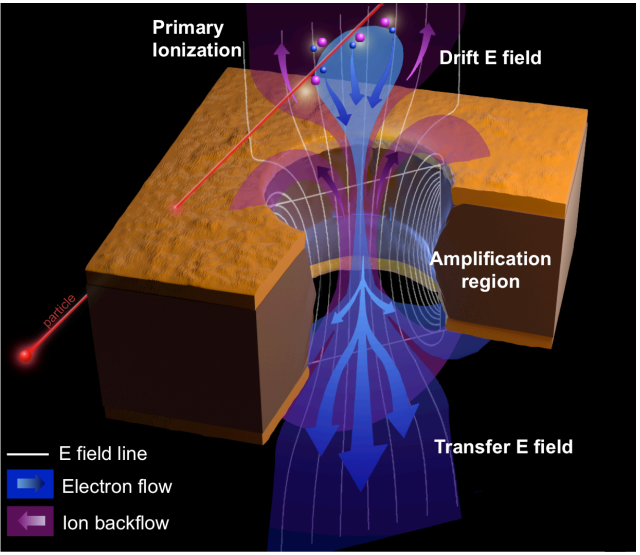
Introduction to Gaseous Detectors
Gaseous Technologies

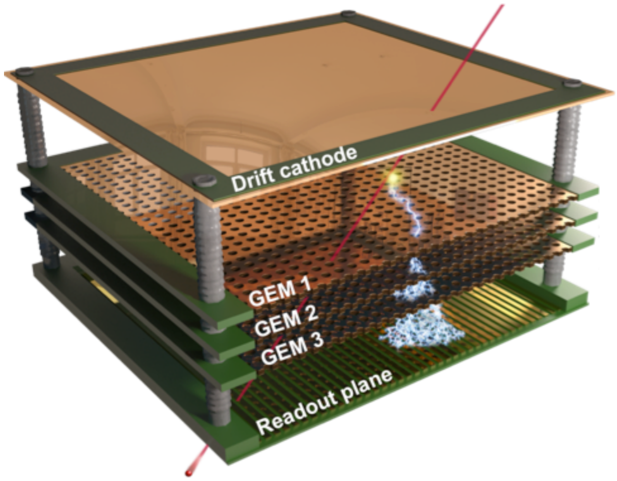
Jeremie A. MERLIN

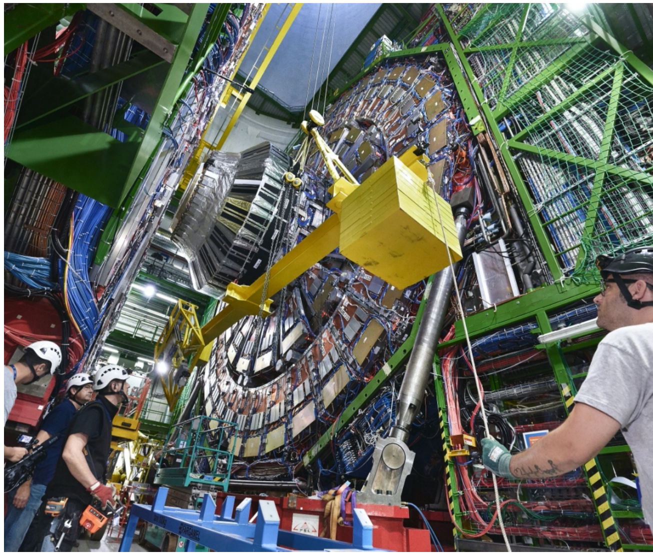
Detector lecture - II

Organized at University of Seoul, Seoul

January, 2024







Introducing Myself

Jeremie A. Merlin
Particle Physicist
Specialized in Detector Physics

- I joined the CMS GEM upgrade project in 2011
- My main responsibility is the coordinate the development of the triple-GEM technology for the CMS upgrade and to manage the production and quality control of the detectors

Contact:
Jeremie.alexandre.merlin@cern.ch

Education

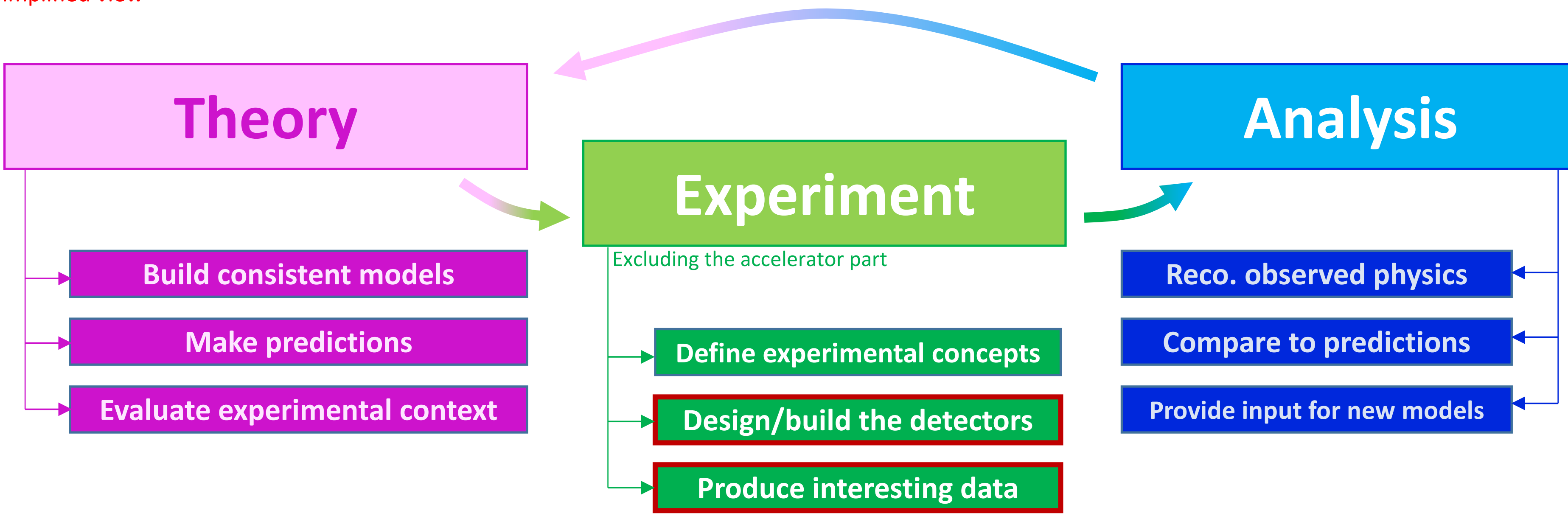
Apr. 2016	**Ph.D in Particle Physics**, University of Strasbourg Thesis: "Study of the long-term sustained operation of gaseous detectors for the high rate environment in CMS" *Conducted at CERN under the supervision of Archana* Sharma *(CERN) and Jean-Marie Brom (Institut Pluridisciplinaire Hubert Curien - IPHC Strasbourg)*
Sep. 2012	**Master in Engineering Sciences and Applied Physics**, Telecom Physique Strasbourg (TPS) Project: "Development of a DAQ prototype for the analysis and the reconstruction of fingerprints on bullet casings for the french national police"
Jul. 2012	**Master in Subatomic and Astroparticle Physics**, University of Strasbourg Thesis: "Study of the aging processes in GEM detectors for CMS" *Conducted at CERN under the supervision of Archana* Sharma *(CERN)*

Responsibilities

Current Sep. 2019	**GEM Phase II Detector R&D Coordinator** *My role is to coordinate the different activities regarding the development of the triple-GEM technology for the CMS application: Optimisation of the detector configuration; Longevity studies; Discharge and crosstalk mitigation; Rate capability optimisation. I am continuously monitoring the progress on the different fronts of developments, I provide technical expertise, define the main timeline and the milestones.*
Current Sep. 2019	**GE2/1 Detector Production Coordinator** *My role is to coordinate the assembly, the quality control and the validation of 300 GE2/1 detectors in various production sites distributed all around the world. Specifically, I provide technical expertise, guidelines and I define the main production schedule and milestones.*
Feb. 2021 Sep. 2017	**GE1/1 Detector Production Coordinator** *My role was to coordinate the assembly, the quality control and the validation of 144 GE1/1 detectors in various production sites distributed all around the world. Specifically, I provided technical expertise, guidelines and I defined the main production schedule and milestones. All the chambers and the spares were successfully produced, tested and delivered in time for the installation in CMS.*
Current Jun. 2016	**CMS Safety Officer** *Deputy Flammable Gas Safety Officer (FGSO). In charge of the safety related to the use of flammable gas in the CMS experiment.*
Current Jan. 2017	**GEM Laboratory Manager** *Responsible for organising the activities in the central GEM production laboratory at CERN. It includes the preparation of the test stands, the management of the safety, the coordination of the various R&D activities and the supervision of the workers and students.*

Introduction

Simplified view



- **Experimental physics - Detector physics**

- What is the final purpose ? → Detect particles
- **How to detect particle ? → Based on the particle/matter interaction processes**
- How to design and build detectors ? → various options

(- How to install and operate detectors)

- **Lets see the cases of:**

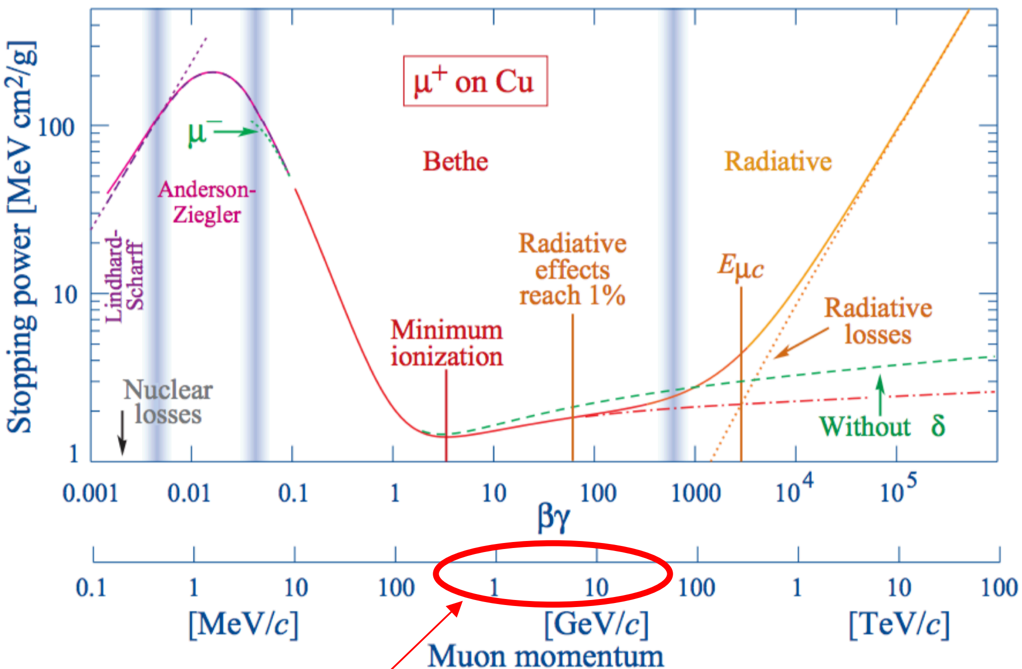
- Charged particles
- Photons
- Neutrons

Charged Particles

Coulomb interactions between charged particle and atomic electrons

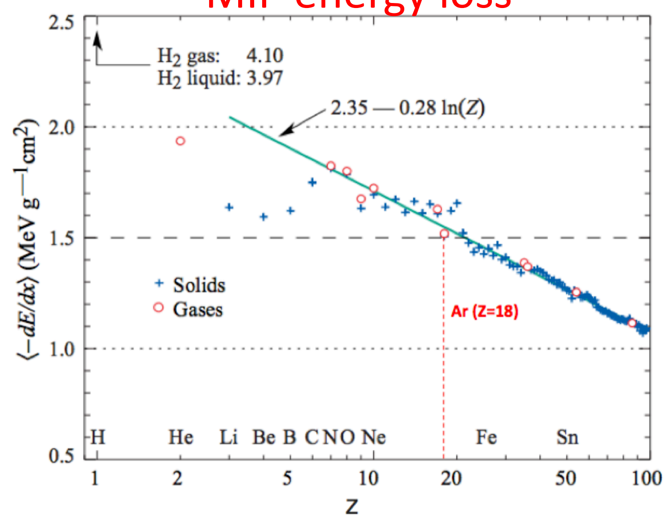
→ Energy loss is derived from the Bethe-Bloch formula:

$$-\left\langle\frac{dE}{dx}\right\rangle = \frac{2\pi e^4 z^2}{m_e c^2 \beta^2} NZ \left[ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 T_m}{I^2}\right) - 2\beta^2 - \delta(\beta\gamma)\right]$$



Interesting energy range close to the minimum ionizing (MIP)

MIP energy loss



With Ar atoms (Z=18):

$$-\left\langle\frac{dE}{dx}\right\rangle = \mathbf{1.53\ MeV\ g^{-1}cm^2}$$

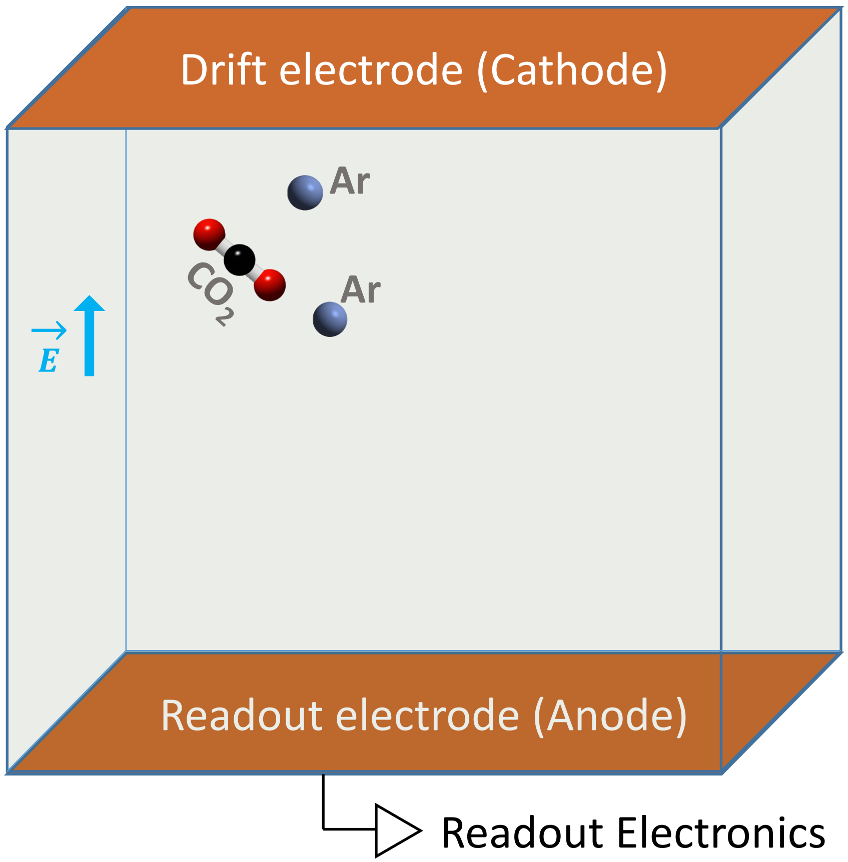
Energy loss in 3mm Ar gas :

$$\Delta E = -\left\langle\frac{dE}{dx}\right\rangle \times \rho \times d = \mathbf{861\ eV/(3mm)}$$

Ionization – total number of primary **e$^-$** :

$$n_T = \Delta E \times \left[\frac{70\%}{W_i(Ar)} + \frac{30\%}{W_i(CO_2)}\right] = 861 \times \left[\frac{0.7}{26} + \frac{0.3}{33}\right] \sim \mathbf{31\ pairs}$$

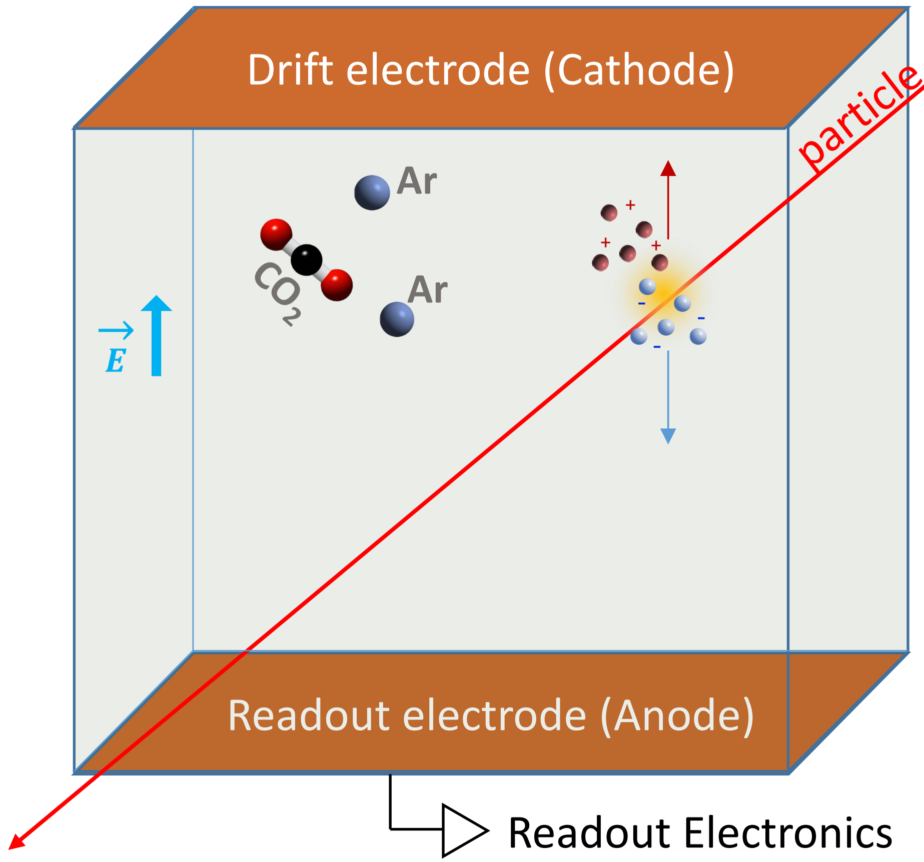
Basic principle of operation



Gaseous detector structure:

- A chamber filled with **gas** (typically Ar:CO_2 70:30%)
- A **cathode** and an **anode** to establish an **electric field**
- A **readout system** connected to the anode

Basic principle of operation



Gaseous detector structure:

- A chamber filled with gas (typically Ar:CO_2 70:30%)
- A cathode and an anode to establish an electric field
- A readout system connected to the anode

- Particles crossing the gas volume may interact with gas → will directly or indirectly release free charges (e^- + ion pairs)
- The free charge is moved toward the electrodes thanks to the electric field
- The moving charge induces current (signals) that can be captured by the readout system

Gas Transport Properties

As seen in the previous sections, most of the particles interacting with a gaseous medium produces free charges by ionization, called the primary charge. This clear signature of the crossing of a particle can be extracted from the gas to produce electrical signals that will be transferred to a data acquisition system. However, the charges moving in the gas will also interact with the atoms before being collected. The understanding of these interactions is necessary for the choice of the gas mixture in particle detectors.

The primary electrons and ions gradually lose their energy in collisions with the gas molecules and diffuse by multiple scattering following a Maxwell distribution for their energy ϵ

$$\frac{dN}{d\epsilon} = F(\epsilon) = C\sqrt{\epsilon}\; e^{-\epsilon/kT} \tag{4.24}$$

with N the number of charges, T the temperature and k the Boltzmann constant. These charges assume the thermal energy of the gas with an average value $\epsilon_T = \frac{3}{2}kT$.

A Gaussian distribution gives the dislocation of the charges at the distance x from the origin and after a time t:

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{\frac{-x^2}{4Dt}} dx \tag{4.25}$$

where D represents the constant of diffusion which depends on the nature of the charges and the medium. We can define the mean free path λ as the average distance between two collisions:

$$\lambda = \frac{1}{N\sigma_{collision}} \tag{4.26}$$

with σ the cross-section of the interaction and N the number of atoms per volume.

Gas Transport Properties

In the presence of a uniform electric field E across the medium, the free charges move along the field direction and accelerate until they reach their drift velocity v_d. Then, the electrical mobility of the charges can be defined as:

$$\mu = \frac{v_d}{E} \tag{4.27}$$

The Einstein's relation shows that the mobility is related to the coefficient of diffusion :

$$\mu = \frac{e}{kT} D \tag{4.28}$$

In the case of electrons moving in a gaseous medium under the influence of an electric field, the drift velocity and thus the mobility are not constant since the electrons can acquire energy between two collisions due to their small mass.

Gas Transport Properties

Townsend gives a simple expression of the electron velocity:

$$v_d^e = \frac{e}{2m_e} E\tau \tag{4.29}$$

where τ is the mean time between collisions. With the ideal gas approximation, the drift velocity becomes proportional to the reduced electric field E/P and the temperature T of the medium, P being the pressure of the gas:

$$v_d^e \propto \frac{ET}{P} \tag{4.30}$$

Since the wavelength of such electrons is comparable to the size of the gas molecules, the interaction cross-section σ, and therefore the time τ, strongly varies with the energy ϵ of the electrons. These variations, described by the Ramsauer-Townsend effect, reach maxima and minima as shown in Fig. 4.12.

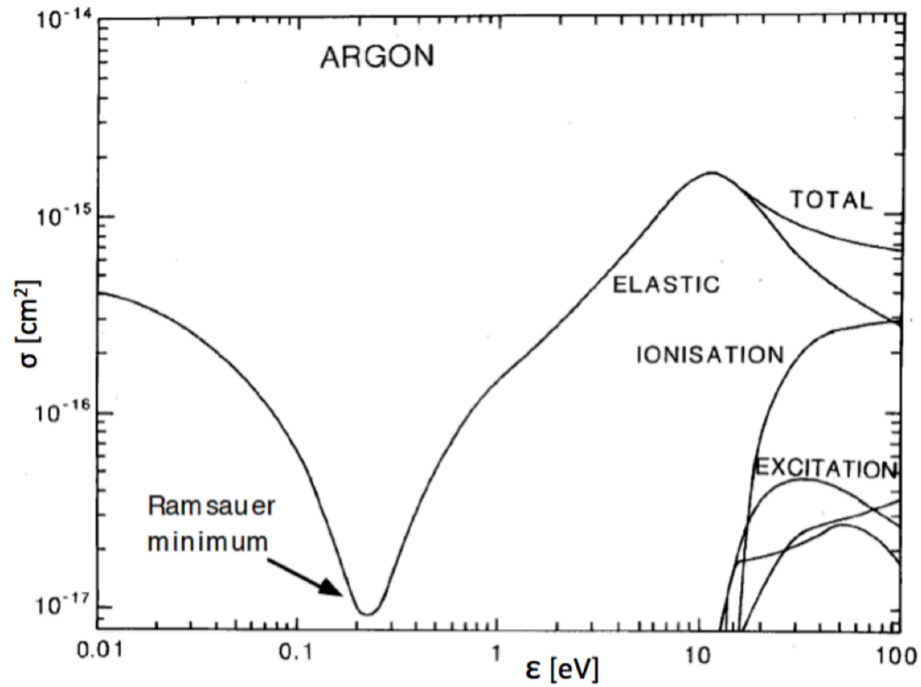
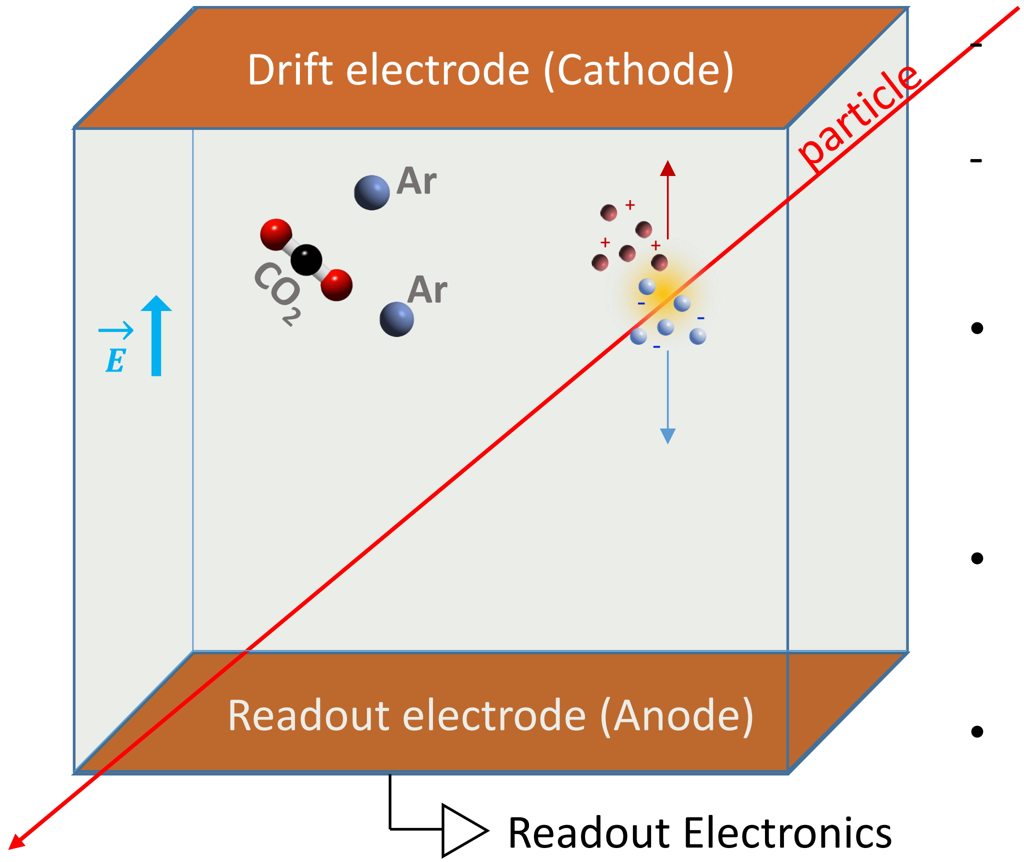


FIGURE 4.12: Interaction cross-section of electrons in Ar.

This relation is particularly important for the operation of gaseous detectors, where the charges freed by an incoming particle move inside of the gas volume to reach a readout electrode. It is interesting to minimize the interaction of the electrons with the medium in order to minimize the diffusion of the charges, which could degrade the performance of detection.

Basic principle of operation

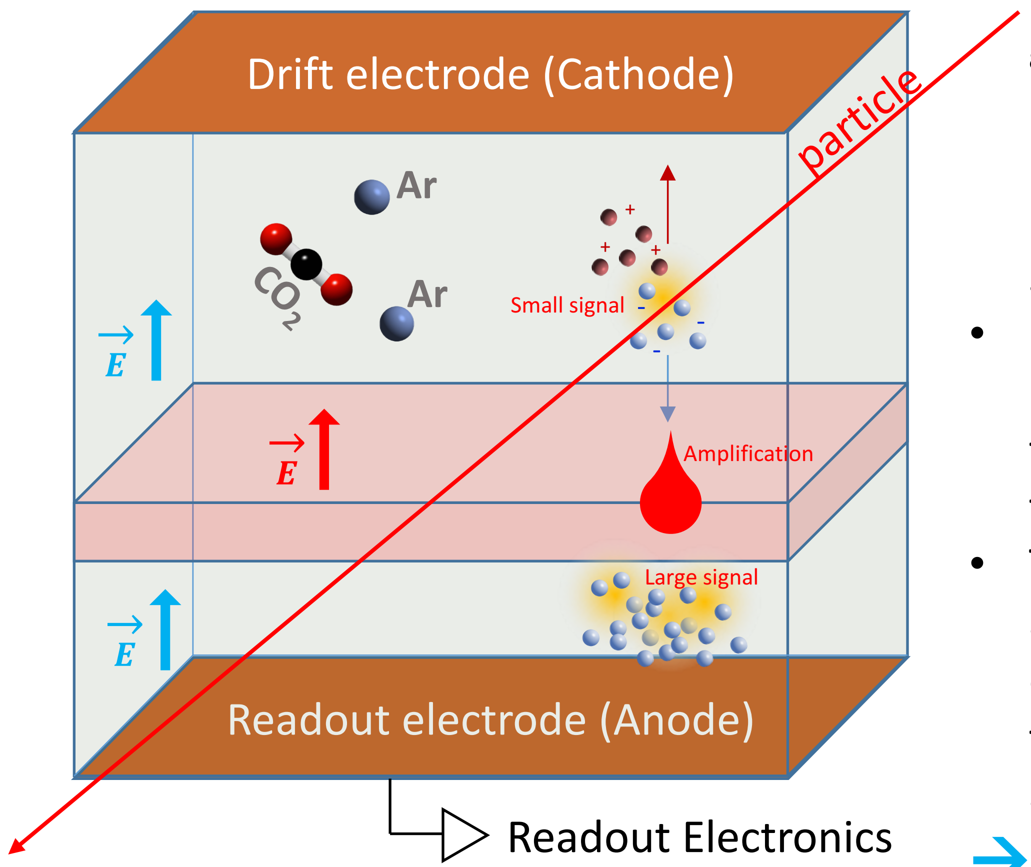


Gaseous detector structure:

- A chamber filled with **gas** (typically Ar:CO_2 70:30%)
- A **cathode** and an **anode** to establish an **electric field**
- A **readout system** connected to the anode

- Particles crossing the gas volume may interact with gas → will directly or indirectly release free charges (e^- + ion pairs)
- The free charge is moved toward the electrodes thanks to the electric field
- The moving charge induces current (signals) that can be captured by the readout system

Basic principle of operation



Readout issues:

- The charge released in a thin gas gap is **small and difficult to readout** : part of the charge can be lost in the gas, the signals can be lost in the electronic noise of the system etc …
- It is common to add a structure inside the gas volume to **amplify** the charge before it goes toward the readout electrode
- The amplification is based on the acceleration of the primary electrons in a high electric field, the excitation of gas molecules and the release more electrons

→ **Electron avalanche**

Amplification Process

In electric fields higher than few kV/cm, the electrons acquire sufficient energy between two collisions to provoke the excitation and/or the ionization of the gas and produce free charges that can ionize further atoms. This chain reaction, also called avalanche, is responsible for the amplification of the primary charge in gaseous detectors. The ionization mean free path is the average distance that an electron can travel before being involved in an ionization process. The inverse of the mean free path is called first Townsend coefficient α and is given by the Korff's approximation:

$$\frac{\alpha}{P} = Ae^{-BP/E} \tag{4.31}$$

where P is the pressure of the gas and A and B are parameters depending on the gas type and on the electric field range. If n is the number of electrons at a given position, after a path dx along the drift direction, the number of electrons after amplification is:

$$dn = n\alpha dx \tag{4.32}$$

Amplification Process

One can therefore obtain the amplification factor M by integrating Equ. (4.32):

$$M = \frac{n}{n_0} = e^{\alpha x} \tag{4.33}$$

In the case of a non-uniform electric field, the Townsend coefficient is a function of the distance x. The amplification factor between x_1 and x_2 can be expressed as:

$$M = exp\left[\int_{x_1}^{x_2} \alpha(x)dx\right] \tag{4.34}$$

The amplification factor thus increases exponentially with the electric field strength but shows a limit around $M = 10^8$ due to the influence of the space charge on the electric field and because of the spread of the avalanches by photon emission. This condition is known as the Raether limit and corresponds to $\alpha x \sim 20$.

Amplification Process

The basic principle of operation of gaseous detectors can be simplified with the example of the parallel plate detector. The signal generated by such detectors is produced when the free charges released by a particle drift inside of the detection medium under the influence of the electric field created by the two electrodes. We distinguish four main operation regimes depending on the magnitude of the electric field in the amplification region. Fig. 4.13 shows the relation between collected charge and the amplification field in the different regions of operation.

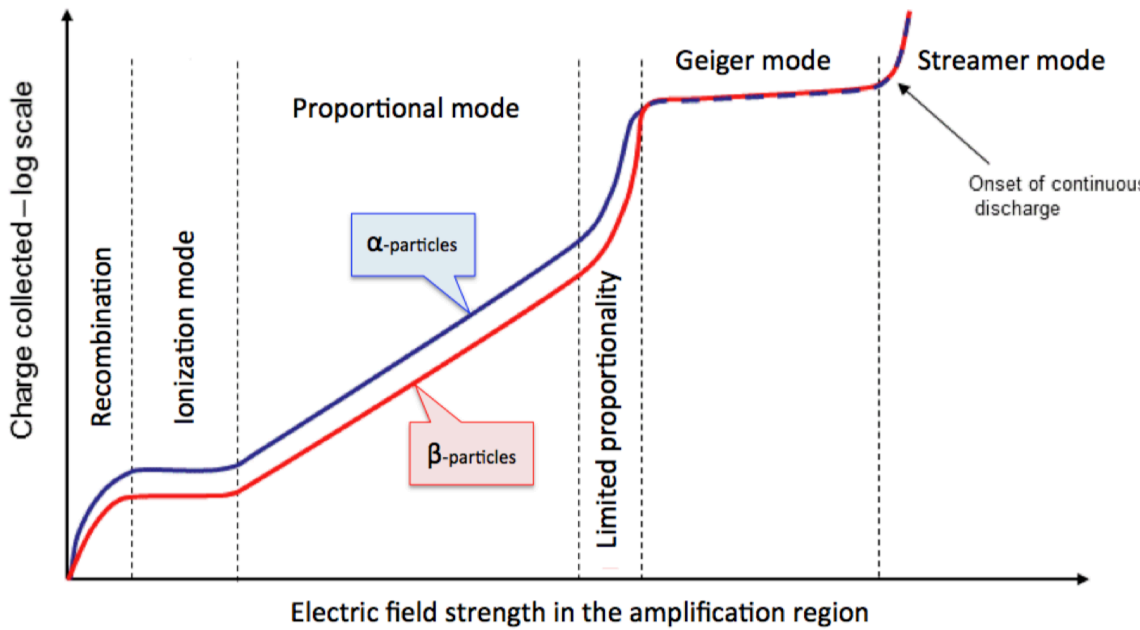


FIGURE 4.13: Gain-voltage characteristics for gaseous detectors showing the different operating modes. The y-axis is refers to the collected charge in logarithmic scale.

Ionization Mode

In the case of highly ionizing events, a large amount of charge is released in the gas and moves along the electric field lines, inducing a large signal on the electrodes (Fig. 4.14). In this mode, called ionization regime, it is not necessary to amplify the primary charge before the collection. Therefore, a relatively low electric field is enough to generate signals above the electronic noise (typically lower than 10 kV/cm). However, for very low electric fields, a significant portion of the primary charge is lost by electron-ion recombination or electron attachment to neutral molecules of the medium.

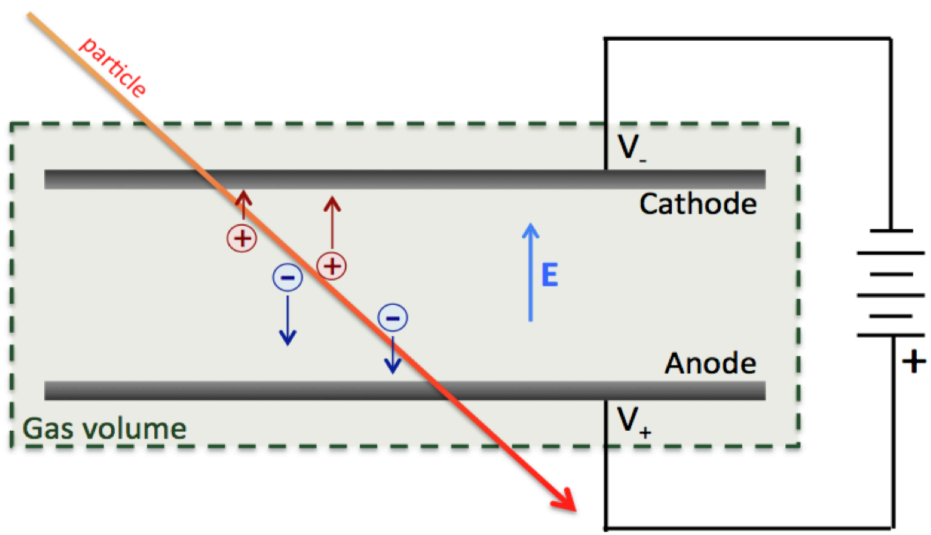


FIGURE 4.14: Schematic representation of ionization chambers.

Amplification Process

Proportional Mode

A large part of gaseous chambers is used to detect charged particles and/or high energy photons. In this condition, the primary charge deposited in the chamber is not large enough to produce signals above the average noise of the readout systems. It is then necessary to amplify this charge before collecting of the signal.

At a certain threshold voltage V_T (depending on the geometry of the detector), a critical electric field E_C is established between the electrodes and is intense enough so that the free electrons trigger further ionization of the gas and produce avalanches. As seen in → the avalanche process depends on the magnitude the electric field and on the properties of the gas mixture. The number of electrons after amplification is proportional to the primary charge (see Equ. (4.32)). The signal produced by proportional detectors is therefore representative to the energy deposited by the crossing particles. Fig. 4.15 shows a schematic view of the amplification process in a proportional chamber.

Proportional Mode

however important to notice that when increasing the field strength, the amplification factor increases and more secondary charges are freed, forming large avalanches. At a certain point, the space charge provokes the distortion of the electric field in the vicinity of the avalanche and lead to a gradual loss of proportionality.

This mode of operation is widely used in gaseous detectors, such as proportional counters, multi-wire chambers and more recently the micro-pattern gaseous detectors.

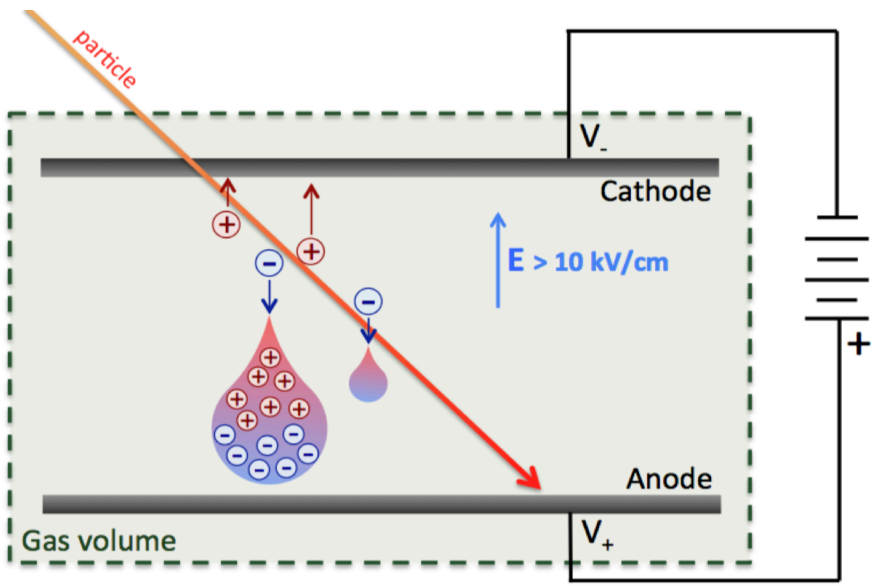


FIGURE 4.15: Schematic representation of proportional chambers.

Geiger Mode

At higher amplification fields, the primary avalanche triggers multiple secondary avalanche mostly by the emission of UV photons or by recombination of avalanche ions on the surface of the cathode . A chain reaction occurs and spreads through the entire detection volume until the process is stopped by a voltage drop on the electrodes or by the space charge of ions in the case of "self-quenching" detectors. The total charge produced after the amplification is thus independent from the initial deposition. This operation regime, called saturation or Geiger mode, is described in Fig. 4.16.

Geiger Mode

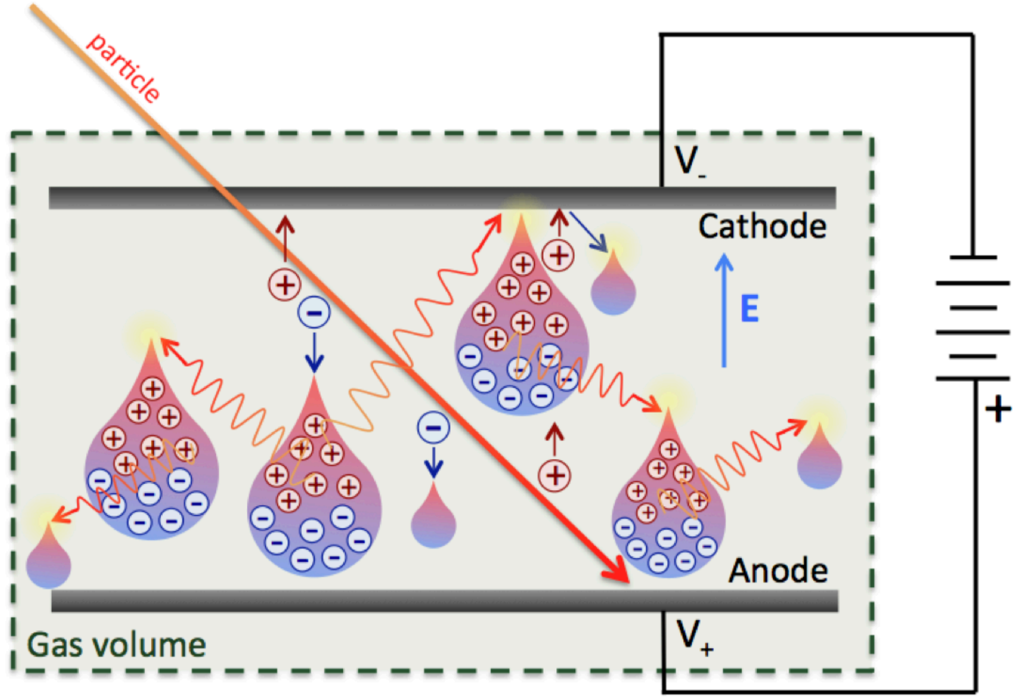


FIGURE 4.16: Schematic representation of Geiger-Muller chambers.

Geiger detectors are essentially used to counts number of particles since the primary charge information is lost during the amplification process. A particular choice of materials and gas composition can increase the interaction probability with certain particles such as gamma rays, α-particles or neutrons in order to make Geiger detectors useful for radio-protection applications. The CMS muon detectors do not operate in Geiger mode

Streamer Mode

At even higher fields, the space charge density in the avalanche becomes comparable to the surface charge density of the electrodes causing the focusing of the field lines toward the avalanche region. Then, the secondary photoelectrons seen in the Geiger mode can drift along the distorted field toward the avalanche region and induce additional avalanches that sum up with the original one, producing a thin plasma filament in the detection medium. This filament, also called streamer, can propagate toward the electrodes and trigger a discharge in the chamber as seen in Fig. 4.17. For most of the detectors, this phenomenon appears when the Raether limit is overcom

Streamer Mode

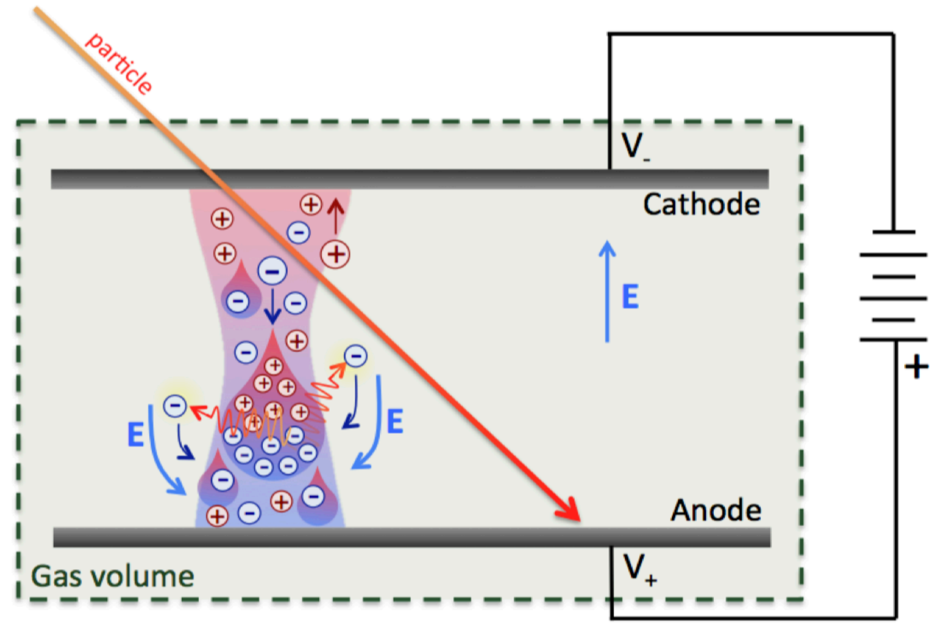
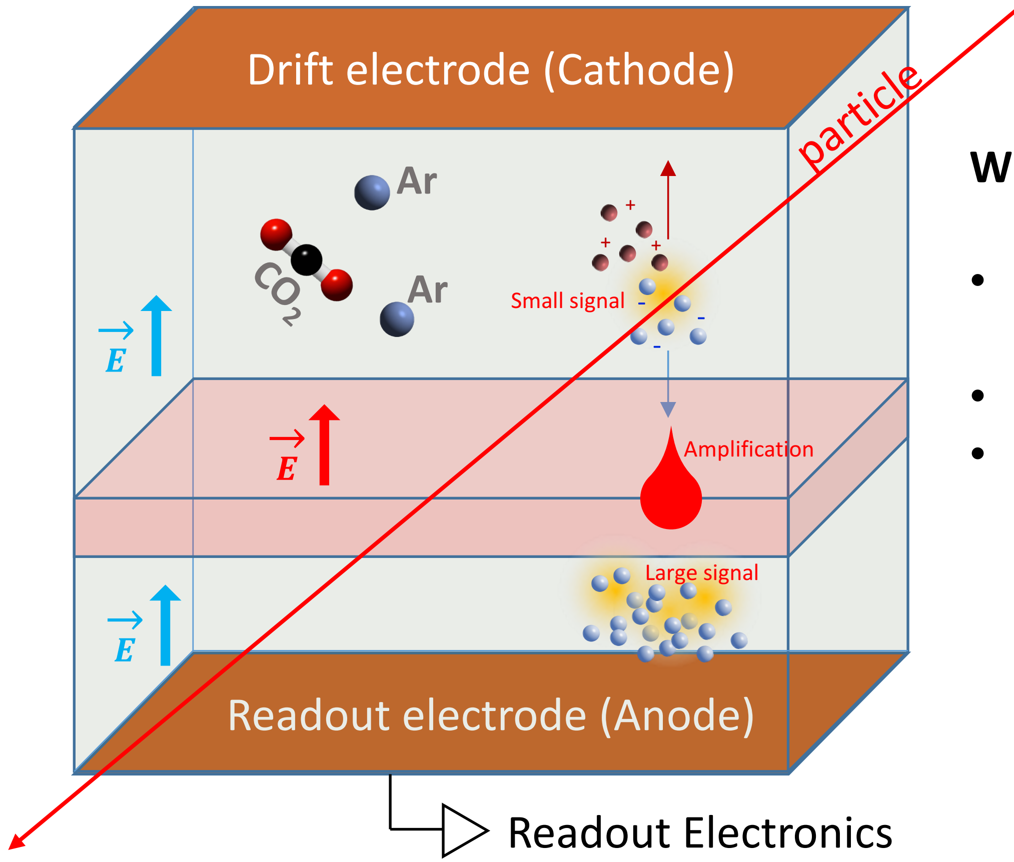


FIGURE 4.17: Schematic representation of a Streamer in parallel plate detectors.

The advantage of the streamer mode is that a simple and cheap structure can produce very large signals. However, the streamers can provoke a powerful breakdown which releases most of the electrostatic charge accumulated in the electrodes. It is customary to cover the electrodes with highly resistive layers to limit the energy and the propagation of the discharges and protect the elements forming the detector as well as the readout electronics.

Basic principle of operation



What next ?

- What gas is suitable for different applications ?
- Why to mix different gases ?
- What is the effect on detector properties ?

Choice of Gas

The choice of the gas is essential to ensure the good operation of particle detectors. As seen in the previous sections, the number of primary charges, the amplification factor and its proportionality strongly depend on the properties of the gas. In addition, specific applications impose experimental requirements that also rely on the choice of gas, such as a high rate capability, a maximum longevity, good time and space resolutions or a low discharge probability. We will focus here on the properties of the mixtures proposed for the upgrade of the CMS end-caps, namely Ar/CO_2 $(70:30)$ and $Ar/CO_2/CF_4$ $(45:15:40)$.

Since most of the polyatomic molecules can de-excite through non-ionizing processes, noble gases are prefered to detect MIPs at relatively low electric field. Among the noble gases, argon gives an acceptable number of electron-ion pairs per unit length for MIP and is relatively cheap compared to xenon or krypton.

Choice of Gas

Not as easy → However, excited argon atoms return to ground state only by the emission of photons with energies higher than 11.6 eV that can induce secondary avalanches (see Slide 21). The addition of ”quenching” gas is thus necessary to absorb these photons and dissipate the energy through non-ionizing processes. In particular, weakly-bound polyatomic molecules, such as CO_2, have a very efficient absorption in the energy range corresponding to the argon emission and they de-excite through vibrational or rotational transitions.

The addition of so-called ”cold” gases also helps to improve the space and time performance of the detectors. For example, molecules such as CF_4 have a large inelastic cross section and can ”cool down” the electrons into energy ranges close to the Ramsauer-Townsend minimum (see Fig. 4.12). The total scattering cross section in Ar then decreases while the electrons drift velocity increases, as seen in Fig. 4.18, resulting in a lower volume diffusion of the electrons (Fig. 4.19).

Choice of Gas

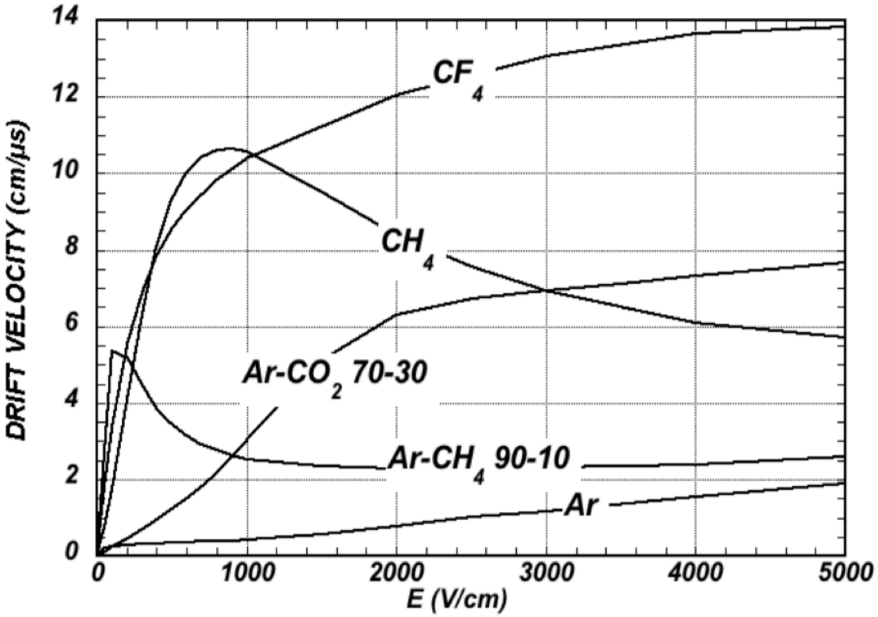


FIGURE 4.18: Comparison of electron drift velocity for different gas species [13].

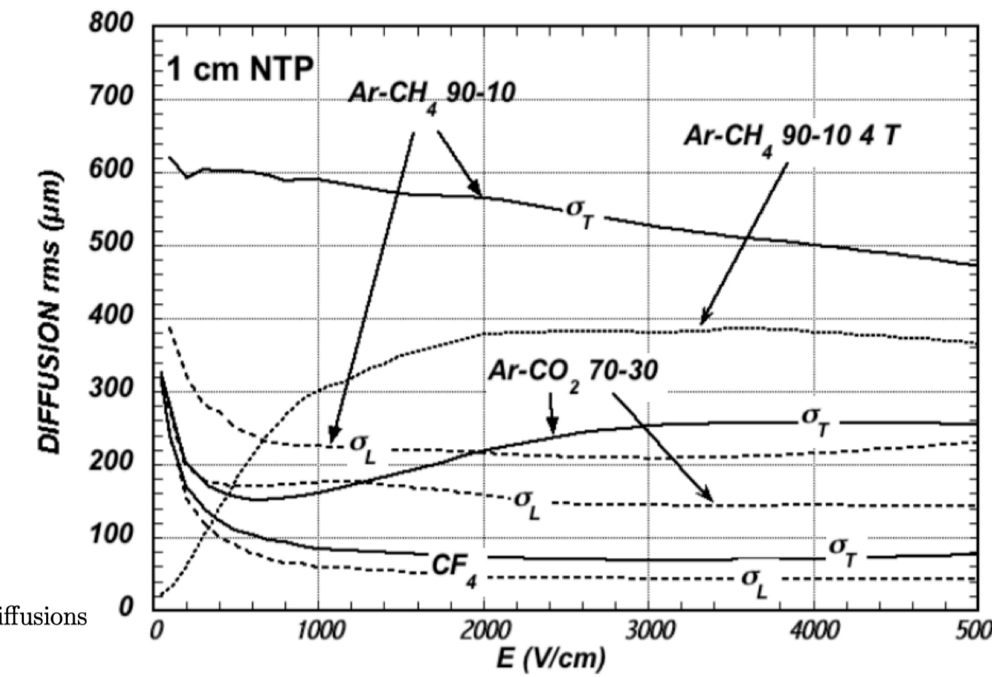


FIGURE 4.19: Comparison of electron longitudinal (σ_L) and transverse (σ_T) diffusions for different gas species.

Choice of Gas

Moreover, for thin gap detectors, the average distance between the primary ionization clusters strongly affects the localization accuracy and the time resolution. The addition of a molecule giving a high number of total ionization per unit length, such as the CF_4, enhances the uniformity of the primary cluster distribution of the mixture and thus improves the performance of the detectors.

However, some molecules can also affect the amplitude the signal induced by particles. For example in CF_4, the electron capture cross section becomes very large in electric fields higher than 8 kV/cm, causing a signal reduction along the drift path.

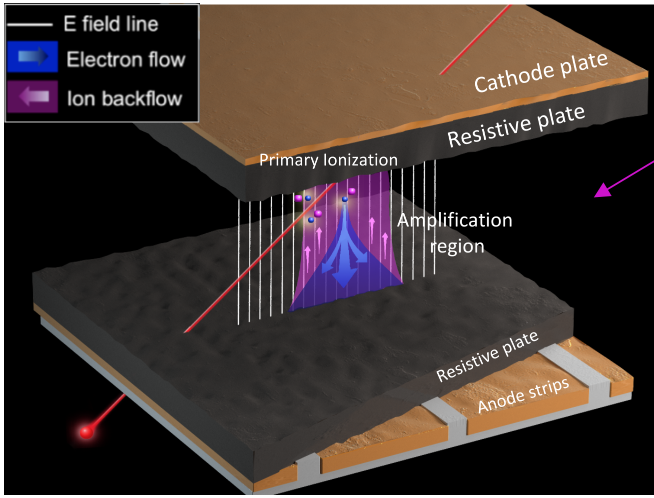
Choice of Gas

Tab. 4.1 shows the detection properties of commonly used gases.

Gas	Z	Density [mg cm^{-3}]	E_X [eV]	E_I [eV]	W_I [eV]	$(dE/dx)_{MIP}$ [keV cm^{-1}]	N_P [cm^{-1}]	N_T [cm^{-1}]
He	2	0.179	19.8	24.6	41.3	0.32	3.5	8
Ne	10	0.839	16.7	21.6	37	1.45	13	40
Ar	18	1.66	11.6	15.7	26	2.53	25	97
Xe	54	5.495	8.4	12.1	22	6.87	41	312
CH_4	10	0.667	8.8	12.6	30	1.61	28	54
iC_4H_{10}	34	2.49	6.5	10.6	26	5.67	90	220
C_2H_6	18	1.26	8.2	11.5	26	2.91	48	112
CO_2	22	1.84	7.0	13.8	34	3.35	35	100
CF_4	42	3.78	10.0	16.0	54	6.38	63	120

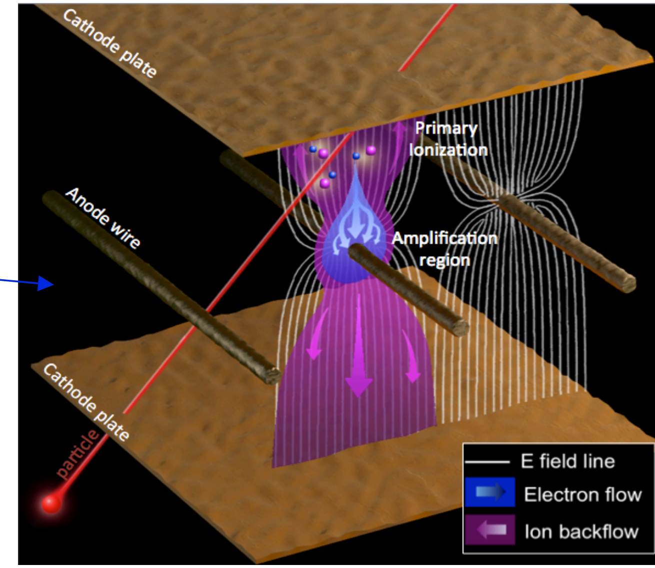
TABLE 4.1: Some properties of noble gases and polyatomic molecules at normal conditions (T : 20 ° C, P : 1 atm). Z is the atomic number, E_X and E_I the first excitation and the ionization energy, W_I and $(dE/dx)_{MIP}$ the average electron-ion pair energy and the differential energy loss, N_P and N_T the primary and total number of pairs per unit length in MIP events.

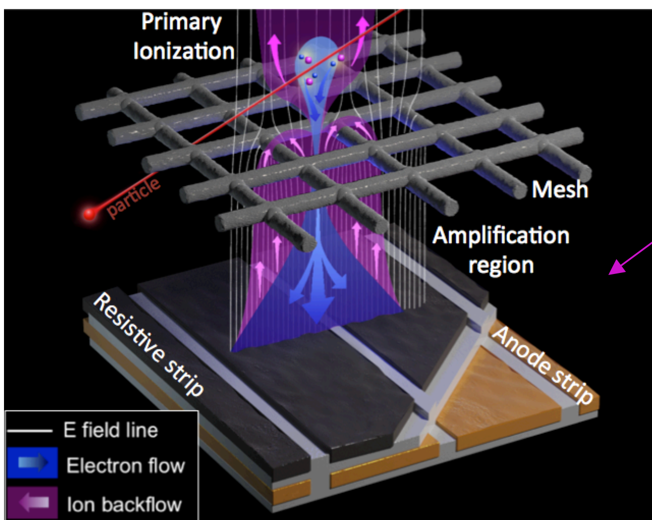
Examples of amplification structures for gaseous detectors



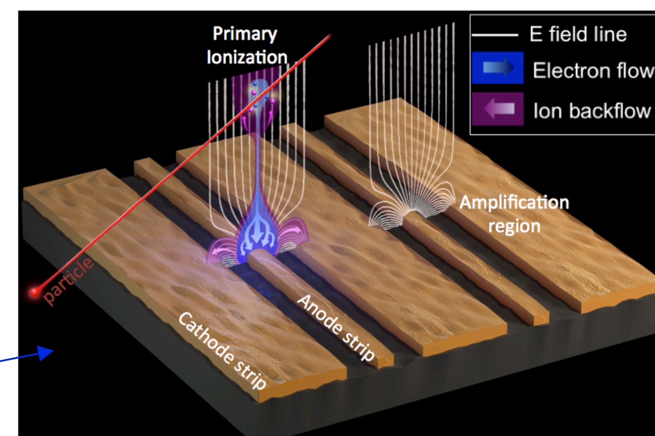
Resistive Plate Chamber (**RPC**): amplification in the gas gap

Multi-Wire Proportional Counter (**MWPC**): amplification in the vicinity of the anode wires





MicroMesh Gaseous Detector (**MicroMegas**): Amplification between a microscopic mesh and the anode plane



Micro-Strip Gas Chambers (**MSGC**): amplification in the vicinity of the anode micro-strips

The end

The end

Thank you

Any Questions ?