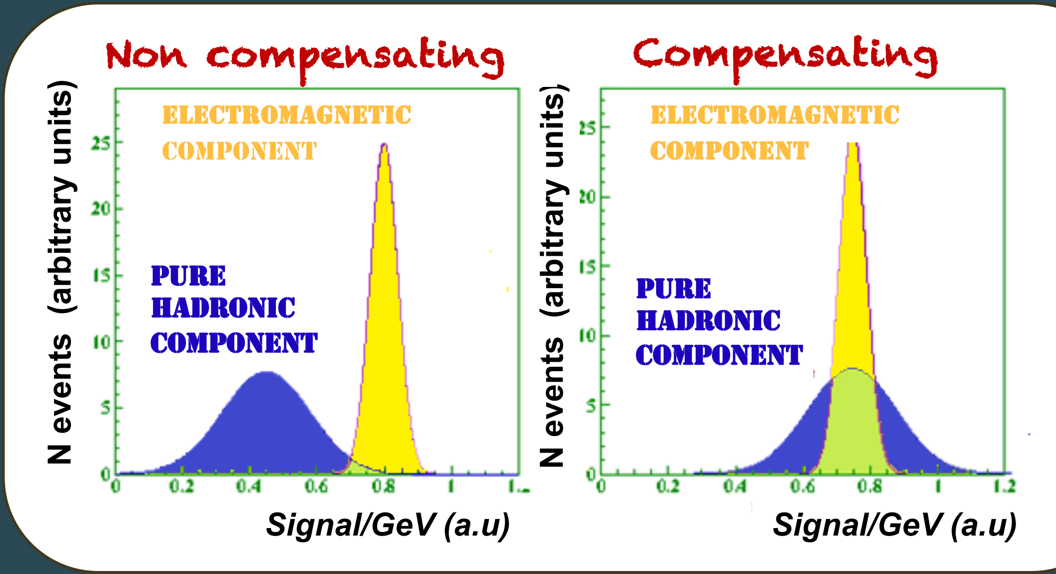
f_{em}, f_{had} $= Fractions\ of\ each\ component$

$f_{had} = 1 - f_{em}$

Large fluctuations from event to event

$$\boxed{\frac{\mathbf{e}}{\mathbf{h}} = 1}$$

Compensanting Calorimeter



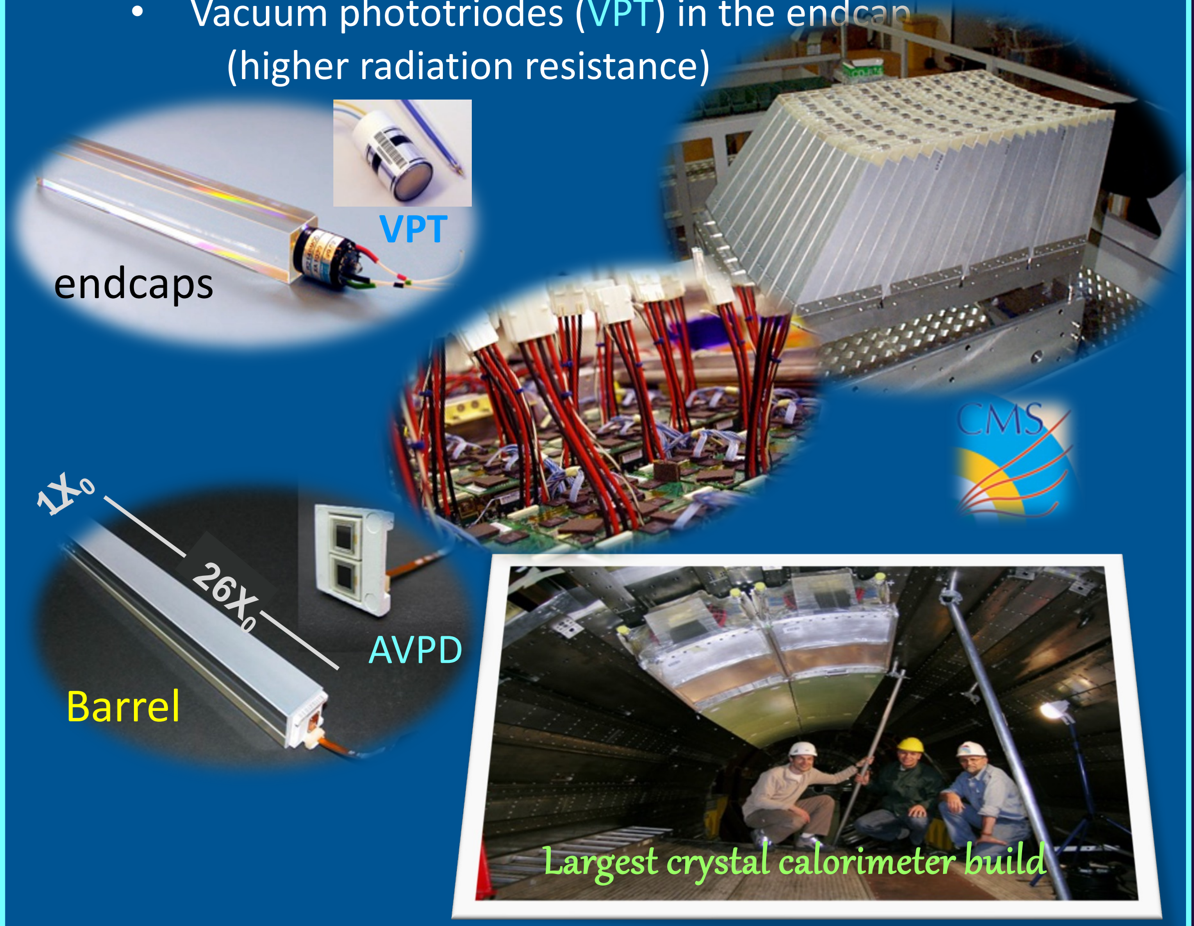
Examples of calorimeters

CMS electromagnetic calorimeter

Homogeneous calorimeter with *scintillator crystals PbWO4*

Coupled to photon detectors

- Avalanche photodiodes (AVPD) in the barrel
- Vacuum phototriodes (VPT) in the endcap
  (higher radiation resistance)



Largest crystal calorimeter build

CMS hadronic calorimeters

Sampling calorimeters

Barrel & endcaps

Brass and plastic scintillator

Hybrid photodioes (HPD)
substituted in 2020 for Si PM

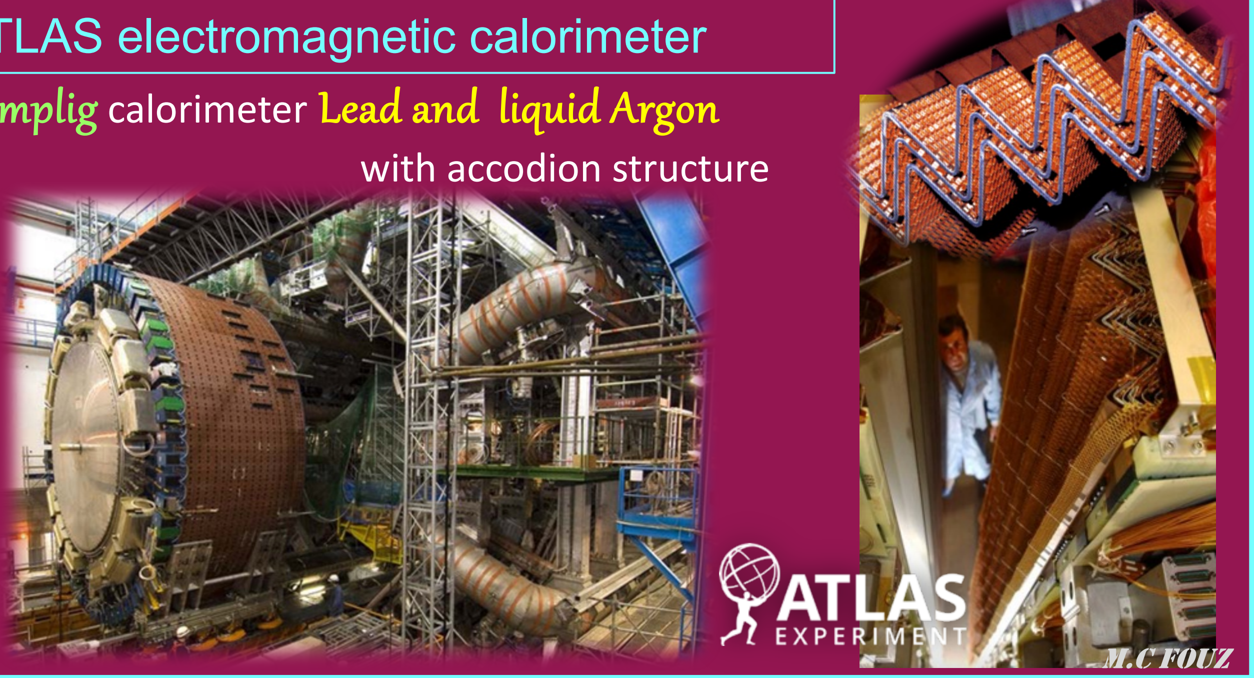
Low angle

Steel with quartz fibers

Photomultiplier tubes(PMT)
(It is outside of the magnetic field)

ATLAS electromagnetic calorimeter

Samplig calorimeter *Lead and liquid Argon*
with accodion structure



Calorimetry challenges for future colliders

The experiments on future colliders are very demanding for all the detectors and, in particular, for calorimeters.

High precision energy measurements

➔ 30%/√E between 50 and 250 GeV (e+e- Higgs Factories: ILC, CLIC, FCC-ee, CEPC)

Not achieved with the calorimeters being used up to now

High radiation levels

➔ Mainly for FCC-hh/SPPC where coverage should go up to |η|~6

High pileup

➔ Up to 1000 for FCC-hh/SPPC

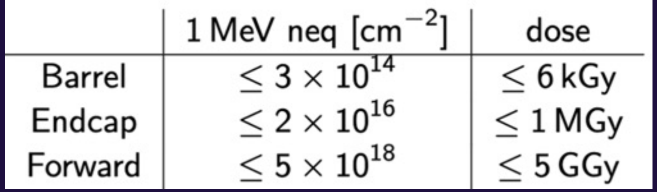
High pileup

➔ Up to 1000 for FCC-hh/SPPC

High Backgrounds

➔ Muon Collider has a big BIB (Beam Induced Background)

FLUKA simulations by M.I. Besana (CERN)



	1 MeV neq [cm^{-2}]	dose
Barrel	$\leq 3 \times 10^{14}$	$\leq$ 6 kGy
Endcap	$\leq 2 \times 10^{16}$	$\leq$ 1 MGy
Forward	$\leq 5 \times 10^{18}$	$\leq$ 5 GGy

Compact detectors, huge segmentation, precise timing, radiation hardness, good energy resolution…

How to improve jet energy resolution

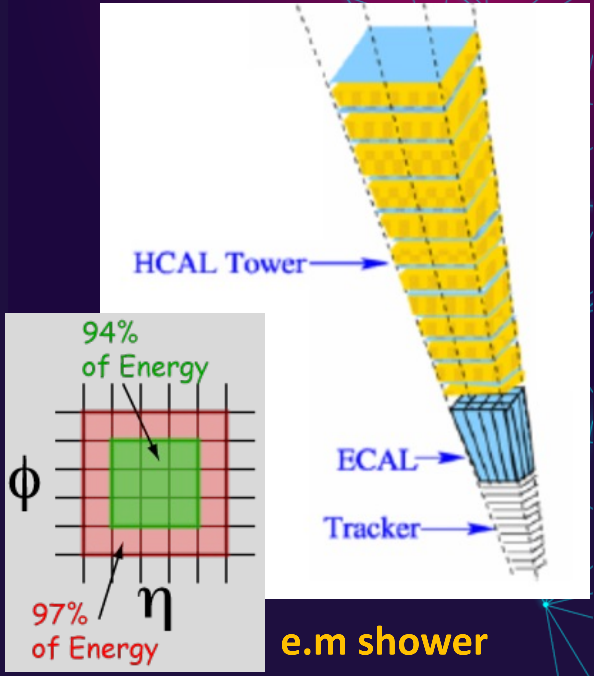
Many R&D activities are ongoing, approaching the problems in different ways

Two main different methods to achieve the needed jet resolution for e+e- colliders:

- High granular calorimeters with embedded electronics to apply PFA (Particle Flow Algoritms). Developed by CALICE Collaboration along more than 20 years (approach also used for the upgrade of the CMS endcap calorimeter for the HL-LHC). Several technologies as active medium under study: Silicon detectors, scintillators, gaseous detectors
- Dual readout Calorimeter

Traditional reconstruction and measurement in calorimeters

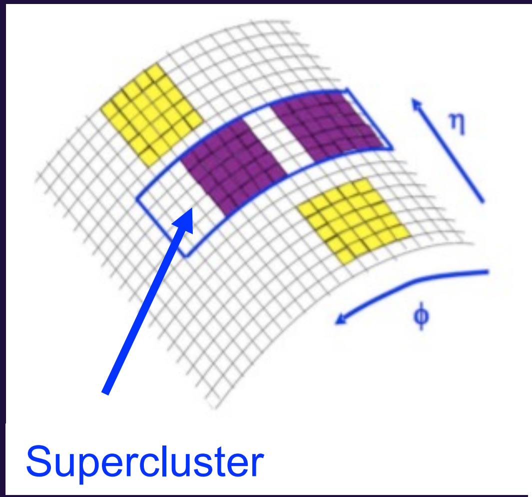
Till nowadays, calorimeters on high energy experiments are segmented forming towers
Each tower provides the energy deposited in it
Due to the topological differences, towers in e.m calorimeter are smaller than in hadronic.
For the same transversal area an e.m calorimeter has more towers than the hadronic



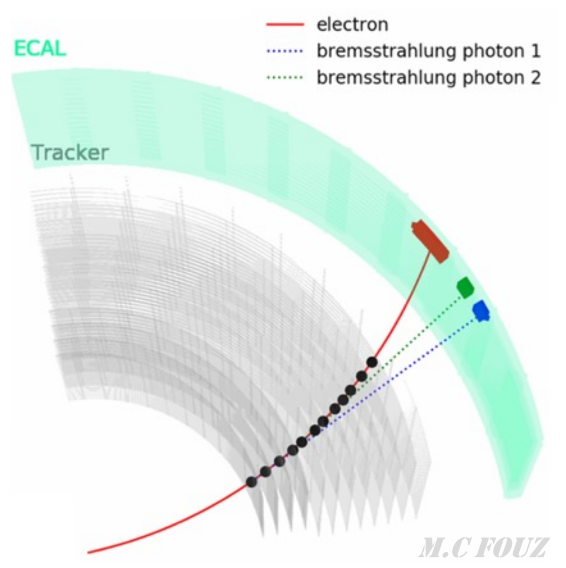
e.m shower

Reconstruction is made using clusterization algorithms

1. Select towers with an signal over a threshold
2. Select the tower with higher signal ➔ Seed
3. Associate the neighbor towers forming a cluster
   Number of towers depends on the calorimeter type (ECAL/HCAL) and design (tower size)
4. Sometimes clusters are associated on superclusters
   To take into account bremstranlung and e+e- pairs from photons coming from the collisions



Supercluster



Energy measurement

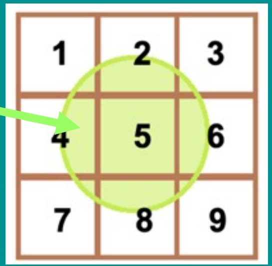
Adding the energy recorded in all the calorimeter towers

Position measurement

Gravity center computation

$$X = \frac{\sum_{i=1}^{9} E_i x_i}{\sum_{i=1}^{9} E_i}$$

e.m shower



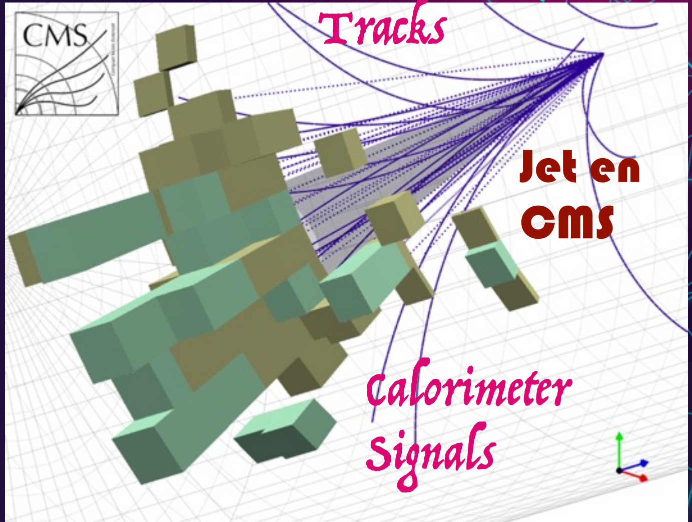
Jets reconstruction

One has to be able to disentangle wich particles are part of jet
Complicate in case of simultaneous collisions producing events overlpas

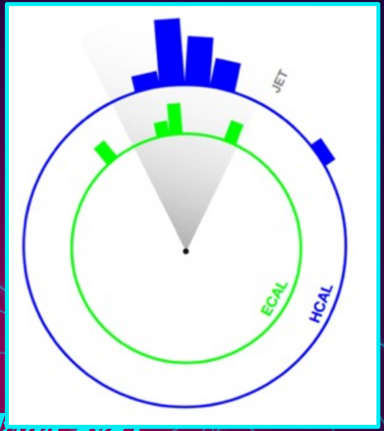
Several algorithms used, most common

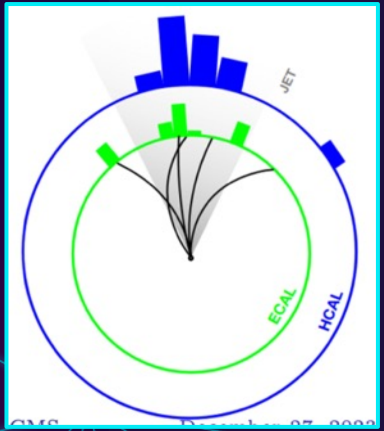
Sequential Clustering Algorithms
Looks the 2 closest particles, if they are close enough it recombine them and procedure is repeated over and over again following the algorithm criterium.

Iterative Cone algorithms
Looks for particles in an un a range η–φ cone. Criteria based in the sum of moments match the cone axis.

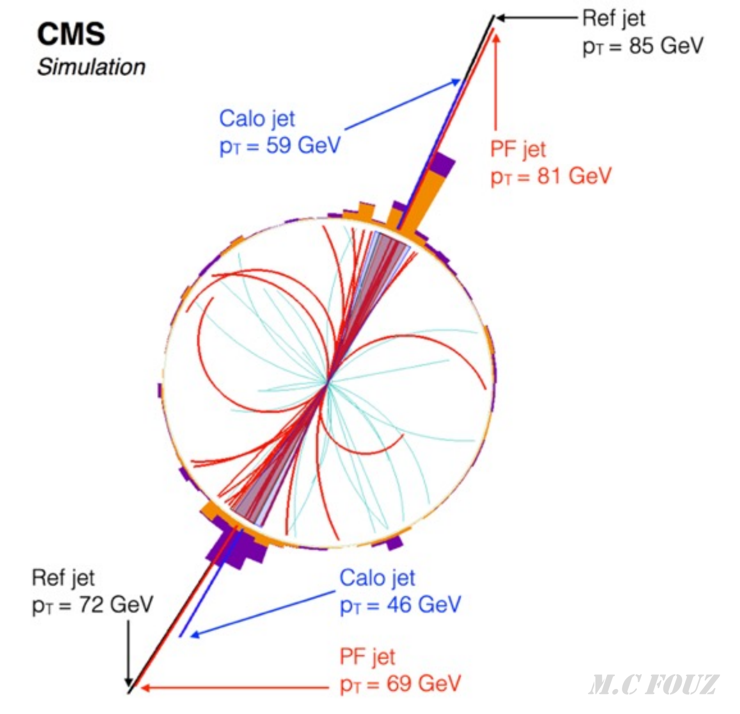


Final reconstruction can be based only on the calorimeters information or combined with the tracker as, e.g on particle flow algorithms (FPA)





PFA produces best measurements that the better they are, the high segmented transversal y longitudinal are the calorimeters



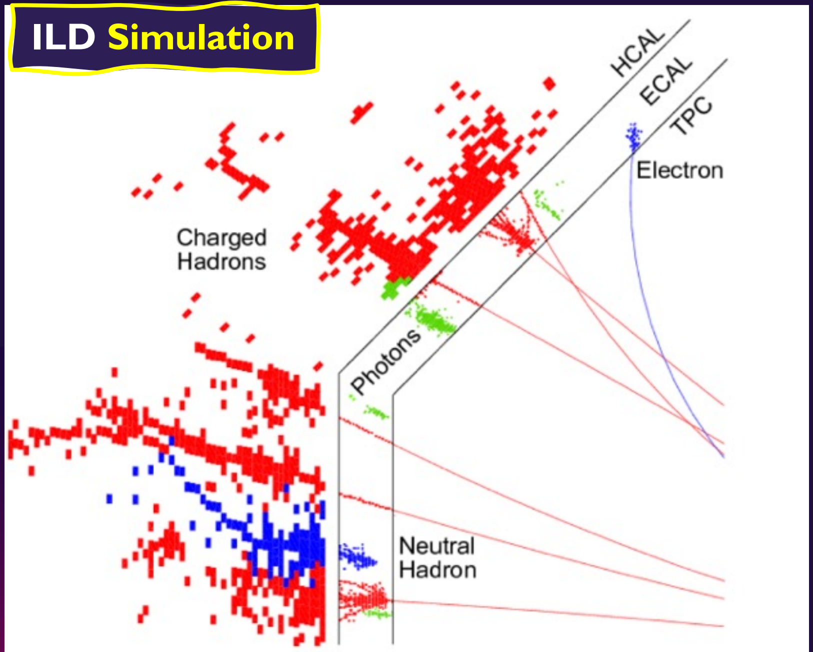
Particle Flow Algorithms

Particle Flow Algorithms – PFA

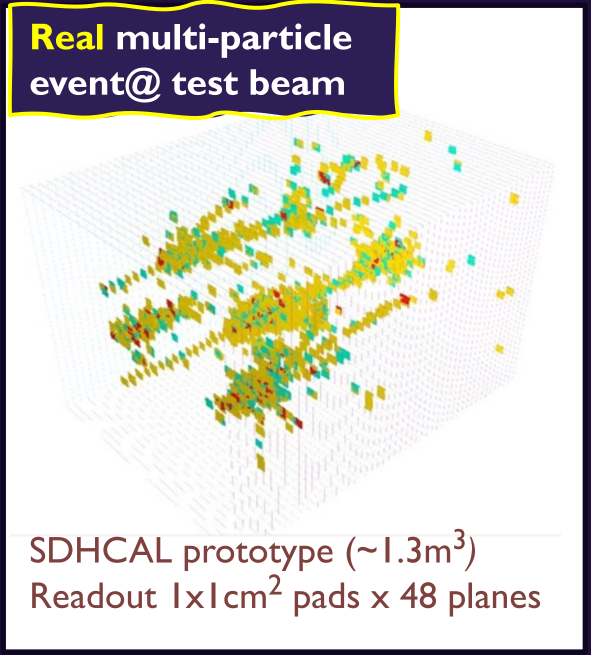
Reconstruct **every single particle** in the event and measure it **only** with the detector providing the best resolution

Average jet composition	PFA reconstruction
60% charged	Measured on the tracker, negligible resolution
30% photons (from π^0 decay)	Measured at ECAL ~10-20% /√(E)
10% neutral hadrons (n, K_L)	Measured at HCAL ~60-100% /√(E)

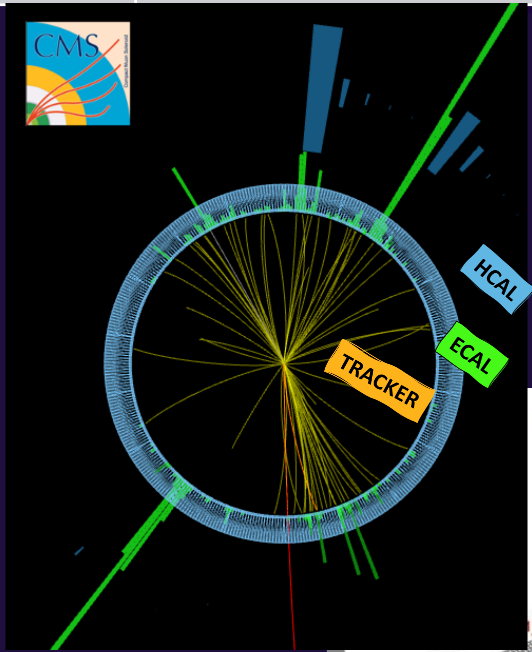
ILD Simulation



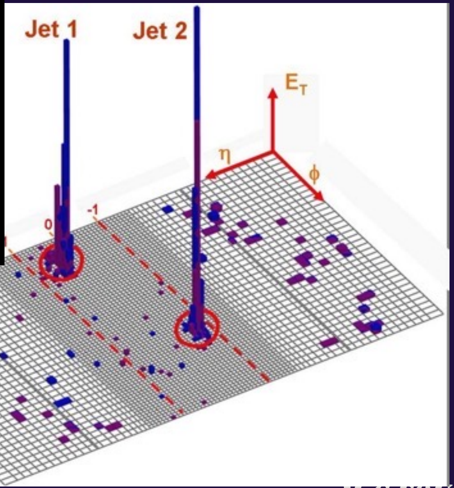
Real multi-particle event@ test beam



SDHCAL prototype (~1.3m^3)
Readout 1x1cm^2 pads x 48 planes



Traditional Calorimeters



Main resolution challenge: **Confusion**

Bad assignment of energy between particles (**software**)
+ overlap in the same readout channel (**granularity**)

Dual readout calorimeter concept

Remember that in a **hadronic calorimeter** there are two components

$$\boxed{Signal = S_{em} + S_{had} = \mathbf{e}f_{em}E + \mathbf{h}f_{had}E}$$

$$f_{had} = 1 - f_{em}$$

$$\boxed{\frac{\mathbf{e}}{\mathbf{h}} = 1}$$

Compensanting Calorimeter

It it would be possible to distinguish in the calorimeter the electromagnetic fraction , compensation is not needed

This can be achieved by using two different materials for producing different light type:

1. Cherenkov light, produced by relativistic particles dominated by electromagnetic components (80% of the hadronic component is not relativistic)

2. Scintillator light

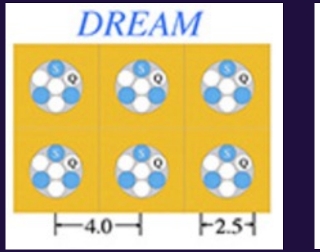
It can be implemented for example using fibers embedded in the calorimeter absorber

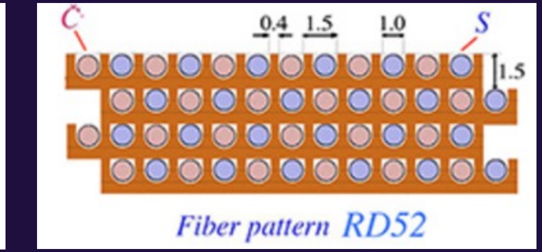
A combination of dual-readout + PFA could also be envisaged

DOUBLE READOUT fiber calorimeter

Geometry based on metal capillaries acting as absorber with inserted fibers

Absorber: brass or steel
Sensor: Scintillator + cherenkov Fibers
Readout: SiPM/MCP-PMT
Dual readout

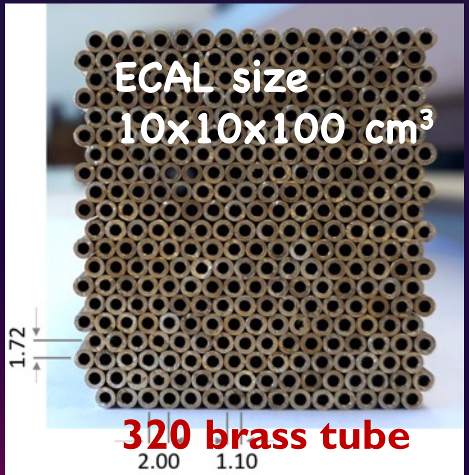




Readout with a SiPM or PMT

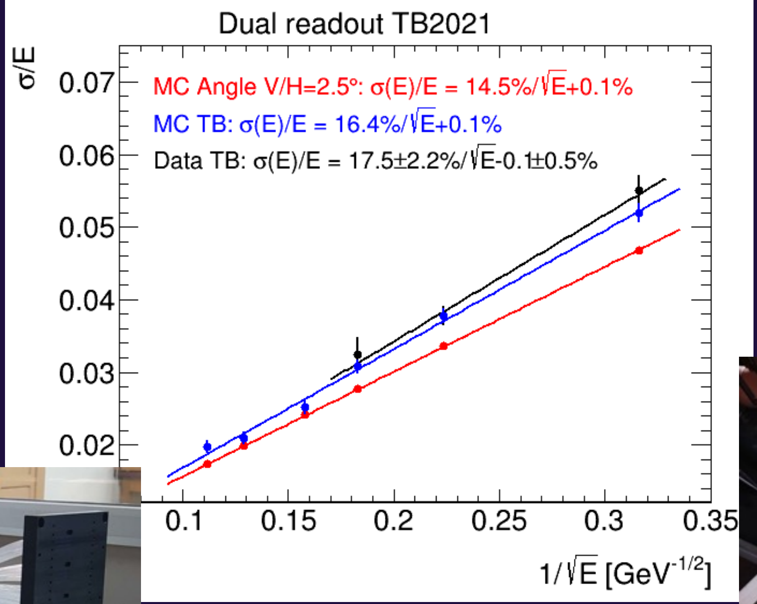
Several prototypes under development

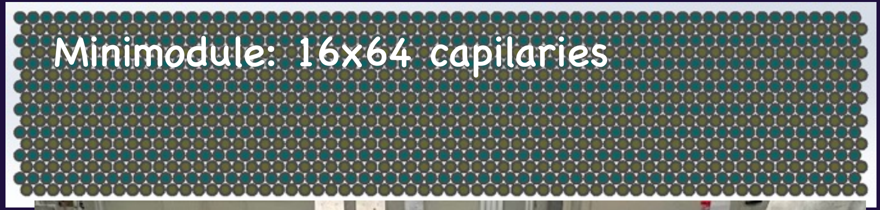
HCAL size 65x65x250 cm^3. → 80 minimodules.



ECAL size 10x10x100 cm^3

320 brass tube





Minimodule: 16x64 capilaries

Questions