CPAN NETWORK ON INSTRUMENTATION AND DETECTORS

TIDPAN 2026 - Taller de Instrumentación y Detectores en Física de Particulas, Astropartículas y Nuclear

Muon Detectors

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TIDPAN 2026

Valencia, June 18th, 2026

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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What is a muon?

and why do I want to detect it?

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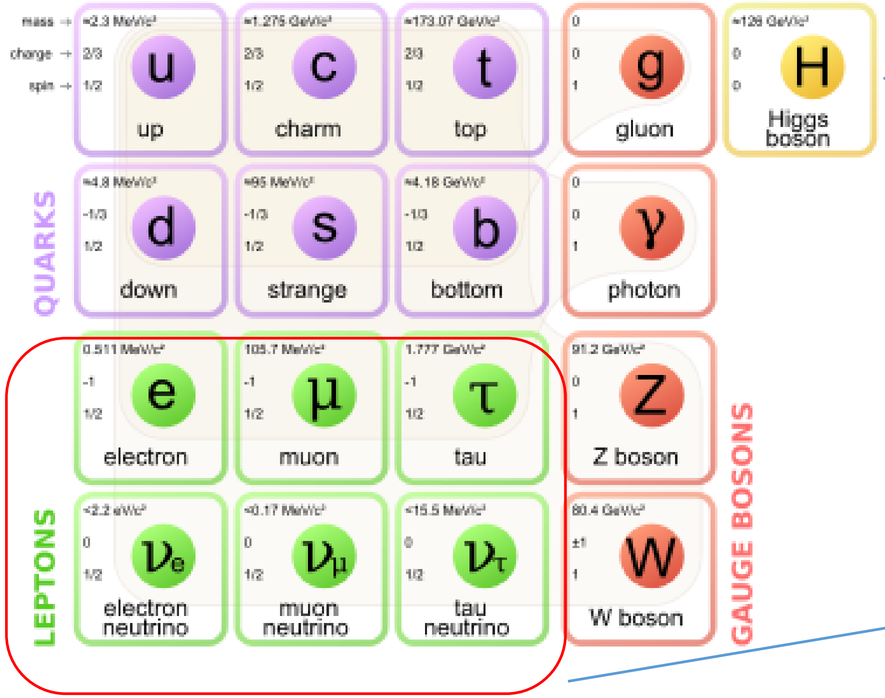
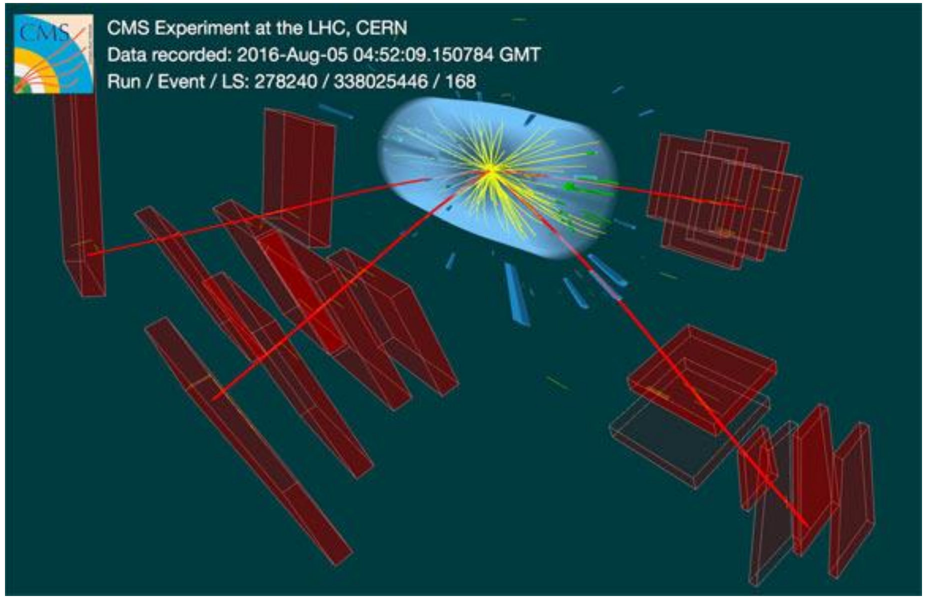
MUON

Their clean experimental signature makes them one of the most valuable particles in modern physics experiments.





Leptons:
No strong force

ELECTRON
Charge -1
Spin ½
Mass ~ 0,511 MeV/c^2

x 207

MUON
Charge -1
Spin ½
Mass ~ 105,66 MeV/c^2 → Highly penetrating
Life-time τ = 2.2 μs → Travel macroscopic distances

Decay:

$$\mu^- \rightarrow e^- \bar{\nu}_e \, \nu_\mu$$
$$\mu^+ \rightarrow e^+ \nu_e \, \bar{\nu}_\mu$$

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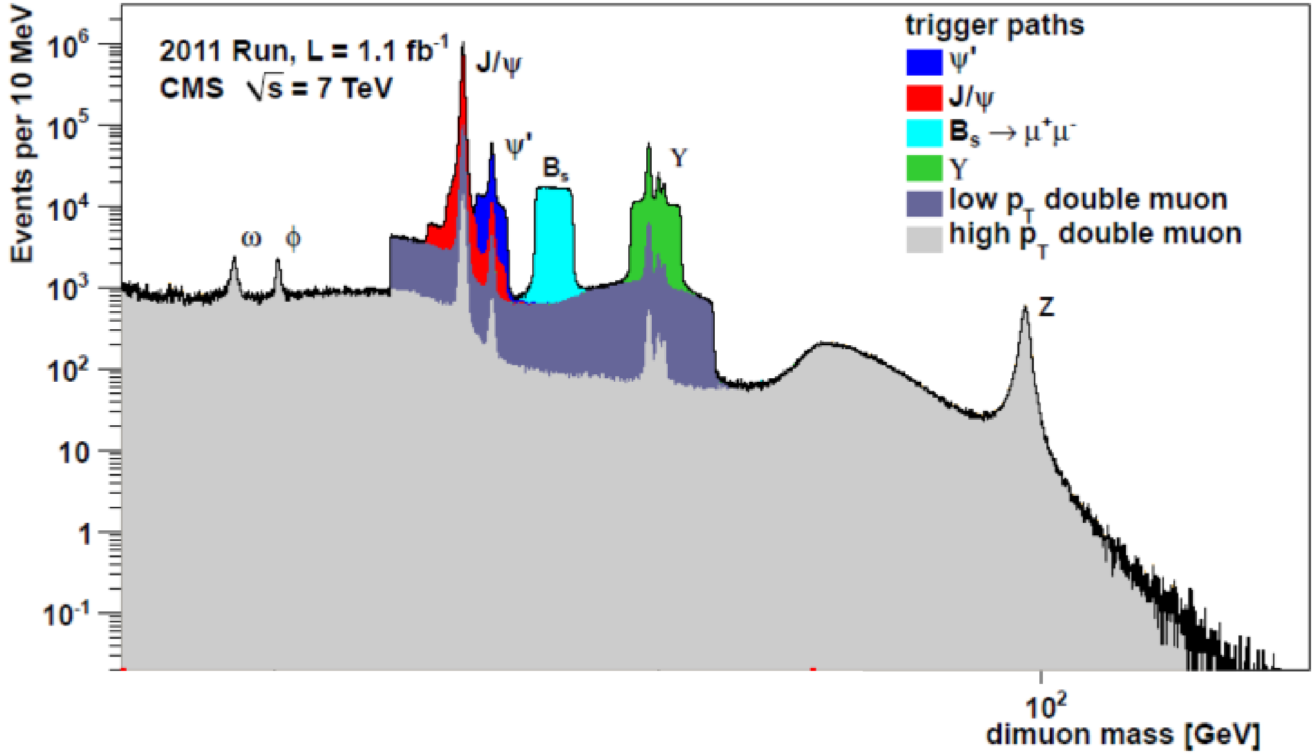
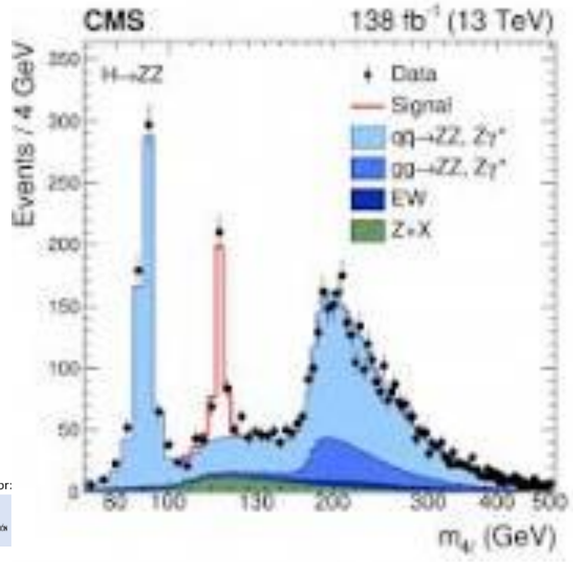
Muons as key observables

- 1974 → J/ψ → μμ (3.1 GeV)
- 1977 → Υ → μμ (9.46 GeV)
- 1983 → W → μν (80.4 GeV)
- 1983 → Z → μμ (91.2 GeV)
- 2012 → H → ZZ* → 4μ (125 GeV)
- 2021-2022 → B_s → μμ precision era
- 2023-2024 → H → μμ observation





The physics became visible because the muons could be reconstructed precisely

They may be rare decays, but the topology is easy to reconstruct and the background is small

Clean final states

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Muon Production

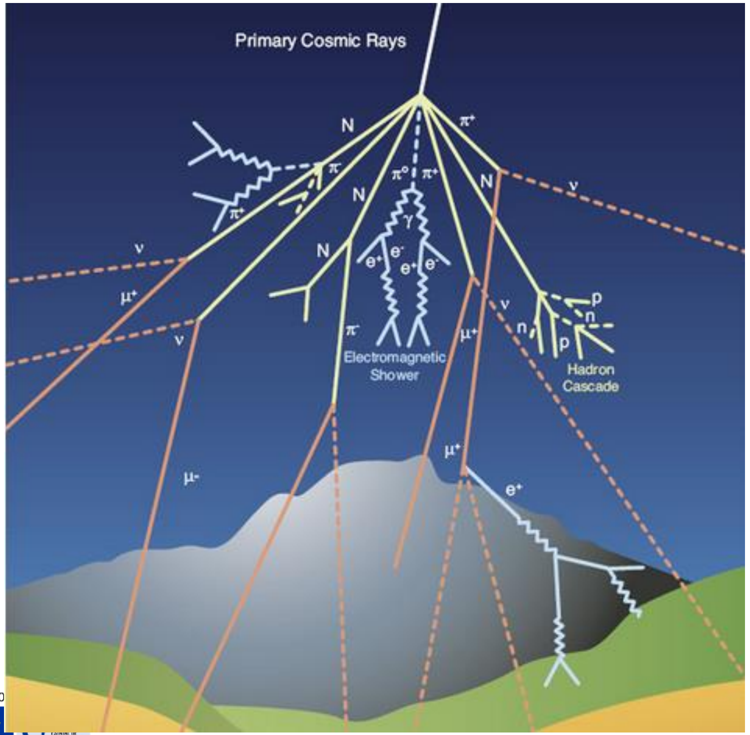
Atmosphere is a gigantic muon source:
Primary cosmic rays (90% protons, 9% Helium, 1% heavier, e, etc)
Secondary: collision with N_2 or O_2 (15-20 km) => pions, kaons => muons

(u$\bar{\text{d}}$) $\pi^+ \rightarrow \mu^+ + \nu_\mu$

(d$\bar{\text{u}}$) $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

μ^+/μ^- ~1.3

p(uud)



At sea level:
~1 muon/cm² min⁻¹

τ ~ 2.2 μs
c·τ ~ 660 m
????

Same way we produce muon beams:
Proton beam + target+ decay+ concrete
PSI, Fermilab, J-PARC and CERN.

Close to speed of light, their time is slower

$$\tau_{lab} = \gamma\tau$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

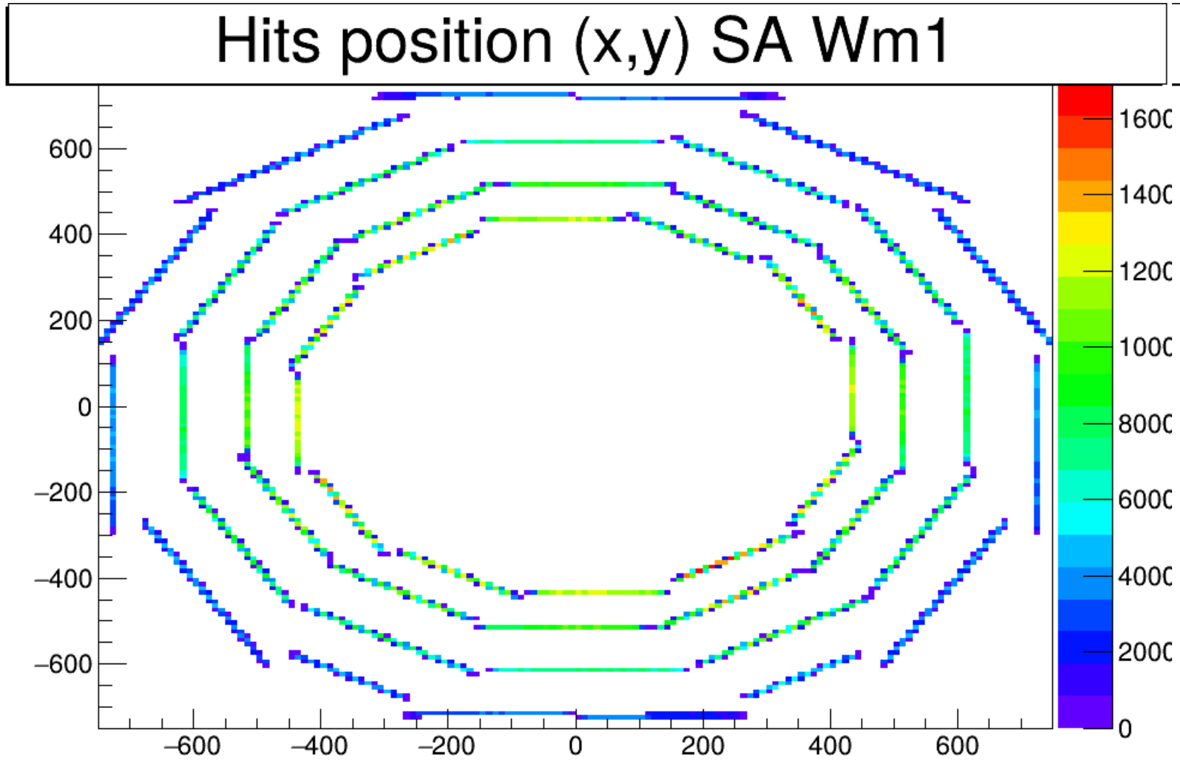
$$L = c\tau_{lab} \approx 66\ km$$

Muons for calibration

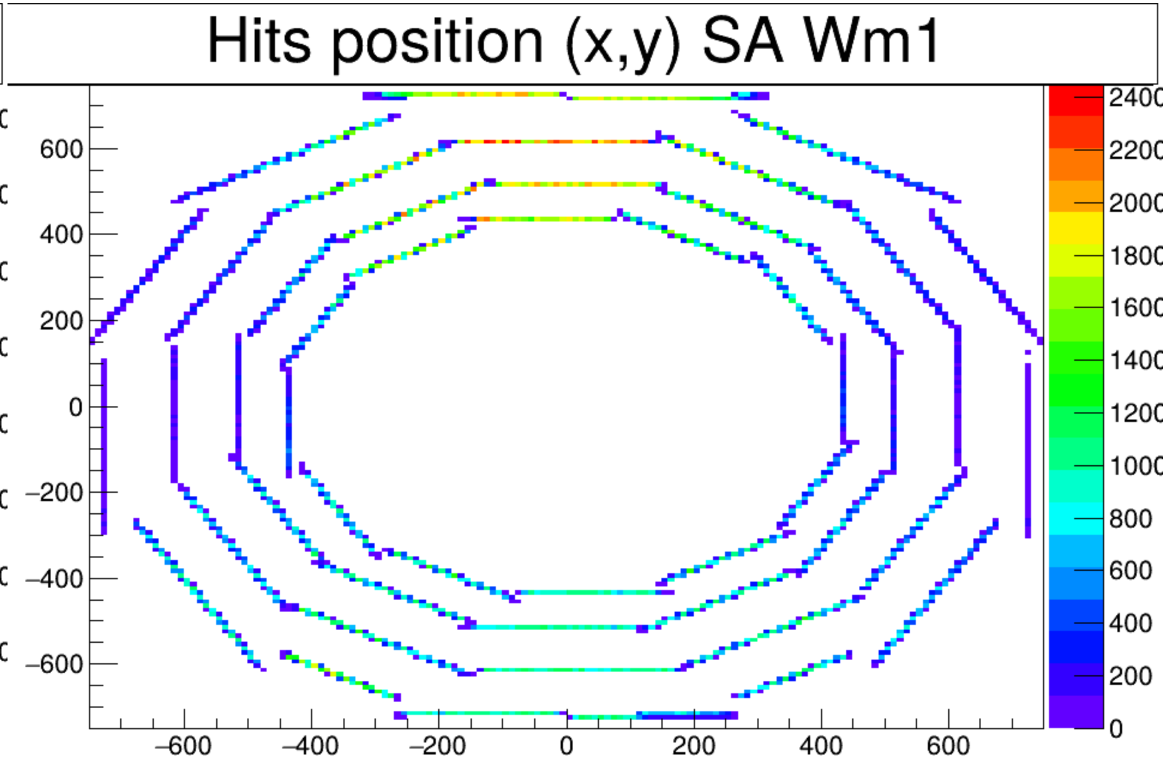
Muons can be:

- Calibration source (cosmic ray data taking routinely at CMS, LHC)

LHC COLLISIONS at CMS



COSMICS at CMS



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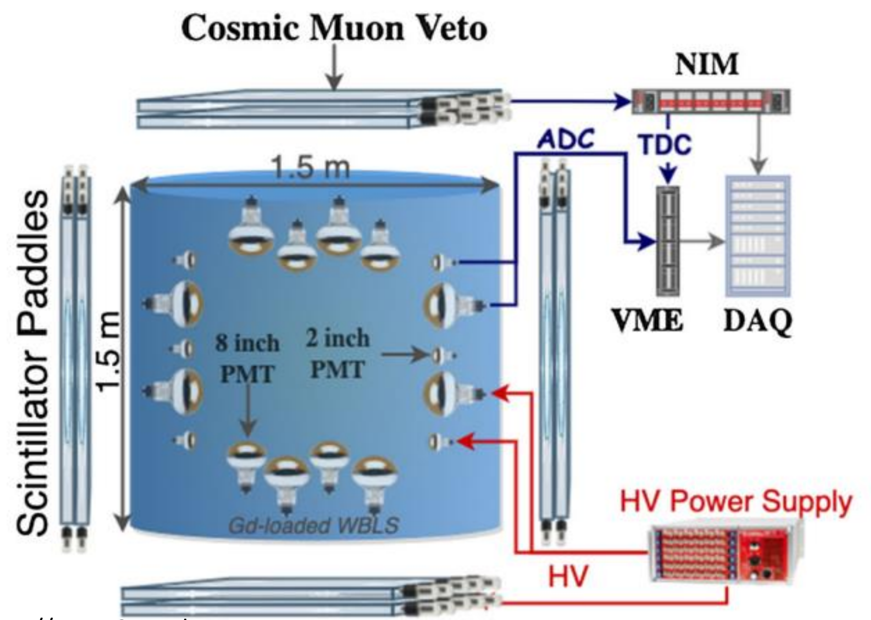
Muons as signal and as background

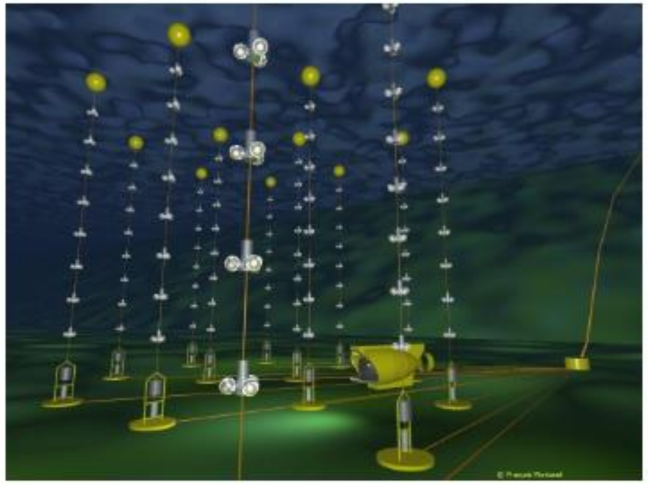
Muons can be:

- Calibration source (cosmic ray data taking routinely at CMS, LHC)
- Background in dark matter experiments and others => **underground**

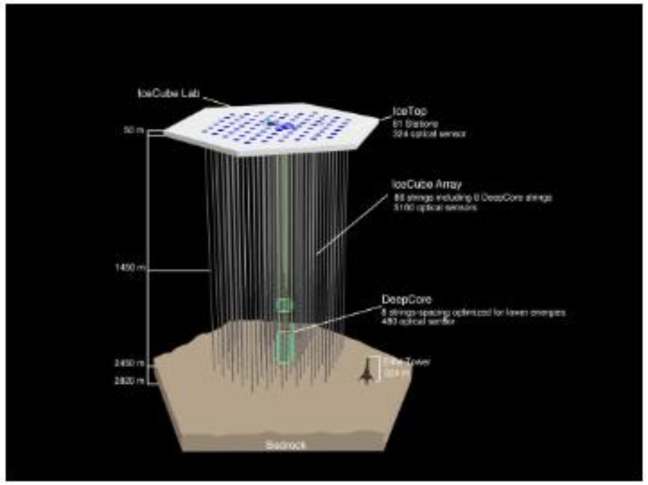
Even if the muon is detected and vetoed,
its by-products mimic rare physics signals.



https://scoap3-prod-backend.s3.cern.ch/media/files/72139/10.1140/epjc/s10052-022-10658-6_a.pdf



Antares, under-water Cherenkov detector in the Mediterranean sea close to Marseille.



The IceCube Neutrino Telescope (Antarctic) is made up of 86 strings with a total of 5,160 Digital Optical Modules that are used to sense and record neutrino events in ice.

Muons in underground neutrino detectors play a dual role:

- **unwanted background**: few thousand meters water equivalent
- **signature**: Muon neutrinos will most of the time interact via charge-current reactions

$$\nu N \rightarrow \mu + X$$

energetic muon in the final state
(muon detected by Cherenkov radiation)

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How Muons loose their energy?

→ *i.e., how to detect them?*

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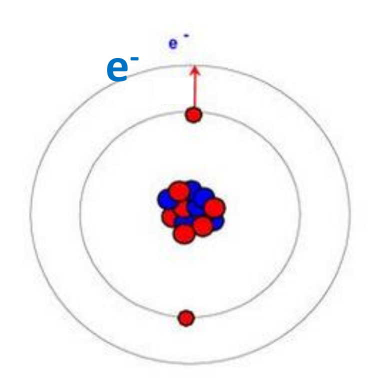
Charged particles: electromagnetic interaction

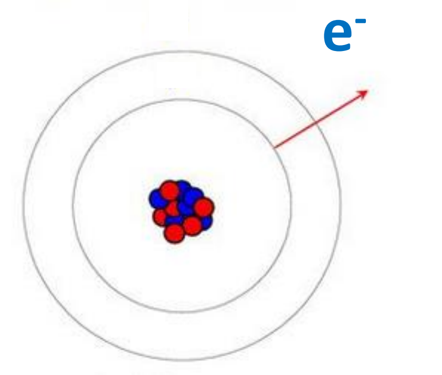
interaction with the atomic electrons

(Inelastic collisions)

Excitation



Ionization



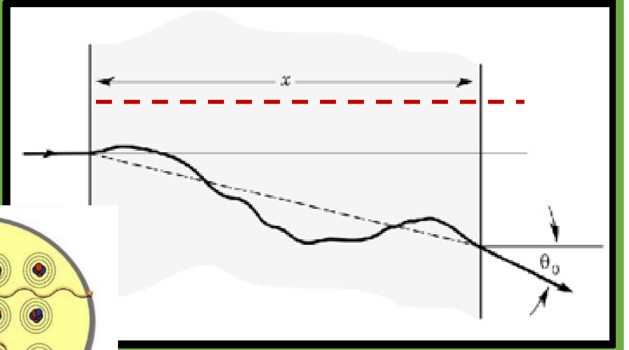
Excitation: Electrons are excited to higher energy states when they absorb energy and subsequently emit photons as they return to lower energy states.

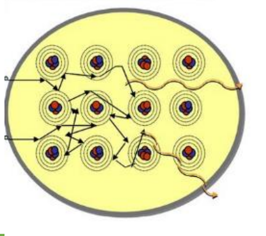
Ionization: the atom looses electrons

Interaction with atomic nuclei

Elastic collisions:

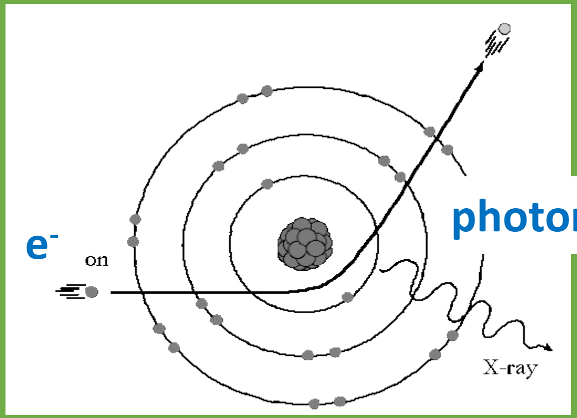
- Multiple scattering: elastic collisions with atomic nucleus.
  - Higher Z, larger dispersion
  - Higher p_t, smaller dispersion





Radiative effects: **Photon emission (Bremsstrahlung)**

- The particle is slowed down or deflected as it interacts with the nucleus, and it may emit a photon, thereby losing energy.



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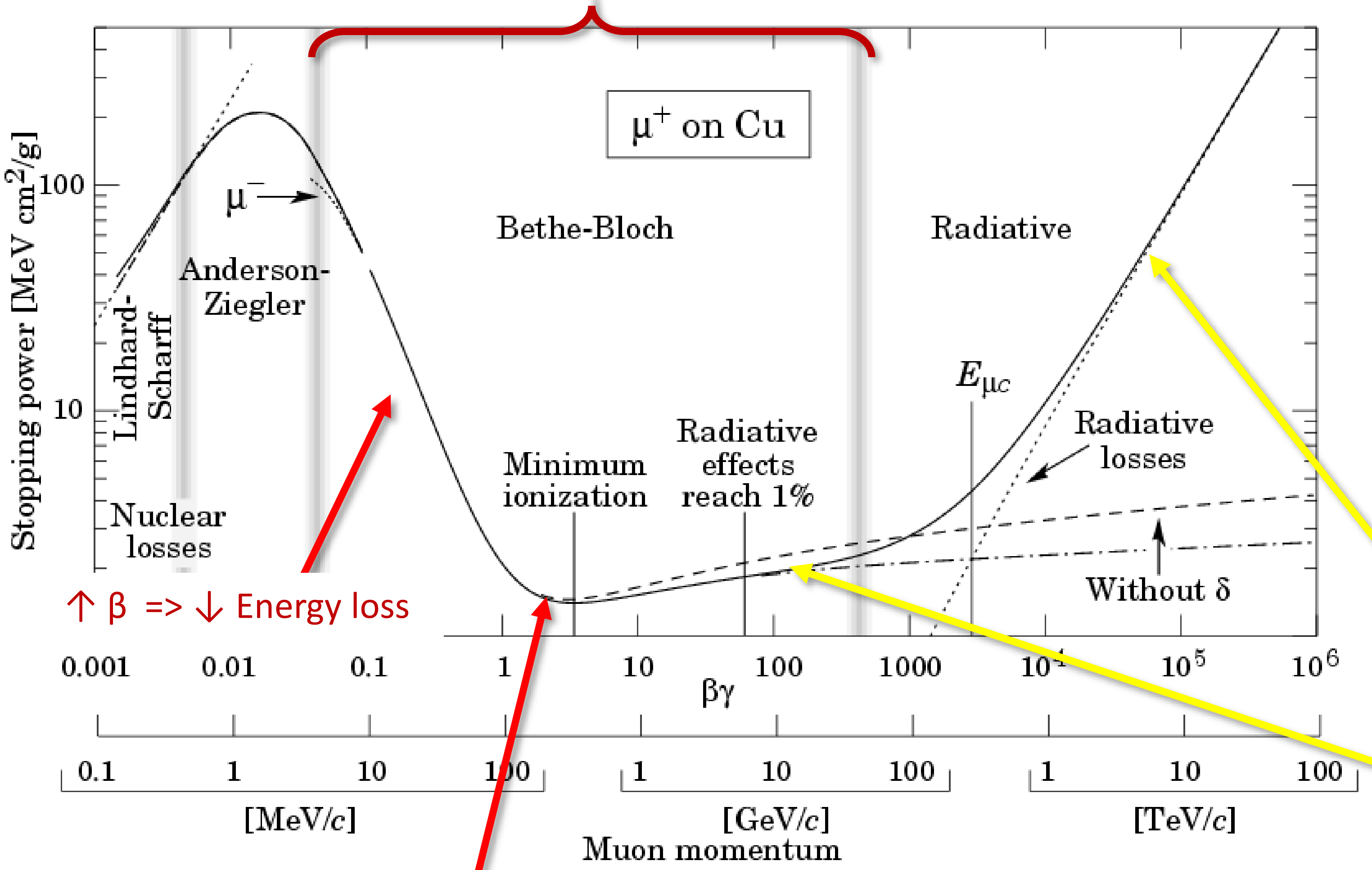
Energy loss in a material by a charged particle

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

Bethe & Bloch formula -dE/dx Stopping power

Average energy lost per unit path length in a material due to collisions with atomic electrons, resulting in ionization and excitation of the medium.



MIP (minimum ionizing particle)

- **Particle charge and speed:** z^2 / β^2
- **Medium properties:** Z / A, I(ionization pot), densidad
- **Relativistic effects** : β·γ and médium polarization (δ)

Radiative region: Energy loss through bremsstrahlung radiation caused by the particle's deceleration or deflection.

Polarization of the medium reduces the ionization energy loss (polarization depends on medium density)

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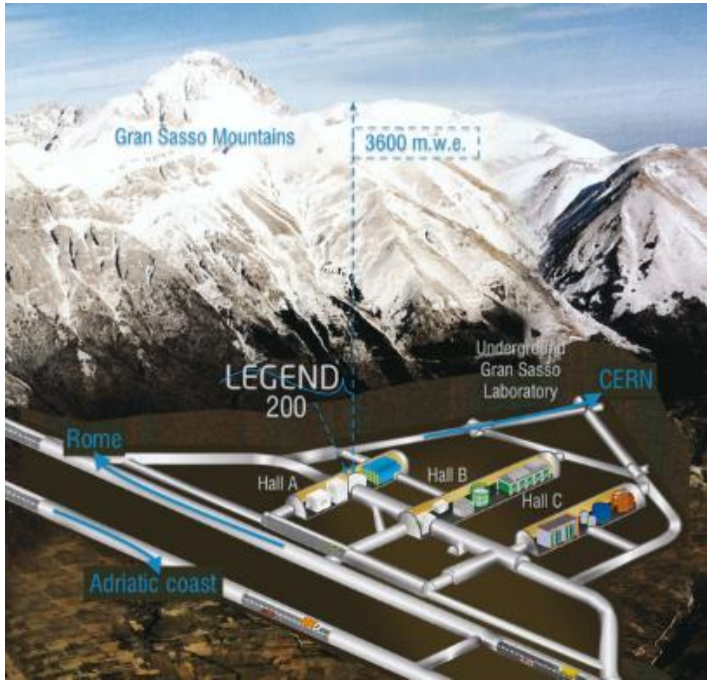
Muons loose little energy

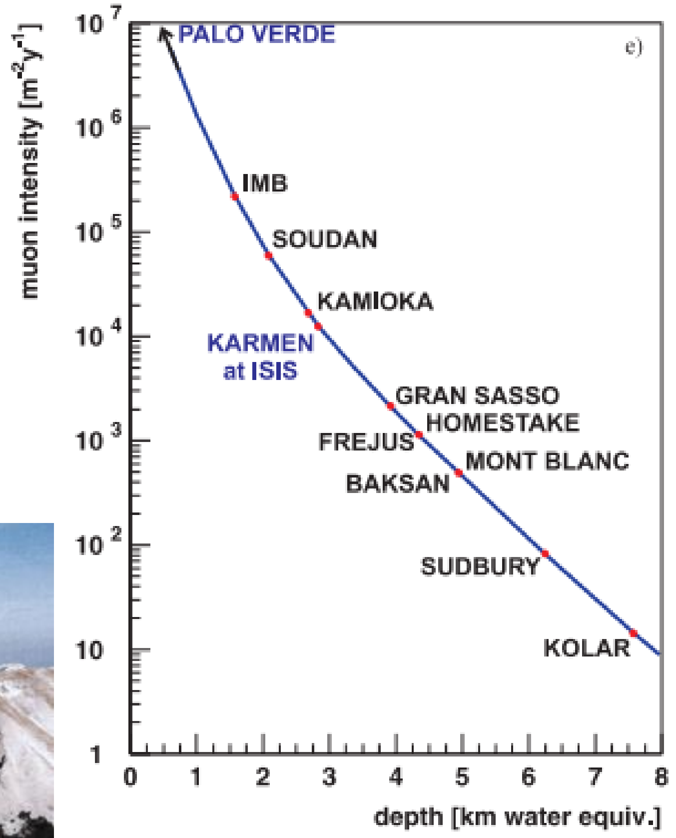
- Muons are often considered Minimum Ionizing Particles (MIPs) because, **over a wide range of energies**, their energy loss in matter is close to the **minimum** of the Bethe–Bloch curve.

- Differently from electrons, **bremsstrahlung** becomes only important **above a few 100 GeV**

- They are the most penetrating charged particles :
  in one meter of iron they lose only ≈1.5 GeV
  (for muons in few GeV to a few tens of GeV)

Surface => 1
100 m rock => 10^{-1}
1000 m rock => 10^{-3} - 10^{-4}
LNGS, Canfranc => 10^{-6}





Heavy enough not to shower, light enough to be produced abundantly, and long-lived enough to cross entire detectors.

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A Little bit of history…

Phys. Rev. 50 (1936) 263

Muons were discovered by Carl D. Anderson and Seth Neddermeyer in a cloud chamber experiment at CalTech in 1936

(Nobel prize for positron discovery in 1936)

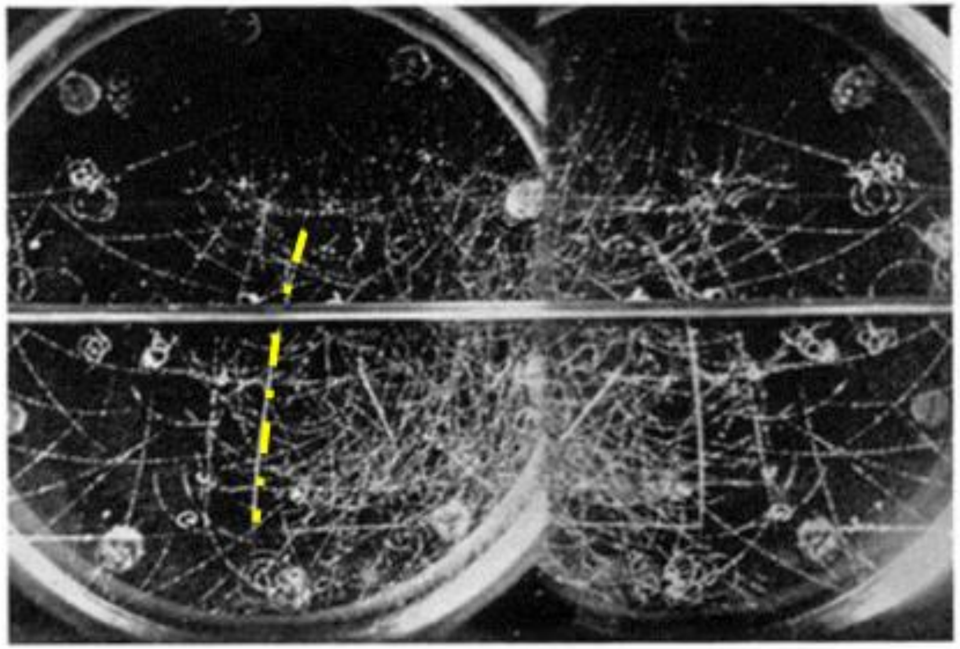

FIG. 13. Pasadena, 4500 gauss. A complex electron shower not clearly defined in direction, and three heavy particles with specific ionizations definitely greater than that of electrons. The sign of charge of two of these heavy particles represented by short tracks cannot be determined, but the assumption that they represent protons is consistent with the information supplied by the photograph. The third heavy track appears above the 0.35 cm lead plate where it has a specific ionization not noticeably different from that of an electron. It penetrates the lead

Cloud chamber

- **Ionizing particle → creates ions (condensation nuclei) → supersaturated vapor condenses on the ions → droplets form along the particle track**
- **Wilson received the 1927 Nobel Prize for the invention of the cloud chamber.**

From cloud chambers to modern muon detectors, the underlying principle remains the same: charged particles ionize matter and leave measurable signatures.

A Brief History of Particle Physics and Detector Instrumentation

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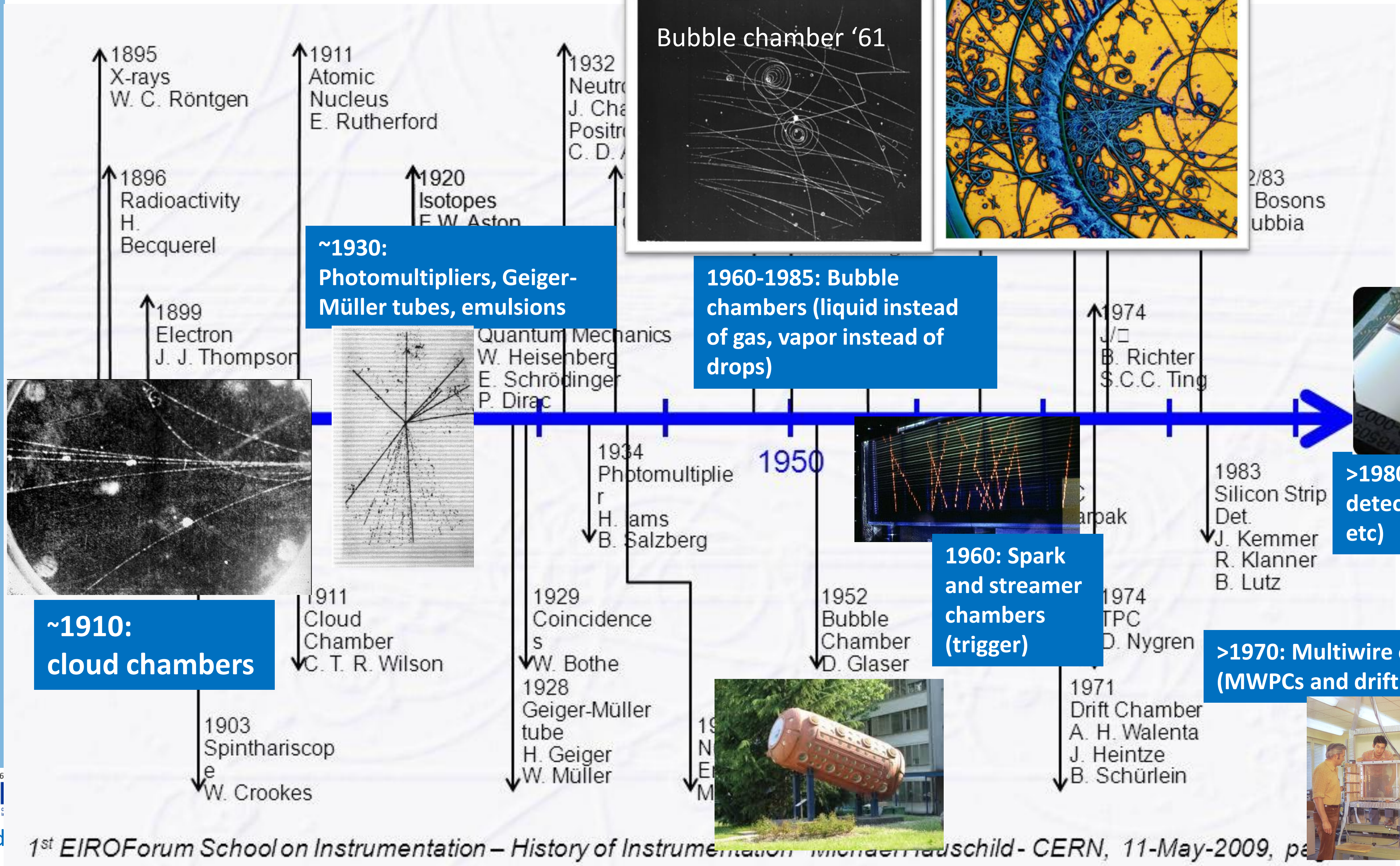
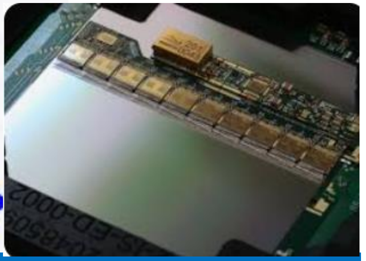


~1910: cloud chambers

~1930: Photomultipliers, Geiger-Müller tubes, emulsions

1960-1985: Bubble chambers (liquid instead of gas, vapor instead of drops)

1960: Spark and streamer chambers (trigger)



>1980: Solid state detectors (Silica, Ge, etc)

>1970: Multiwire chambers (MWPCs and drift chambers)

C. F. Bed

Radiation detectors

Muons can be detected by all of them!!!

Ionization

Semiconductors

Gas/Liquid

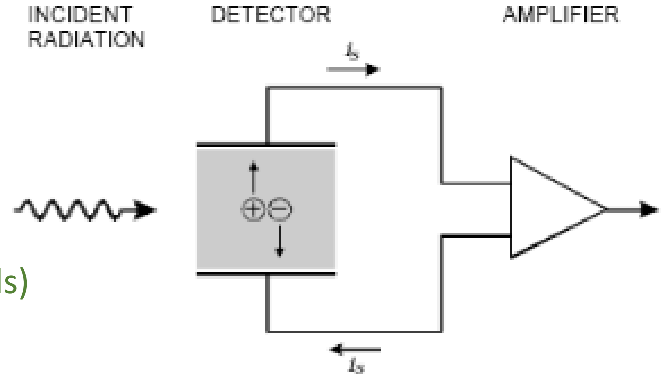
Ionization/excitation typical energies:

- 1-5 eV semiconductors
- 10 eV scintillation
- 30 eV gaseous

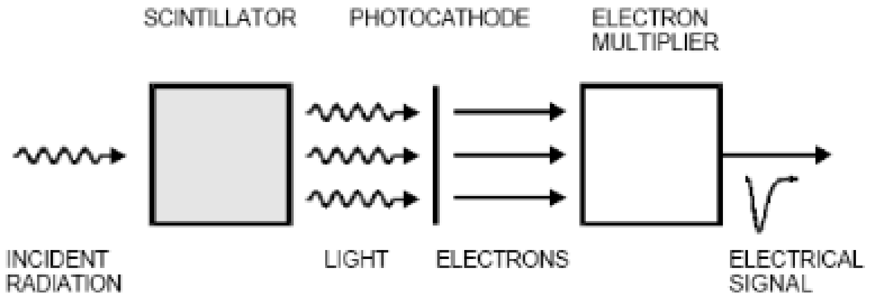
Excitation

Scintillation

- Electron- ion pair (gas/liquids)
- Electron- hole (semiconductors, metals)



Direct detection of radiation :
Radiation generates electrons that are sent to an electronics system



Indirect detection of radiation :
Radiation generates light that in turns, generates electricity through a photosensor

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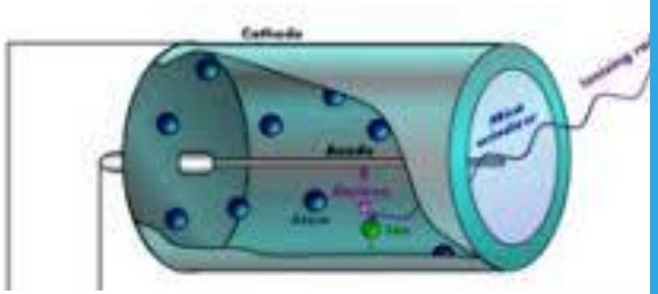
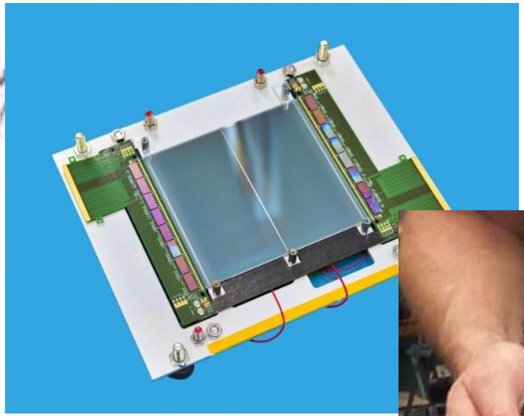
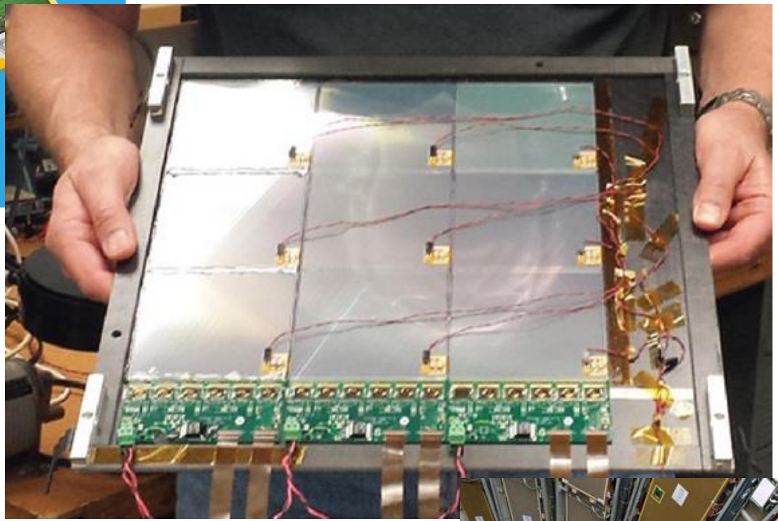
Radiation detectors

Muons can be detected by all of them!!!

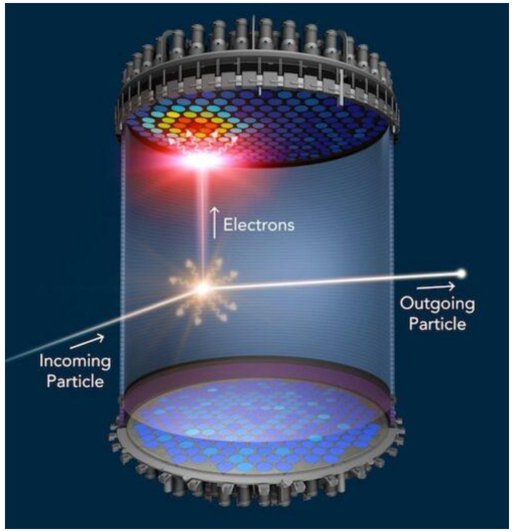


Gaseous

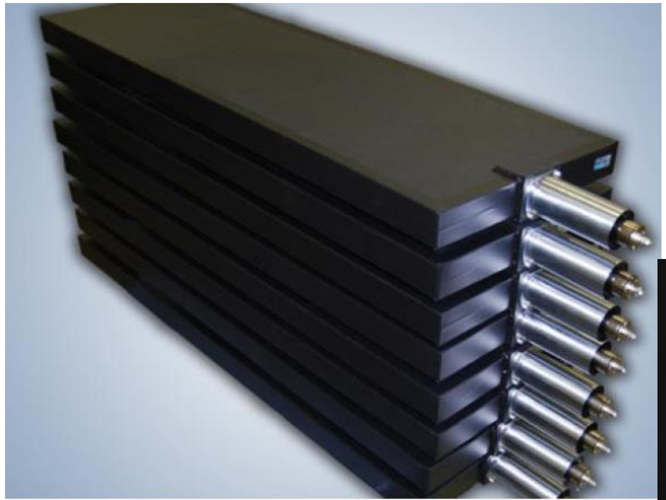




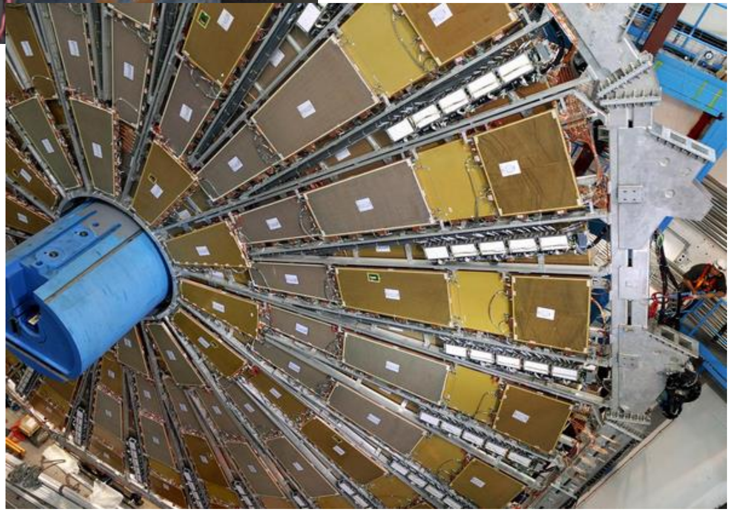
Solid state



Liquid scintillator



Plastic scintillators



Gaseous

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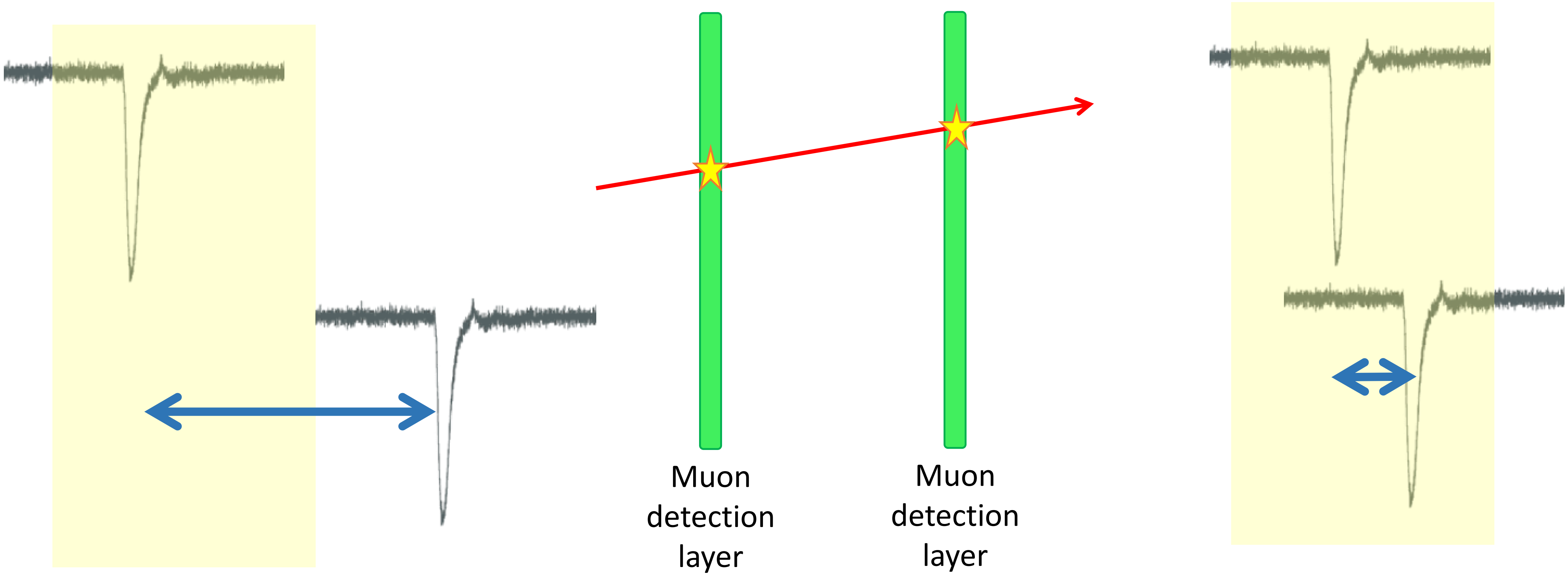
How to detect a muon?

Usually you want to make sure the signal from your detector is not noise.

This is usually granted by the **coincidence** of signals from neighbouring detectors



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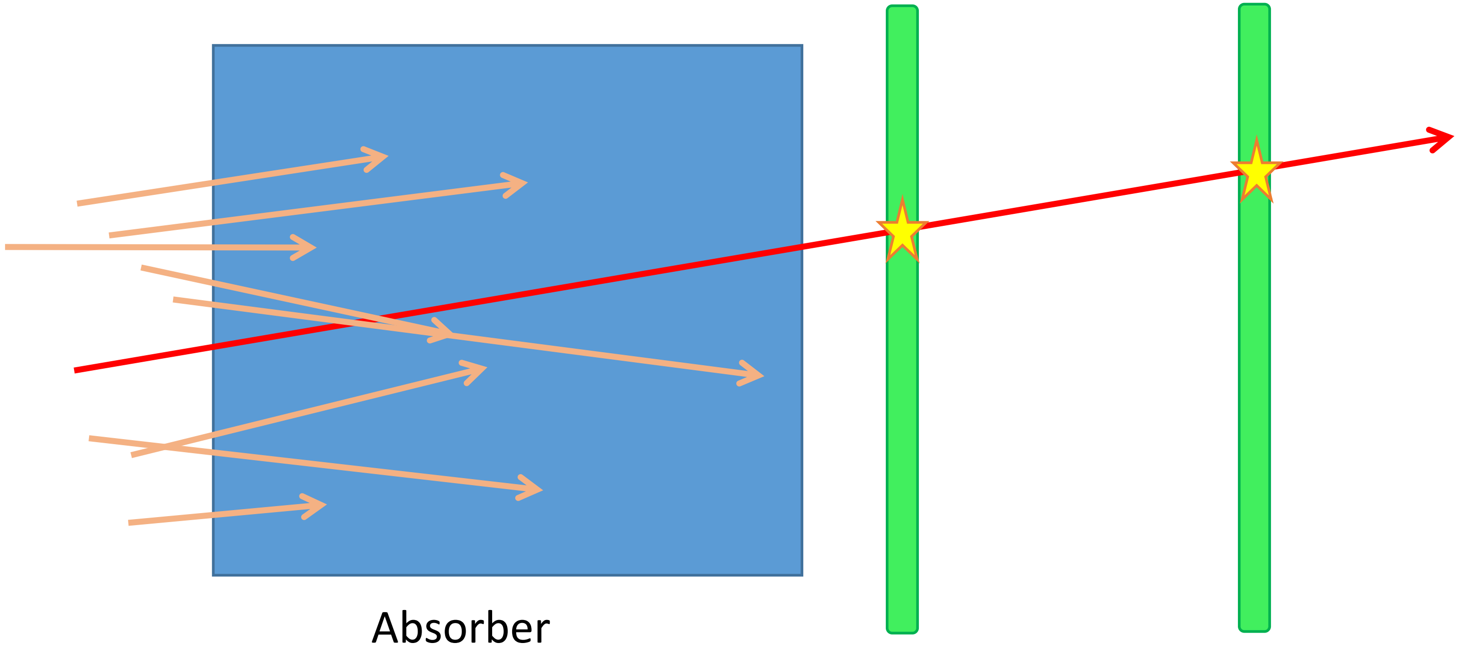
How to identify a muon?

To ensure it is a muon, you need to make sure it is the only particle left.

Enough **absorber** that will stop all particles except muons and neutrinos (but you will not detect them…)



Absorber

High Z materials
Usually instrumented (calorimeter)

Muon detection layer

Muon detection layer

Interaction length (λ_I):
distance over which a high-energy hadron (proton, pion, kaon, neutron, etc.) travels in a material before undergoing a strong nuclear interaction.

$$P(x) = e^{-x/\lambda_I}$$

After 1 λ_I => 37% survive
After 2 λ_I => 14% survive
…
After 6 λ_I => 0.25% survive

Usually 12 λ_I calorimeters at LHC energies

Iron = 16.8 cm, copper = 15 cm..

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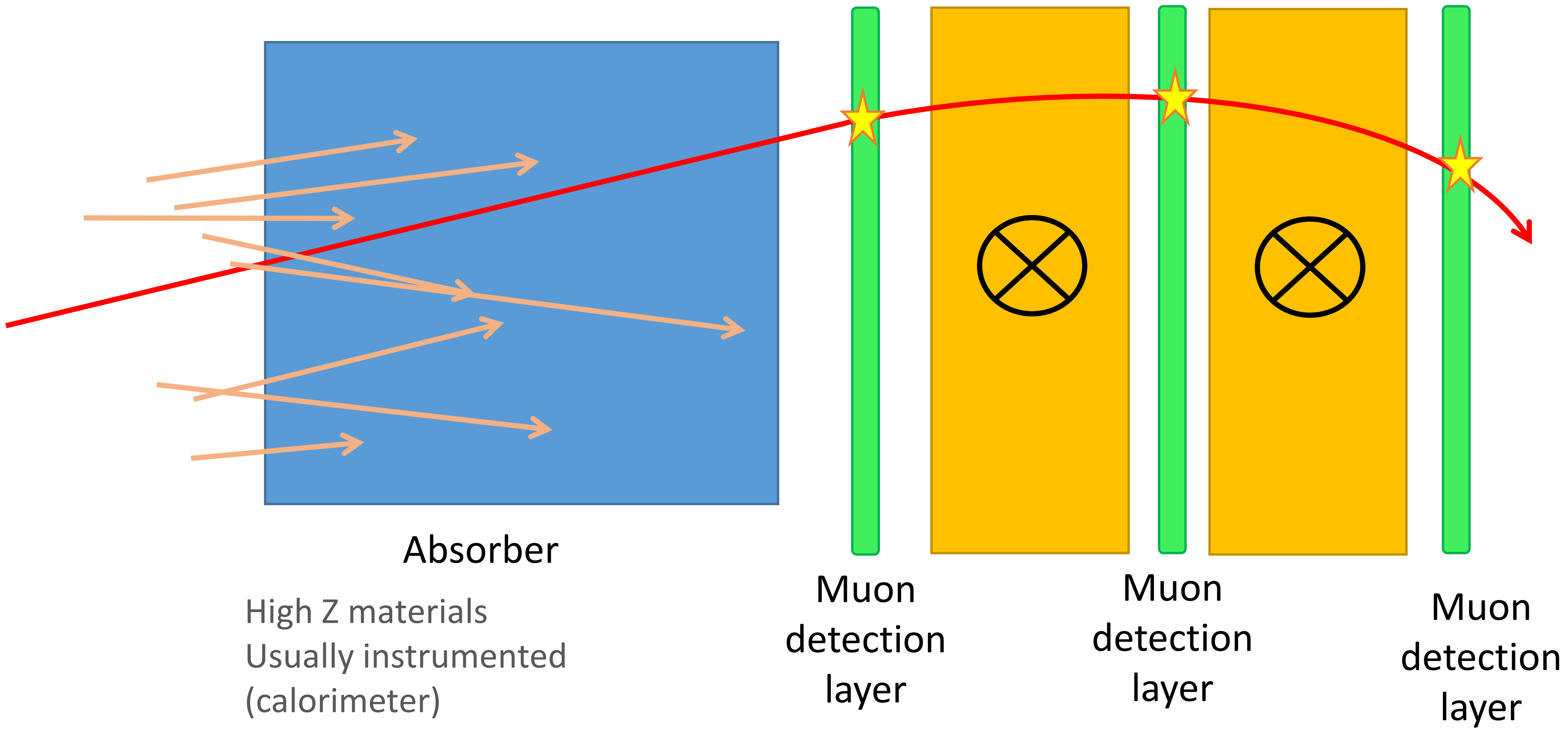
How to measure a muon?

Now you are sure you have a muon, but likely you want to say something about its energy…

Curvature of the muon in the magnetic field is proportional to the momentum of the muon



Curvature in a magnetic field:

$$R\,[m] \simeq \frac{p\,[GeV/c]}{0.3\,B\,[T]}$$

100 GeV muon in 1T field, 333 m….

Large fields, large muon systems

Positive and negative muons bend in opposite direction

How to measure a muon?

Sagitta

$s = R - R\cos(\theta/2) = R\,(1 - \cos(\theta/2))$

For small angles:

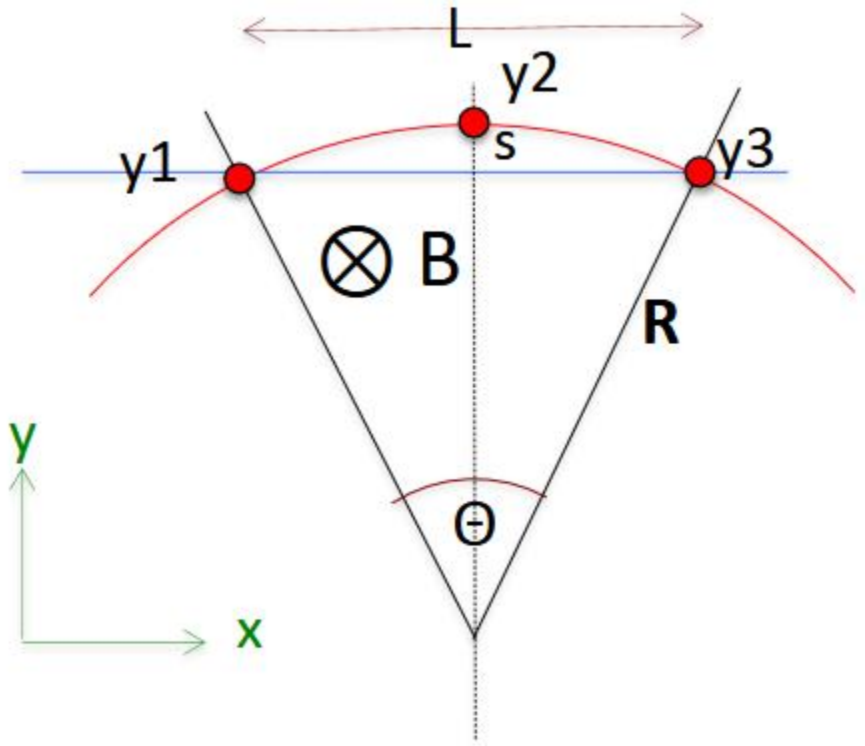
$\cos(x) \approx 1 - x^2/2$

$s \approx R\,\theta^2/8$

$s \approx L^2/ 8R$

$s \approx 0.3\,B\,L^2/8\,p_T$

Bending in an homogeneous field



$$\frac{\delta p}{p} \simeq \frac{\delta s}{s}$$

The momentum resolution is directly determined by how accurately the sagitta can be measured.

$$s \propto \frac{1}{p}.$$

Difficult to measure high energy muons with precision, they bend little

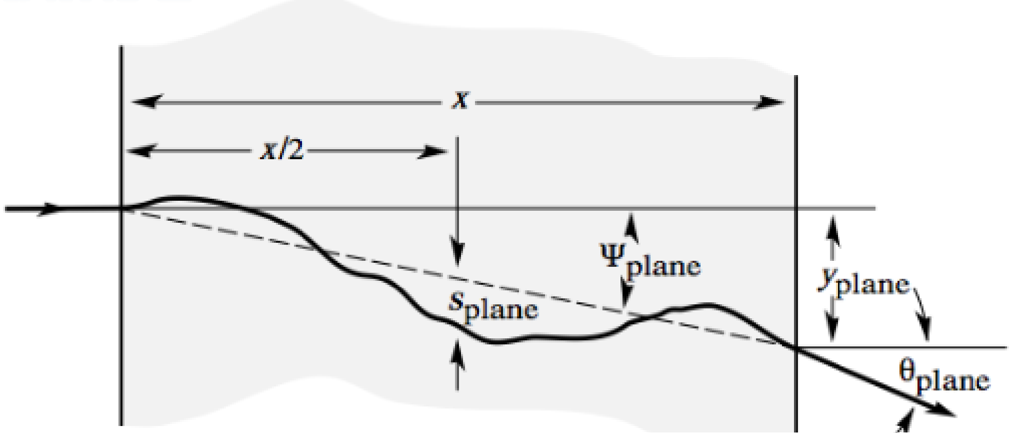
Large muon detectors, and ALIGN LARGE ESTRUCTURES (civil engineering problem)

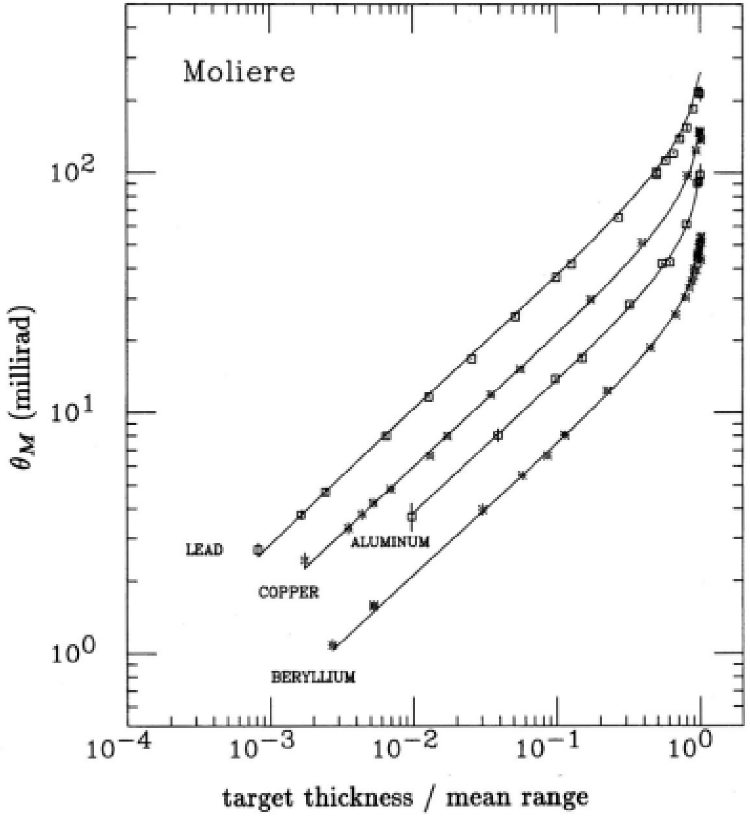
Multiple scattering

Charged particles: large number of small scattering processes when traversing matter

They are small, but many, they accumulate

They result in a change of the particle's direction (Θ) and a displacement of its position (or exit point)





Highland formula

$$\theta_0 = \theta_{plane}^{rms} = \frac{13.6\text{MeV}}{\beta pc} z\sqrt{x/X_0}\,[1 + 0.038 ln(x/X_0)]$$

- p = momentum,
- $\beta = v/c$,
- x = material thickness,
- X_0 = radiation length.

$$\theta_0 \propto \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

- **Lower momentum => More scattering**
- **Greater thickness and density of material => More scattering**

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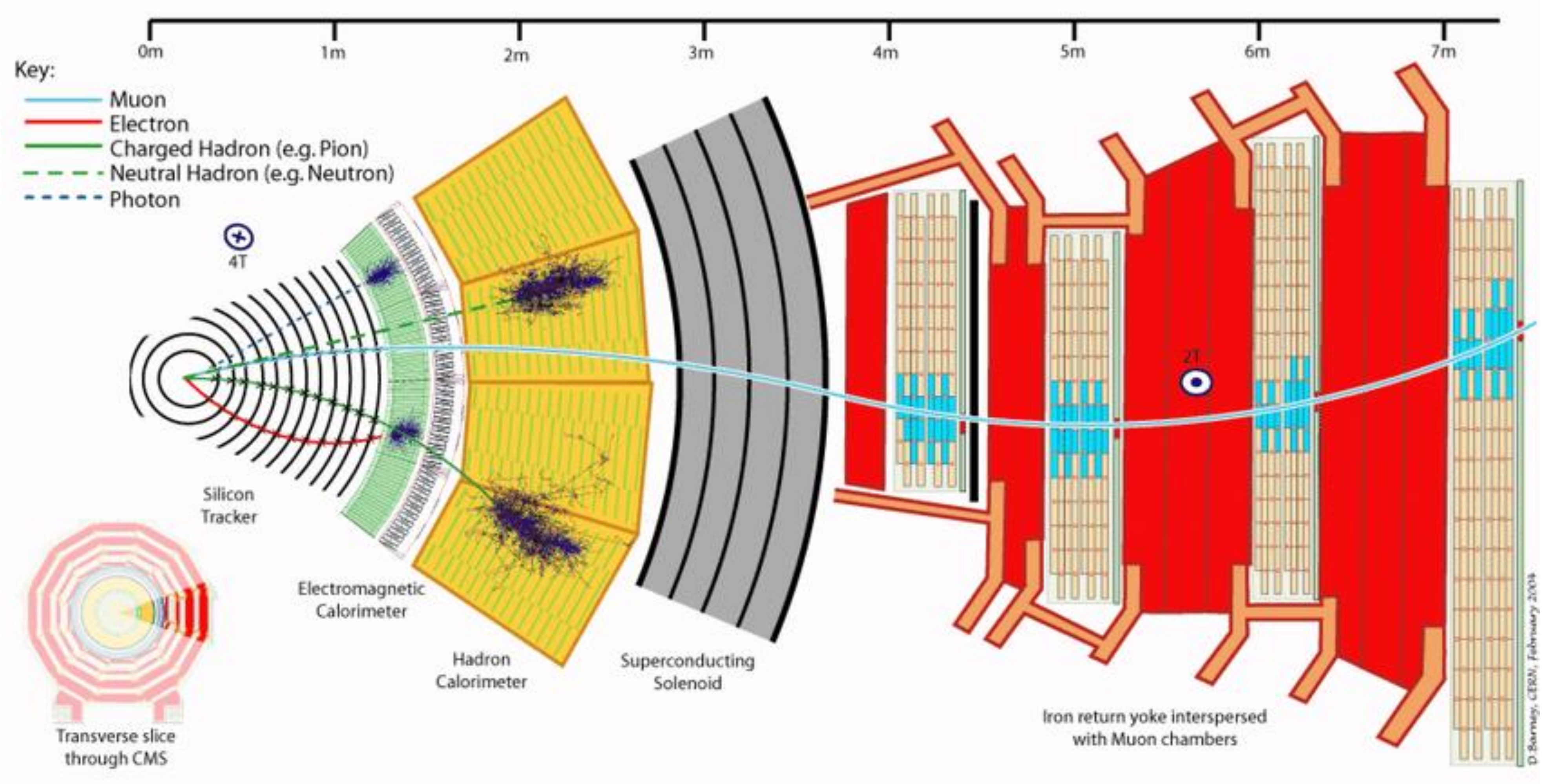
How to measure a muon?

Muon systems: large, external part of the detector, embedded or after enough absorber, inside a B field



Muon systems: type of magnet (iron-core, air-core, ...) , precision requirements, **area** to be covered, **cost** & maintenance → Price usually determines technology (gaseous detectors)

Gaseous detectors

- A charged particle ionizes the gas molecules, creating ion–electron pairs.

They move in all directions and lose their energy through collisions with the gas molecules (thermalization).
If an electric field is applied to the gas, ions and electrons experience forces in opposite directions and drift along the field lines:

ion→cathode   electron→anode

Coulomb interaction between the electric field of the particle and of the molecules of the medium produce electron-ion pairs

$\Rightarrow X + p \rightarrow X^{+} + p + e^{-}$

Excitation: $Ne + p \rightarrow Ne^{*} + p$

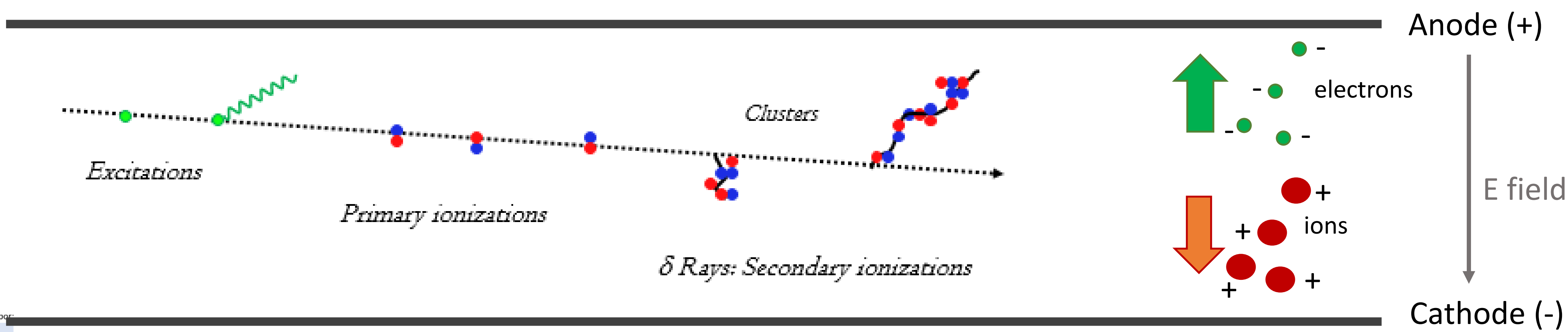
$Ne^{*} + Ar \rightarrow Ne + Ar^{+} + e^{-}$ (*Penning* effect)

Multiple ionizing collisions follow Poisson distribution

$$P_k^n = \frac{n^k}{k!} e^{-n}$$

n : average
k : actual number

A second ionization process can occur with δ ray electrons: primary electrons with enough energy to ionize the gas: effects on the total number of ionization electrons !! (and spatial resolution as well)



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Gaseous detectors: Ionization

$$N_e = \frac{\Delta E}{W}$$

- W≈25−35 eV/pair

MIP in Argon => ~100 electrons/cm

GAS	Density g cm^{-2}	E_X eV	E_I eV	W_I eV	dE/dx keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
Ne	0.839 10^{-3}	16.7	21.6	30	1.45	13	50
Ar	1.66 10^{-3}	11.6	15.7	25	2.65	25	106
Xe	5.495 10^{-3}	8.4	12.1	22	6.87	41	312
CH_4	0.667 10^{-3}	8.8	12.6	30	1.61	37	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
i-C_4H_{10}	2.49 10^{-3}		10.6	26	5.67	90	220
CO_2	1.84 10^{-3}	7	13.8	34	3.35	35	100
CF_4	3.78 10^{-3}	10	16	54	6.38	63	120

E_x , E_i : first excitation and ionization potentials
W_i : average energy per ion pair
N_P , N_T : primary and total ion pairs per cm for 1 proton

- ✓ In gaseous detectors typically ~100 ion/electron pairs are produced by a MIP in 1 cm of gas
- ✓ To be compared to ≈24.000 hole/electron pairs produced in 300 µm of Si.
- ✓ The typical noise level of a signal amplifier is ~1000 e^-

➡ We need **amplification**!!

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Gaseous detectors: Avalanche Multiplication and Gas Gain

Townsend Avalanche

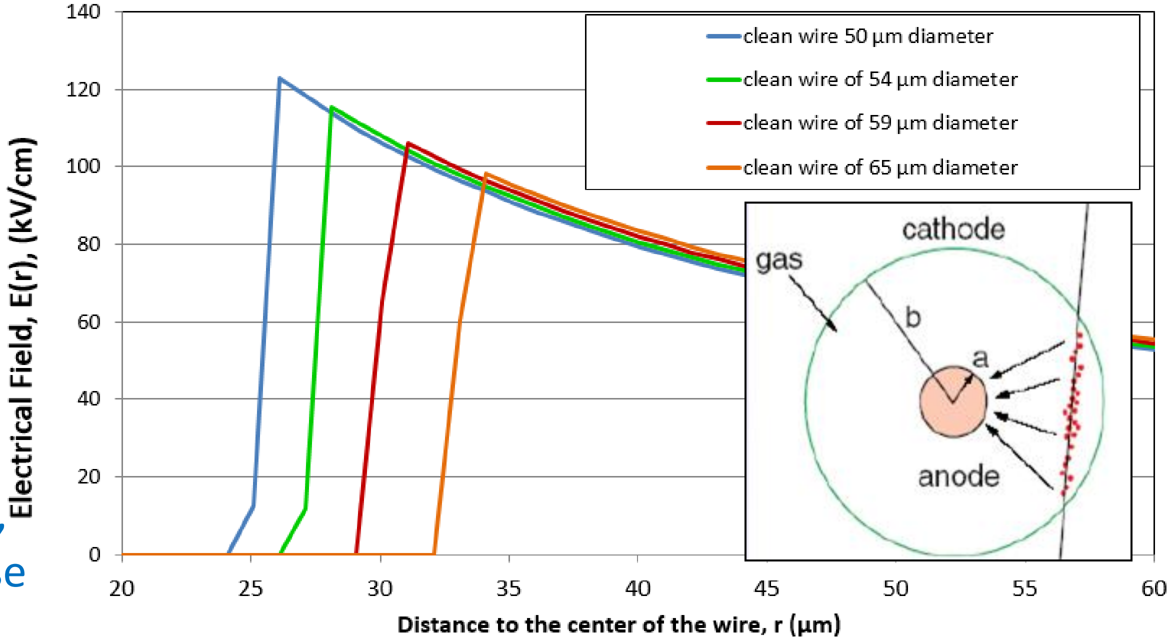
Near thin anode wires, GEM holes or Micromegas meshes:

$E \sim 50\text{–}100\ \text{kV/cm}$

Electrons acquire enough energy to ionize new atoms.

First Townsend coefficient (α)

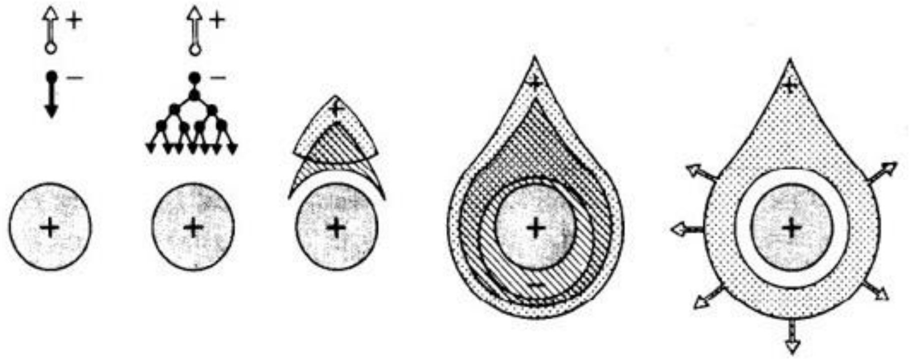
$$\alpha = \frac{\text{number of ionizing collisions}}{\text{unit length}} \qquad N(x) = N_0 e^{\alpha x} \qquad G = e^{\alpha d}$$



If the electric field is sufficiently high, an electron is accelerated and gains enough energy to ionize a gas molecule, producing a new electron. The process repeats itself, giving rise to an electron avalanche.

Electron avalanche

(a measurable charge pulse is induced on the readout electronics).



The gain (G), or gas amplification factor, is defined as

$G = n/n_o$

n= total number of electrons after multiplication

n_0=number of primary electrons in the absence of multiplication

Thus, the gain represents the factor by which the initial ionization charge is amplified within the detector.

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Gaseous detectors: discharges

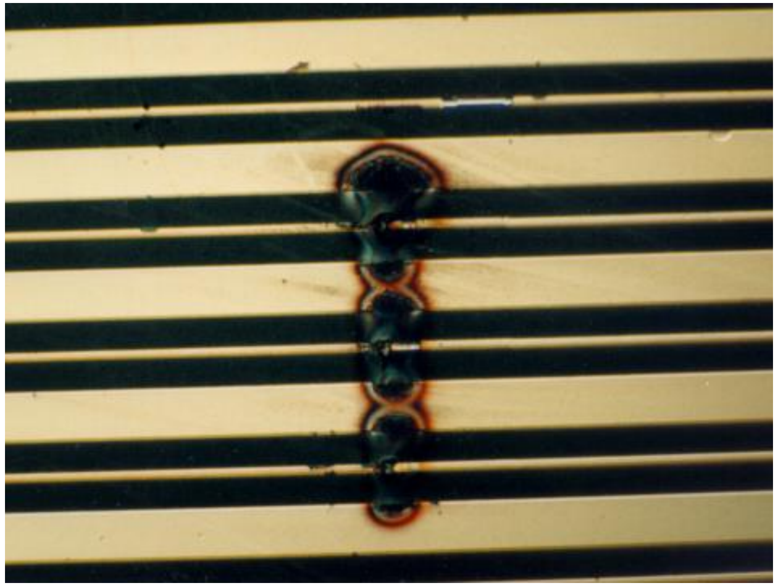
Avalanche growth is not unlimited.

Raether limit:
$N_{crit} \sim 10^7 - 10^8$ electrons.

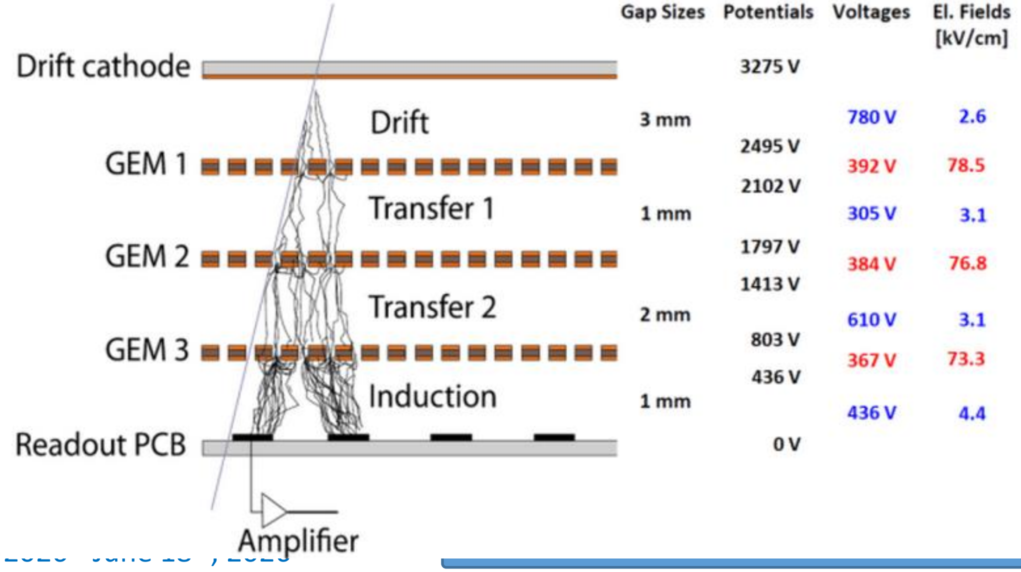
Beyond this:
- Space charge builds up.
- Streamer formation occurs.
- Full discharge (spark) may develop.

Consequences
- Dead time
- Electronics damage
- Detector ageing

Mitigation
- Resistive electrodes (RPCs)
- Segmented GEMs
- Resistive Micromegas
- Optimized gas mixtures
- Multi-stage amplification



MSGC (1994)
Micro-Strip Gas Chambers



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Gaseous detectors: Operation modes

Depending on the **applied voltage**, different operating regimes can be identified:

Recombination region

Electrons recombine with positive ions before reaching the anode.

Ionization region

Electrons reach the anode, but no gas multiplication occurs.

Proportional region

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

As a result, the deposited energy can be measured.

Limited proportionality region

Saturation effects become significant.

Strong photoemission leads to the development of secondary avalanches.

Geiger region

Massive photoemission occurs throughout the detector volume.

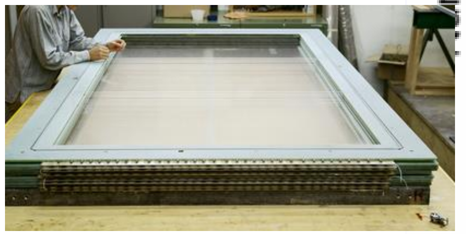
The pulse amplitude is no longer related to the initial ionization, so energy measurements are not possible.

Continuous discharge region

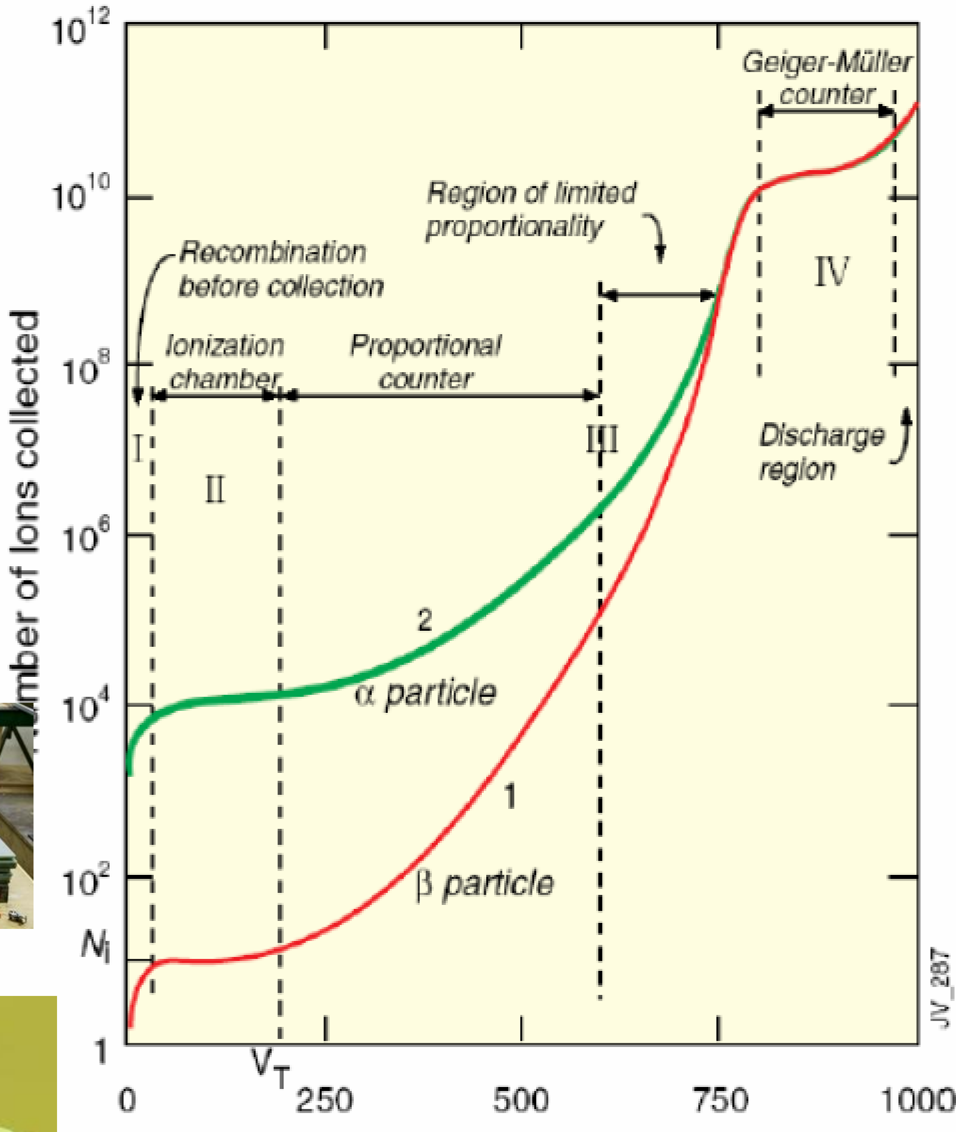
The detector enters a self-sustained discharge state and can no longer operate properly.

Ionization chamber

Proportional counter



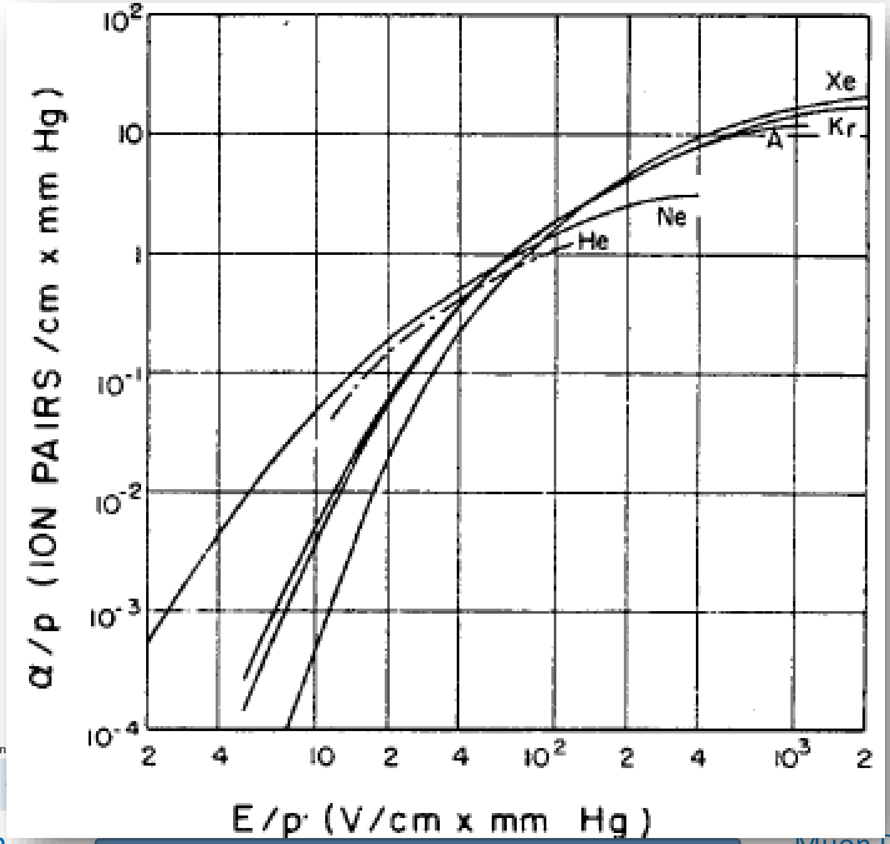
Geiger-Müller counter

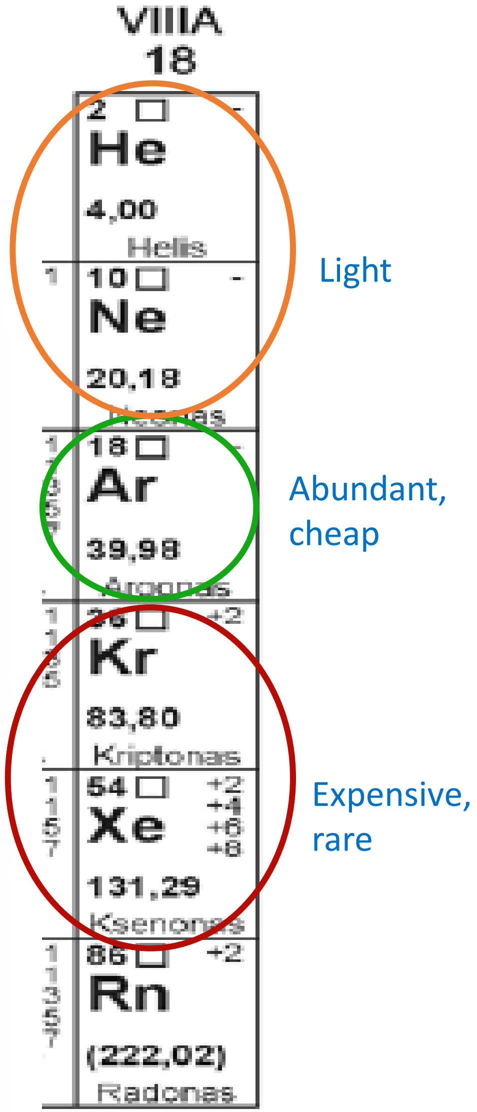


Gaseous detectors: Choice of gas

Gaseous detectors typically use noble gases because they require the lowest electric fields to initiate electron avalanches.

Argon is widely used due to its low cost and favorable operating characteristics.





Pure noble gases: unsuitable for proportional operation because excited atoms emit UV that can trigger secondary avalanches and discharges.

Noble gases are mixed with molecular additives such as CO_2 or iC_4H_{10}. They act as quenchers by absorbing excitation energy through non-radiative processes (vibrational, rotational), suppressing UV photon emission.

Also, some gases exhibit electron attachment and vibrational excitation channels, which reduce the probability of secondary avalanche formation (electronegative)

The combined effect of photon quenching and electron moderation allows gaseous detectors to operate stably at high gains, typically up to $\sim 10^4$ - 10^5.

GWP in Muon Detectors

- Mixture cost can range from 1 CHF/m³ (Ar/CO_2) to more than 100 CHF/m³ ($Ar/CO_2/CF_4$).
- Typical flow 10 m³/h for about 300 days/year

→ Gas cost can range from 72 kCHF (Ar/CO_2) up to 7.2 MCHF for ($Ar/CO_2/CF_4$)

Table 8.4 Greenhouse gas properties related to global warming.

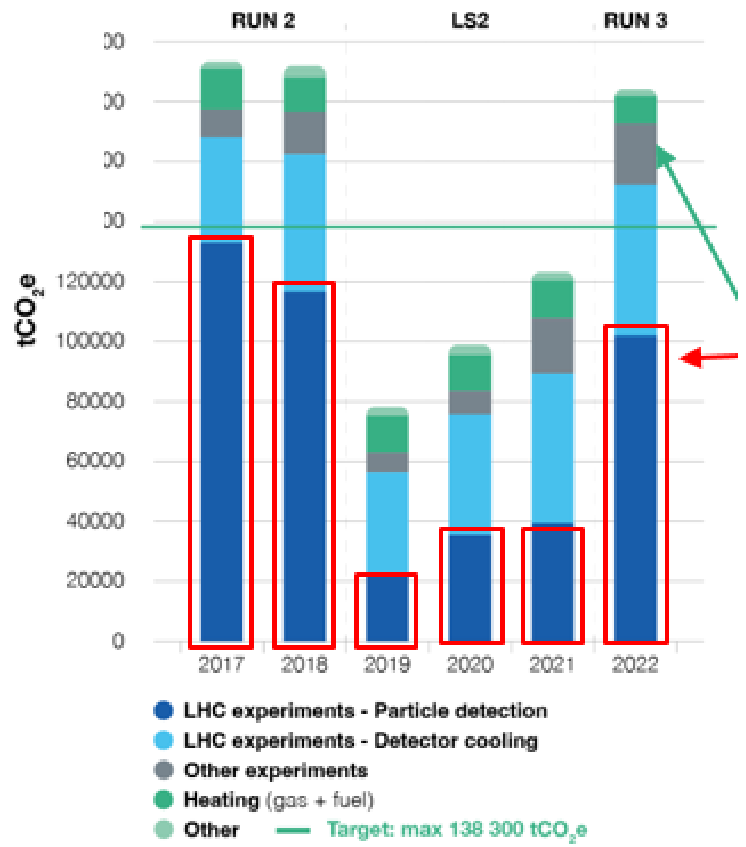
Gas	Residence time / y[a]	Relative instantaneous radiative forcing	Global warming potential (GWP)[c]
CO_2	50–200[b]	1	1
CH_4	12	43	23
N_2O	115	250	296
CFC-11	45	15 000	4 600
CFC-12	102	19 000	10 600
HCFC-22	12	13 000	1 700
CCl_4	35		1 800
C_2F_6	10 000		11 900
SF_6	3 200		22 200

[a] Most of the atmospheric lifetime values are taken from Additional Reading 1.

[b] Reported residence time values for carbon dioxide are highly variable. Differences are associated with the way in which oceanic uptake is measured, particularly whether the surface layer or the entire ocean is considered in the calculation.

[c] GWP values are obtained by integration over a 100 y period. Obtained from Blasing, T.J. and S. Jones, *Current greenhouse gas concentrations*, <http://ediac.esd.ornl.gov/pns/current_ghg.html> (February 2004). These values relate to direct effects; interactions of CFCs with ozone in the lower stratosphere may reduce the amount of radiation into the lower atmosphere, contributing to a cooling effect. The GWP values would be correspondingly reduced.

GWP: Global Warming Potential

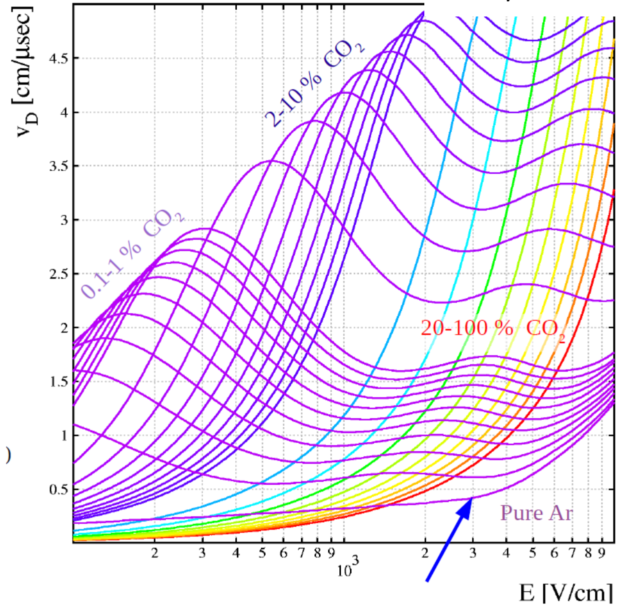


Several of the gases used in experiments have a very large GWP

The new EU Regulation (2023) calls for the total elimination of HFCs by 2050

Gaseous detectors: Electron drift and diffusion

Drift velocities computed by Magboltz at Ar/CO2 at 3 bar



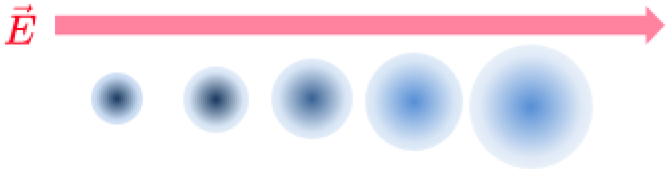
Drift

Electrons and ions move under electric field (µ mobility) $v_d = \mu E$

TYPYCAL DRIFT VELOCITY

- electrons ($v_d \sim$ cm/µs)
- ions ($v_d \sim$ cm/ms) (~1000 slower)

Diffusion

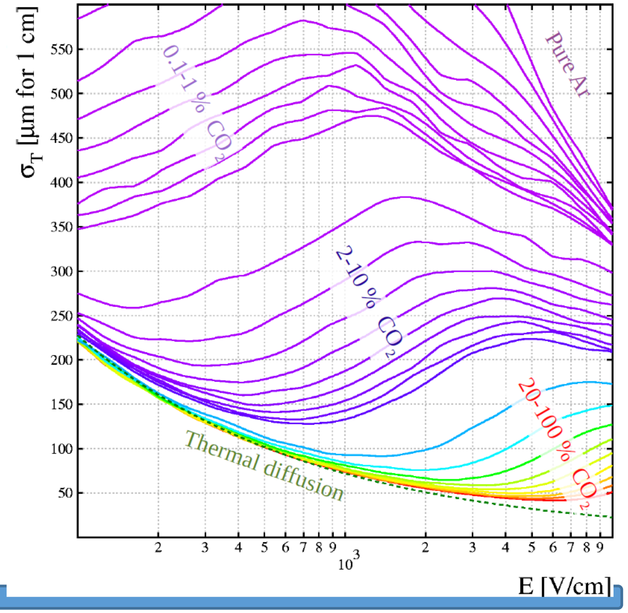


Thermal collisions broaden the cloud:

$\sigma = 2Dt$

- Transversal diffusion related, typically, to spatial resolution
- Longitudinal diffusion related, sometimes, to time resolution

Gas mixtures are often selected as much for their diffusion properties as for their gain characteristics.



Consequences

- Spatial resolution degradation.
- Limits maximum drift length.
- Critical for TPCs and large drift chambers.

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Aging in Gaseous Detectors

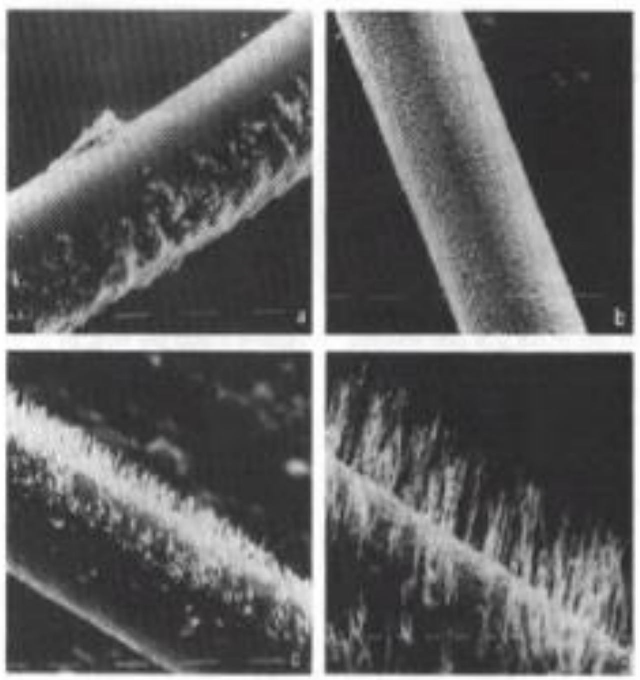
Aging refers to the gradual degradation of detector performance caused by prolonged exposure to radiation and accumulated charge. Typical effects:

- Gain loss
- Increased dark current
- Reduced efficiency
- Higher discharge probability
- Mechanical and chemical damage

Aging Parameter
Detector lifetime is usually characterized by:

$Q_{int}=\int I\,dt$

Integrated charge per unit length or area
• GEMs: >100 mC/cm²



Main Aging Mechanisms

Polymer Deposition

Avalanche-induced dissociation of gas molecules:
CF_4, CH_4, iC_4H_{10} → free radicals
Development of deposits in the form of tiny whiskers (polymerization of chemical elements in the gas)
•anode wires , GEM foils , Micromegas meshes

Cathode Damage

- Surface modification
- Increased resistivity
- Secondary electron emission changes
- Can lead to Malter currents and self-sustained discharges:
  - Positive ion accumulation → charging of insulating layer → field emission → self-sustained avalanches

Mitigation Strategies
✓ Highest purity gas mixtures
✓ Careful material selection (low outgassing)
✓ Gas purification and recirculation
✓ Resistive protection layers, low currents
✓ Distributed amplification (GEMs)
✓ Extensive irradiation qualification tests
✓ Fluorinated gas additives (e.g. CF_4) to suppress polymer deposition (careful…)

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Some examples of gaseous detectors

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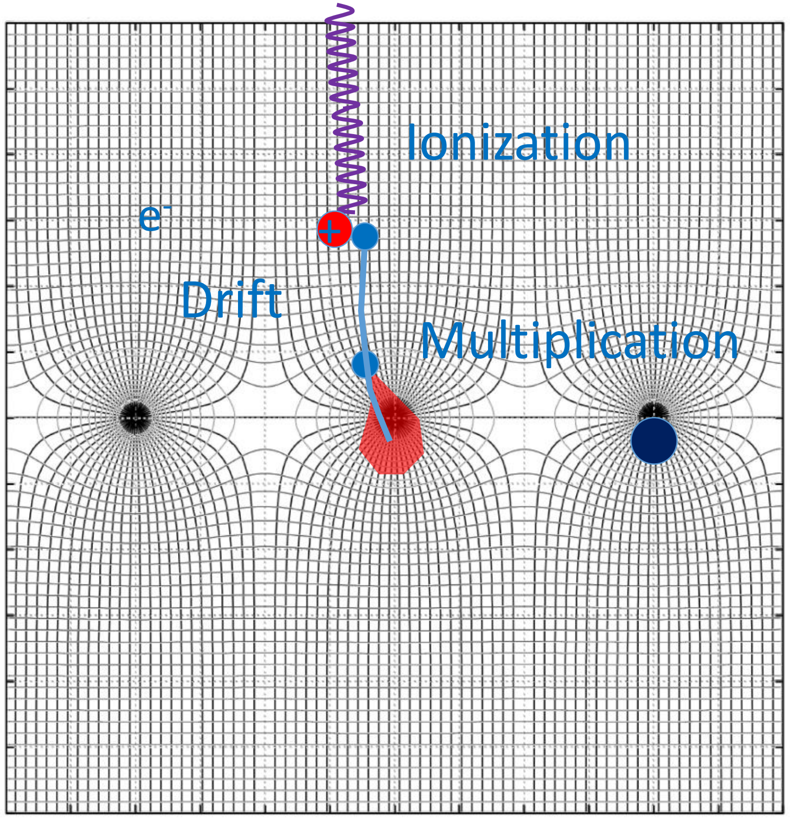
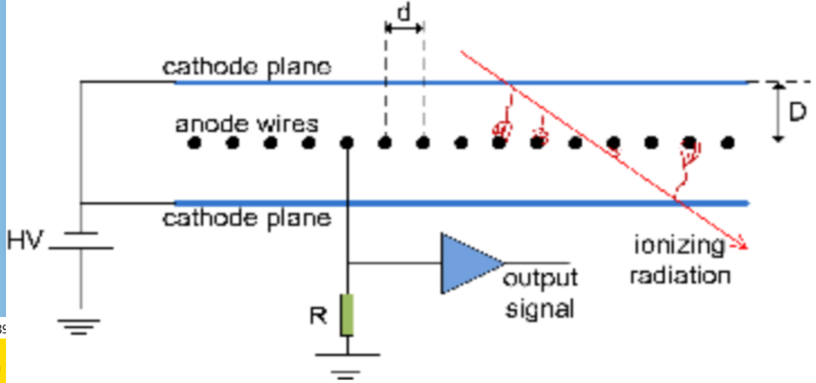
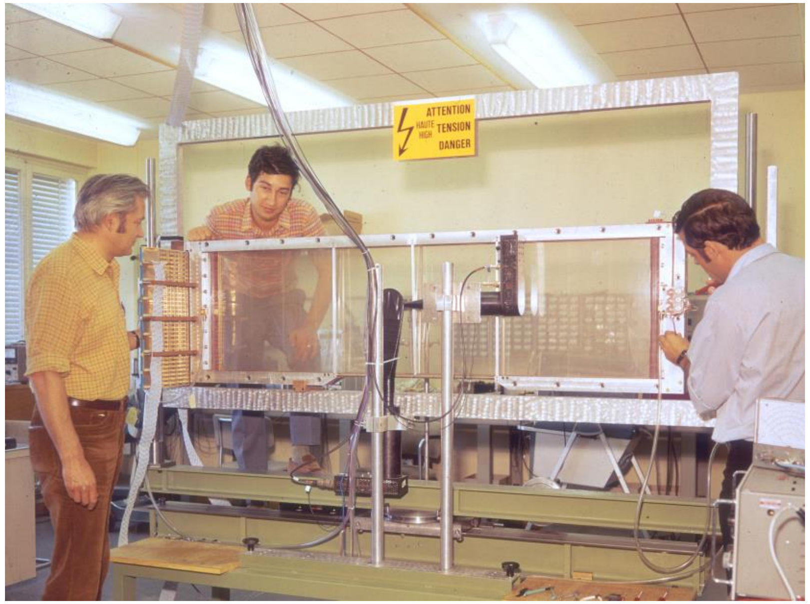
Cofinanciado por la Unión Europea
AGENCIA ESTATAL DE INVESTIGACIÓN

MWPC: Multiwire Proportional Chamber





FIRST LARGE MWPC (CERN 1970)



Georges Charpak
(Nobel Prize in 1992)

Nucl. Instr. Meth. 62(1968)282

Major breakthrough in gaseous detectors:

- Signal can be connected to the electronics chain and into the computer
- Photography scanning could be abandoned

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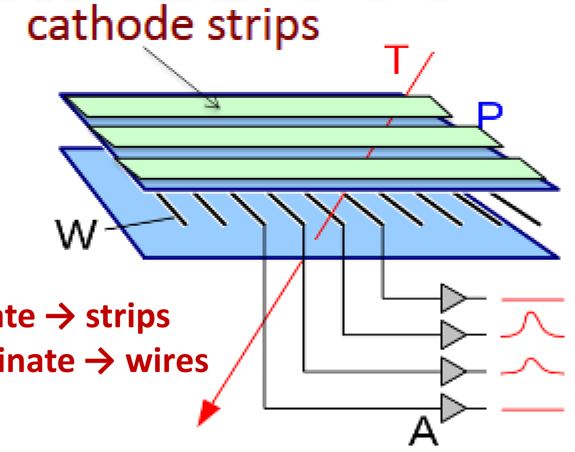
Proyecto PID2023-14889

From MWPC to CSC, TGCs

- Several approaches to extract the

2nd coordinate from MWPCs were used:

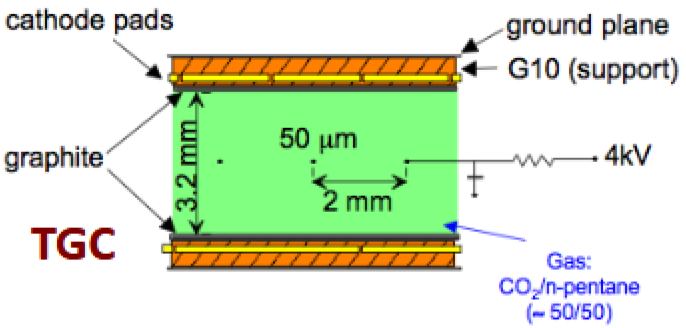
- Crossed wire planes
- Charge division: resistive wires read out from the two sides
- Time division: comparing the signal arrival time at the two wire ends



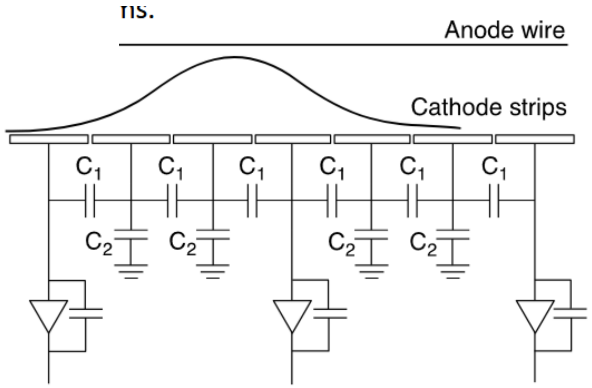
Fine coordinate → strips
Coarse coordinate → wires

Segmented cathode planes, picking up the induced signal, leading to a number of variants of the MWPCs:

- **Cathode Strip Chambers (CSCs)**
- **Thin Gap Chambers (TGCs) (triggering)**



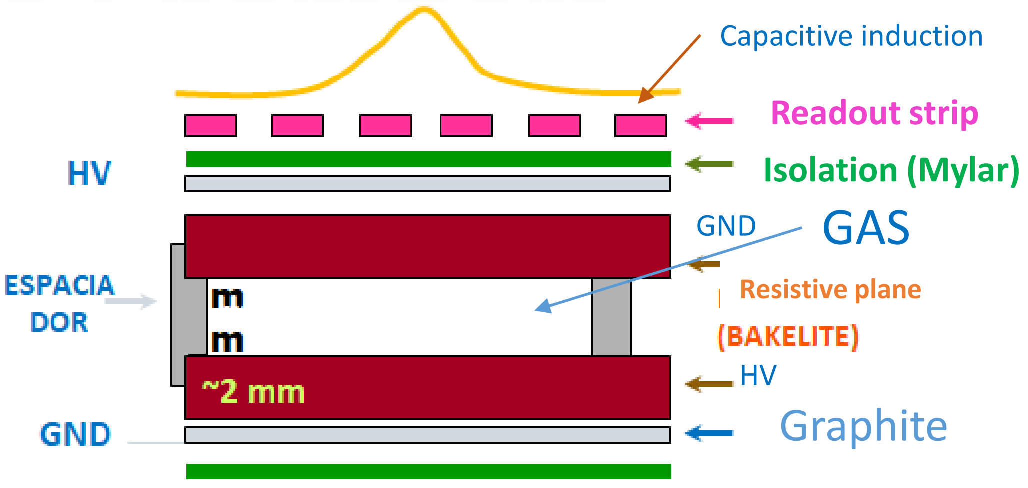
- Gas: $Ar/CO_2/CF_4$
- Gap: 5–10 mm
- Gain: 10^5
- Resolution: 50–150 μm
- Timing: ~5 ns
- Rate capability: several kHz/cm²



Fast, precise and good operation in high-background environments.

RPC: Resistive Plate Chambers

- RPCs are composed of two parallel resistive electrodes operated at high voltage (typically ~9 kV) and separated by a gas gap
- The resistive plates limit the current and suppress discharges.
- The gas avalanche induces a charge on external readout strips.
- Thanks to the fast development of the avalanche, RPCs provide excellent timing performance, with time resolutions of about 1 ns.
- They can work in avalanche mode (Gain~10^7) or streamer mode (Gain~10^9)



•CMS RPC system.
•ATLAS RPC barrel trigger.
•BELLE and many neutrino experiments.

Advantages
- Excellent timing (~1 ns)
- Used in the trigger
- Cost-effective

Limitations
- Moderate spatial resolution (~0.1-1 cm)
- Rate capability limited by electrode resistivity (~700 Hz/cm^2)

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Proyecto PID202

DT and MTD: Drift Tubes

- Drift chambers allow great precision (~100 µm) with few channels (very cost effective).
- They measure the drift time between the primary ionization and the arrival of the electrons at the anode.
- The electron drift velocity depends on the reduced electric field E/p and the gas mixture.

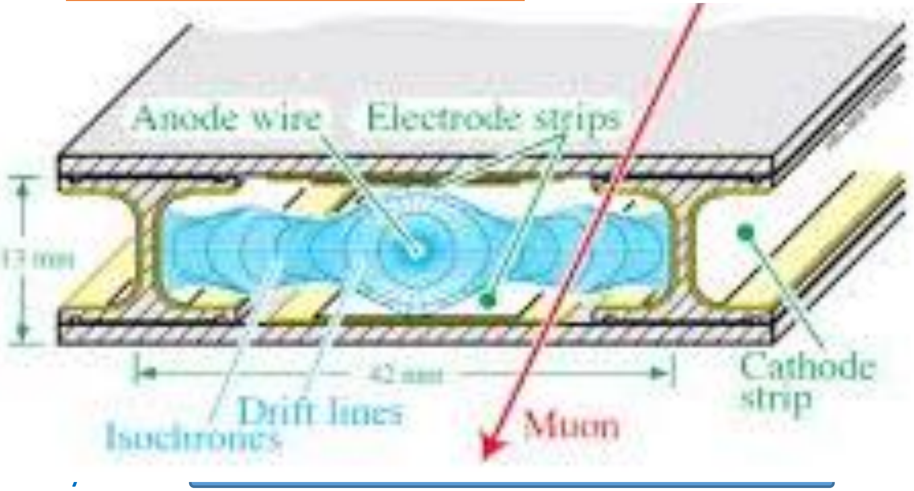
> - Gas: Ar/CO_2 (85/15) CMS – (93/7) ATLAS
> - Voltage: ~3600 V (CMS) 3080 V (ATLAS)
> - Gain: 10^4–10^5
> - Max drift: ~400 ns (CMS) – 700 ns (ATLAS)
> - Single tube spatial resolution: 85 µm (ATLAS) –250 µm (CMS)

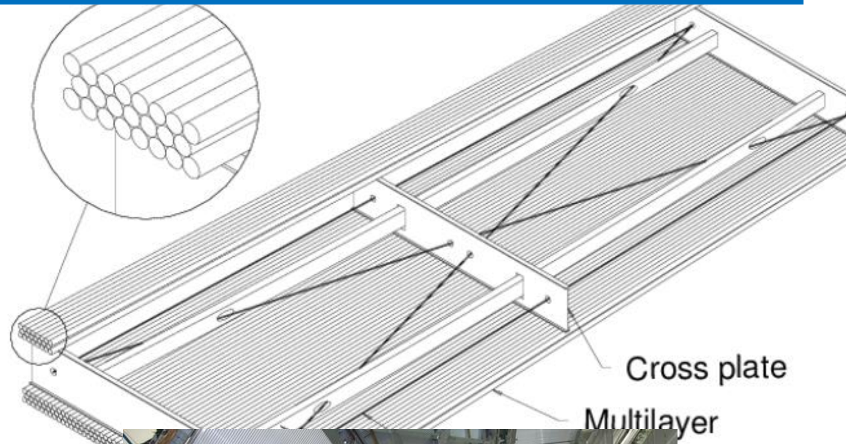
Advantages
- Very precise tracking.
- Reliable long-term operation.
- Ideal for low-background environments.

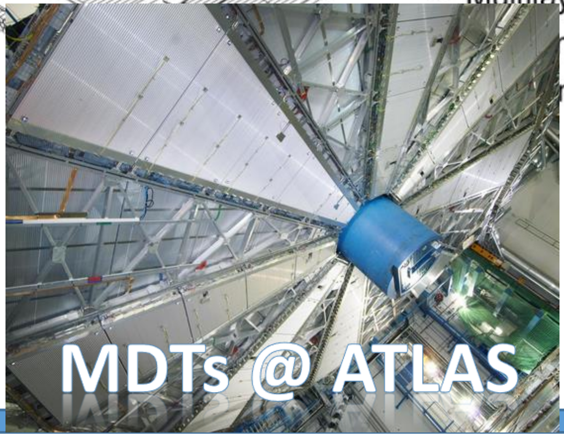
Limitations
- Slow response.
- Not suitable for extremely high particle rates.

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

V_D=Drift velocity (~50 µm/ns)







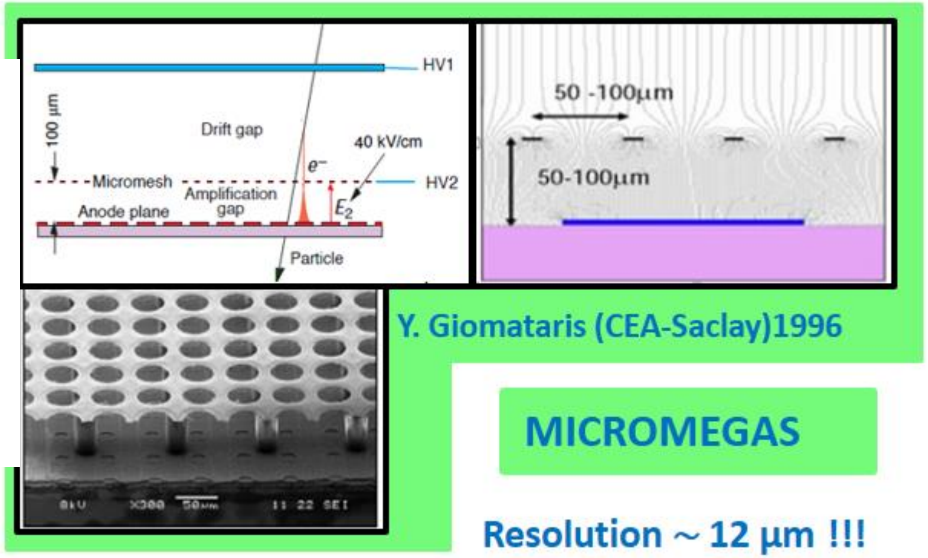
MPGD: Micropattern Gas Detectors

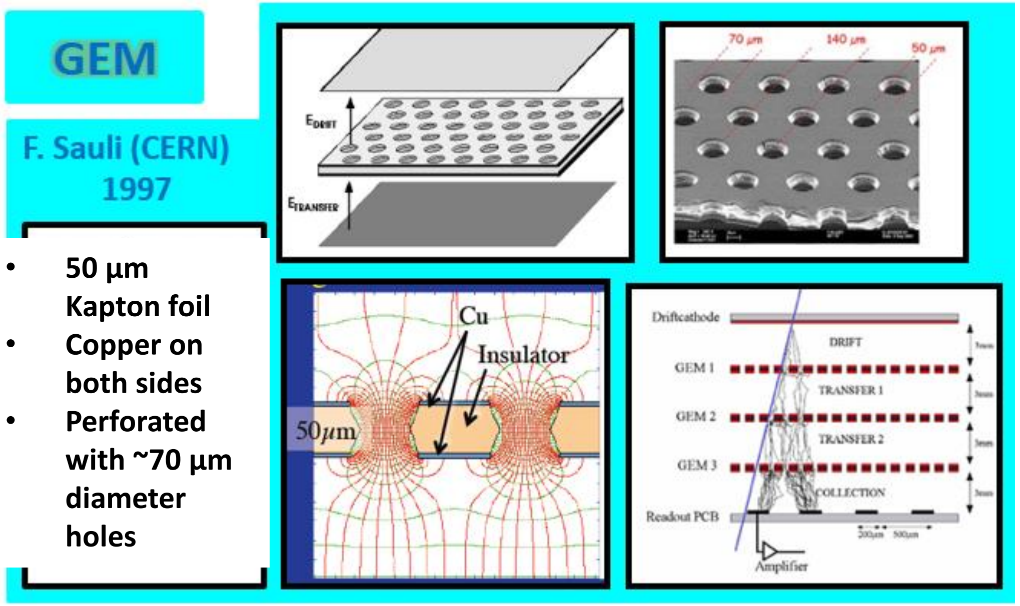
- Extremely thin amplification gap (~50–100 µm, compared to 2 mm in RPC)
- Produced using PCB-like photolithographic manufacturing techniques, enabling high precision and excellent reproducibility.
- Excellent spatial and time resolution, with high radiation tolerance.

Common features
- Micro-fabricated amplification structures
- Gain ~10^4
- High electric fields (40–100 kV/cm)
- Spatial resolution ~50–100 µm
- Rate capability >10 MHz/cm²
- Excellent radiation tolerance
- Low ion backflow

Main technologies
- **GEM**: amplification inside microscopic holes
- **Micromegas**: amplification in a thin mesh-anode gap

- **Conductive metallic mesh suspended above the readout plane**
- **Amplification gap 50–150 µm**
- **Insulating pillars defining and maintaining the gap**





Pile up GEMs

MPGDs represent the state-of-the-art gaseous detector technology for high-rate environments at the HL-LHC.

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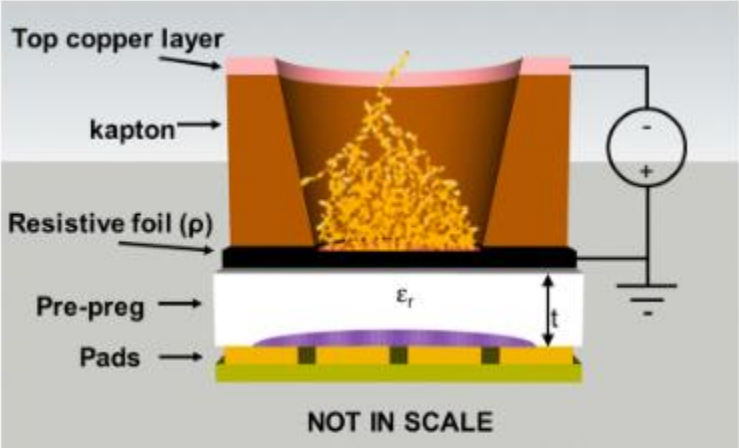
Emerging MPGD: uRWELL

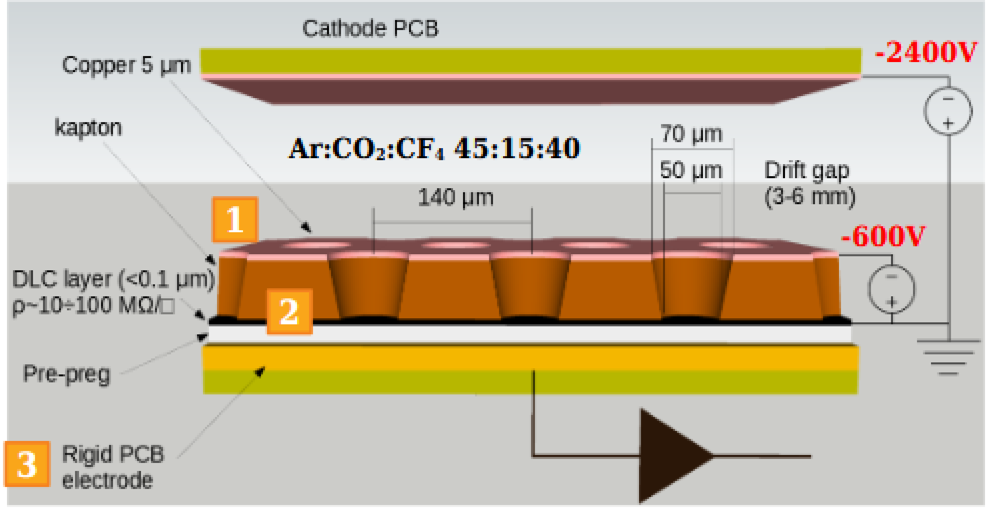
μRWELL

- Single-amplification-stage MPGD derived from GEM technology.
- Amplification in WELL structures etched on a Kapton foil.
- Resistive layer provides intrinsic spark protection.
- Simpler construction than multi-GEM detectors.
- Spatial resolution: ~100 μm.
- Rate capability: O(100 kHz/cm^2–MHz/cm^2).
- Candidate technology for large-area tracking and timing applications.

Combines GEM-like amplification with Micromegas-like spark protection in a compact and cost-effective design.

The μ-RWELL is a Micro Pattern Gaseous Detector (MPGD) composed of only two elements: the μ-RWELL_PCB and the cathode. **The core is the μ-RWELL_PCB**, realized by coupling three different elements:





1. **a WELL** patterned kapton foil acting as **amplification stage** (GEM-like)
2. a **resistive DLC layer (Diamond-Like-Carbon)** for discharge suppression with surface resistivity ~ 50÷100 MΩ/□
3. a standard readout PCB

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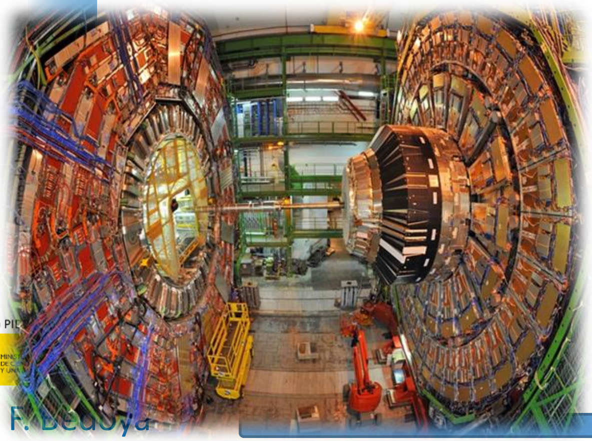
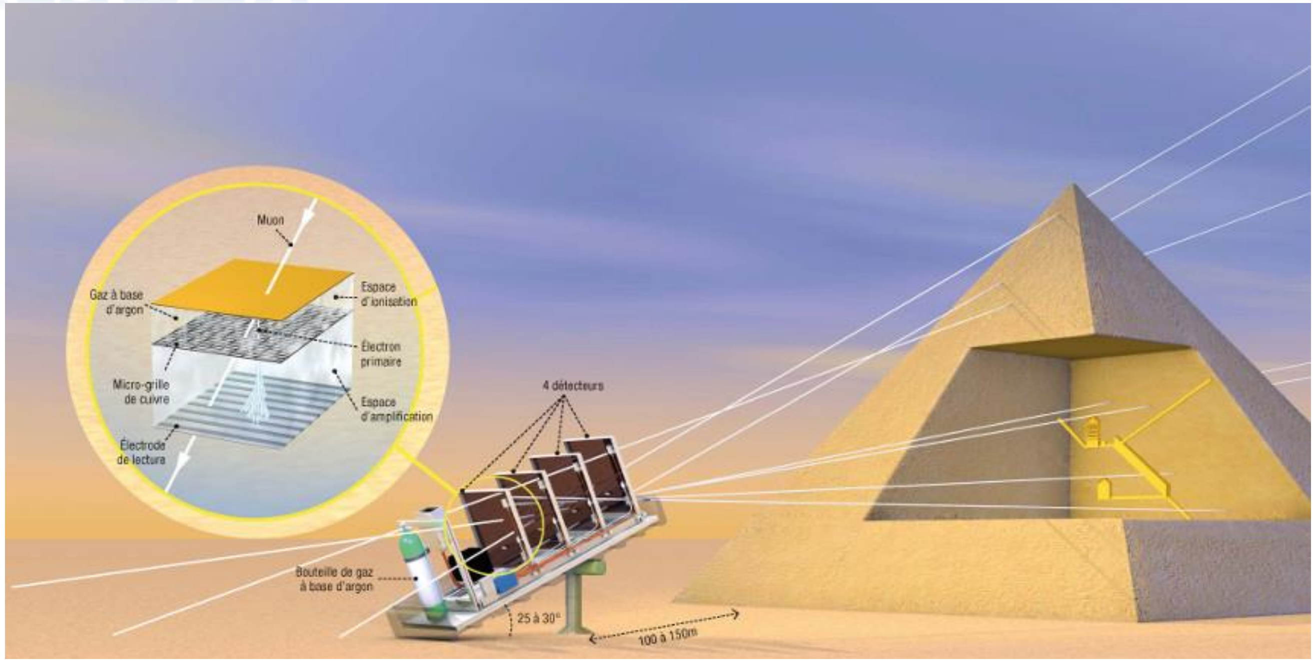
Summary of Muon detectors comparison

Technology	Spatial Resolution	Time Resolution	Rate Capability	Typical Role
DT	80–120 μm	few ns*	~10^2 Hz/cm^2	Precision tracking +trigger!
CSC	50–150 μm	3–7 ns	few kHz/cm^2	Precision tracking + trigger
RPC	5–10 mm	1–2 ns	~1 kHz/cm^2	Fast trigger
TGC	1–3 mm	<5 ns	~10 kHz/cm^2	Fast trigger
GEM	50–100 μm	3–5 ns	>10 MHz/cm^2	Precision tracking + trigger
Micromegas	~100 μm	3–5 ns	>10 MHz/cm^2	Precision tracking



Muography

Muon radiography uses cosmic-ray muons to obtain images of structures that would otherwise be inaccessible.
First applied by Luis Alvarez in 1970 search for hidden chambers inside the Egyptian pyramids.
http://lappweb.in2p3.fr/~chefdevi/Work_LAPP/Arche/alvarez_70.pdf

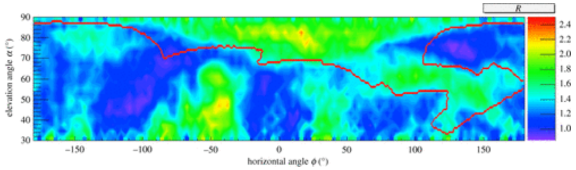


Arqueology

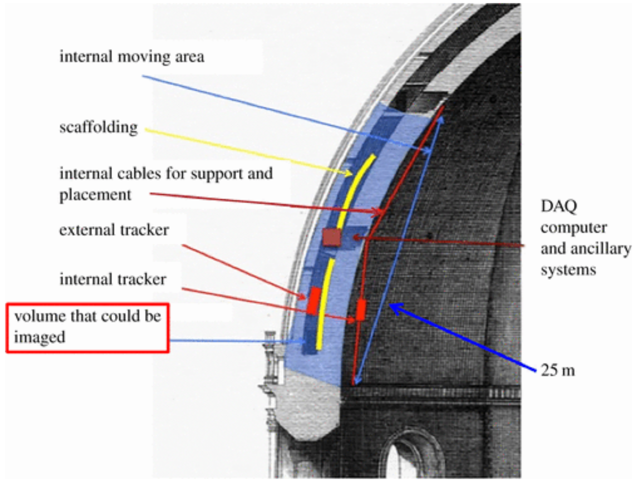
November 2017
Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons
https://www.nature.com/articles/nature24647

Civil infrastructure

Search for hidden tunnels and cavities beneath Mount Echia (Naples).
https://doi.org/10.1098/rsta.2018.0057
Scintillator bars + SiPMs.



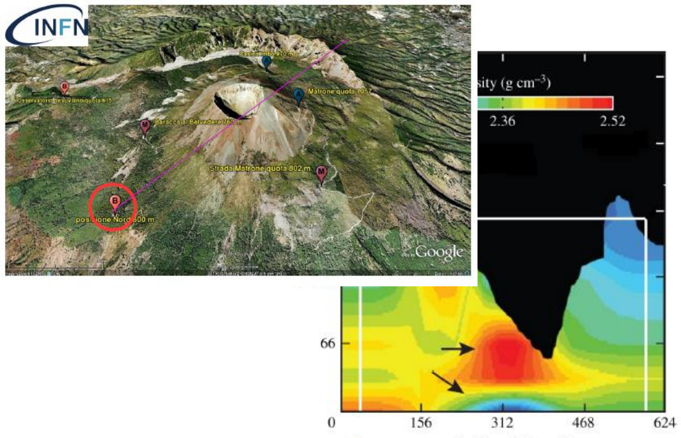
Structural stability of the dome of Santa Maria del Fiore in Florence.
https://doi.org/10.1098/rsta.2018.0136
The system employed two drift-chamber detectors placed on opposite sides of the dome

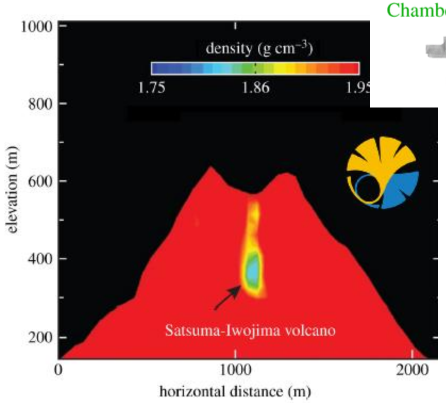


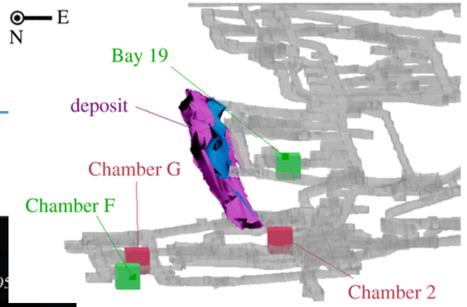
Muography

Vulcanology & Mining

Monitoring of Mount Vesuvius using muon radiography.
https://doi.org/10.1098/rsta.2018.0050
plastic scintillators + SiPMs.



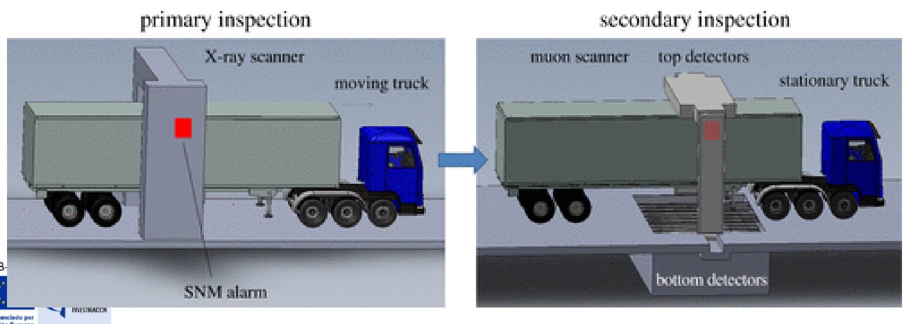




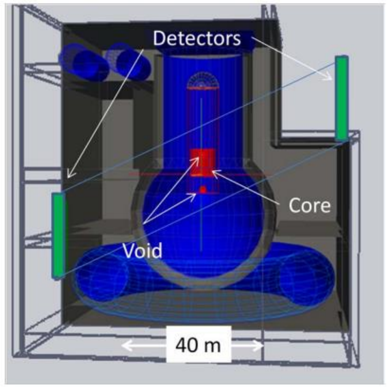
Uranium and lead ore exploration in the McArthur River (Canada) and Pend Oreille (USA) mines.
https://doi.org/10.1098/rsta.2018.0061

Nuclear industry, borders security

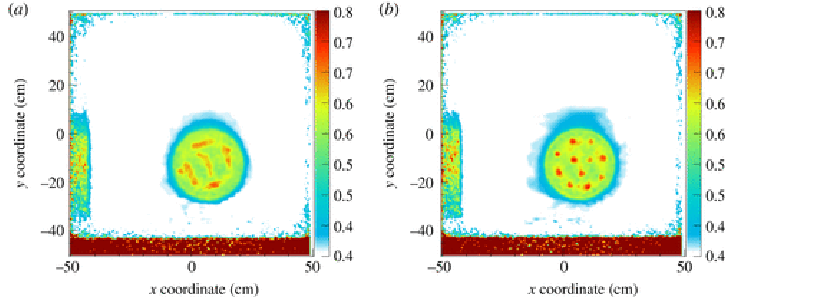
Border security and cargo inspection
Muon tomography, X-ray imaging, gamma-ray imaging, and combined techniques are used to inspect trucks and shipping containers.
https://doi.org/10.1098/rsta.2018.0051



Fukushima reactors inspection
https://arxiv.org/abs/1209.2761



Nuclear waste inspection
https://doi.org/10.1098/rsta.2018.0048



TIDPAN 2026 - Taller de Instrumentación y Detectores en Física de Partículas, Astropartículas y Nuclear

CPAN NETWORK ON INSTRUMENTATION AND DETECTORS

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Proyecto PID2023-148896NB-

Muon Detectors: Summary

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- Muon systems are a fundamental component of modern particle physics experiments and, due to their large dimensions and cost constraints, gaseous detectors remain the preferred technology for their instrumentation.

- The operation of gaseous detectors is based on ionization, electron transport and avalanche multiplication, with detector performance strongly influenced by the gas mixture and electric-field configuration.

- Over decades, gaseous detector technologies have evolved from wire chambers to modern micro-pattern detectors, providing continuous improvements in spatial resolution, timing performance and rate capability.

- Detector operation is limited by phenomena such as discharges and ageing, which require dedicated mitigation strategies and careful detector design.

- Modern GEM, Micromegas and emerging µRWELL detectors technologies have extended the capabilities of gaseous detectors into the HL-LHC era, and future muon systems will combine high precision, fast timing and operation in extreme radiation environments.

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Questions?

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