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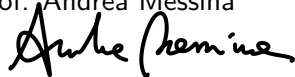
Characterization of the CYGNO experiment proto- type during the underground campaign at LNGS

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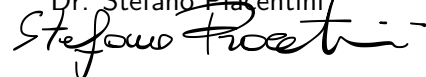
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Tesi di Laurea Magistrale. Sapienza University of Rome

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I believe our future depends powerfully on how
well we understand this cosmos in which we
float, like a mote of dust in the morning.

Carl Sagan, Cosmos

Figure 0.1. A picture of the Milky Way, our galaxy, I acquired during the night between 21 and 22 July 2020. The result is obtained by averaging 4 picture of 3 minutes each. The camera adopted was a Canon EOS 80D with a lens Samyang 16mm f/2.0 ED and ISO 800. The stability of the camera was given by an equatorial mounting EQ2. A home-made step by step motor allowed to follow the movement of the stars in the sky in the 3 minutes of each photo. The post processing was performed through Photoshop for the elaboration of the final result.

a mamma Tiziana

Abstract

The CYGNO collaboration is a dedicated research group with a primary focus on establishing a high-resolution Time Projection Chamber (TPC) employing optical readout through gas electron multipliers (GEMs) at the INFN Gran Sasso Laboratories (LNGS). Its innovative setup consists of a helium/fluorine gas mixture at atmospheric pressure and the use of a CMOS camera and fast photomultiplier tubes (PMTs) for directional Dark Matter search and solar neutrino spectroscopy. The goal is to achieve a 3D tracking, with head tail capability, and background rejection down to $\mathcal{O}(\text{keV})$ energy, in order to explore the $\mathcal{O}(\text{GeV})$ mass range both for SI and SD coupling.

During my thesis project, I actively participated in the underground commissioning of the LIME detector of the CYGNO experiment at LNGS. This prototype, which featured a 50-liter detector equipped with an sCMOS camera and four PMTs, plays a pivotal role in validating the project's scalability. Throughout my thesis work, I had the privilege of gaining hands-on experience across various research aspects, encompassing technical aspects of the prototype and extensive data analysis.

From the PMT perspective, my main contribution included conducting an initial assessment of the diffusion coefficient of ionized electrons in the gas mixture, specifically along the direction parallel to the drift field. Subsequently, my focus shifted towards integrating PMT and camera data to achieve a comprehensive 3D reconstruction of particle tracks within the detector. To facilitate this integration, I curated a clean dataset of events where the association between camera and PMT data was unambiguous. This dataset proved invaluable for a thorough examination and optimization of the experiment's reconstruction algorithms. In addition to these tasks, I engaged in the critical challenge of distinguishing between the signatures of electronic recoil (ER) and nuclear recoil (NR) events. Specifically, I conducted a comparative analysis between two dataset, one of which had a high rate of nuclear scattering events through the use of an external source of Americium-Beryllium. In the context of dark matter research, the ER/NR discrimination is paramount, as only the latter events provide information suggestive of a possible presence of Weakly Interacting Massive Particles (WIMPs).

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Introduction

The field of particle physics has undergone remarkable advancements since the pioneering work of Weinberg and Salam in 1968, leading to the development of the Standard Model (SM) of particles. It stands as the most elegant and comprehensive framework for understanding the fundamental forces and particles that make up our universe. Experimental validations of this model have been abundant, culminating in a significant confirmation in 2012 with the discovery of the Higgs boson, the final missing piece of the puzzle.

However, despite its successes, the Standard Model has its limitations. Most notably, it does not account for the evident force of gravity, which has pointed out some flaws in the understanding of the universe since the early 1930s. The current cosmological model, known as Λ CDM, posits the existence of an invisible substance constituting roughly 85% of the total cosmic matter budget, for which there is still no incontrovertible evidence. This enigmatic component is referred to as dark matter. The quest to understand dark matter has led to the prevailing hypothesis that it is composed of elementary particles, potentially capable of extending or complementing the Standard Model. Among the numerous candidates, Weakly Interacting Massive Particles (WIMPs) emerge as the front-runners. They consist of non-relativistic particles, with $\mathcal{O}(100)$ GeV masses, that weakly-interact with SM particles and are stable enough to justify their abundant presence in the actual universe. Experimental techniques developed for their detection on Earth can be categorized into three groups: accelerators, aiming to produce them; indirect detectors, designed to find ordinary particles resulting from interactions with dark matter particles; and direct detectors, focused on studying possible scatterings between ordinary and dark matter particles. The last two detection approaches are justified by what's known as the Standard Halo Model. An extensive halo of WIMPs pervades the entire Milky Way galaxy, extending to our solar system. Due to the proper motion of our star, a dark wind flows through the Earth in the direction of the Cygnus constellation.

Within the realm of direct research, the experimental challenge is notably demanding due to the low event rate of dark matter (DM) scattering, typically on the order of $\mathcal{O}(1 \text{ evt kg}^{-1} \text{ year}^{-1})$. Two crucial considerations, consequently, must be taken into account. First, it is imperative to meticulously characterize the background signal of the detector and, to the extent possible, minimize noise interference. This is primarily achieved by siting experiments in underground laboratories (to shield them from cosmic rays), surrounding them with dense shielding materials (further protection against radiation) and applying fiducialization to isolate the intrinsic detector background. Additionally, the ability to discern the temporal and directional

modulation of the signal is crucial. Due to Earth’s annual orbital motion, the event rate is expected to vary periodically throughout the year since the relative motion respects the dark wind. Furthermore, considering Earth’s rotation, which results in changing orientations relative to the Cygnus constellation, an additional modulation in the particle’s arrival direction is expected. A measure of such variations would represent stronger evidence of a dark matter measure with respect to a simple rate evaluation. To this end, each detection technique presents its own strengths and weaknesses, finding optimal use depending on the mass range under investigation (and the assumed spin of the WIMP). Within the $\mathcal{O}(1\text{GeV} \div 100\text{GeV})$ range, Time Projection Chambers (TPCs) using noble gasses or liquids emerge as exceptionally effective detectors due to their high sensitivity and directional capabilities.

In this context, I had the opportunity to contribute to Dark Matter research through collaboration with the CYGNO experiment of the National Institute of Nuclear Physics (INFN). It consists of a research group with the main focus on establishing a high-resolution TPC with a volume of $\mathcal{O}(30)\text{ m}^3$ at the INFN Gran Sasso Laboratories (LNGS). When particles travel through the active material of the detector, release energy in various forms, including ionization. The primary goal of this TPC is to detect the ionization signal employing an optical readout technology using gas electron multipliers (GEMs). The experiment’s innovative approach adopts a helium/flourine gas mixture at atmospheric pressure and incorporates a CMOS camera and fast photomultiplier tubes (PMTs). The setup is designed for direct and directional Dark Matter searches as well as solar neutrino spectroscopy. The overarching objective is to achieve 3D tracking capabilities with head-tail sensitivity and background rejection down to the $\mathcal{O}(\text{keV})$ energy, enabling exploration of the $\mathcal{O}(\text{GeV})$ range of Weakly Interacting Massive Particles (WIMPs) for both spin-independent (SI) and spin-dependent (SD) couplings.

During my thesis project, I actively participated in the underground commissioning of the Long Image ModuLE (LIME) detector of the Cygno experiment at LNGS. This prototype, housing a 50-liter TPC and equipped with an sCMOS camera and four PMTs, is the final step of an R&D phase with the goal of validating the project’s scalability.

The goal of this work consists in the characterization of the reconstruction algorithms of the detector, i.e. the processes that from the digital information of the two optical devices reconstruct the physical features of the tracks traveling the detector. From the PMT perspective, I conducted an initial assessment of the diffusion coefficient of primary ionized electrons in the gas mixture along the direction parallel to the drift field. Then I focused on validating the integration between PMTs and camera readout. In the scope of a 3D reconstruction, the timing information of the phototubes must be correlated to the spatial one coming from the pictures. Within this goal, I curated a clean dataset of events where the association was unambiguous. The outcome of this effort is the validation of the pre-existing association algorithm, for the first time, through an *in situ* study. Finally, I engaged in the critical challenge of distinguishing between the signatures of electronic recoil (ER) and nuclear recoil (NR) events. In the context of dark matter research, this ability is paramount, as nuclear recoil events provide information suggestive of a possible presence of WIMPs. While nuclear scatterings tend to produce denser tracks compared to electronic ones, inherent challenges such as signal saturation and diffusion hindered clear separation

within the LIME detector. I conducted a comparative analysis between two dataset, one of which had a high rate of nuclear scattering events through the use of an external source of Americium-Beryllium (AmBe). This allowed the evaluation of qualitative cuts able to select, with promising efficiencies, NR events.

The thesis is structured as follows:

In Chapter [1](#) I introduce the dark matter question, the evidences that suggest its existence and the features of possible WIMP candidates. Then I pass discussing the basics of dark matter direct detection and the actual state-of-art.

In Chapter [2](#) I present in detail the experimental technique adopted by the CYGNO collaboration, its long term program and its actual prototype LIME. I then go in details about the reconstruction algorithms and I conclude mentioning the next steps along the road-map of the experiment.

In Chapter [3](#) I summarize all the results obtained in the underground commissioning at LNGS. At the beginning, I consider the results of the camera and the PMTs separated while, at the end, I discuss a combination of the two reconstruction strategies.

In Chapter [4](#) I present an analysis on tracks differentiation through the use of camera reconstructed variables. I then apply it to a dedicated AmBe data-taking at LNGS in the scope of an initial ER/NR separation.

In the Conclusions [5](#), I perform a short summary of the entire commissioning and I report a prospective on future developments.

Chapter 1

Introduction to Dark Matter direct detection

One of the most perplexing enigmas in modern physics is the existence of dark matter – an elusive and mysterious form of matter that neither emits nor interacts with electromagnetic radiation. Despite its enigmatic nature, dark matter's gravitational influence has become apparent through its effects on the motion of galaxies and galaxy clusters, shedding light on the gaps in our current understanding of the cosmos. Cosmology suggests that approximately 85% of the entire matter in the Universe is possibly made up of this dark matter and the prevailing hypothesis is that it consists of non-baryonic particles. In this chapter, I will start presenting the main reasons for suspecting the existence of such exotic matter and the available models regarding its particle nature. Great emphasis is given, in particular, to the range of mass $\mathcal{O}(1\text{GeV} \div 100\text{GeV})$ and to the WIMPs candidates because of direct interest for my thesis work. I then shift my focus on the description of the Standard Halo Model and the basic concepts of dark matter direct detection: I present the typical recoil energies based on the active material considered and the features of the temporal and directional modulation of a dark matter signal. I conclude discussing the actual explored dark matter regions in a graph "mass vs cross-section" for spin-independent (SI) interactions and how the low mass range is still widely unexplored as an introduction to the Cygno project.

1.1 Dark matter evidences

1.1.1 Galaxy rotation curves

The rotation curve of galaxies, i.e. the circular velocity profile of the stars and gas in a galaxy as a function of their distance from the galactic center, is one of the most clear and convincing hint of the existence of dark matter. In the appendix of his seminal paper in 1970 [1], K. Freeman evaluated the radius at which the rotation curve of the M33 galaxy was predicted to peak under the assumption of an exponential distribution of matter. In addition he measured the entire rotation curve of the galaxy through the shift caused by the Doppler effect on the 21 cm

Hydrogen line.

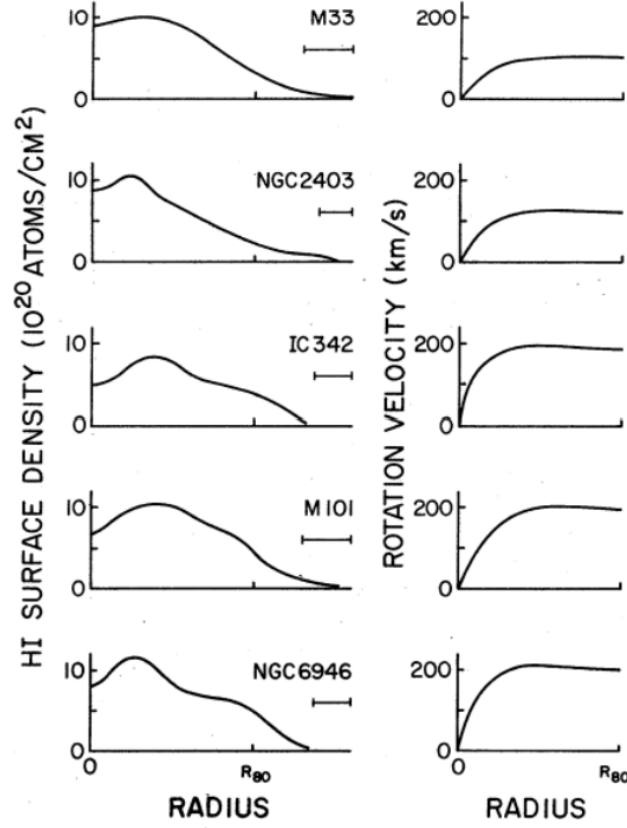


Figure 1.1. On the left the hydrogen surface density profile, on the right the rotation curve of five galaxies as obtained by [2]. The bars under the galaxy names indicates the average radial beam diameter (i.e. the effective spatial resolution).

The result of the comparison was striking because, as it is shown in Fig. 1.1, that refers to a successive work on more candidates [2], the curves showed a *flat* behaviour at large distances from the center of the galaxy, differently from what expected. From the Newtonian dynamics, in fact, we obtain that:

$$v(R) = \sqrt{\frac{G \cdot M(R)}{R}} \quad (1.1)$$

where:

- R is the distance from the galactic center;
- G is the gravitation constant
- $M(R) = \int_R \rho(\vec{r}) d\vec{r}$ the visible mass density profile

So at large R , where the mass density seems to go to zero, v is expected to decrease as $v \propto 1/\sqrt{R}$ and the only way to explain this flat evidence is the introduction of a new, invisible, source of matter.

1.1.2 Galaxy clusters

Another gravitational evidence of DM comes from galaxy clusters: the biggest gravitationally bound structures of the Universe, formed by $\mathcal{O}(100 \div 1000)$ galaxies and hot stars.



Figure 1.2. An image of the Coma cluster, the one studied by F. Zwicky in the first work suggesting the existence of dark matter

As pointed out by [3], in 1933 [1], the astronomer Fritz Zwicky studied the redshift of various galaxy clusters and noticed a large scatter in the apparent velocities of eight galaxies within the Coma Cluster [4]. From this observation he had the idea to apply the Virial theorem [1.2]:

$$2T + V = 0 \quad (1.2)$$

where the potential energy is defined as

$$V = -\frac{1}{2} \sum_i \sum_{i \neq j} \frac{Gm_i m_j}{r_{ij}}$$

and the gravitational radius R_G is defined as:

$$R_G = 2 \left(\sum_i m_i \right)^2 \left(\sum_i \sum_{i \neq j} \frac{Gm_i m_j}{r_{ij}} \right)^{-1}$$

So stated, he could write the energy potential as

$$V = -GM^2/R_G \quad (1.3)$$

The total mass M of the cluster can be estimated by the product of the number of observed galaxies, $\mathcal{O}(800)$, and their average mass, 10^9 solar masses as suggested

¹Note that this was a previous analysis with respect to the Galaxy rotation one but, at that time, didn't convince the entire community to the existence of dark matter until the work of Freeman came out

by Hubble. On the other hand, R_G can be seen as a good estimation of the size of the system and setted to the value of $\sim 10^6$ light years. We can infer the kinetic potential through Eq. [1.2](#) and, since statistical mechanics gives as the relation

$$\langle v^2 \rangle = \frac{2T}{M},$$

we can, at the end, deduce the expected velocity dispersion of the Coma cluster. He found a theoretical value of ~ 100 km/s in contrast with the observed value of ~ 1000 km/s and concluded the need of an additional source of mass: the name "dark matter" enters in the literature for the first time.

In 1937, Zwicky proposed another article [5](#) in which he extended his analysis on the Coma cluster now with the purpose to infer the needed mass of the galaxies. Using the same approach of the previous article (but with some updated value of the parameters) and assuming the average absolute luminosity for cluster galaxies of 8.5×10^7 times that of Sun, he reached the value:

$$\frac{M}{L} \sim 500 \frac{M_\odot}{L_\odot} \quad (1.4)$$

where $M_\odot$ and $L_\odot$ are the Solar mass and luminosity.

Using the values actually adopted by modern cosmology, the factor decrease to ~ 8.3 but the conclusion is the same: it still points to the dark matter existence.



Figure 1.3. A picture of the so called Bullet cluster, The pink halo represent the X-ray emission generated by the, baryonic, intergalactic gas. The blue one is the mass distribution inferred by the gravitational lensing effect.

Another piece of evidence for the existence of dark matter (DM) arises from the phenomenon known as "gravitational lensing." According to General Relativity, massive objects can alter the spacetime geometry, causing the trajectory of a photon passing near them to deviate. This gravitational effect can lead to optical phenomena, such as the apparent position of a star being altered when it is situated behind a massive object or even the creation of multiple images. Importantly, gravitational

lensing depends not only on visible matter but also on dark matter.

One illustrative example can be found in the case of the Bullet Cluster, as shown in Figure 1.3. The Bullet Cluster results from the collision of two smaller sub-clusters, with the pink halo representing the electromagnetic signal produced by the collision. During such collisions, the intergalactic gas of the two sub-clusters interacts electromagnetically, causing it to heat up and emit light. However, the gravitational lensing effect remains largely unaffected by the collision, and the inferred mass distribution is depicted by the blue halo. This observation suggests that a significant portion of the cluster's total mass content is not significantly influenced by the collision event.

1.1.3 Cosmic Microwave Background

I conclude this section presenting the information that can be extracted on DM from the Cosmic Microwave Background (CMB), a radiation in the microwave regime that fills all space in the observable universe. This represents the main argument in agreement with the Big Bang theory and gives information on the amount of DM in the universe.

Assuming *homogeneity* and *isotropy* on large scales, one is lead to the Friedmann-Robertson-Walker (FRW) metric for the space-time of the universe [6]:

$$ds^2 = -dt^2 + a^2(t) \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega \right) \quad (1.5)$$

where k is the so called curvature parameter and where I define the Hubble constant as:

$$H = \frac{\dot{a}}{a} \quad (1.6)$$

The dynamics of the universe is determined by the Einstein Equation;

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} \quad (1.7)$$

where the R , $g_{\mu\nu}$ and $R_{\mu\nu}$ can be calculated from Eq. 1.5 and the energy-momentum tensor $T_{\mu\nu}$ must be assumed as input. In the assumption of a perfect fluid and in a co-moving frame, it can be chosen in the form

$$T_{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & -p & 0 & 0 \\ 0 & 0 & -p & 0 \\ 0 & 0 & 0 & -p \end{pmatrix} \quad (1.8)$$

so that the Einstein equation assumes the form:

$$\begin{aligned} H^2 &= \frac{8\pi G}{3} \rho - \frac{k}{a^2} \\ \frac{\ddot{a}}{a} &= -4\frac{\pi G}{3} (\rho + 3p) \end{aligned} \quad (1.9)$$

Nowadays observations tell us that we live in a flat space ($k = 0$) with an actual value of the Hubble parameter $H_0 = 69.8 \text{ km Mpc}^{-1} \text{ s}^{-1}$ and this allows us to define the critical density and the density parameter:

$$\rho_{crit,0} = \frac{3H_0^2}{8\pi G} \quad \Omega_{I,0} = \frac{\rho_{I,0}}{\rho_{crit,0}} \quad (1.10)$$

where the subscript I runs all over the possible source of energy: radiative, matter, dark energy, curvature. Each of this sources implies a different dependence of ρ_I on $a(t)$ because of the continuity equation

$$\nabla_\mu T^\mu_\nu = 0 \quad \rightarrow \quad \dot{\rho} + 3\frac{\dot{a}}{a}(\rho + p) = 0 \quad (1.11)$$

in the form:

- **Matter (baryonic and DM):** $p = 0 \rightarrow \rho \propto a^{-3}$
- **Radiation:** $T^\mu_\mu = 0 \rightarrow p = \rho/3 \rightarrow \rho \propto a^{-4}$
- **Dark Energy:** $T^\mu_\mu \propto g^\mu_\mu \rightarrow p = -\rho \rightarrow \rho = \text{const}$

In conclusion, the Friedmann equations [1.9](#) can be written in the parametric form:

$$H^2 = H_0^2 \left[\frac{\Omega_r,0}{a^4} + \frac{\Omega_m,0}{a^3} + \frac{\Omega_k,0}{a^2} + \Omega_{\Lambda,0} \right] \quad (1.12)$$

that is a six-parameter relation, called ΛCDM , and is the most commonly endorsed model of Cosmology today.

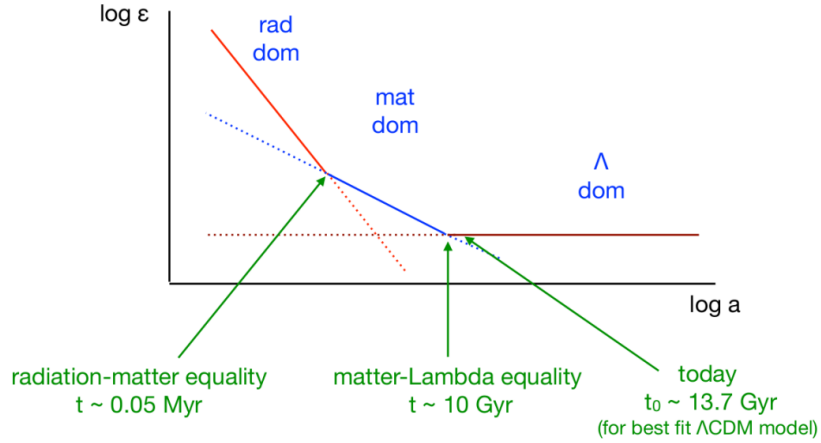


Figure 1.4. Evolution, in double log scale, of the universe density with the scale factor a [7](#). The universe starts off radiation dominated, becomes matter dominated and then wins the cosmological constant.

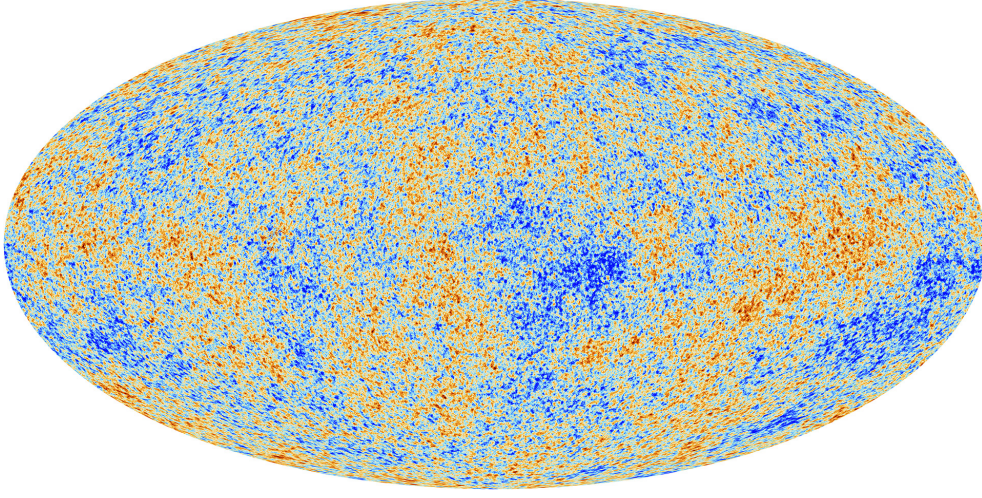


Figure 1.5. Cosmic microwave background anisotropies from the Planck satellite. Figure by ESA https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB

At the beginning the Universe was hot and dense, with the radiation contribution dominating (Fig. 1.4). When the matter domination started, the universe was a plasma of electrons and baryons in thermal equilibrium that started to form atoms only when the expansion of space time decreased the temperature. Now that there are mostly neutral elements, photons are much more free to travel and they still stream the universe in the form of CMB. The cosmic microwave background appears as a black body radiation with a temperature $T_0 = (2.7255 \pm 0.0006)\text{K}$ [8] and not perfectly uniform in all directions because characterized by small fluctuations of order $\Delta T/T \sim 10^{-5}$ as depicted in Fig. 1.5. These anisotropies are a rich source of information: they allow us to understand the reason for the actual structure of the universe (at big scales) and to infer the cosmological parameters of the Friedmann equation 1.12.

The CMB also provides a significant hint about the existence of dark matter. In fact, the anisotropies are due to density perturbation at the time of photon decoupling and their subsequent evolution, to reach the actual features of the universe, would give a value of $\Delta T/T \sim 10^{-4}$ without considering non-baryonic DM.

On the other hand, the angular properties of the CMB can be modeled by an expansion in spherical harmonics:

$$\frac{\Delta T(\theta, \phi)}{\bar{T}} = \sum_l \sum_{m=-l}^{m=l} a_{lm} Y_l^m(\theta, \phi) \quad (1.13)$$

and power spectrum is defined as:

$$C_l = \left\langle |a_{lm}|^2 \right\rangle_m \quad (1.14)$$

where the brackets indicate an average over m . The value of the C_l as function of l , superimposed with the best fit provided by eq. 1.13, is shown in Fig. 1.6 [9].

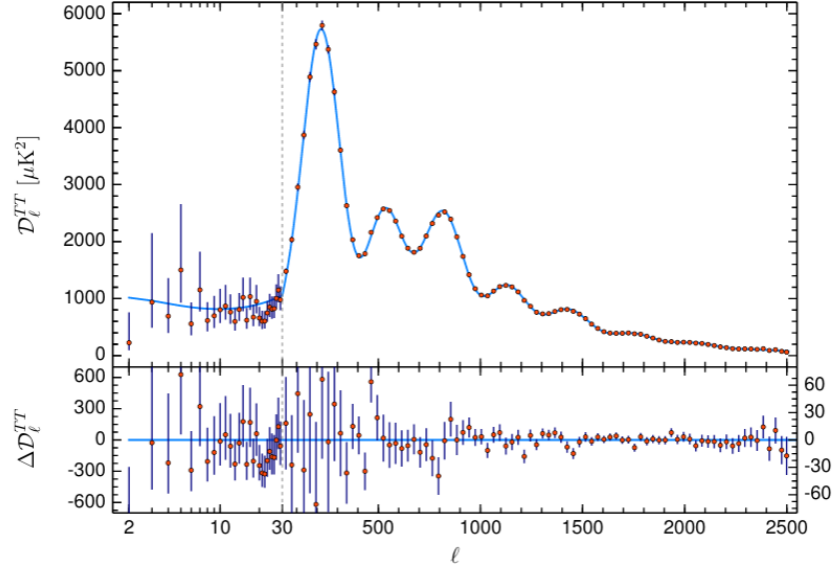


Figure 1.6. Angular power spectrum of CMB temperature. The y variable is $D_l^{TT} = l(l+1) C_l / (2\pi)$; the solid line represents the standard cosmological (Λ CDM) model and the bars the cosmic variance.

The relative height of the peaks gives information on the different components of the universe and the baryon matter density can be deduced from the ratio between the odds and the even peak amplitudes. The results of the fit to the Λ CDM parameters performed by the Planck collaboration gives²:

$$\begin{aligned}\Omega_b h^2 &= 0.02237 \pm 0.00015 \\ \Omega_{DM} h^2 &= 0.1200 \pm 0.0012\end{aligned}\tag{1.15}$$

Not only must Dark Matter be taken into account, but it also appears to represent the primary matter ingredient of our universe.

1.2 A dark matter candidate: WIMPs

By the late 1980s, the hypothesis that the missing mass of the universe consists of one or more yet-unknown subatomic particle species had gained enough support to become established as the leading paradigm for dark matter. Physicists stopped searching for hidden cosmic objects like brown dwarfs, red dwarfs or black planets but started looking for intergalactic gas of DM particles.

Although our understanding of dark matter remains limited, we can already state some general properties it must satisfy as a particle:

- It is not baryonic in nature;

²the h is a way physicist adopt to evaluate the uncertainty over the value of the Hubble constant $H_0 = h \cdot 3.2aHz$

- it is electrically neutral and colorless, otherwise we would have already found it;
- it is stable on a cosmological timescale, since it hasn't decayed yet;
- it has at the most weak interaction with the Standard Model particles;

Furthermore, the majority of the scientific community supports the idea of a "cold" dark matter, which means it is non-relativistic and explains the formation of large-scale structures. The hypothesis became dominant with the work of M. Davies et al. [10] because of the resemblance between their simulated distribution of dark matter halos and the one of the galaxies in the CfA survey. Even though the possibility of the existence of a "hot" DM is not excluded, it is however constrained to be at most $\mathcal{O}(1\%)$ of the total dark matter content of the universe by numerical simulation [11]. I will proceed with the assumption of cold particles, focusing on explaining their characteristics.

1.2.1 Standard Model Neutrinos

When considering the dark matter question from the perspective of the standard model of particle physics, the three neutrinos clearly stand out: they experience only the weak force, are fermions and, last but not least, they exist. In fact, they served as an important gateway particle, leading astrophysicists to begin the foundation of the physics of rare events. Neutrinos are too light to satisfy the DM conditions: this conclusion started to appear since a work of Zeldovich and Gershtein in 1966 [12] and can be explained with a simple calculation.

Let m_i the mass of the i -th neutrino, hence the relic density is (from PDG [13] review "Neutrinos and Cosmology"):

$$\Omega_\nu h^2 = \sum_{i=1}^3 \frac{m_i}{93 \text{ eV}} \quad (1.16)$$

The best laboratory constraint on neutrino masses comes from tritium β -decay experiments [14] that point the following upper limit:

$$m_\nu < 2.05 \text{ eV (95\% C.L)} \quad (1.17)$$

This limit applies to all the mass eigenvalues and gives an upper limit for [1.16]:

$$\Omega_\nu h^2 < 0.07 \quad (1.18)$$

which simply means that they are not abundant enough to be the dominant component of dark matter (see the expected value at the end of Sec. [1.1.3]). In conclusion, they are not any more considered as viable candidates, at least in their SM form, but they still represent an important template for the class of WIMPs.

1.2.2 WIMPs

Weakly Interacting Massive Particles (WIMPs) are particles with a mass in range $m_W \sim 1 \text{ GeV} \div \text{TeV}$ and tree-level interactions with the W and Z gauge bosons, but not with gluons or photons. They are the most studied dark matter candidates because they naturally have the correct relic density and may be detected in many ways. Sometimes it is referred to as the "WIMP miracle" because the mass, in the electroweak scale, not only fits very well in the DM question but also in the gauge Hierarchy problem.

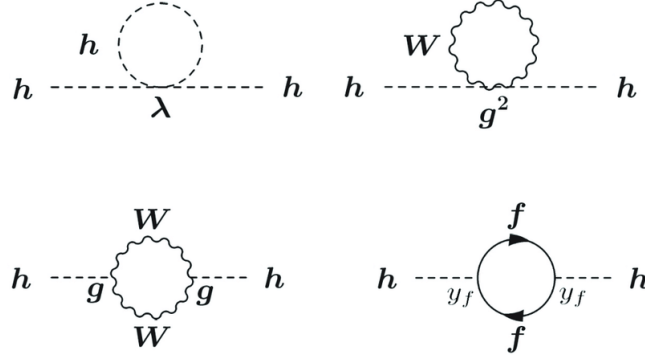


Figure 1.7. One loop diagrams that contributes to the corrections of the Higgs mass in the SM landscape

The Hierarchy problem is the question of why the physical mass of the Higgs boson ($m_h \sim 125 \text{ GeV}$) is so small. In fact the one loop correction to the Higgs mass (in the formalism of cut-off regularization) appears as:

$$\Delta m_h^2 \sim \frac{\lambda^2}{16\pi^2} \int^\Lambda \frac{d^4 p}{p^2} \propto \lambda^2 \Lambda^2 \quad (1.19)$$

where λ is the weak coupling. The first available scale of new physics is the Planck scale $M_{Pl} = \sqrt{\hbar \cdot c / G} \sim 10 \times 10^{19} \text{ GeV}$ that returns an unnatural value of the experimented Higgs mass. A new physics in the scale less than $\sim 1 \text{ TeV}$ would eliminate this problem [15].

From the cosmological perspective [16], dark matter may be produced in a simple and predictive manner as a thermal relic of the Big Bang [17]. Because the Universe was very hot during its earliest history, all kinds of interesting particles, known or unknown, were present in great abundance. Then it cooled down to a temperature T below the DM mass m_χ and the number of these particles became Boltzmann suppressed by a factor:

$$e^{-m_\chi/T}$$

This process is mitigated by the expansion of the universe until the dark matter quantity becomes constant to a value called thermal relic density. This "freeze out" equilibrium is shown in Fig. 1.8 and described by the Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2) \quad (1.20)$$

where n is the density variable, $\langle\sigma_{Av}\rangle$ is the mean cross section and n_{eq} is the density at the equilibrium.

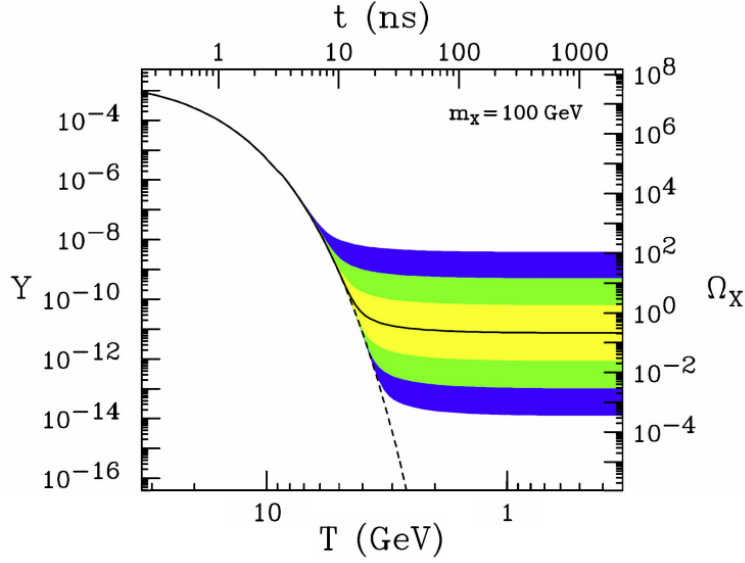


Figure 1.8. Co-moving number density Y (left) and resulting thermal relic (right) of a 100 GeV particle as a function of temperature (bottom) and time (top). The solid line is for an annihilation C.S. that yield the correct relic density, while the shaded ones are for C.S. correct by a factor 10, 10^2 and 10^3 from this value. Picture borrowed from [16]

The first term on the right takes into account the expansion of the Universe, while the second one depends on n^2 because the usual interactive model is

$$\chi + \bar{\chi} \rightarrow \phi + \phi^*$$

where a couple of DM particles goes to a couple of SM ones. Usually in literature it is useful to refer to DM through the co-moving number density

$$Y_\chi \equiv \frac{n_\chi}{s} \quad (1.21)$$

where s is the entropy density. Since the entropy is constant for a system in thermal equilibrium, s is proportional to the co-moving volume of the Universe ($s \propto a^{-3}$). From a rough point of view, Eq. 1.20 identifies the freeze out when $n\langle\sigma_{Av}\rangle = H$ so I can write the DM density parameters today as:

$$\Omega_\chi h^2 = \frac{\rho_\chi^0}{\rho_{crit}} h^2 = \left(\frac{s_0 h^2}{\rho_{crit}} \right) m_\chi Y_\chi^0 \quad (1.22)$$

In the freeze out assumption that $Y^0 = Y^f$, where f refers to the equilibrium condition, we obtain:

$$\begin{aligned} \Omega_\chi h^2 &= \left(\frac{s_0 h^2}{\rho_{crit}} \right) m_\chi Y_\chi^f = \left(\frac{s_0 h^2}{\rho_{crit}} \right) m_\chi \frac{n_\chi^f}{s^f} \sim \\ &\sim \left(\frac{s_0 h^2}{\rho_{crit}} \right) m_\chi \frac{H^f}{s^f \langle\sigma_{Av}\rangle} \propto \frac{1}{\langle\sigma_{Av}\rangle} \end{aligned} \quad (1.23)$$

From dimensional considerations, the WIMP cross section can be evaluated as:

$$\langle \sigma_{Av} \rangle \propto \frac{g_{weak}^4}{m_\chi^2} \quad (1.24)$$

and inserted in eq. 1.23, for the desired relic abundance (tab. 1.15), gives a mass $m_\chi = \mathcal{O}(\text{TeV})$. This is the WIMP miracle: weak-scale particles freeze out with the desired DM density factor.

Although the WIMP paradigm is highly appealing, no definitive evidence of its existence has been discovered yet within the expected mass range of approximately $1 \text{ GeV} \div \text{TeV}$. However, the lower mass region, below the GeV, is still theoretically motivated and, with the proper mechanisms, it is possible to reproduce the correct relic density [18]. This is why a particular attention is dedicated to "low mass" dark matter candidates.

1.3 Dark matter direct detection

1.3.1 Basics of direct detection

Until now, all the evidence of the existence of DM comes from its gravitational effects but to confirm its existence (together with the ΛCDM model) we have to detect it. Different experimental techniques have been developed in order to detect dark matter on Earth and they can be separated into three categories: accelerators, aiming to produce them; indirect detectors, designed to find ordinary particles resulting from interactions with dark matter particles; and direct detectors, focused on studying possible scatterings between ordinary and dark matter particles. The latter aims to observe the transferred energy-momentum of DM particles scattering with ordinary matter nuclei and in this section I will go deeper in this approach [19] because it is the one related to my thesis work.

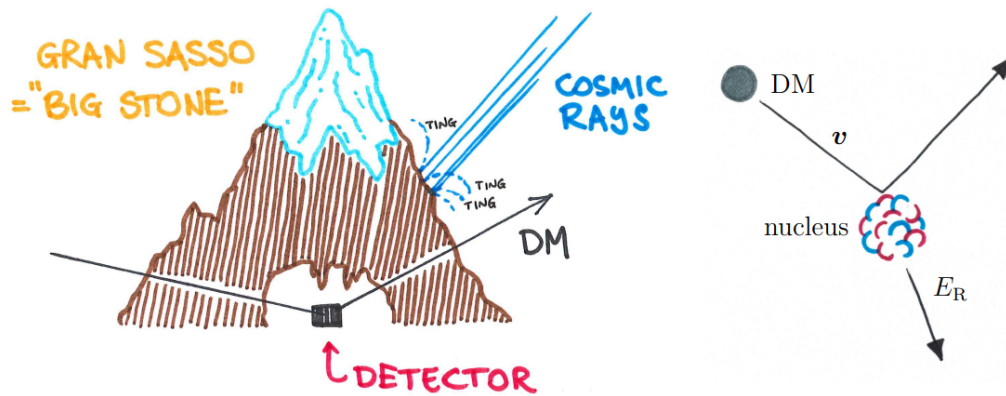


Figure 1.9. Basics of direct DM detection. Picture borrowed from the great Appendiciario by E. Nobile [19]

1.3.2 Density and velocity distribution

In order to achieve the expected rate of DM events, two important parameters must be obtained: the density and the velocity of the DM on Earth, 8.2 kpc from the center of our galaxy. For this reason it's of primary importance to build a model that, from the theoretical assumptions and evidence presented in the previous sections, describes the DM distribution in the Milky Way (MW). This model is called Standard Halo Model (SHM) [20,21].

Let be $f(\vec{x}, \vec{v}, t)$ the phase space distribution of DM and assume that:

- The MW halo is in a stationary regime:

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{x}} + \frac{\partial \Phi}{\partial \vec{x}} \cdot \frac{\partial f}{\partial \vec{v}} = 0 \quad (1.25)$$

where Φ is the potential

- The MW halo is self-consistent (the distribution generates the potential):

$$\nabla^2 \Phi = 4\pi G \rho = 4\pi G \int f d^3 \vec{v} \quad (1.26)$$

- It is an isotropic, isothermal sphere with density profile

$$\rho(r) \propto r^{-2} \quad (1.27)$$

In this case, Eq. [1.25] gives a Maxwellian distribution of the velocities:

$$f(\vec{v}) = \frac{1}{\mathcal{N}} \exp\left(-\frac{3|\vec{v}|^2}{2\sigma^2}\right) \quad (1.28)$$

where $\mathcal{N}$ is a normalization constant.

As a first consequence of these hypotheses, the halo has a flat rotation curve (as asked from the evidences presented in Sec. [1.1.1]) and the circular speed is related to the velocity dispersion σ by $\sigma = \sqrt{3/2}v_c$. In addition, the density distribution is formally infinite even though the MW is finite and the particles with a speed greater than the escape speed ($v_{esc} = \sqrt{2|\Phi(r)|}$) will not be bound to our galaxy. This is usually taken in account by truncating the velocity distribution at the local escape speed $v_{esc}(R_0)$.

The standard parameters that characterize the SHM are indeed the ones presented in Tab. [1.1], with their actual assumed values, and they are of great interest in direct dark matter search because directly measurable.

	value	measurement techniques
local density $\rho(R_0)$	0.3 GeV cm^{-3}	kinematic of nearby stars or mass modelling [22]
local circular speed $v_c(R_0)$	220 km s^{-1}	from proper motion of sgr A* [23] or by Jean analysis using tracer stars [24]
local escape speed $v_{esc}(R_0)$	554 km s^{-1}	from the speed of high velocity stars identified by different surveys [25, 26]

Table 1.1. List of the main observables of the standard halo model (used for directed dark matter detection research) together with their assumed value and the main techniques adopted to evaluate them. The uncertainties over that values can be appreciated looking at the Biography linked in the table together with a deep view on the specific techniques.

1.3.3 Scattering kinematics

From the point of view of kinematics, I will now consider the case of a non-relativistic and elastic collision as depicted in Fig. 1.10, that I also use to define a notation for the variables in role.

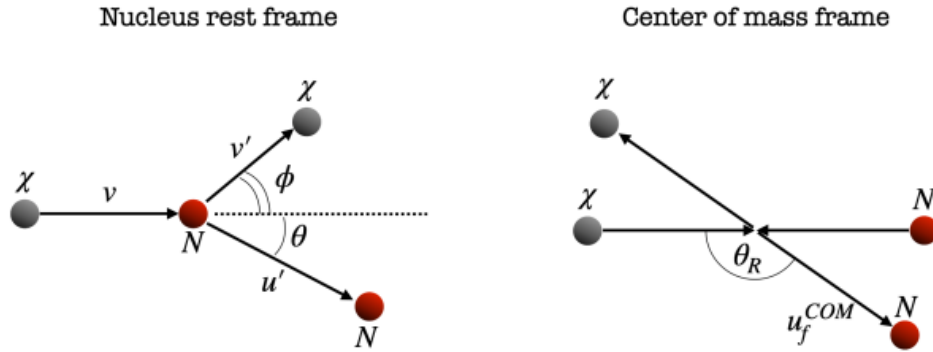


Figure 1.10. Sketch of the elastic scattering between a DM particle χ and a nucleus N in the typical reference frames adopted in physics. Picture borrowed from S. Piacentini [27].

From the three momentum conservation:

$$\begin{aligned} m_{DM} v &= m_{DM} v' \cos(\phi) + m_N u' \cos(\theta) \\ 0 &= m_{DM} v' \sin(\phi) - m_N u' \sin(\theta) \end{aligned} \quad (1.29)$$

hence:

$$\begin{aligned} v' \cos(\phi) &= v - \frac{m_N}{m_{DM}} u' \cos(\theta) \\ v' \sin(\phi) &= \frac{m_N}{m_{DM}} u' \sin(\theta) \end{aligned} \quad (1.30)$$

and by squaring

$$m_{DM} (v')^2 = m_{DM} v^2 + \frac{m_N^2}{m_{DM}} (u')^2 - 2 m_N v u' \cos(\theta) \quad (1.31)$$

Together with the conservation of the kinetic energy, given by the assumption of elastic scattering, and the definition of reduced mass

$$\mu \equiv \frac{m_{DM} m_N}{m_{DM} + m_N} \quad (1.32)$$

this last equation gives a formula for the nuclear recoil energy:

$$E_R \equiv \frac{1}{2} m_N (u')^2 = 2 \frac{\mu^2}{m_N} v^2 \cos^2(\theta) = \frac{\mu^2}{m_N} v^2 (1 - \cos(\theta_R)) \quad (1.33)$$

with θ_R the scattering angle in the center of mass reference frame.

Eq. 1.33 gives the minimal energy produced by a DM-nucleus scattering and points to the fact that not all nuclei are equally valid to detect any possible dark matter energy. Set the velocity by the SHM and $E_R|_{min}$ by the sensibility of the detector, the choice of the target selects a mass window of greater sensibility .

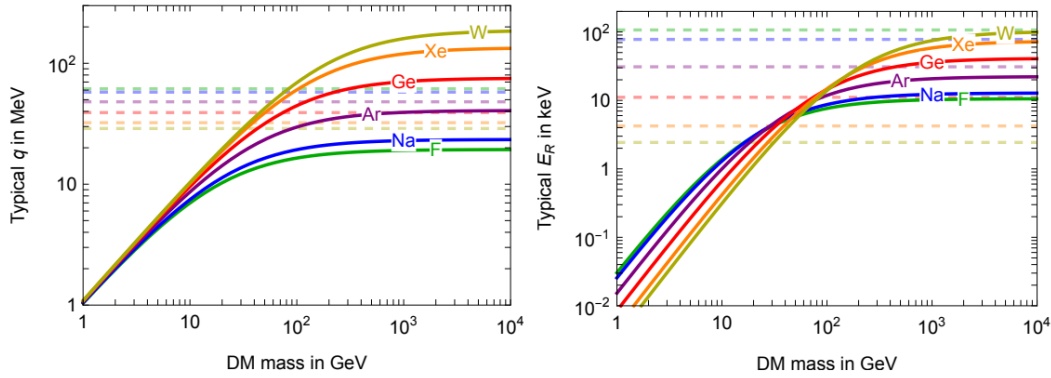


Figure 1.11. Typical momentum transfer (on the left) and recoil energy (on the right) as a function of the DM mass for different targets. Figure taken from [19]

Fig. 1.11 shows the typical momentum transfer and recoil energy for different targets and suggests the reason why we consider only interactions of DM with nuclei and not with the whole atom, or part of it. Assuming a typical momentum transfer of $q \sim 10$ MeV, the corresponding de Broglie wavelength is:

$$\lambda = \frac{h}{q} \sim 120 \text{ fm}]. \quad (1.34)$$

On the other side, the radius of a nucleus can be estimated by $R_N \sim 1.25 A^{1/3}$, where A is the mass number, and usually it is of $\mathcal{O}(\text{fm})$. Being the de Broglie wavelength usually much bigger than an atomic nucleus, we assume that the scattering with DM particles is "coherent": the nucleus isn't seen as a bound state but as a unique object. In Fig. 1.12 a plot resuming the conditions for a coherent DM-nucleus scattering

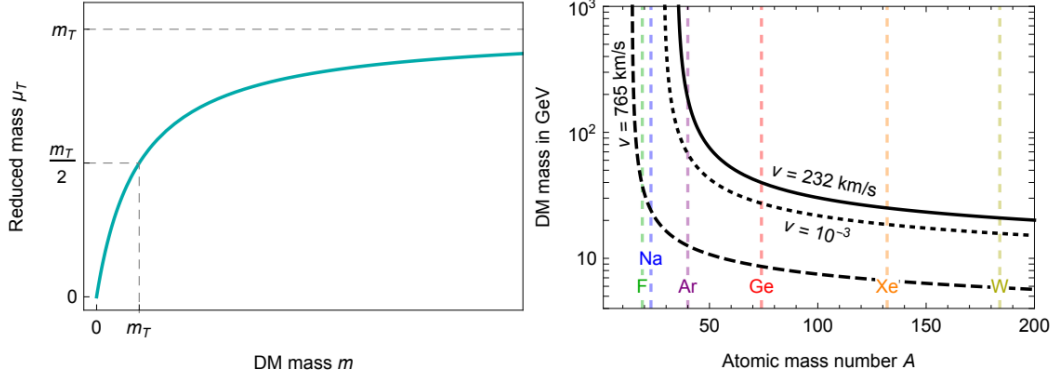


Figure 1.12. On the left a plot of the reduced mass μ_T , for fixed m_T , as a function of m . On the right the condition for a DM-nucleus coherent scattering in function of the mass number A . For a given target, DM masses below the black line, representing the adopted wind velocity, scatter coherently. Figure from [19].

1.3.4 Events rate and cross section: why go underground?

The scattering cross section for a DM particle is defined as:

$$\frac{dN_e}{dV dt} \equiv n_T n v \sigma_T(v) \quad (1.35)$$

with N_e the number of events and n (n_t) the densities of DM particles (targets). Dividing by the detector density I pass to the scattering rate per unit mass:

$$\frac{dN_e}{dM dt} = \frac{d\mathcal{N}_T}{dM} n v \sigma_T \quad (1.36)$$

with $\mathcal{N}_T$ the number of targets.

For a compound detector, as the one that my thesis deals with (Ch. 2), denoting with $\xi_{i,T}$ the numerical abundance of the i -th nuclide in the detector, it results that

$$\frac{d\mathcal{N}_T}{dM} = \frac{\chi_{i,T}}{\sum_j \chi_{j,T} m_{j,T}} = \frac{\xi_{i,T}}{m_{i,T}} \quad (1.37)$$

that inserted in 1.36 gives the scattering rate within the specific nuclear species i . Considering now the fact that the SHM gives a velocity distribution for DM particles and $n = \rho(R_0)/m$, I finally write the differential scattering rate for energy recoil:

$$\frac{dN_T}{dM dt dE_R}(E_R, t) = \frac{\rho(R_0)}{m} \left(\sum_i \frac{\xi_{i,T}}{m_{i,T}} \right) \int_{v_{min}(E_R)}^{v_{esc}} d^3v f(\vec{v}, t) v \frac{d\sigma_T}{dE_R}(E_R, \vec{v}) \quad (1.38)$$

where I accounted for the fact that not all velocities give a detectable recoil due to the detector sensitivity.

The crucial quantity to be determined is therefore the differential cross section

and, since we don't know what DM is, it is usually written as the sum of a spin-independent (SI) and a spin-dependent (SD) part. Following [19], I present a quite model independent parametrization of the differential cross section:

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2} \left[\sigma_0^{SI} F_{SI}^2(q^2) + \sigma_0^{SD} F_{SD}^2(q^2) \right] \quad (1.39)$$

where the F are form factor that, in our non-relativistic case, are approximated with their zero-momentum value of 1. Regarding the cross sections:

$$\begin{aligned} \sigma_0^{SI} &= \frac{\mu^2}{\pi} \left[Z f_p + (A - Z) f_n \right]^2 \\ \sigma_0^{SD} &= \frac{\mu^2}{\pi} \frac{J+1}{J} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle \right]^2 \end{aligned} \quad (1.40)$$

In the SI case, the standard assumption is the isosinglet condition (i.e. $f_p = f_n$) that returns

$$\sigma_0^{SI} = \sigma_p \frac{\mu^2}{\mu_p^2} A^2 \quad (1.41)$$

with σ_p the DM-proton cross section and μ_p their reduced mass.

In this approximation, the cross-section is $\propto v^{-2}$ and we are finally ready to compute the last quantity of [1.38]: the velocity integral. Assuming $v_{esc} \rightarrow \infty$ and borrowing the form of $f(\vec{v})$ from SHM:

$$\frac{dR}{dE_R} \propto \int_{v_{min}}^{\infty} \frac{1}{v} \exp \left[- \frac{|\vec{v} + \vec{v}_E|^2}{v_0^2} \right] d\vec{v}$$

where $\vec{v}_E$ is the velocity of Earth, that encodes the temporal dependence of $f(\vec{v})$, and that will be neglected in the following few steps. The final equation gives, by mean of [1.33]:

$$\frac{dR}{dE_R} = \frac{R_0}{r E_0} \exp \left[- \frac{E_R}{r E_0} \right] \quad (1.42)$$

where

$$E_0 = \frac{1}{2} m_{DM} v_0^2 \quad r = 4 \frac{m_{DM} m_N}{(m_{DM} + m_N)^2} \quad R_0 = \int_0^{\infty} \frac{dR}{dE_R} dE_R \quad (1.43)$$

The final result of this section reveals that DM particles deposit a small amount of energy in ordinary nuclei, moreover with an exponentially falling rate and no peculiar features or resonances. Fig. [1.13] shows exactly this behaviour for a more complete calculation and, just to give an order of magnitude, the total rate expected is about³ $\mathcal{O}(1 \text{ evt kg}^{-1} \text{ y}^{-1})$. Because of this low event rate, the general strategy requires experiments with a huge amount of active material and a long period of running.

³Assumed Argon as target element, $m_{DM} \sim 10 \text{ GeV}/c^2$ and $\sigma^{SI} \sim 10^{-38} \text{ cm}^2$

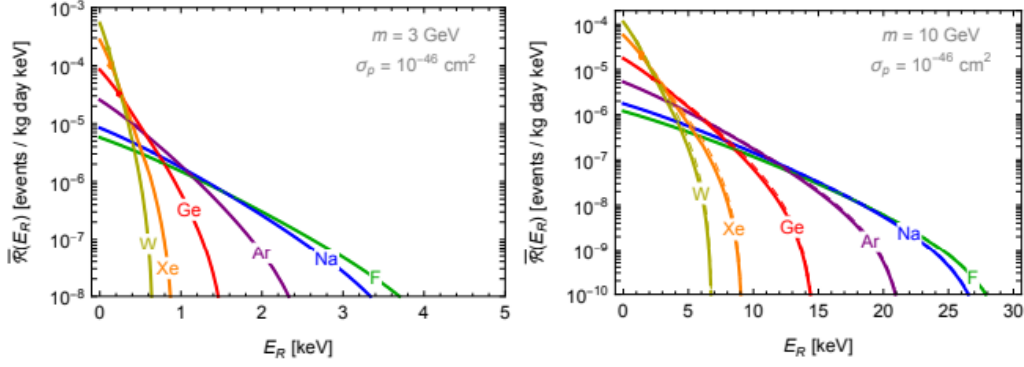


Figure 1.13. Annual-average rate spectra for the SI interaction for different target nuclei. The two plots refers to different DM masses and the value of σ_p is fixed to the value shown. Figure from [19].

To enhance the effectiveness of these experiments, it is essential to minimize background events, primarily stemming from cosmic rays and internal radioactivity. For the former, the natural choice is to locate the experiment underground: the materials constituting the Earth's crust acts as a shield and can protect the detector from being exposed to the cosmic rays. In Fig 1.14 it is shown how the cosmic muon flux (taken as example because really penetrating) is reduced in some underground laboratory facilities in the world. In addition, most of the experiments are also equipped with additional artificial shielding and active veto systems capable of reducing environmental background in a more specific way. Commonly employed materials are lead (prized for its density of target nuclei), polyethylene (prized for its high neutron capture) and copper. On the other hand, purging volumes with gases like nitrogen can help to drive out airborne radioisotopes like radon. However, cosmic ray muons can penetrate deep underground and generate high-energy neutrons, which can enter the detector volume, mimicking a Dark Matter nuclear recoil signal. This neutron production can occur through various mechanisms, including muon capture, photo-nuclear reactions from electromagnetic showers, deep-inelastic muon-nucleus interactions, and hadronic interactions of nucleons with pions and kaons produced in hadronic showers. Consequently, besides passive shielding, it is imperative to anticipate neutron background by understanding the surrounding materials.

For the internal noise, shielding is insufficient since the experiment itself can contain radioisotopes that emit detectable signals through decay. To ensure the experiment's reliability, the rate of such events must be reduced to below 1 part per billion (ppb) and some approaches must be employed:

- Elimination of radioisotopes through purification techniques and meticulous control of the detector's exposure to the atmosphere. However, this approach is highly experiment-specific and not always feasible.
- Active screening of the materials: analysis of the decay spectra of all the elements of the experiment followed by a simulation of how these sources would

appear to the detector.

- Applying fiducialization: identify specific regions of the apparatus where noisy events are mainly collected.

In conclusion, addressing the challenges of low event rates, cosmic ray interference and internal radioactivity are crucial aspects to consider in the pursuit of Dark Matter detection. These efforts require a combination of experimental scale, underground positioning, shielding, and meticulous material analysis to ensure the reliability of the experiments.

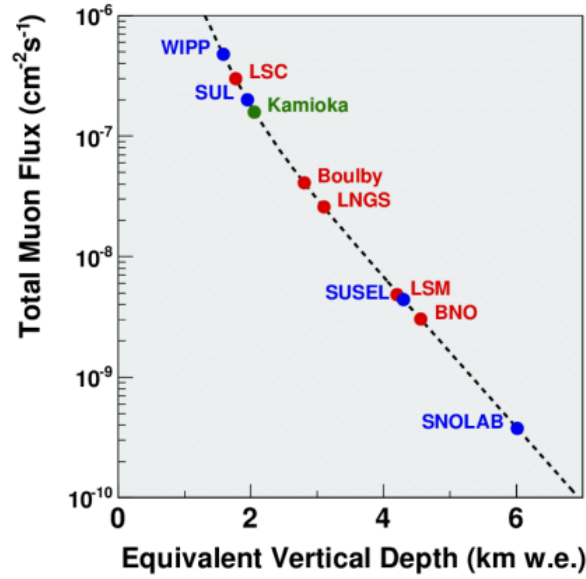


Figure 1.14. Intensity of muons vs. depth for different underground laboratory facilities. In particular note the position of LNGS because of direct interest in my thesis work. Picture taken from [28] even though it is not the real source.

1.3.5 Dark matter modulation

Until now, the focus has been on the event rate integrated over time, but not on the potential time structure of the rate itself. This time dependence is due to the fact that Earth orbits around the Sun, so that half of the year we flow into the WIMP wind and the other half out of it. In fact, the direction of the Sun through WIMP halo is in the direction of the constellation Cygnus, along the galaxy plane so we expect a larger rate in the summer with respect to the winter [1.15]. The effect on the signal is an *annual modulation* of the event rate that can be approximated to:

$$\frac{dR}{dE_R}(E_R, t) \sim \frac{dR}{dE_R} \left[1 + \Delta(E_R) \cos \frac{2\pi(t - t_0)}{T} \right] \quad (1.44)$$

where T is the period of revolution, t_0 is a phase and $\Delta(E_R)$ is the modulation amplitude that, due to the $\sim 60^\circ$ of inclination of Earth orbit and the revolution

velocity $v_{orbit}/v_{sun} \sim 0.07$, is of order $\mathcal{O}(1 \div 10\%)$ [29].

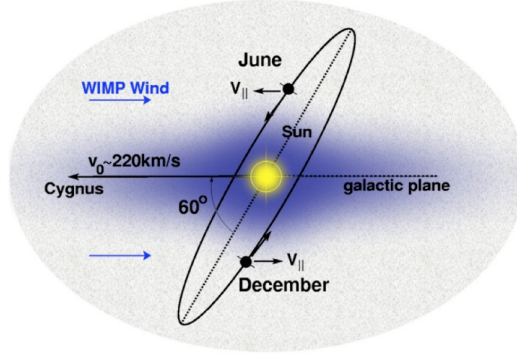


Figure 1.15. Schematic view of the relative motion of Earth with respect to the WIMP halo due to the revolution of our plane around the Sun

An evidence of such modulation would be a great proof of dark matter existence as a WIMP particle and a fundamental tool to trust the SHM. For this reason, the claim of the DAMA collaboration of the first observation of such temporal structure (Fig. 1.16) cannot be omitted. Even though it's a report still under debate, it engendered a great deal of excitement in the field, promoting studies in direct dark matter detection sectors.

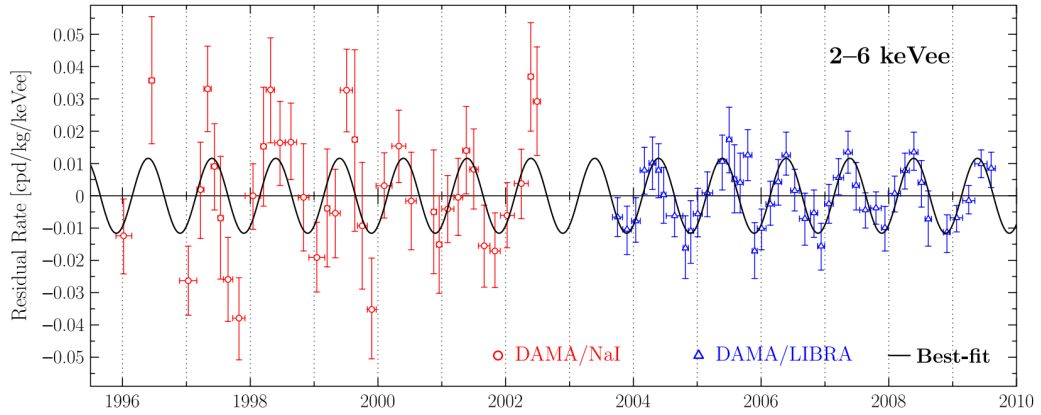


Figure 1.16. The residual rate measured by DAMA/NaI and DAMA/LIBRA as function of time. Plot made by [29] with the data from [30, 31]. The superimposed sinusoidal fit gives consistent results with the SHM expectations.

In addition, detectors can be made sensitive to the direction of the NR induced by DM. The Earth's motion produces a direction dependence of the recoil spectrum that always peaks towards the Cygnus constellation. In the lab frame, this direction changes during the day (Fig. 1.17) and depends on the experiment location too, thus providing an independent and complementary analysis between the various researches in the world.

A daily modulation in directionality could be visible with sensitive detector and,

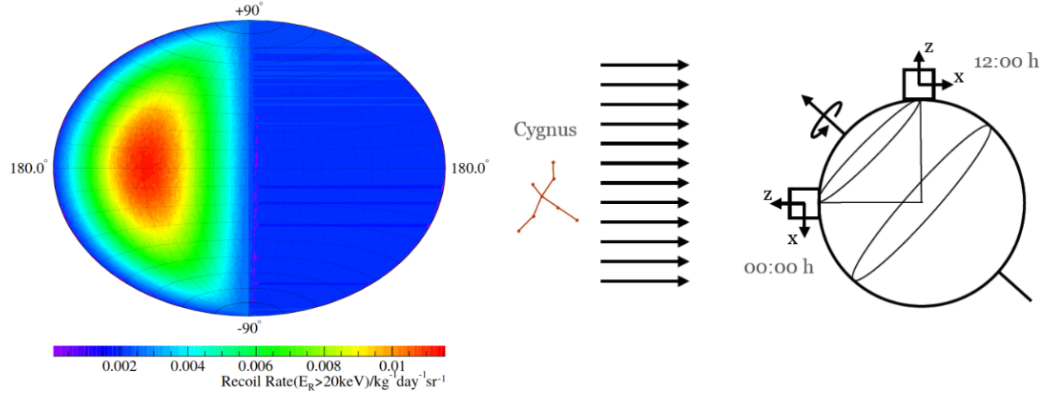


Figure 1.17. On the right, directional recoil rate for a standard halo WIMP of $m_\chi = 100 \text{ GeV}$. Figure from [32]. On the left, Earth rotation around its axis with respect to the WIMP wind. Picture taken from [33].

assuming SHM, the dependence is given by [32]:

$$\frac{dR}{dE_R d\cos\gamma} \propto \exp \left[-\frac{1}{v_0^2} \left[\left(v_{orb}^{\parallel} + v_{sun} \right) \cos\gamma - v_{min} \right]^2 \right] \quad (1.45)$$

The angular distribution of the NR in the Cygnus direction would have a population an order of magnitude bigger than the opposite direction (Fig. 1.17), allowing a clear distinction of DM signal over a flat isotropic background.

1.3.6 Sensitivity today

Since, until now, we have no incontrovertible evidence of dark matter, the only conclusions that we can state are constraining on the possible DM features. A typical parameter space studied in this sense is the plot of the SI cross-section in function of the WIMP mass (Fig. 1.18). The results come from different experiments (see [13] "SI cross section limits for dark matter particle on nucleon") and here some general consideration about the plot:

- The green area corresponds to the 90% C.L. excluded region;
- The non accessible area doesn't extend up to infinite σ even though it's not shown the upper limit. In fact there is the "Earth shielding" and it means that if the cross-section were too high, DM would be absorbed by atmosphere not reaching the experiments;
- The neutrino floor is a region in which the background events from the coherent scattering of neutrinos on the nuclei can't be neither neglected or reduced. A more formal treatment can be found in [34].
- The region $m_\chi > 1 \text{ GeV}$ is very much excluded by the experiments XENONIT and LUX [35, 36];

- The $\mathcal{O}(\text{GeV})$ region is instead still promising even though more experimentally involved because of the low energy NR it corresponds to. Within the $\mathcal{O}(1\text{GeV} \div 100\text{GeV})$ range, Time Projection Chambers (TPCs) using noble gasses or liquids emerge as exceptionally effective detectors due to their high sensitivity and directional capabilities.
- The sub GeV range is instead better investigated by means of $\mathcal{O}(\text{eV})$ sensible apparatus like solid state detectors (bolometers and semiconductors). In this context, the experiments that published the most recent constraint on dark matter cross-section are CDEX [37] and SuperCDMS [38];
- The closed regions denote the DM constraints as evaluated from the NR annual modulation reported by the DAMA collaboration [39].

Simultaneously with the quest for more sensitive detectors, there are ongoing and promising research efforts aimed at expanding the accessible parameter space while maintaining a comparable energy threshold. In this context, the Migdal effect [27] and photon bremsstrahlung [40] represent compelling avenues of investigation.

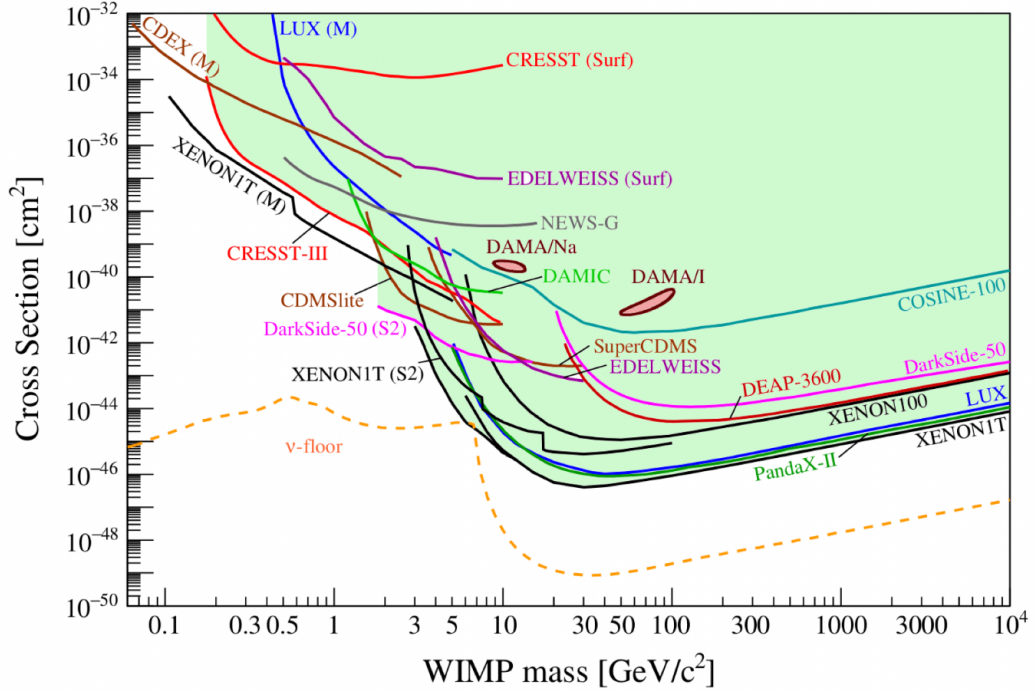


Figure 1.18. State-of-the-art of DM direct detection expressed as the SI cross-section constraints in function of the possible WIMP mass. The curves are obtained assuming the value in Tab. 1.1 for the parameters of the SHM. The green area is the mostly excluded region. Picture borrowed from [41]

Chapter 2

The Cygno experiment

The Cygno collaboration [42] is a dedicated research group with the primary focus on establishing a high-resolution Time Projection Chamber (TPC) employing optical readout through gas electron multipliers (GEMs) at the INFN Gran Sasso Laboratories (LNGS). Adopting a helium/fluorine gas mixture as active material, its intent is to probe the still mostly-unexplored $\mathcal{O}(\text{GeV})$ DM mass range. The setup consists of a CMOS camera and fast photomultiplier tubes (PMTs) for directional Dark Matter search. Actually the experiment is at the end of its R&D phase with the commissioning of the LIME prototype in the underground laboratories of LNGS. In the following chapter, I delve into a detailed presentation of the CYGNO approach, discussing its experimental strategy and the expected performances. Subsequently, I provide a comprehensive overview of the LIME prototype, its key features and reconstruction algorithms. This discussion is essential to gain a thorough understanding of the work conducted during my thesis. I conclude presenting insights into the future steps envisioned for the CYGNO program and into the region it aims to explore in the "mass vs. cross-section" diagram.

2.1 The goal of the CYGNO experiment

2.1.1 The experimental approach

A TPC [43] is a detector filled with liquid or gas, combined with an intense electric field, that is able to detect the energy release of a particle traveling through its active material. This energy release can be produced in different ways but the CYGNO experiment adopts ionization as main channel of investigation¹. When a particle passes through the TPC, ionizes the inner material and the generated electrons drift towards the anode because of the Lorentz force. The main advantage of this approach, in the scope of directional detection, is the high accuracy in the reconstruction of the particle track. In contrast to other prominent experiments in the field, such as Xenon or DarkSide, the CYGNO project adopts gasses as its detection medium, rather than liquids. This choice is motivated by the aim to achieve unparalleled accuracy in the reconstruction of particle paths setting it apart

¹Particles can also loss energy in the detector through excitation of the molecules or heat

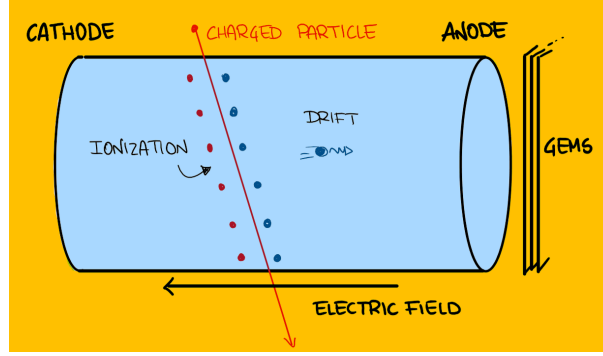


Figure 2.1. Scheme of a cylindrical TPC. A particle traveling in the active material ionizes it and the generated electrons drift toward the anode due to the presence of an electric field.

as a promising player in the pursuit of directional DM detection.

Once the electrons reach the anode, they must pass an amplification stage in order to produce a detectable signal. This is achieved in CYGNO by a triple stack of GEMs, each one increasing the signal by a factor of $\sim 10^2$.

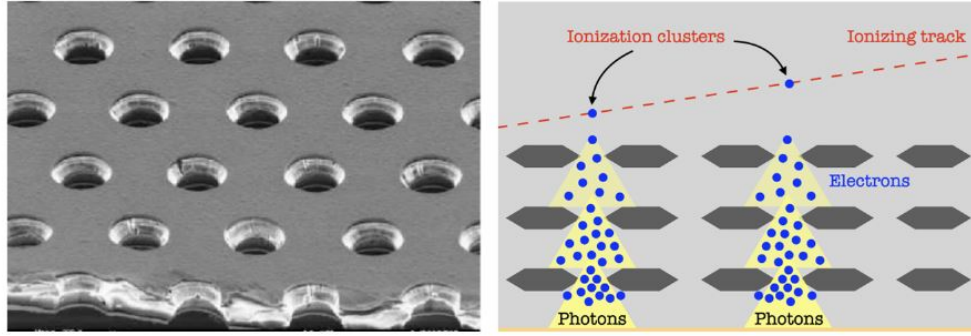


Figure 2.2. On the left a GEM foil seen under an electron microscope. On the right a schematic drawing of the multiplication process performed by the three stack of GEMs.

A GEM is a kapton foil of thickness about $50\,\mu\text{m}$, clad on each side by a thin copper layer ($5\,\mu\text{m}$) and chemically pierced by a high density of holes. Applying a voltage difference between the two copper sides results in a high electric field in the holes: the drifted electrons enter the holes and are multiplied by an avalanche process. The main result of this massive production, is the excitation of the molecules of the material and a subsequent emission of photons. The efficiency of this process depends on the scintillating properties of the active matter and in sec. [2.1.3](#) I present the gas mixture adopted by the CYGNO collaboration.

The most important features of a gaseous TPC are the following:

- it is a 3D tracking system (hence adapt for directional detection) that allows large volumes of sensible material instrumented with a relative small amount of readout channels;

- the measurement of the ionization allows a good signal/background discrimination based on the energy deposit of the track;
- the gas mixture can be changed in order to be sensible to different DM mass regions;
- it works at room temperature and atmospheric pressure;
- it can be built a working experiment up to 100 m^3 of active material [44,45].

2.1.2 Optical readout

The photons produced in the amplification stage are acquired to infer the properties of the original particle. The main device for the optical readout consists of a sCMOS-based optical sensor: a camera based on active pixel sensor (APS) technology developed on complementary metal-oxide semiconductors (CMOS). In recent years, it has been proved that the high granularity and rate capability of micro-pattern gaseous detectors (like GEMs) are very well coupled with pixelated light sensors. The Cygno collaboration proved [46] excellent performances in the energy range needed for DM detection and beyond [47-50]. In addition, these devices have two great advantages:

- They can be easily produced, because they have commercial applications too;
- They have an intuitive acquisition of the signal: looking to a picture that clearly shows the track of a particle allows a fast and clear understanding on what is happening in the gas.

In addition, by means of a proper lens, a large area (up to 1 m^2) can be acquired with a single sensor without losing the spatial resolution of the pixel effective size ($100\text{ }\mu\text{m}$). In order to achieve a 3D reconstruction, the signal of the drifted electrons is used to evaluate the position on the plane orthogonal to the drift field, while the drift time is used to evaluate the remaining z coordinate. Unfortunately, the sCMOS devices have a too low frame rate for a complete 3D reconstruction and this is the reason why the CYGNO experiment employs additional fast photo-sensors (PMTs or SiPMs) in order to achieve the missing temporal information.

2.1.3 Gas Mixture

The CYGNO experiment employs a gas mixture of active material:

- 40% of tetrafluoromethane (CF_4): it is a scintillating material with the secondary peak of light emission in the grater quantum efficiency range of the camera [51].
- 60% of helium (He): it is meant to be the main target to test DM interactions, allowing the access to the GeV mass range (see section 1.3)

The He/CF₄ proportions have been chosen by the CYGNO collaboration as the best compromise between detector stability, given by the former, and light yield by the latter [52, 53]. From the point of view of the transport properties, Fig. 2.3 and 2.4 show the diffusion coefficients and the drift velocity as a function of the drift field. These evaluations were performed with the program Garfield [54] and a dedicated introduction to the meaning of these variables can be found in Appendix A

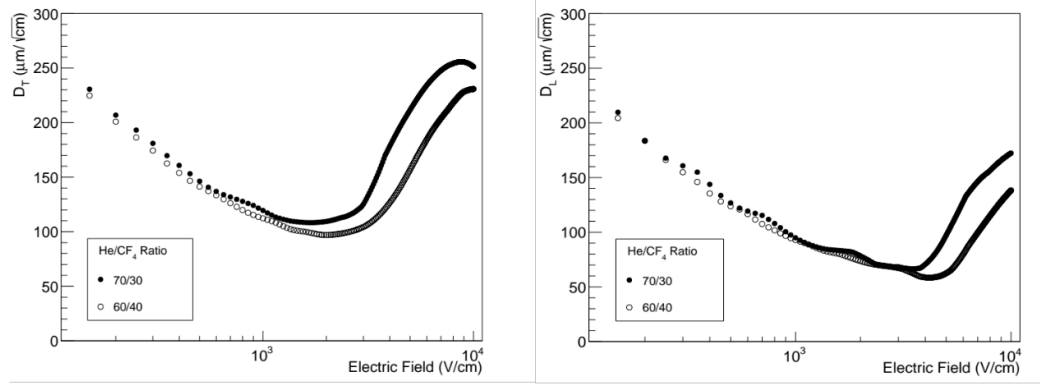


Figure 2.3. On the left and on the right, respectively, the transverse and the longitudinal coefficient of diffusion as calculated by the software Garfield. Note that this coefficients refers to what is identified with f in Appendix A and during the thesis. For each case, two different proportions of the gas mixture are considered. The accuracy of these simulations is estimated to be around 10%. Picture from [55].

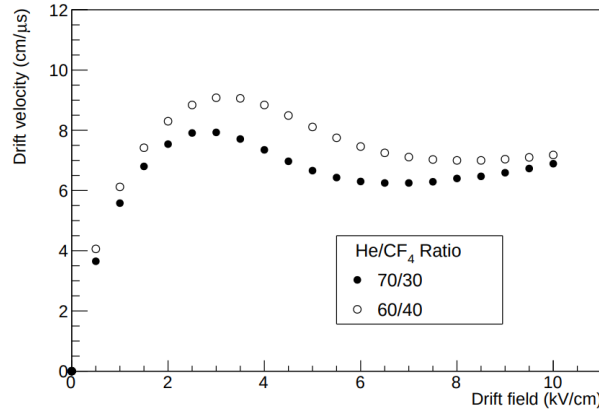


Figure 2.4. Electron drift velocity as function of the drift field for two possible gas mixtures as calculated by the software Garfield. The accuracy of this simulation is estimated to be around 10%. Picture from [55].

Regarding the ionization properties of He/CF₄, Tab. 2.1 summarizes some important parameters useful to estimate the energy loss and the ionization yields of fast charged particles in gases [13]. The number of primary ionizations N_P follows a Poisson statistics and allows to define the theoretical detector efficiency as the probability of having at least one interaction [56]. In formula:

$$\epsilon = 1 - P_0^{N_P} = 1 - e^{-N_P} \quad (2.1)$$

Gas	density mg cm ⁻³	E_I eV	W_I eV	$dE/dx _{min}$ keV cm ⁻¹	N_P cm ⁻¹	N_T cm ⁻¹
He	0.179	24.6	41.3	0.32	3.5	8
CF ₄	3.78	16	35-52	6.38	53-63	120

Table 2.1. Properties of noble and molecular gases at NTP (Normal temperature and pressure). E_I : first ionization energy; W_I : average energy for creation ion pair; $dE/dx|_{min}$ N_P N_T : differential energy loss, primary and total number of electron-ion pair per cm, for unit charge MIP. Values from [13].

The total number of pairs released in a medium (in absence of recombination) is, by average, given by:

$$N_T = \frac{\Delta E}{W_I} \quad (2.2)$$

where ΔE is the total energy loss and W_I the electron-ion pair energy cost. Regarding the differential energy loss in mixture materials, with relative mass concentrations ρ_i , we have:

$$\frac{dE}{dx} = \sum_i \rho_i \cdot \left[\frac{dE}{dx} \right]_i \quad (2.3)$$

As an example, lets consider the case of a MIP. With a $W_i \sim 42$ eV and a typical energy loss of:

$$-\frac{dE}{dx} = 2 \cdot \rho_{mixture} \text{ MeV/cm} \sim 300 \text{ eV/mm} \quad (2.4)$$

it returns a mean value of ~ 3 ionizations/mm with about 2 electrons per cluster

In Sec [1.3], I explained how DM is expected to interact mainly with nuclei, producing nuclear recoils. This type of signal must be differentiated from the background that is composed by:

- electronic recoils (ER), generated by photons, electron, or cosmoics rays that interact electromagnetically with the atomic electrons that are, as a consequence, extracted from their bound state;
- Other nuclear recoils (NR), generated by the interaction of alpha particles and neutrons with the atomic nucleus.

The differentiation of these two signatures is necessary and, how anticipated at the beginning of the section, the Cygno experiment operates this separation thanks to the different ionization produced by ERs and NRs. In this scope, MC simulations with GEANT and SRIM software [42], respectively, have been developed and one of the most interesting results is shown in Fig. [2.5]. The range of the recoiling track as a function of the recoil energy is presented and some immediate considerations come out:

- NR up to 100 keV provides tracks with a size less then a 1 mm, hence spot-like with a dimension dominated by diffusion effects;

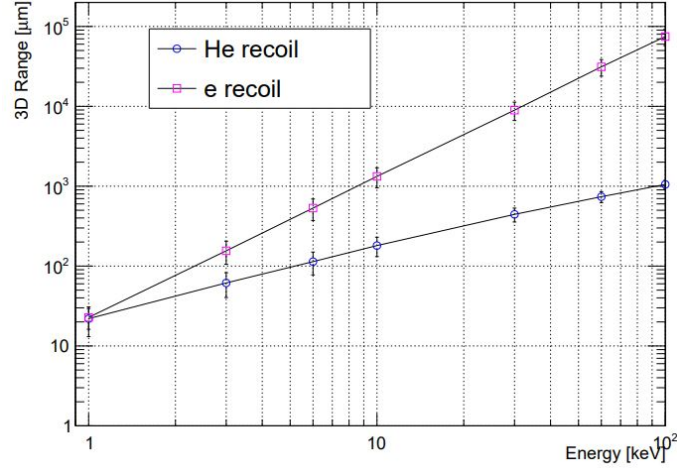


Figure 2.5. Average 3D range of electronic and He-recoils as a function of the recoil energy as simulated by GEANT and SRIM software. The results refers to the considered He/CF₄ gas mixture adopted by the CYGNO collaboration.

- ER are spot-like for low energies but above 10 keV they show an extended structure;
- one of the main variable of ER/NR discrimination should be the track energy density.

Regarding the last point, it is relevant to underline that NRs deposit energy in a different way than ERs: while the latter transfer efficiently the kinetic energy to the gas ionization, the latter dissipate energy through inelastic scatterings. In this context, the ER signal are measured in keVee (keV *electron equivalent*), while the NR in keVnr, with a relation of the form:

$$E_{detected}(\text{keVee}) = QF \cdot E_{recoil}(\text{keVnr}) \quad (2.5)$$

The evaluation of the *Quenching factor* (QF) is performed by means of a SRIM simulation of each element of the gas mixture (other elements, in addition to the ones presented in this thesis, are considered). Fig. 2.6 presents the results as function of the NR energy 57.

2.1.4 CYGNO roadmap

The techniques outlined in the previous section have been tested since 2015 following a staged plan (Fig. 2.7) that involves:

- PHASE_0: built and analysis of the response of different prototype of the experiment. The final step is the installation of the 50 liter LIME prototype underground at LNGS with the goal of studying the performances in a low background environment and validate MC simulations. References on the built and studied prototype can be found in 58 and 55;

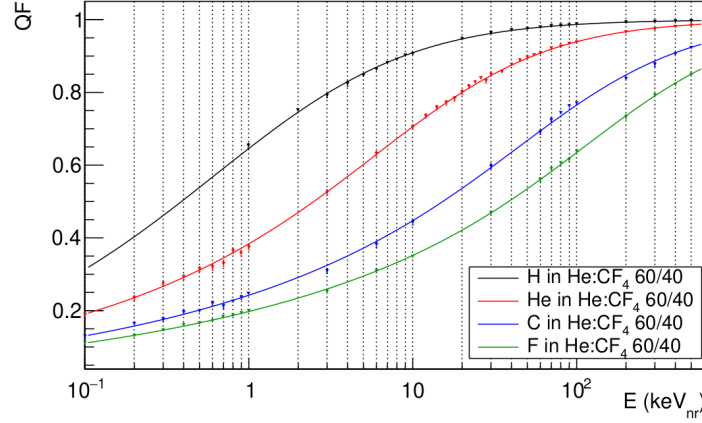


Figure 2.6. Quenching Factor as a function of the NR energy for the various elements of the Cygno gas mixture as simulated by the SRIM software. Picture extracted from [57].

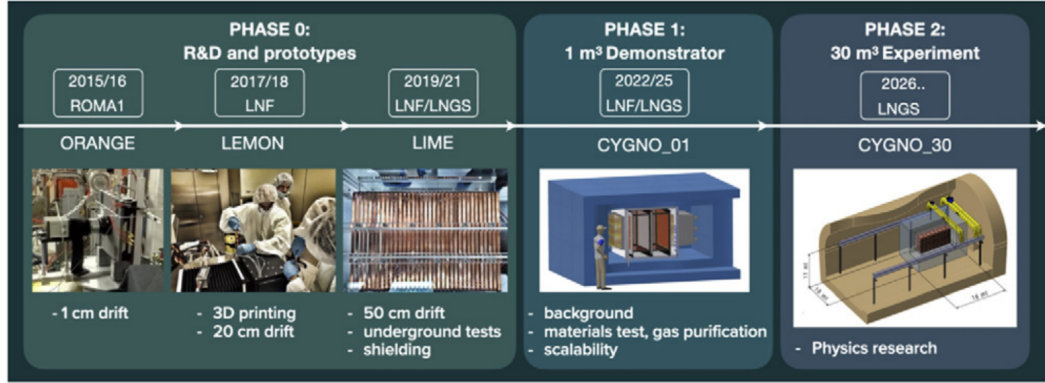


Figure 2.7. CYGNO project road-map, from R&D (Phase 0), demonstrator (Phase 1), to the experiment (Phase 2).

- PHASE_1: developing a 1 m³ demonstrator to test the scalability of the experiment while studying and minimizing the internal background due to the radioactivity of the apparatus materials;
- PHASE_2: propose a larger experiment 100 m³ to explore the 1 - 10 GeV DM mass region.

2.2 The LIME prototype

2.2.1 Description of the prototype

The Long Imaging ModuleE (LIME) detector [59] is the actual prototype of the CYGNO experiment. It consists of a squared-box TPC with a height of 50 cm and a 33×33 cm² transverse area and it was built at Laboratori Nazionali di Frascati (LNF). It's now collecting data underground at LNGS and with different shielding configurations in order to validate the CYGNO approach in a low pile-up config-

uration. Its goal is the qualification of the materials adopted for the construction as a function of the intrinsic background and the evaluation of their suitability. In addition, a key point is the comparison with the MC simulations in order to determine the actual feasibility of the experiment.

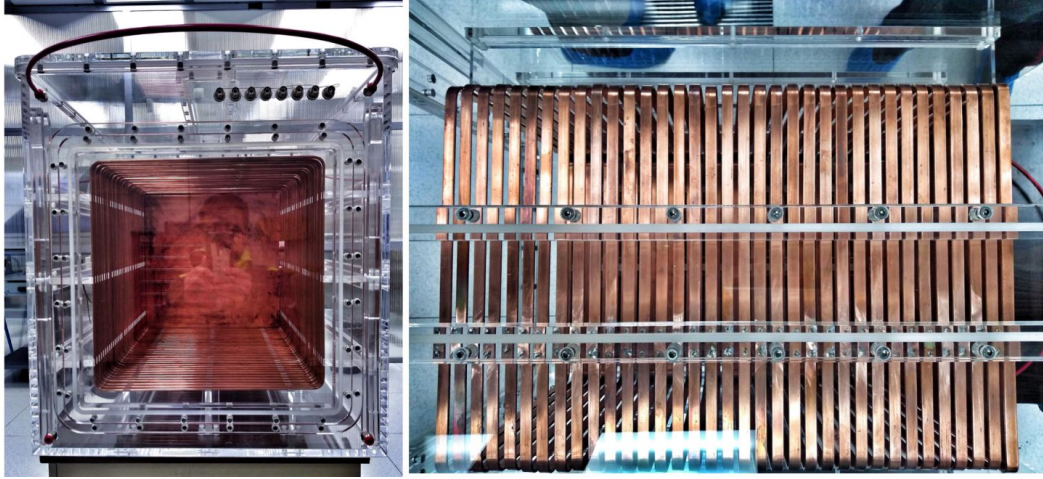


Figure 2.8. A front and transverse view of the LIME prototype. You can also see the mirror image of Davide taking the photo.

Gas vessel and field cage

The active matter is the already presented He/CF₄ gas mixture at a very small over-pressure, with respect to the atmospheric one, contained in a 10 mm thick PMMA box. The field cage has a square section of 330 mm × 488 mm and consists of a series of 34 copper rings that end with a 0.5 mm thin copper cathode. Each ring is 10 mm thick and is placed at a distance of 4 mm from each other. On the other side, 3 stacks of GEMs with 50 μm size holes and distant 2 mm from each other, take place. The distance of the face of the vessel from the GEM stack is 1 mm to allow efficient transmission of light to the outside.

External sources

The upper face of the vessel includes a 5 cm wide and 50 cm long window sealed by a 150 μm thick EFTE layer. This allows low energy photons (down to keV energy) to enter the gas volume from an external artificial ⁵⁵Fe radioactive source used for calibration purposes. A plastic trolley is mounted on such a window, free to move along it and a source holder is positioned at its base. The effect of this 5 cm holder is the collimation of the produced radiation. In Fig. 2.9 a view of the mechanism adopted to move manually the plastic trolley. An accuracy of $\Delta z = 1$ cm is estimated on the position of the holder.

External shielding

LIME has worked since 2022 producing a good agreement with the expected response and passing different stages (called RUNs²) based on the type of shielding adopted.

²In the rest of the thesis, RUNs refers to the different stages of LIME, while runs refers to a specific groups of data that will be described in Sec. 2.2.2

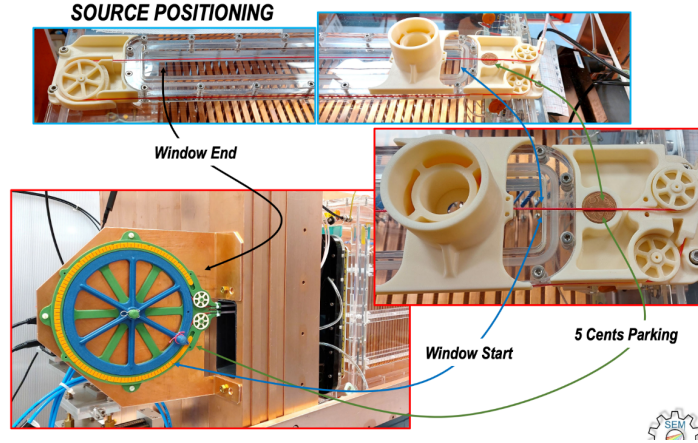


Figure 2.9. A detailed view of the mechanism employed within the LIME prototype to move the plastic trolley on the field cage. This trolley hosts an ^{55}Fe radioactive source used for calibration purposes.

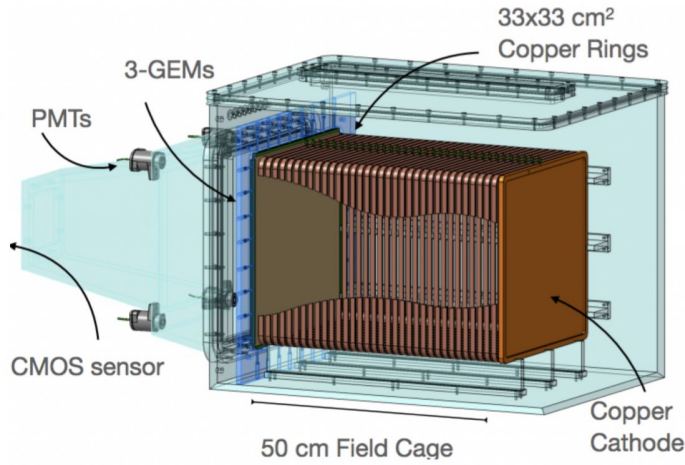


Figure 2.10. Sketch of the LIME prototype setup.

In Tab. 2.2 a summary of the configurations.

Read out system

On the side of the GEM stack, a black PMMA conical structure is fixed to allow the housing of the optical devices. In this way, the light produced by the avalanche process is collected by a scientific CMOS camera and a set of 4 PMTs, as sketched in Fig. 2.10.

The camera chosen for the LIME commissioning is the Hamamatsu Orca Fusion scientific CMOS-based camera [60]. In the following (Fig. 2.11 and Tab. 2.3), a list of the main features of the device and its spectral quantum efficiency. In order to acquire the whole GEM surface, the camera is coupled with a Schneider Xenon 0.95/25-0037 lens [61] in the configuration of 25.6 mm of focal length, an aperture of 0.95 and placed 62.3 cm from the GEMs.

Name of the RUN	location	shielding
RUN 1	LNF	no shielding
RUN 1	LNGS	no shielding
RUN 2	LNGS	4 cm of copper
RUN 3	LNGS	10 cm of copper

Table 2.2. Different LIME configurations during it's campaign. The main relevant difference between the various stages (called RUNs) is the different shielding of the prototype, both natural and artificial.

Camera parameter	Value	Unit
Dimensions	2304×2304	$px \times px$
Pixel size	6.5×6.5	μm^2
QE @ 600 nm	70 %	
readout noise	0.7	electrons r.m.s
dark current	0.5	electrons/px/s
exposition	$30 \div 10^4$	ms

Table 2.3. A table resuming the main parameters value of the camera adopted in the LIME commissioning. More details in [60].

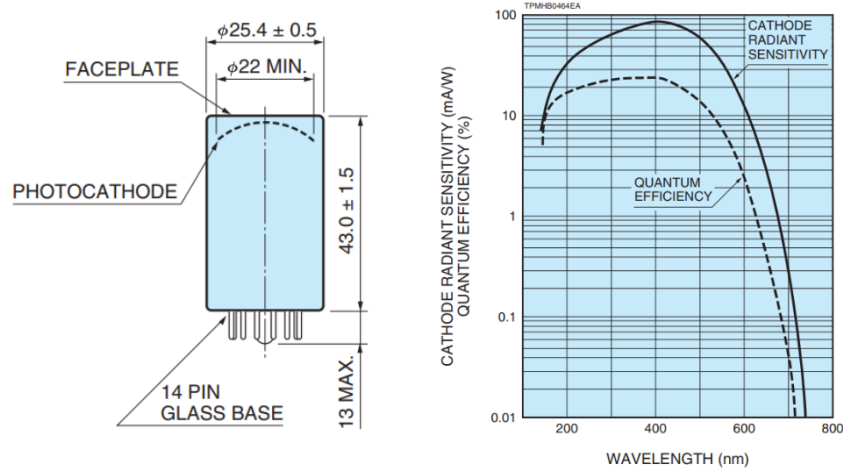


Figure 2.12. On the left a schematic draw of the PMT geometrical properties, measures in mm. On the right its spectral response.

The PMTs chosen for LIME are the Hamamatsu Photomultiplier Tubes R7378A [62]. In Fig. 2.12 and Tab. 2.4 a summary of their geometrical properties, of their differential QE and of their main values of interest.

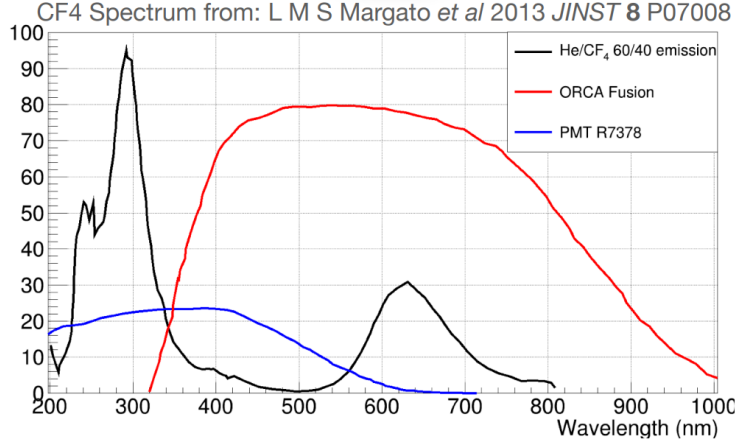


Figure 2.11. Spectral quantum efficiency of the Orca Fusion camera compared with the one of PMTs and the scintillation emission of He/CF₄.

PMT parameter	Value				Unit
	PMT1	PMT2	PMT3	PMT4	
Spectral response	160 to 650				nm
Peak wavelength	420				nm
Supply Voltage	772	772	770	800	V

Table 2.4. A table resuming the main parameters value of the PMTs adopted in the LIME commissioning. The different choice for the supply voltages is the result of an inter-calibration procedure treated in [\[63\]](#).

Working configuration

Through two HV generators, a ISEG HPn 500 and a CAEN A1515TG, the following typical conditions are imposed:

- an electric field in the active volume of $E_{drift} = 0.83$ kV/cm
- an electric field in the transfer gaps between the GEMs about $E_{gap} = 2.5$ kV/cm
- a potential difference between the GEMs of 440 V

The gas mixture, susceptible to deterioration, is continuously flushed with new gas at a rate that goes from 1 to 20 l/h. The exact value depends on the specific run taken in account because different loss in pressure came out during the campaign and a re-circulation system has been operated from RUN3 at LNGS. First of all I want to highlight that all the results present in this thesis have been obtained with a gas flow that allowed a stable response of the detector. In addition, a daily z scan with a ⁵⁵Fe source is performed in order to assess the current light yield and calibrate the energy scale.

2.2.2 DAQ and trigger system

The LIME prototype has a data acquisition system that includes both the pictures from the camera and the voltage signals from the PMTs. Specifically, the fast devices are read by a 12-bit digitizer (DGTZ) with a sampling rate of 750 Hz and 1024 sample stored. The dynamical range of the board is 1 V, and therefore the actual voltage signal can be easily recollected from the ADC digital output. We usually refer to the 12-bit digitized signal from a PMT as waveform (WF).

An event in LIME is defined as the physical process that produces:

- a picture from the camera (camera event);
- a set of four WFs (one for each PMTs) correspondent to the same time interval (PMTs event).

A Trigger and Data Acquisition System (TDAQ) [64] has been designed to accommodate the two readout paths: one for the fast signals coming from the PMTs, implemented in VME and NIM modules, and the other one for the images provided by sCMOS camera based on the Hamamatsu proprietary software. The paths are controlled by a server where the TDAQ online software is implemented in the MIDAS framework. The TDAQ online software performs the following operations: the configuration of the detector, the readout of the detector, the monitoring of the data flow, the data permanent storage, the queries to the online database and the slow control operations such as the monitoring of the gas and high voltage systems.

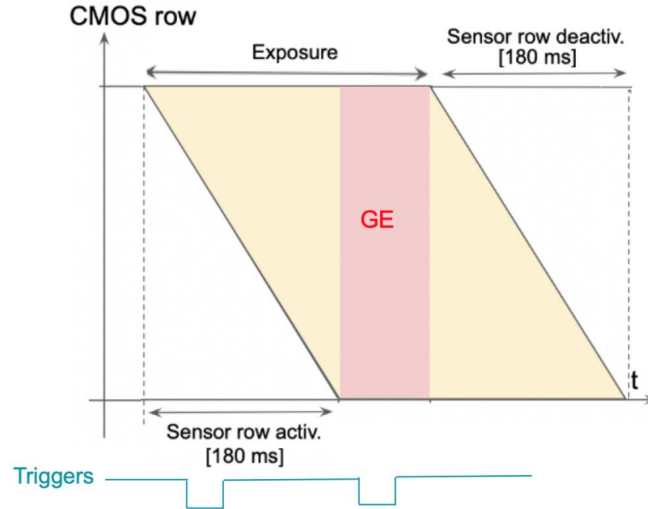


Figure 2.13. Graphical description of the camera operation mode. In the horizontal axis there is time, while in the vertical one the rows of the sensor. The interval in which each row is simultaneously active is called Global Exposure (GE).

The typical running configuration of the system is the following: the camera is exposed for a given amount of time (typically about 300 ms) in a continuum mode. It starts activating its rows sequentially from the top, taking ~ 180 ms for the full activation of the sensor. When the rows are all active at the same time, we are in the

so-called Global exposure (GE) condition (see Fig. 2.13). After it, the deactivation of the rows starts, and it takes the same amount of time as the activation. The exposure is defined as the time interval for which any row of the camera is open.

In the whole exposure window, the PMTs events are sent into a leading edge discriminator and triggered if at least 2 WFs exceed a fixed voltage threshold. Furthermore, the trigger is vetoed for $10 \mu s$ in order to avoid triggering on possible PMT after-pulses. If, during the total exposure, a trigger occurs, the pictures and the WFs are saved, otherwise not. A run is defined as the group of ~ 400 images and relative trigger events recorded.

A particle traveling through the gas mixture is intended to induce a track in the photo and a set of 4 WFs in the PMTs. An interesting and important observation is the fact that, due to the activation time of the camera rows, a saved PMT signal doesn't necessarily correspond to a track in the picture. Unless the trigger signal happens in the GE window, in fact, a particle could ionize the gas in a region where the line of the camera are deactivated with the result of partially appearing in the picture or not appearing at all.

In conclusion Fig. 2.14 shows a collected picture of the camera with the relative PMTs WFs.

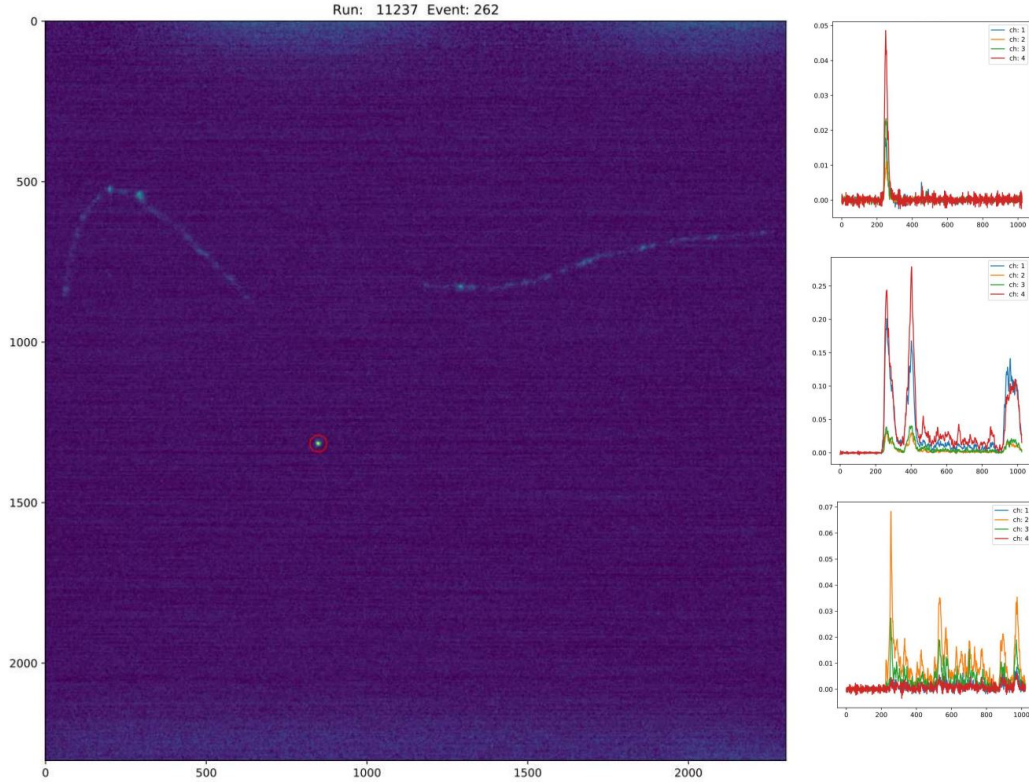


Figure 2.14. An example of collected image (camera event). Three tracks are clearly visible and the same number of sets of WFs (PMTs events) is available. In the assumption of a perfectly working acquisition, a one-to-one association can be stated.

2.3 Reconstruction algorithms

By reconstruction algorithm I mean the process that, from the digital information of the two optical devices, reconstructs the physical features of the tracks travelling the detector. In this section I present the two procedure for the optical devices of LIME.

2.3.1 Camera: cluster algorithm

The tracks on a picture are identified by clustering the light recorded in the camera image with a dynamic algorithm that is able to recognize small spots of light as good as long track. It consists of four steps that will be detailed in the following:

- a zero suppression to reject electronic noise of the sensor;
- the correction for the lens vignetting
- a super-clustering step to reconstruct long tracks assuming polynomial-shaped trajectories;
- a smaller clustering step to find residual short deposits.

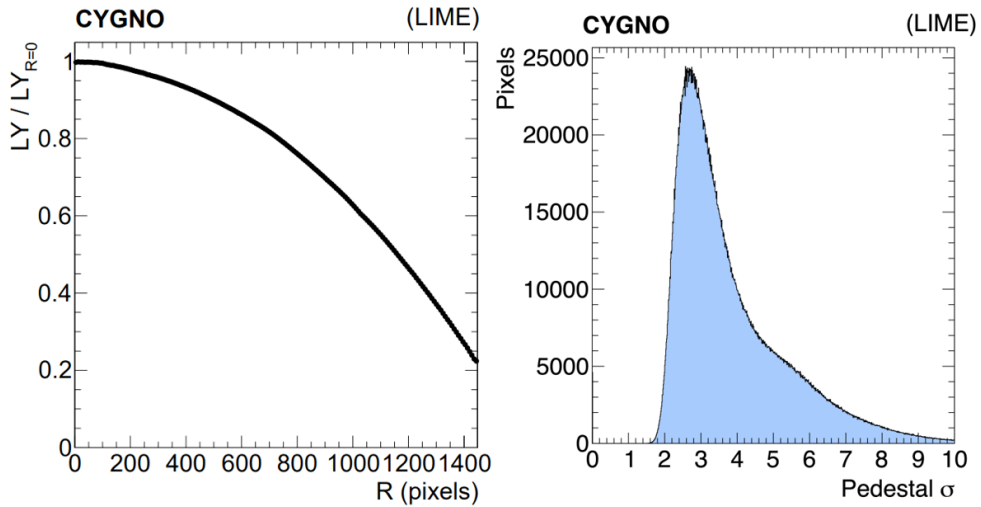


Figure 2.15. On the left the vignetting effect due to the optics coupled to the camera, on the right the distribution of the pixels rms in one pedestal run. Picture from [59].

Zero suppression

The sensor noise is the presence of an offset in the camera detection (present even in absence of signal) due to the electronic noise of the amplifier onboard of each pixel and a dark current that flows in each camera photo-diode (values in Tab. 2.3). This noise is evaluated in dedicated runs (*pedestal runs*) of about 100 images with the V_{GEM} set to 200 V. In each of these runs the average value of the pixel counts, together with the standard deviation, is evaluated and the relative distribution considered (Fig. 2.15). In the reconstruction procedure, the mean value is subtracted

to each value of the pixels of the various pictures while the rms is used to define a threshold. If a pixel has a number of counts bigger than $1.1\langle rms \rangle$ it's said to be passed. Since the long tail of the noise distribution corresponds to pixels at the top and bottom boundaries of the sensor (Fig. 2.16), 250 pixel rows in these regions are excluded from the reconstruction (11% of the sensor).

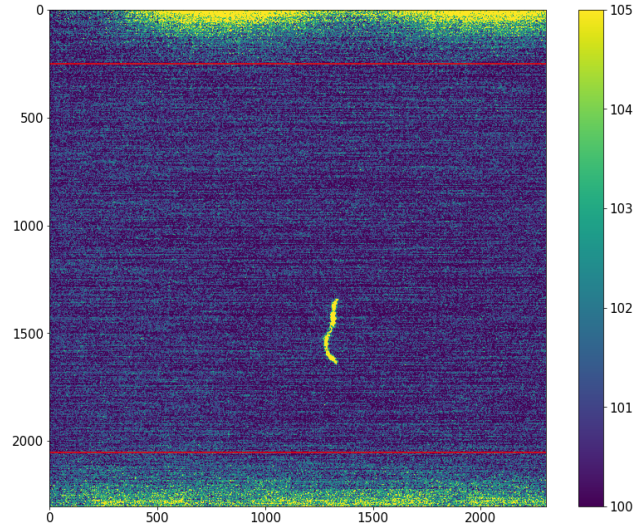


Figure 2.16. Picture acquired by the DAQ system. The color-range has been set in order to highlight the noisy bands at the top and the bottom of the figure. The red lines represents the region excluded by the camera reconstruction algorithm.

Optical vignetting

A Schneider Xenon 0.95/25-0037 lens is coupled with the camera and an evaluation of the vignetting effect is performed, i.e. the reduction of detected light between the central and the peripheral region. This study is performed taking images of a uniformly illuminated white surface and Fig. 2.15 shows a drop of collected light as a function of the radial distance from the center. A 20% loss is measured and a correction of the image is operated by means of this result.

Super-clustering

The resolution of the resulting image is now reduced by forming *macro-pixels*, by averaging the counts in 4×4 pixels matrices: this is needed to reduce the combinatorics of the following procedure. On such a new picture, a median filter is applied and an additional electronic noise suppression is performed [55]. To the same picture, the iterative cluster algorithm can start. In order to first clean from long tracks, the program looks for possible trajectories compatible with polynomial lines of increasing orders, ranging from 1 (straight line) to 3 as a generalization of the RANSAC algorithm [65]. If a good fit is found, the super-cluster is formed, it is removed from the picture and the procedure is repeated. From Fig. 2.17 it can be noted that this step is able to differentiate overlapping tracks, assigning the energy deposit only to one of the superimposed particles. Once no more candidates can be found, the program passes to the last step.

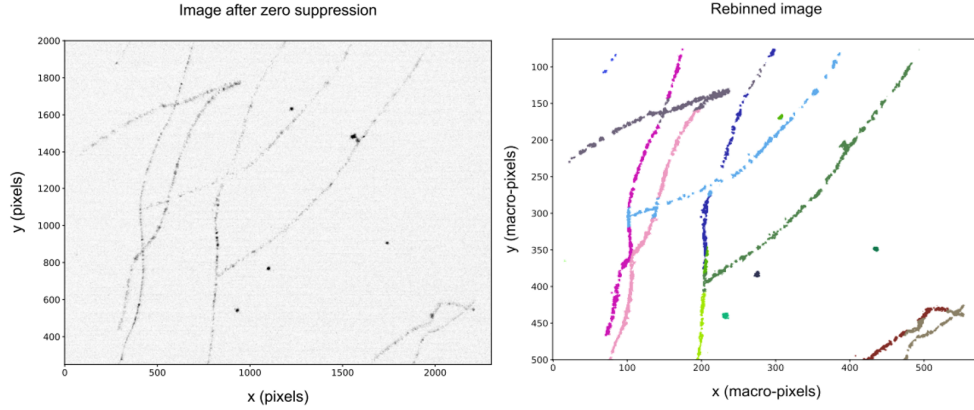


Figure 2.17. On the left a collected picture full of tracks and on the right the ones recognized by the clustering algorithm. Different colors are used to identify different tracks. Picture from [59].

Search for small clusters

In the end small clusters are searched in the picture without long tracks. For this purpose, small radius energy deposits are formed with IDBSCAN [66]. The effective gathering radius for pixels around a seed pixel is 5 and small clusters are, in this way, formed. That's all: the cluster from any iteration is merged in a unique collection and we have the track candidates.

2.3.2 Camera: cluster shape observable

The interaction of different particles with the gas mixture of LIME have been recognized as 2D projections of the initial 3D trajectory and saved as a table of numbers counting the detected photons. It results, as consequence, the possibility to identify several cluster variables that can be used to characterize the energy deposits and discriminate their nature.

The main variables are:

- **sc_size** and **sc_nhits**: the number of pixel of the super-cluster. In the second one only the pixels that passes the zero-suppression threshold are counted;
- **sc_integral**: the sum of the counts of all the pixels in the cluster;
- **sc_rms**: the RMS of the counts of the pixels in a cluster;
- **sc_length** and **sc_width**: a SVD (singular value decomposition) on the $x \times y$ matrix of the pixels belonging to the cluster is performed. The eigenvector found are interpreted as the two axes of a 2D ellipse and the respective eigenvalues as the corresponding magnitude: length (the bigger) and width. The procedure better works for elliptic clusters or stright lines. In this context, the direction along the major axes is called *longitudinal* while the orthogonal one *transverse*³;

³A different labelling will be used during the thesis referring the *longitudinal* and *transverse* direction with respect to the drift field

- `sc_tgausssigma` and `sc_lgausssigma`: standard deviation of the transverse-longitudinal cluster profile;
- `sc_xmean` and `sc_ymean`: x and y position of the cluster baricenter;
- `sc_xmin` and `sc_ymin`: minimum and maximum value of the x coordinate of a track. The same exists for the y axis.

2.3.3 PMTs: waveforms and charge collection

The charge collected by the PMTs gives information on the event energy release in the detector because it is proportional to the light produced after the GEMs and, then, to the ionized electrons (see Sec. 2.4 for a more detailed discussion). In formula:

$$L_i = K \cdot Q_i \quad (2.6)$$

with i that runs over all the possible PMTs (called channels) and K the same for all them.

From the definition of current

$$I = \frac{dQ}{dt} = \frac{V}{\mathcal{R}}$$

we obtain the main relation:

$$L_i = K \cdot \frac{\int_{t_0}^{t_1} V_i(t) dt}{\mathcal{R}} \quad (2.7)$$

with $\mathcal{R}$ the Fan-in/fan-out termination of 50Ω to which the PMTs are connected. In Fig. 2.18 an example of PMTs event.

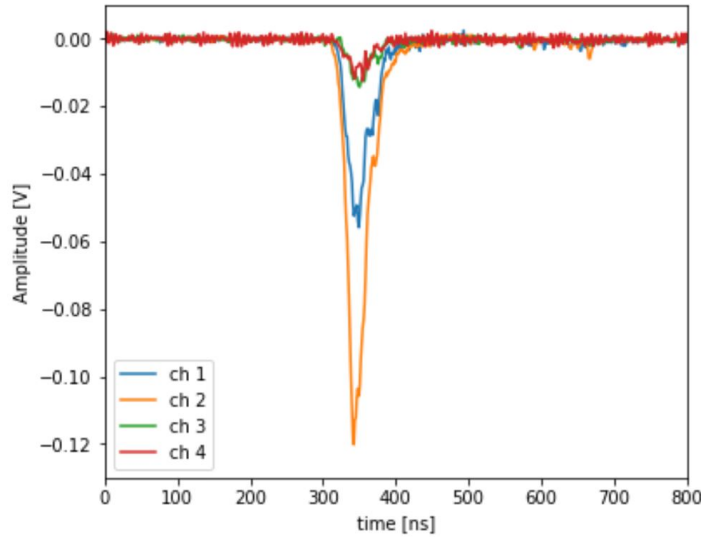


Figure 2.18. An example of a typical set of WFs triggered by the DAQ system. The four channels refer to the four recording PMTs.

2.3.4 PMTs: reconstruction algorithm

The main role of PMTs is to supply temporal information about the acquired tracks, consequently, the principal focus of the algorithm must be the spatial reconstruction. The coordinates on the GEM plane inferred by camera and PMTs can be matched and an association of the WFs with the relative clusters can be performed [63]. Independently from this, the PMT's analysis can go above the main goal of cluster matching, performing energy analysis too.

As sketched in Fig. 2.19, the light seen by a PMT depends on the distance R of the device from the track projection on the GEM plane. This is the reason why in the previous Fig. 2.18, the event presented a different amplitude for each channel.

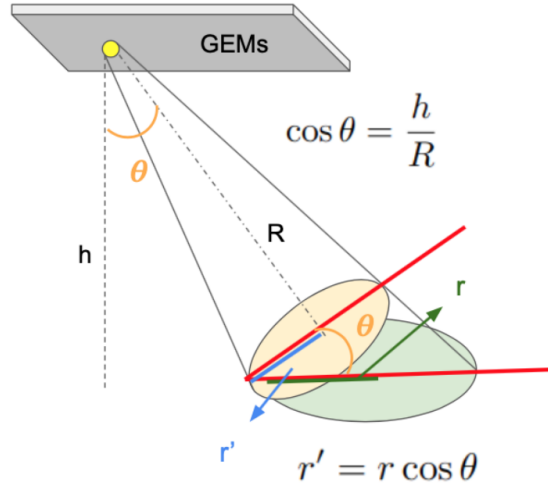


Figure 2.19. A schematic drawing of the PMT geometrical acceptance. Picture taken from [63].

From geometrical arguments this dependence should go as:

$$L_i = \frac{L}{R_i^\alpha} \quad \alpha = 3 \quad (2.8)$$

where L_i is the light seen by the i -th PMT and L is the light intensity of the source on the GEM plane. The vertical distance h is set, by construction, to $h = 19$ cm. This result comes from the fact that the light propagates isotropically from the source, hence following an inverse square law of the distance. In addition we have to take in account the fact that the PMT aren't radially aligned to the light source but presents an inclination $\cos \theta = h/R$ that adds the remaining power.

The validation of this dependence was carried out by specific measurements [67] providing a dependence on R_i much closer to the fourth power (Fig. 2.20). In Chapter 4 I consider and verify possible geometrical reasons of such a scaling and I propose alternative optical motivations. All in all, for the analysis of the LIME data we will follow the result of the measurements and assume the following equation to be valid:

$$Q_i = C_i \frac{L}{R_i^\alpha} \quad \alpha = 4 \quad (2.9)$$

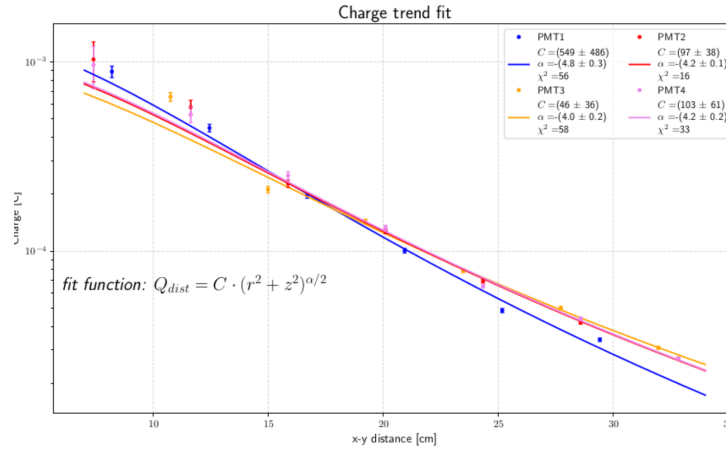


Figure 2.20. Experimental evaluation of the charge collected by the four PMTs as function of the distance from the light source. Picture from [67].

with C_i some inter-calibration constants evaluated by means of a dedicated study of the collaboration [63].

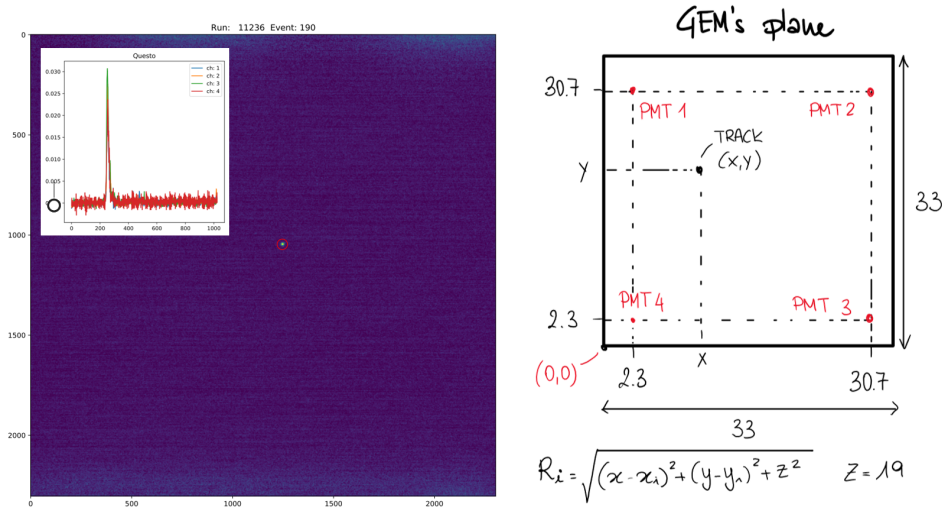


Figure 2.21. On the left an example of point like track: a cluster very localized in the GEM plane and with the relative WFs showing a single peak. On the right the coordinate reference frame of the PMTs. All the measures are in cm.

The four obtained relations are then used, by mean of a Bayesian fit, to infer the value on the common light L and the x, y position (see Fig. 2.21) of the track. I will now go in details considering the case of point-like tracks (Fig. 2.21) because they allow the presentation of the regression algorithm without the further complication of the track shape.

In Bayesian inference, the Bayes' theorem is used to update the initial probability of a model or a parameter as more information become available.

The theorem states that:

$$p(\vec{\theta} | \{x_i\}, \alpha) = \frac{p(\{x_i\} | \vec{\theta}, \alpha) \pi(\vec{\theta} | \alpha)}{\int p(\{x_i\} | \vec{\theta}, \alpha) \pi(\vec{\theta} | \alpha) d\vec{\theta}} \quad (2.10)$$

where:

- x_i are the datas, in our case the 4 charges seen by the PMT obtained integrating the WF in a 50 sample size window around their peak;
- $\vec{\theta}$ the list of parameters to infer, in our case (L, x, y) ;
- α are the fixed hyper-parameters of the relation. In our case they are the power α and the C_i ;
- $\pi(\vec{\theta} | \alpha)$ the prior *pdf* (probability density function) of the parameters;
- $p(\{x_i\} | \vec{\theta}, \alpha)$ the likelihood of the parameters. It is the model assumed;
- $p(\vec{\theta} | \{x_i\}, \alpha)$ the posterior *pdf*; our goal.

In the reconstruction algorithm the choice of the prior is simple: the position of the cluster (x, y) follows a flat distribution on the GEM plane ($33 \times 33 \text{ cm}$) without the possibility of exiting. L instead is allowed only to assume positive value.

One the other hand, the likelihood is:

$$p(\{x_i\} | \vec{\theta}, \alpha) = \prod_i \mathcal{N}(\{x_i\} | \mu_i(\vec{\theta})) \quad (2.11)$$

so the charges Q_i have a normal distribution centered at

$$\mu_i = C_i \frac{L}{((x - x_i)^2 + (y - y_i)^2 + z^2)^{\alpha/2}}$$

with a σ arbitrarily fixed at 10% of μ_i .

The integral of Eq. [2.10](#) over all the parameter space is needed and is computed by means of a Metropolis-Hasting Markov Chain Monte Carlo (MCMC) implemented in BAT (Bayesian Analysis Toolkit) [\[68\]](#) and a C++ set of libraries. The sampling is performed by means of 12 parallel MCMC chains for a total of 1.2×10^6 number of steps. In Fig. [2.22](#) the posterior *pdf* of the fit of a specific event.

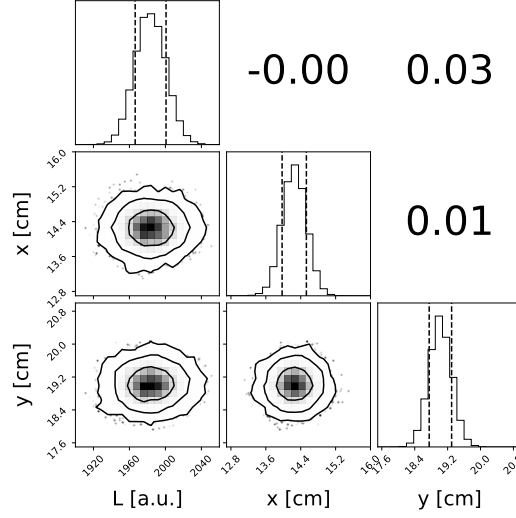


Figure 2.22. Graphical representation of the joint posterior *pdf* of the fit over one event. The three different colors represent the credible region at 68%, 95%, 99.7% of the bi-dimensional *pdfs* or of the uni-dimensional ones (obtained by marginalization)

2.4 Signal generation inside LIME

Once presented the strategy of the CYGNO experiment, especially in the case of the LIME prototype, we can predict the features of a signal produced inside the detector. During a real data taking we compare this prevision with the actual measurements for a complete check of consistency. I underline that the discussion taken in the following adopts typical values and simplistic assumptions on the physics in game. The aim is to achieve a global understanding of the signal generation and not a deep analysis.

The initial steps of the production of a signal are listed in Tabs. 2.5 and then appears two possible paths depending on which optical device we are interested in.

Camera

The photons produced by the GEMs travel toward the camera and a factor of geometrical acceptance (ϵ_Ω) must be applied to take in account only the photons that effectively reach the sensor. Given the focal length f and the aperture a of the camera and its distance d from the GEMs, the geometrical acceptance is calculated as [49]:

$$\epsilon_\Omega = \frac{1}{(4(1/\delta + 1) \times a)^2} = 1.2 \cdot 10^{-4} \quad (2.12)$$

with $\delta = f/(d - f)$.

The remaining photons then are converted to (photo)electrons with a yield set by the Quantum Efficiency of 70% (Fig. 2.11) and the camera reads them as count through a nominal conversion factor of 0.24 electrons for counts. Putting all together we obtain a mean value of 560 counts for a particle of 0.5keV_{ee} that corresponds to ~ 47 counts for single ionized electron. LIME is able, in principle, to detect a single

Step	Description	Factor	Single e^-	0.5 keV
Ionization [13]	A electron-ion pair is produced for every $W \sim 42$ eV of energy release	$\frac{1}{42} e^-$	$1 e^-$	$12 e^-$
Drift	Electrons drift in the gas in the direction of the anode. They are diffused (assumed no loss of electrons) and partially absorbed by the gas.	95%	$0.95 e^-$	$11.4 e^-$
Amplification [49]	Electrons are amplified by the avalanche process of the GEMs	$2 \cdot 10^6$	$1.9 \cdot 10^6 e^-$	$2.3 \cdot 10^7 e^-$
Scintillation [49]	Electrons excite the molecule of CF_4 producing photons	$0.07 \text{ ph}/e^-$	$1.33 \cdot 10^5 \text{ ph}$	$1.6 \cdot 10^6 \text{ ph}$

Table 2.5. First steps for the generation of a signal inside LIME. The first column describes the process under consideration while the right ones show the typical factor of amplification. "Single e^- " refers to the signal, updated at each row, released by a single electron of ionization, "0.5 keV" to a track of such energy.

ionizing electron.

PMTs

For PMTs, the optical acceptance is obtained by the same procedure of Sec. 2.3.4

$$\epsilon_{\Omega} = \left(\frac{A}{R^2} \right) \cdot \left(\frac{a h}{R} \right) = \left(\frac{A \cdot h}{4\pi R^3} \right) \cdot \left(\frac{a h}{R} \right) = 1.5 \cdot 10^{-4} \quad (2.13)$$

The first term in each step represents the geometrical contribution while the second one is a guess of the additional experimented factor. I assume the adimensional constant $a \sim 1$ and the track located at the center of the GEM plane. The Q.E. is set to 25% by Fig. 2.12. The (photo)electrons are finally multiplied by the dynode succession by a factor $2 \cdot 10^6$ and the collected charge is returned as a WF. The X-ray produced by an iron radioactive source releases a 5.9 keV_{ee} track that induces in the PMTs a charge of 0.2 nC. Approximating the iron WF with a rectangle of 60 ns we obtain a corresponding potential drop of:

$$\Delta V = \frac{Q \cdot R}{\Delta T} = 0.2 \text{ V} \quad (2.14)$$

Transposing the obtained value of charge in case of a single ionizing electron and assuming the temporal window of integration of $\Delta T = 17$ ns (parameter from data-sheet [62]), we obtain a signal of ~ 4 mV.

2.5 Overground commissioning at LNF

As a conclusion of the section regarding the LIME prototype, I present two important studies conducted during the RUN 1 configuration at LNF. At that time, only images collected by the sCMOS sensor were available and they were in a free-running mode (i.e. without trigger) and 200 ms exposure.

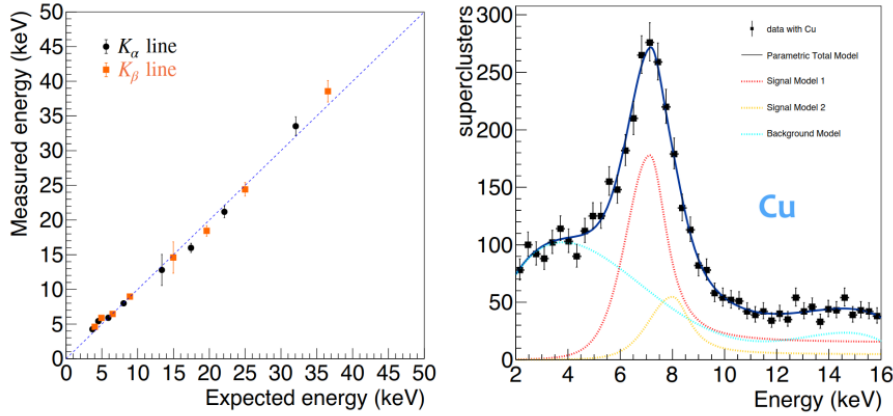


Figure 2.23. On the Right the energy spectrum and the fit (illustrated in the paragraph) of the 8 keV line of copper. On the left the linearity response of the prototype to ER signals).

First of all, I discuss the linearity response of the detector in energy. A compact multi-target source was adopted: a sealed ^{241}Am primary source was selectively moved in front of the materials listed in Tab. 2.6. Each of them, in response, emitted a X-ray radiation in the detector through the usual window and at two different lines called K_α and K_β .

For each source, the spectrum was evaluated by considering the distribution of the reco-variable `sc_integral` and then the data points for the calibration curve were obtained with a fit procedure. Each (K_α and K_β) peak was fitted by a Cruijff function while the background was modelled with a Bernstein polynomial of order n (with n up to 5), with the parameters fixed to the value obtained in a no-source run. In Fig. 2.23 we find, on the right, an example of energy spectrum fit where the `sc_integral` variable is converted from arbitrary units (AU) to keV adopting the Fe runs for absolute energy scale calibration. On the left the resulting dependence is plotted and a good linearity response, together with an energy resolution of 13%, emerges.

Another important result coming from the overground campaign at LNF is the evaluation of the energy threshold of LIME [59], i.e. the minimal energy that the detector is able to measure from a particle passing in the TPC. This value has been estimated as the energy level at which the energy contribution of *fake clusters* can't

Material	Energy K_α [keV]	Energy K_β [keV]
Ca*	3.69	4.01
Ti*	4.51	4.93
Fe	6.00	6.40
Cu	8.04	8.91
Rb	13.37	14.97
Mo	17.44	19.63
Ag	22.10	24.99
Ba	32.06	36.55

Table 2.6. X-ray emitted by the multi-target source. The elements with * weren't activated with the Am but with the Fe source.

be disentangled from real clusters. A *fake cluster* is defined as the cluster randomly reconstructed by neighboring pixels exceeding the zero-suppression threshold. In Fig. 2.24, I show the distribution of the variable `sc_integral` for an Fe run, for a no-source run and for a pedestal run. In this latter case, no signal contribution of any particle interacting in the TPC is expected, hence all the reconstructed clusters are identified as *fake*. From the value at which the energy distribution of this latter events become negligible, the energy threshold of LIME is set to $E > 400 \text{ ph} \sim 300 \text{ eV}$.

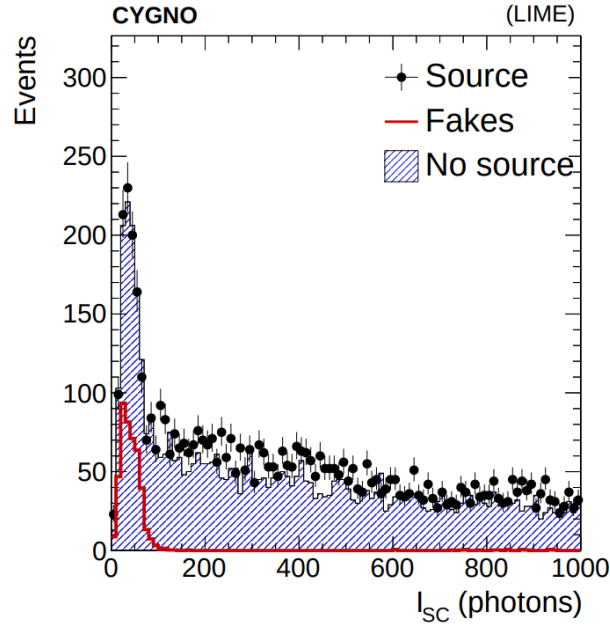


Figure 2.24. Light integral `sc_integral` of the reconstructed clusters. In black the dataset of iron runs, in blue of no-source runs and in red of pedestal runs.

2.6 Future CYGNO projects

2.6.1 PHASE_1: the CYGNO-04 detector

Once the LIME prototype will be optimised and assessed, the project will move to PHASE_1, with the aim of studying and minimizing material radioactivity on a real experiment scale. The detector TDR was submitted to INFN and the project is shown in Fig. 2.25.

The active volume of the detector will be contained in a transparent PMMA vessel, in order to lower the material's intrinsic radioactivity and the vessel will ensure gas tightness, for the total 0.86 m^3 volume, with it's 20 mm thick walls.

The field cage will be made of a kapton foil with printed copper strips to form rings, see Fig. 2.26. It will be supported by an acrylic structure, being able to produce a uniform electric field using low radioactive materials. Two of those field cages will be installed side by side in the gas vessel, with a common cathode in between them. In the other end of the field cages are installed the amplification stages, constituted by a two GEMs stack of $500 \times 800 \text{ mm}^2$, at $\sim 500 \text{ mm}$ from the cathode. The sensitive volume inside of the field cages will be of 0.4 m^3 . On the lateral sides of the TPC there will be two covers, made of sanded black PMMA, to shield the four cameras and twelve PMTs from unwanted reflected light. The DAQ system will be able to collect synchronized data from the sCMOS cameras and PMTs.

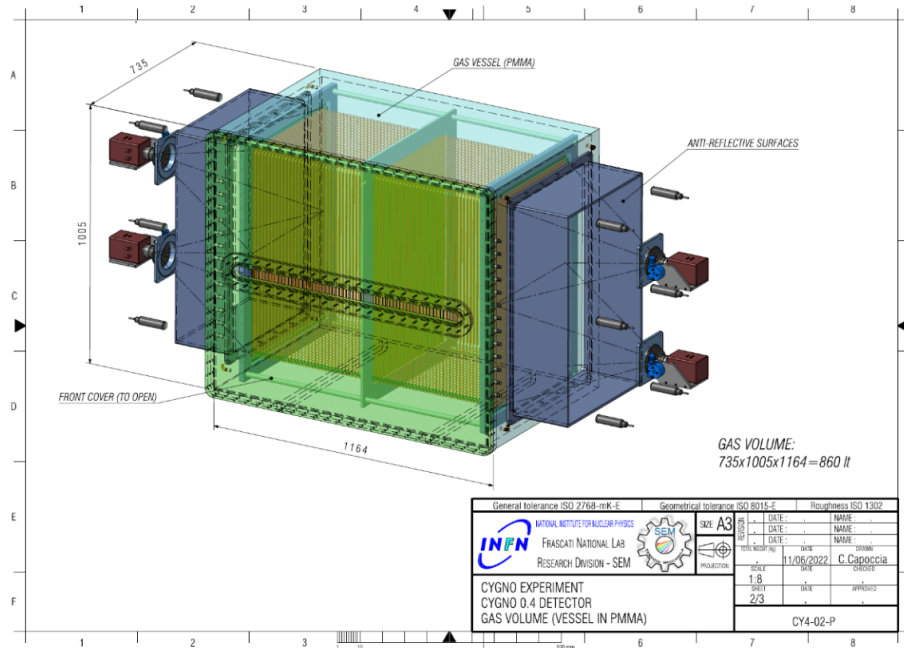


Figure 2.25. vessel and camera assembly for the CYGNO-04 detector.

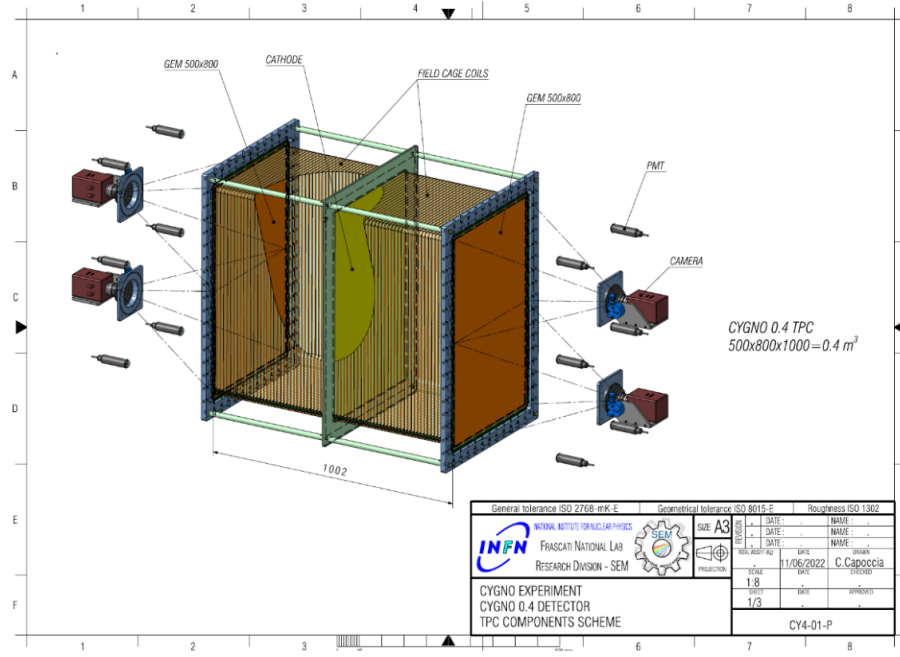


Figure 2.26. Field cage and GEM frame assembly sketch out for the CYGNO-04 detector.

2.6.2 PHASE_2

A CYGNO detector with a volume of the order of several tens of cubic meters would have the sensitivity needed to contribute to the search and study of DM in the $\mathcal{O}(\text{GeV})$ mass region, both for SI and SD coupling. In addition, in the case of signals or evidence of interactions incompatible with ordinary matter, the directional capability of the detector would be fundamental to confirm the galactic origin of the detected signal as DM, and determine its properties. Furthermore, such a detector could provide the first directional measurements of solar neutrinos from the pp chain. Regarding this final stage, the collaboration has developed a study about the expected sensitivity to DM search of a 30 m^3 apparatus in the Bayesian approach [27, 57]. Since the experiment is still in a preliminary phase and the response of the CYGNO approach is under evaluation, only a forecast of the future results is available.

In Fig. 2.27 it is presented the expected DM NR signal distribution in the 2D Galactic coordinates [69] for helium on the left and fluorine on the right, with 1 keV_{ee} energy threshold induced by, respectively, 10 GeV and 100 GeV mass WIMP [70]. Fig. 2.28 shows the expected SI limits for a 30 m^3 CYGNO-like detector with full head-tail discrimination and an angular resolution of 30° with two possible energy thresholds: 1 and 0.5 keV_{ee} . The shape of the limits mirrors the different nuclear composition of the gas mixture. The kink at around 0.9 GeV correspond to the transition from hydrogen-dominated to helium-dominated recoils, while a 3 GeV from helium to fluorine. Promising sensitivity is, at the end, expected for the CYGNO experiment that, together with its directional capabilities, would provide a decisive evidence of DM existence and origin. Thanks to fluorine, and possibly to isobutane, a sensitivity for SD interaction is also expected [57].

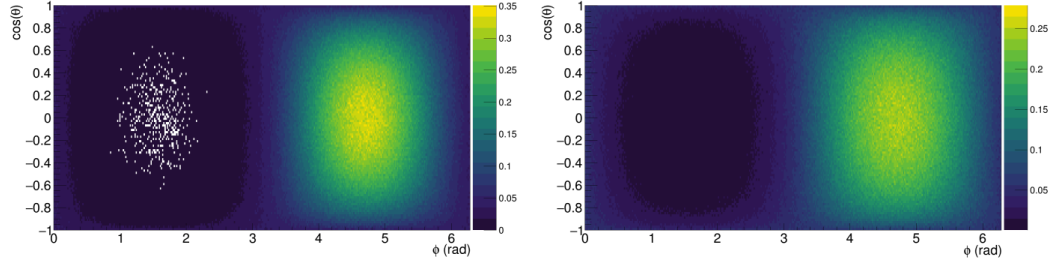


Figure 2.27. Angular distribution of the nuclear recoils induces by DM particles in Galactic coordinates as returned by a MC simulation. Two examples are considered: on the left, helium recoils by a 10 GeV DM; on the right, fluorine recoils induces by a 100 GeV one.

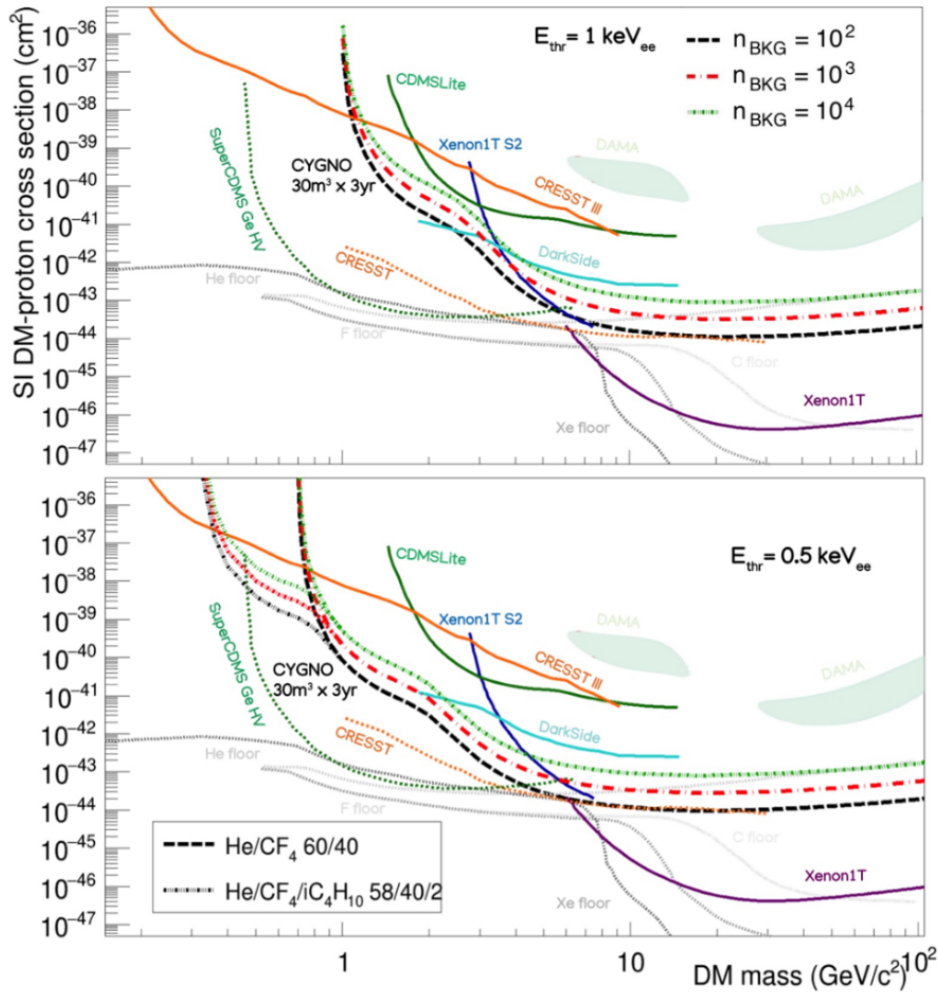


Figure 2.28. SI 90% C.I. for WIMP-nucleon cross section for 30 m³ CYGNO detector and 3 years of exposure in two different energy threshold: 1 and 0.5 keV_{ee}. The dashed curves corresponds to the actual gas mixture adopted by the collaboration for different hypothesis of background events. The continuous lines corresponds to the actual bounds while the densely dotted ones shows the future expected limits. The different grey curves show the neutrino background levels for various targets [71].

Chapter 3

LIME underground commissioning at LNGS

In this chapter, I present the main results reached by the collaboration during the underground commissioning at Laboratori Nazionali del Gran Sasso (LNGS). The aim is to close up the work presented in the previous chapter, characterizing the reconstruction algorithms employed in the campaign. I start considering the trigger rate as determined by the camera and the PMTs and I present a first row evaluation of the event rate. Following this, I delve into the discussion of the camera reconstruction performances, with a focus on comparative analysis with Monte Carlo (MC) simulations. In the second part of the chapter, I shift to the PMT reconstruction algorithm presenting the evaluation of the energy spectrum and a measure of the longitudinal diffusion. The last section is dedicated to a combined study of the camera and PMTs algorithms. Taking as reference the position of the clusters inferred by the sensor, I present the actual performances of PMTs to reconstruct the spatial distribution of iron spots. In addition, I discuss a study of the scaling law for the light seen by the PMTs in relation to distance, assuming that the position of the events is provided by the camera.

Overview of the underground campaign

The LIME underground commissioning at LNGS began in the autumn of 2022 and is currently progressing according to its roadmap. This dedicated campaign takes place in the underground laboratories of LNGS, with the primary goal of validating the CYGNO approach in a low pile-up environment. The cavern's high shielding significantly reduces the energetic flux of cosmic radiation by six orders of magnitude, making the natural radioactivity of the rock the primary source of signal. In such conditions, the internal radioactivity of the materials used in LIME becomes a significant contributor to the total radioactive budget, allowing for a thorough qualification of these materials.

The working conditions of the experiment are resumed in Tab. [3.1](#) and they refer specifically to the RUN 2 shielding configuration, the one that I analyze in this chapter. The LIME RUN 2 dataset comprises data collected over a four-week period with an artificial shielding thickness of 4 cm of copper, as detailed in [\[72\]](#). This data

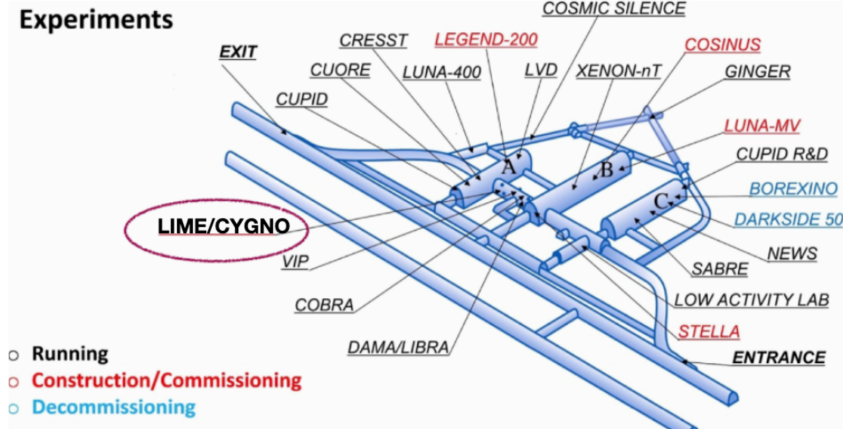


Figure 3.1. Exact location of the LIME prototype at LNGS.

drift field	0.83 kV/cm
drift velocity	5.8 cm/ μ s
GEM voltage	440 V
gas flow	20 l/h
camera exposure	300 ms
PMT threshold	2 mV

Table 3.1. Working conditions adopted during the RUN 2 configuration of the underground commissioning at LNGS.

collection phase started on February 15th and concluded on March 9th, encompassing a total of 4383 runs. The dataset is mainly divided in:

- **Background (bkg) runs:** these runs are collected in the absence of any external radioactive source. The recorded signal consists of natural radioactivity from the cavern and the internal radioactivity of the detector;
- **z-scans:** these runs are conducted daily in presence of an external ^{55}Fe source. A z-scan consists of a group of five runs, each characterized by a different position of the source relative to the GEM plane;
- **Iron calibration runs:** these runs involve placing an iron source at a specific position, usually at $z = 25$ cm from the GEM plane. By analyzing the signal induced by the X-ray source, an energy calibration is established for all background runs conducted around the same time.

Currently, the campaign is in the RUN 3 phase, and the commissioning is expected to conclude in 2024 with the implementation of a final configuration that includes an additional 40 cm of water shielding.

3.1 Trigger and cluster rate evaluation

The trigger system of LIME aims to filter out irrelevant or spurious events, selecting only signals originating from particles interacting with the gas mixture. Understanding the performance of this selection is fundamental, and the evaluation of the trigger rate represents a crucial initial assessment of the LIME underground commissioning. In Fig. 3.2 (left), the distribution of the number of trigger events per frame is presented. A frame corresponds to a time interval of 480 ms, and the rate can be evaluated using a Poissonian fit:

$$r_{\text{trg}} = (4.09 \pm 0.08) \text{ Hz} \quad (3.1)$$

The need for a fit arises because the DAQ system does not record data with zero triggers. Consequently, the rate cannot be calculated as the mean number of events per frame divided by the frame's time interval.

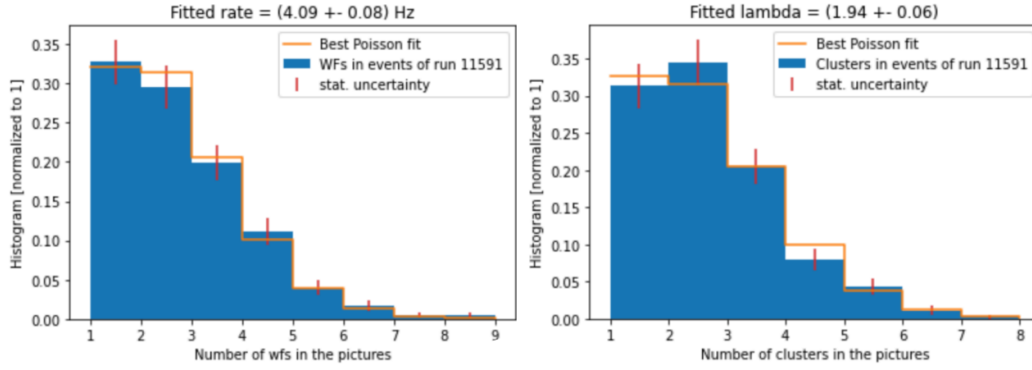


Figure 3.2. From left to right: the distribution of waveforms and clusters per frame during the background RUN 2 data-taking.

A similar analysis can be performed from the camera's perspective. In Fig. 3.2 (right), the distribution of the number of reconstructed clusters per frame is presented. Only camera events with at least one cluster are considered. In this case, a frame corresponds to a time interval of 300 ms, which is the exposure time for each row of the sensor. Employing a similar Poissonian fit as before, we obtain a camera cluster rate of:

$$r_{\text{cls}} = (6.5 \pm 0.2) \text{ Hz} \quad (3.2)$$

Based on this result, the raw rate of clusters originating from particle interactions in the gas mixture of LIME can be determined using the following equation:

$$r_{\text{cls}}^{\text{phys}} = F(r_{\text{cls}} - r_{\text{fake}}) = (4.76 \pm 0.27) \text{ Hz} \quad (3.3)$$

where $r_{\text{fake}} = 2.23 \text{ Hz}$ represents the event rate of *fake* cluster (evaluated in a dedicated study by the collaboration [73]), and $F = 1.124$ serves as a corrective factor added due to the "dead" bands in the frame (Sec. 2.3.1).

In conclusion, there is a relative qualitative agreement between the trigger and

cluster rates. However, it is essential to emphasize that these rates represent a raw measure of the real physical event rate. As illustrated in Fig. 3.3 triggered events and reconstructed clusters encompass only a portion of the signals of interest. This is due to dead times in the acquisition system, energy thresholds, and the incorporation of signals from other physical processes. The ultimate goal of a detector is to infer information about the complete set of particles interacting with the gas, and achieving a comprehensive evaluation requires a thorough characterization of the detector, its trigger system, and its reconstruction algorithms. In this regard, Monte Carlo (MC) simulations play a pivotal role, as they provide valuable feedback that will ultimately lead to an operational relationship between a physical event in the detector and an event in the readout devices.

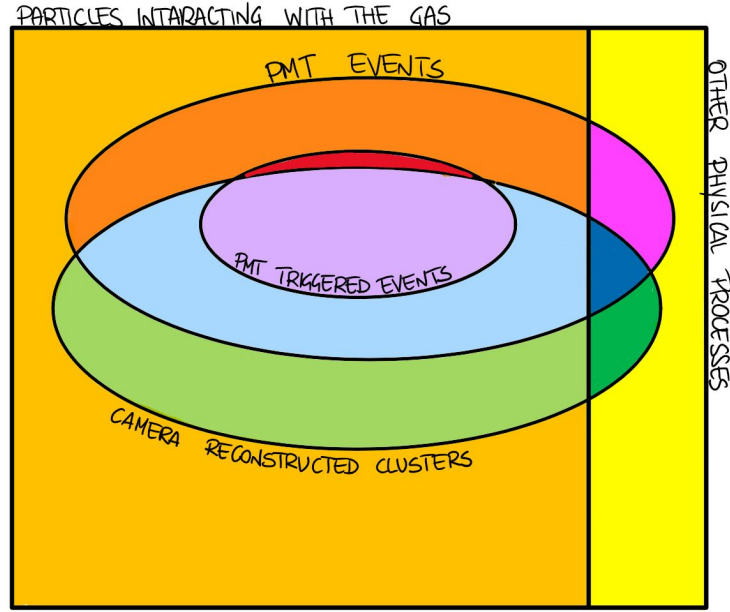


Figure 3.3. Diagram illustrating the relationship between signals of interest originating from particles traveling inside the TPC of LIME and the triggered events and reconstructed clusters. The recorded events constitute a subset of the entire range of signals due to inefficiencies, dead times, and energy thresholds. Examples of 'other physical processes' include thermal fluctuations and electronic noise. Diagram not in scale.

3.2 Camera analysis

3.2.1 Transverse diffusion of ionized electrons

In Fig. 2.3 I have presented the expected behavior of the diffusion effect on primary ionization electrons in the LIME gas mixture. I will now discuss an analysis I developed to measure the transverse diffusion coefficient conducted in the RUN 2 configuration. For this purpose, I employed some runs, called "z-scans", where an iron radioactive source is positioned at various distances from the GEM plane as detailed in Tab. 3.2. The strategy involves assuming the z-position of the iron spots to be that of the external source and examining how the distribution of the clusters

size changes at each step of the scan. This is a simplistic assumptions since, even if collimated, the ^{55}Fe X-rays enter the TPC with an aperture of $\sim 20^\circ$. However this effect is symmetric in z and it doesn't affect the average z position of the ^{55}Fe spots.

run	step	distance from GEMs [cm]	n. pictures
12170	1	5.02	401
12171	2	15.05	403
12172	3	25.05	403
12173	4	35.11	404
12174	5	46.58	402

Table 3.2. Steps of the z scan procedure. Each run has been performed in the same day and the column "step" refers to a labelling of the Cygno collaboration reported for convenience.

cut	motivation
$\text{sc_integral} > 1000 \text{ counts}$	it corresponds to $\gtrsim 1 \text{ keV}$ tracks (Sec. 2.4). Even considering a fluctuation in the LY of 30%, this cut doesn't exclude the 5.9 keV iron spots while deletes the noisy low energy events.
$0.152 \cdot \text{sc_tgausssigma} > 0.1 \text{ mm}$	being $100 \mu\text{m}$ the distance between the holes in the GEM, a cluster with a lower size is mostly consistent with an event on the sensor. By this a mean a track that interacts directly with the pixels of the sensor instead of coming from the TPC.
$\text{sc_rms} > 6 \text{ px}$	it cuts over random thermal fluctuations of the sensor that are accidentally identified as clusters. Selection described in [59].
$R(\text{sc_xmean}, \text{sc_ymean}) < 900 \text{ px}$	it is considered only the central region of the plane to avoid the sensor noisy bands at the contour (see Sec. 2.3.1).
$0.152 \cdot \text{sc_length} < 20 \text{ mm}$	iron spots are expected to be order 1 cm (see Fig. 2.5).
$\text{sc_width}/\text{sc_length} > 0.8$	connected to a small length, we expect a round shape.

Table 3.3. Cuts for the iron cluster selection. 0.152 is the conversion factor from px to mm and $R()$ states for radius centered in the middle of the GEM plane.

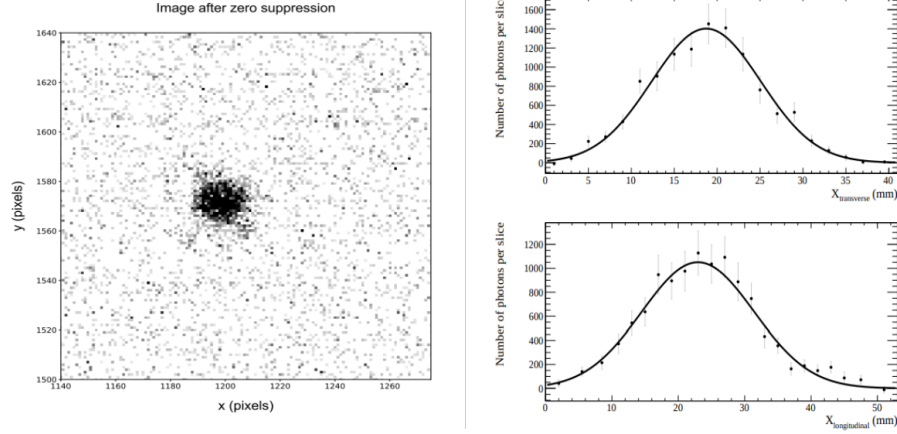


Figure 3.4. On the left the zoom of a picture showing a luminous spot indicating a X-ray ER due to the ^{55}Fe external source. On the right the profile along the major and minor axes of a similar spot. The two variable used in the analysis of this section are the two σ of the fitting Gaussian of these profiles. Image taken from [59].

First of all, iron spots discrimination is needed (Fig 3.4): I have to consider only the round iron clusters over the whole zoo of tracks (long cosmics, twisted electrons, ecc...). For this reason I apply the cuts listed in Tab 3.3.

The selection has been tested and refined during the underground campaign and, as a hint of its validity, I show the new energy and spatial distribution of the clusters in Fig.3.5. They exhibit a good energy resolution about 10%. The peak has a value of 7500 samples and is identified with the 5.9 keV of ^{55}Fe . Thus a conversion of 630 samples for a 0.5 keV results, in good agreement with the expectations (Sec. 2.4). The spatial distribution is compatible with the position of the source and the aperture. We believe that the previous cuts are therefore able to select iron induced events with reasonably good purity and efficiency.

Once the cuts are applied, I can assume the variables `sc_tgausssigma` and `sc_lgausssigma` (see figure 3.4 for an intuitive description) as a good estimation of the dimensions of the iron clusters and I consider their distribution with z . The mean value of such distributions and the relative uncertainty¹ is plotted in Fig. 3.6, for both directions. A fit through the best model:

$$\sigma(z) = \sqrt{\sigma_0^2 + f_T^2 z^2} \quad (3.4)$$

(justified in Appendix A) is superimposed. An uncertainty $\Delta z = 1$ cm, uncorrelated for each point, is assumed for the position of the X-ray source due to the accuracy of trolley mechanism. The inference is performed using the function `curve_fit` of the Python library `scipy.optimize` and the resulting parameters are presented in Tab. 3.4.

The outcomes of this study are the following:

- the two behaviors present a different σ_0 because the camera reconstruction systematically identifies the bigger dimension as the length. Specifically,

¹evaluated as the standard deviation of the distribution divided by the square root of the entries.

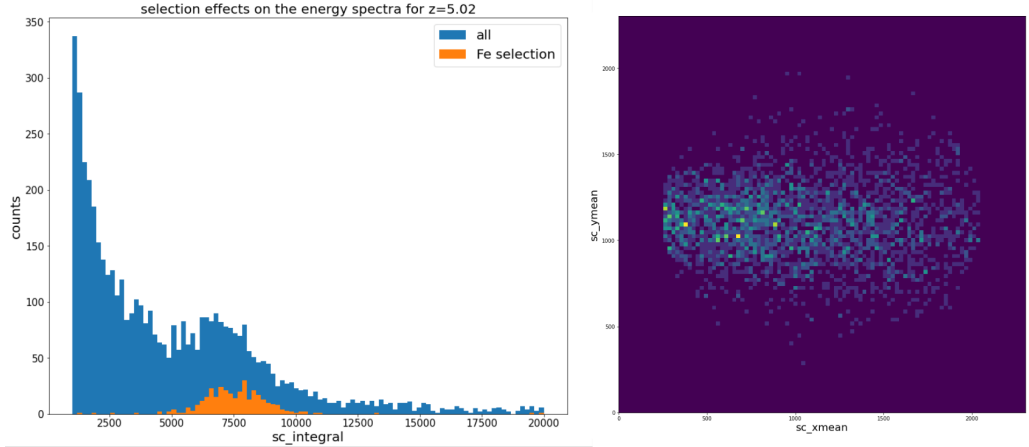


Figure 3.5. Effects of the cuts listed in Tab. 3.3 on the reconstructed clusters of a z-scan. On the left the effect on the energy spectrum for one of the runs. A good energy resolution (about 10%) appears. On the right, the effect on the spatial distribution over all runs. The resulting shape is consistent with the expected aperture and the position of the iron source.

	simulated	Axis	fitted
$\sigma_0 [\mu m]$	x	Major	622 ± 12
	x	Minor	509 ± 6
$f_T [\mu m / \sqrt{cm}]$	125 ± 12	Major	139 ± 2
		Minor	125 ± 1

Table 3.4. Table of the inferred parameters of the model 3.4 describing the transverse diffusion of a set of iron clusters as function of their z position. Also the expected diffusion coefficient from Fig. 2.3 is presented. The x states for missing simulated value.

the major-axis σ_0 is greater than the minor-axis σ_0 which aligns with our expectations;

- also the f_T factors differ, despite the expectation that diffusion should not depend on the considered direction;
- the diffusion coefficients are statistically consistent with the simulated values;

To summarize, the camera reconstruction algorithm is able to detect the diffusion of the iron clusters along the direction parallel to the GEM plane and the diffused shape follows, with good agreement, the model presented in Eq. 3.4. Nevertheless, I have presented a methods that only fits over the statistical uncertainties ignoring the systematics. An underestimation of the error on the fitted parameter could explain the inconsistency between the two directions on the plane.

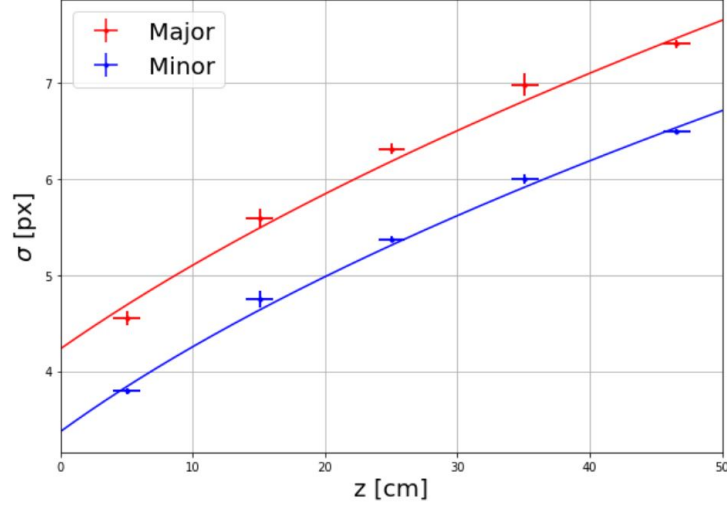


Figure 3.6. Transverse-size of iron clusters with respect to the z position of their external source. A fit of the model [3.4](#) is superimposed. The two behaviors presented refer to the major and the minor axes of the clusters.

3.2.2 Signal saturation

In addition to diffusion, another effect emerges to depend on z even though this was something not expected and that actually represents one of the main subjects of interest of the collaboration: the saturation of the GEM gain. Plotting the energy spectra of the iron clusters selected in the previous section in function of z , a dependence on z comes out (Fig. [3.7](#)).

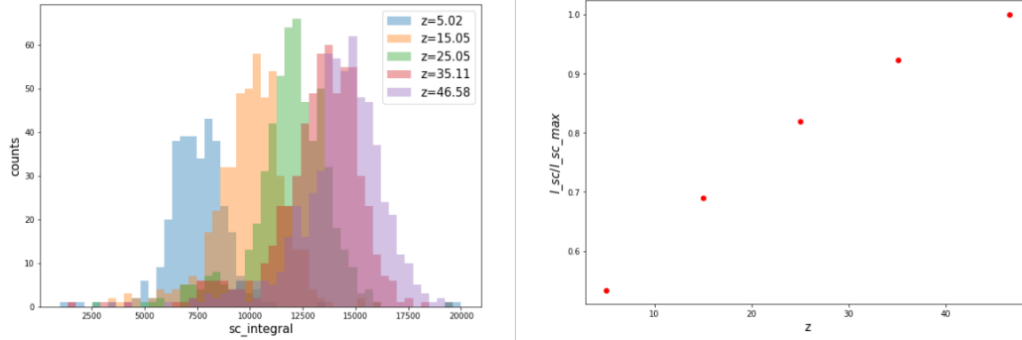


Figure 3.7. On the left, the energy spectrum for the iron selected clusters of a z -scan: what appears, is a growing of the energy at which the iron is peaked. On the right the relative peak position in function of z .

The effect can be interpreted in the following way. During the amplification process, the channels across the GEM foils are filled with ions and electrons produced in the avalanches. In recent years, several studies [\[74\]](#) have shown that for high-gain operations, the amount of charge produced by a single avalanche is already sufficient to change locally the electric field. This effect, that at the end corresponds to a saturation of the signal, gets worse as the drift electrons are concentrated in a

single region. Low z means low drift path and hence low diffusion, so the ionized electrons are more concentrated in a single region increasing saturation. For the same argument, at high z the saturation is instead mitigated.

3.2.3 Energy spectrum and comparison with MC

At the end of this section, I present the background energy spectrum obtained by the camera reconstruction in the RUN 2 configuration superimposed to the MC simulation. The former is obtained as the distribution of the variable `sc_integral` converted in keV by means of the absolute calibration scale supplied by the various Fe calibration runs.

On the other hand, the MC plot is the result of different steps:

- First of all we consider the internal and external background activities. The former was performed by a material screening of all the components of LIME. The latter was measured in Hall C at LNGS by the Sabre collaboration, for the gamma flux, and by P. Belli et al. [75] for the neutron one;
- Secondly, the measured background activities and fluxes are taken as input for a MC simulation of the energy release of particles in the detector. The results are shown in the Figs. 3.8 and 3.9
- Then a digitization process is added. By this, I mean the realization of pictures, as the one produced in normal data-taking, containing simulated tracks;
- Finally the cluster reconstruction algorithm is applied to these pictures and the reconstructed variables are directly compared to the ones of real data.

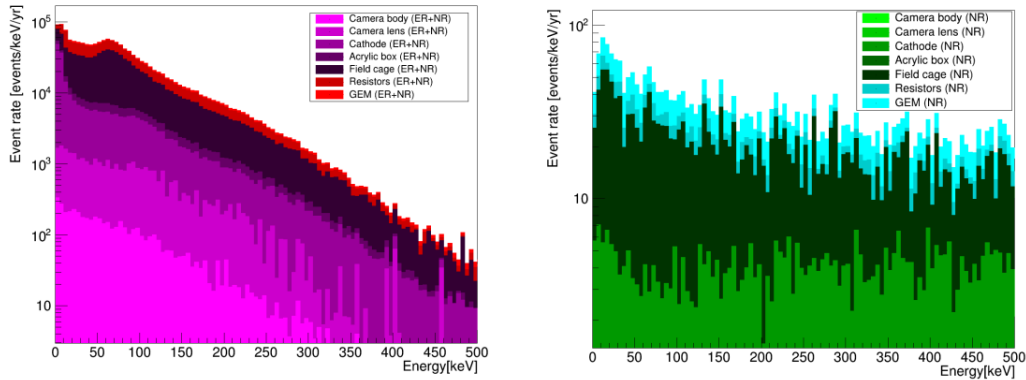


Figure 3.8. Simulation of the expected internal background spectra in LIME. On the left the one induced by electronic recoils, on the right by nuclear recoils. Simulation performed by Flaminia di Giambattista.

Fig. 3.10 shows the comparison between a background dataset of runs and the relative MC simulation. The comparison is performed looking to the distributions of the reconstructed variable `sc_integral` (converted in keV) normalized to the same lifetime. In addition, the cuts listed in Tab. 3.5 are applied in both cases to reduce

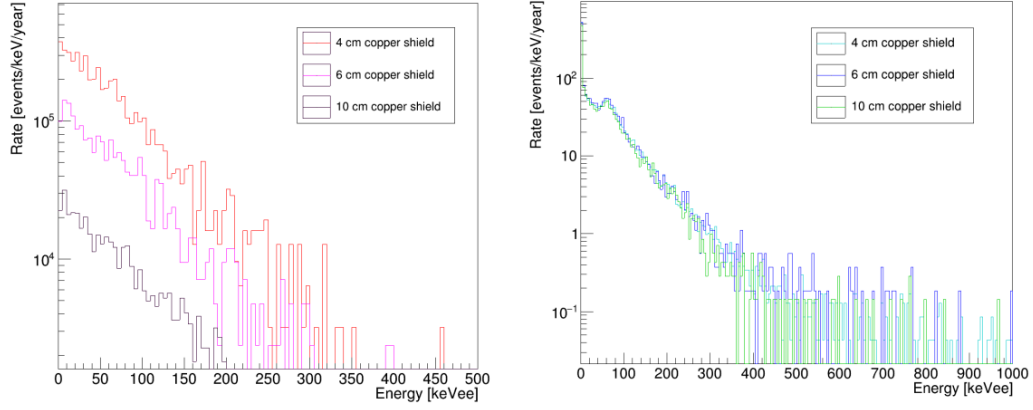


Figure 3.9. Simulation of the expected external background spectra, in LIME, for different shielding configurations. On the left the one induced by nuclear recoils, on the right by electronic recoils.

the noise of the sensor.

The two energy spectra qualitative agree, confirming a first success of the collaboration on achieving a data-MC validation. The distributions are not perfectly consistent and a difference in the low and high energy range emerges. These represent an important feedback that will allow the parallel work of analysis and simulations to consistently characterize the various aspects of the detector.

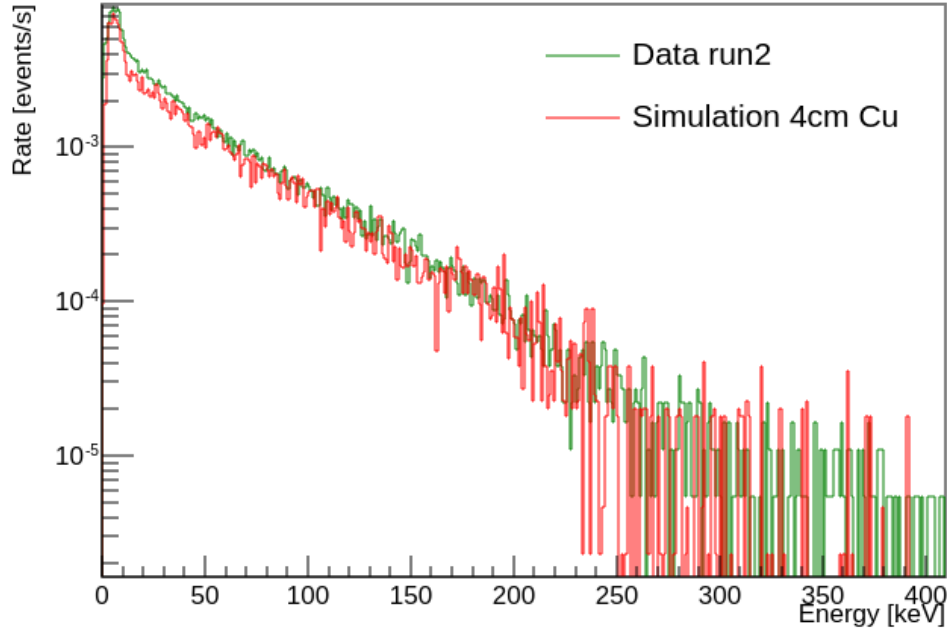


Figure 3.10. Comparison between the camera energy spectrum and the MC expectation.

cut	motivation
$0.152 \cdot \text{sc_tgausssigma} > 0.5 \text{ mm}$	it cuts events on the sensor. The threshold is so high (compared to the one applied for iron spots Tab. 3.3) that some real events could be deleted. Since the same cut is applied on MC simulation, the comparison is still allowed
$\text{sc_rms} > 6 \text{ px}$	it cuts over random thermal fluctuations of the sensor that are accidentally identified as clusters. Selection described in [59]
$R(\text{sc_xmean}, \text{sc_ymean}) < 900 \text{ px}$	it is considered only the central region of the plane to avoid the sensor noisy bands at the contour (see Sec. 2.3.1)
$(\text{sc_xmin} > 200) \ \& \ (\text{sc_max} < 2100)$	it is considered only the central region of the plane to avoid the sensor noisy bands at the contour (see Sec. 2.3.1)

Table 3.5. Cuts for comparison between background data e MC simulation in RUN 2 configuration. 0.152 is the conversion factor from px to mm and $R()$ states for radius centered in the middle of the GEM plane.

3.3 PMT analysis

3.3.1 Longitudinal diffusion

I have already emphasized that, when electrons drift toward the anode, are subjected to multiple Coulomb scattering that produces a diffusion of the signal. This process has been considered in the transverse direction but has consequences in the direction parallel to the drift field too. Electrons can vertically collide with a gas molecule bouncing backward because of the impact and a spread in the arriving time of the electrons appears in PMTs. Again, a dependence on the z position of the cluster is expected (Appendix A).

For this study, I consider the z -scan listed in Tab. 3.6 and the first step is the selection of the iron events from all the possible signatures.

The full procedure is the following:

- All the collected WFs, of each run, are smoothed by means of a moving average algorithm with a windows size of 10 samples;
- The amplitude is normalized to the same value;
- From all the events, I consider only the ones that present a clear peak in, at least, 2 channels and at the same time (within a window of 15 samples). The request of a single peak corresponds to a localized release of energy of the

runs	step	distance from GEMs [cm]	pic. per run
12170 - 11585	1	5.02	401
12245	1.5	11.02	401
12171 - 11586	2	15.05	403
12246	2.5	21.05	403
12172 - 11587	3	25.05	403
12173 - 11588	4	35.11	404
12174 - 11589	5	46.58	402

Table 3.6. Steps of the z scan procedure. Each run has been performed in the same day and the column "step" refers to a labeling of the Cygno collaboration reported for convenience.

track and is consistent with the signature provided by an iron X-ray. The tool used for the identification is the function `find_peaks` of `scipy.signal`;

- For each selected event the FWHM (Full Width Half Maximum) of the channels is evaluated. The tool adopted is the function `peak_widths` of `scipy.signal`
- Adopting a Gaussian approximation of the shape of the WFs, the width of the distribution is evaluated as $\text{width} = \text{FWHM}/2.35$. The mean value over the channels of the σ is adopted as a measure of the longitudinal diffusion and the $\text{std}/\sqrt{N_{\text{channels}}}$ as it's uncertainty;

In Figure 3.11, some examples of the selected events, with their FWHM indicated. The validity of the selection is checked by looking (after the reconstruction of the events) at their spatial distribution plotted in the left side of Fig. 3.12. On the right side instead, the distribution of the width as a function of the z position of the source. In this last case the values are expressed in cm through the following conversion:

$$\text{width [cm]} = \text{width [ns]} \cdot v_{\text{drift}} [\text{cm/ns}] = (\text{width [AU]} \cdot \frac{4}{3} [\text{ns/AU}]) \cdot v_{\text{drift}} [\text{cm/ns}] \quad (3.5)$$

where the factor $4/3$ is the DGTZ sample time ($1/750 \text{ MHz}^{-1}$) while v_{drift} is the drift velocity of the ionized electrons and, given the working conditions of LIME, is set to the value of $5.8 \text{ cm}/\mu\text{s}$ (Fig. 2.4).

The mean value, and relative uncertainty, of the width distribution with respect to the z coordinate is plotted in Fig. 3.13 together with the best fit of the model (Appendix A):

$$\sigma_L = \sqrt{\sigma_0^2 + f_L^2 \cdot z} \quad (3.6)$$

An uncertainty $\Delta z = 1 \text{ cm}$, uncorrelated for each point, is assumed on the z position of the X-ray source due to the accuracy of the trolley mechanism. The inferred results are listed in Tab. 3.7

A good agreement turns out between the expected and the measured value of

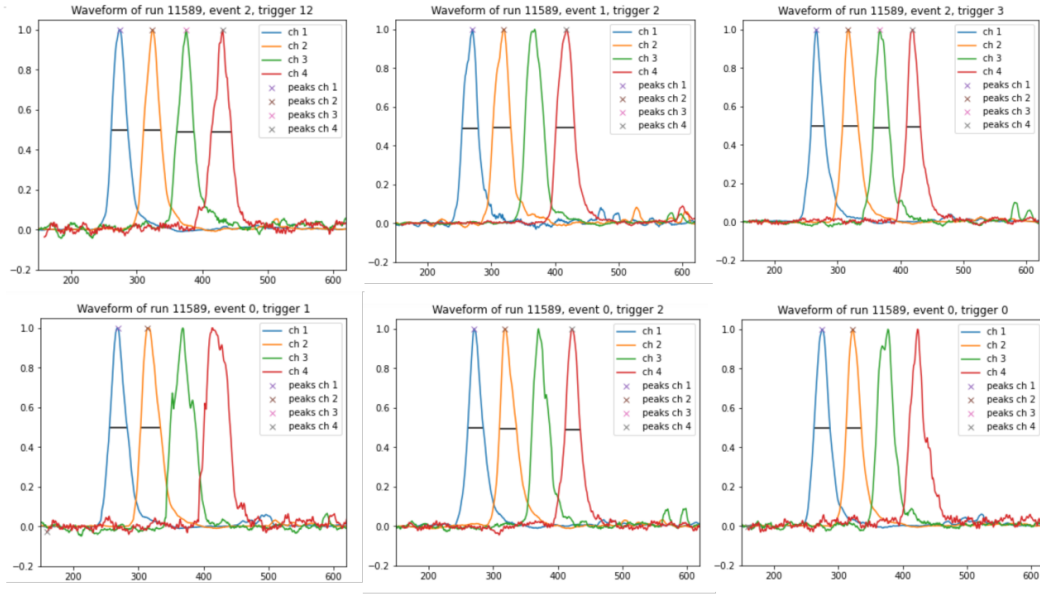


Figure 3.11. Examples of events passing the peak selection discussed in the section. Each case presents at least 2 channels passing the imposed conditions and the FWHM and the peak position are indicated. The shift between the peaks is added manually for a better visualization.

the longitudinal diffusion coefficient. However I highlight that I performed a fit only over the statistical uncertainties of the data. An underestimation of the error over the fitted parameters is expected.

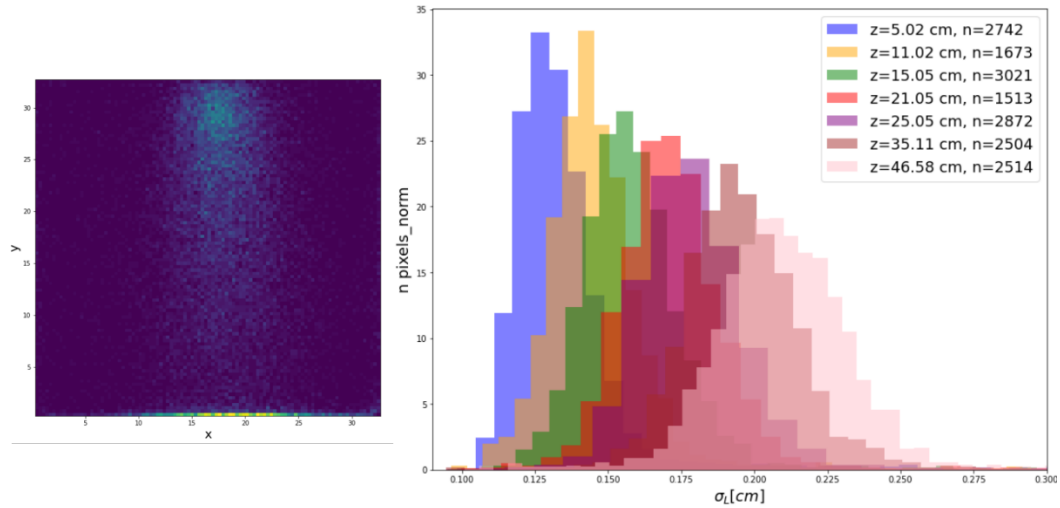


Figure 3.12. On the left the spatial distribution of the events surviving the one peak selection. It is consistent with the aperture expected and the position of the iron source. On the right the width distribution of that events for each z position of the scan.

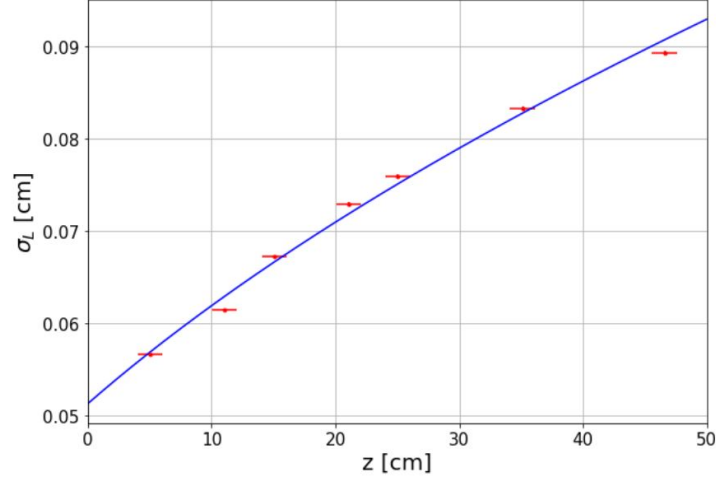


Figure 3.13. Behavior of the longitudinal width of iron WFs as function of the z position of the external source. A fit of the model 3.6 is superimposed.

		simulated	fitted
Longitudinal	$\sigma_0 [\mu m]$	x	512 ± 10
	$f_L [\mu m / \sqrt{cm}]$	96 ± 10	109 ± 2

Table 3.7. Table of the inferred parameters of the model in Eq. 3.6 describing the longitudinal diffusion of a set of iron WFs as function of their z position. Also the expected diffusion coefficient from Fig. 2.3 is presented. The x states for missing simulated value.

3.3.2 Energy spectrum

The PMT reconstruction aims to infer the position of a track and its energy from the signal recorded by the four channels. Although the main goal is the spatial reconstruction, the ability of identifying the particle energy release is an important hint of consistency. In this section, I present a first evaluation of the energy spectra performed by the fast optical devices [76].

First of all, it is necessary to address an important question. To evaluate the light collected by the PMTs and to use it as an input for the algorithm, we need to evaluate the time integral of the WF. However, choosing the integrating window requires careful consideration since the objective is to reconstruct the single energy deposits of a track. With this in mind, a slicing of the WF is adopted and the energy reconstructed from each section is summed up to obtain the real energy.

In detail, the procedure is the following:

- Each waveform is regularly sampled by means of windows of 50 samples length. This is the typical width of an iron WF and its enough localized for a first approach.
- For each sample, the charge is evaluated and the *reco* algorithm is performed;

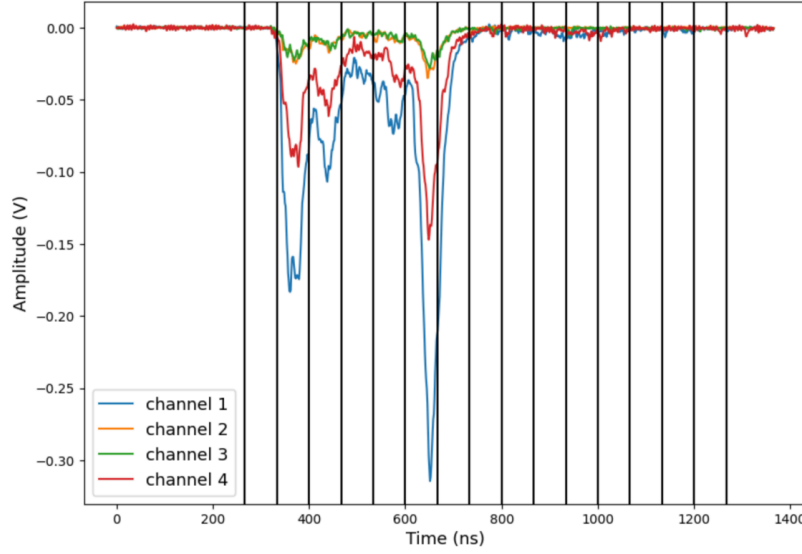


Figure 3.14. Sampling of a long event on the PMTs for the energy reconstruction algorithm.

- All the negative integrals are ignored and the resulting L of each sample in a waveform are summed together to reach the total luminosity of the track;
- The spectrum is achieved by the distribution of the evaluated luminosity and is compared with the one obtained by the camera reconstruction (Fig. 3.15). To perform this comparison, a cut on the events on the sensor is applied to the camera *reco* (events that, by definition, can't be seen by the PMTs) and a normalization to the same lifetime is performed.

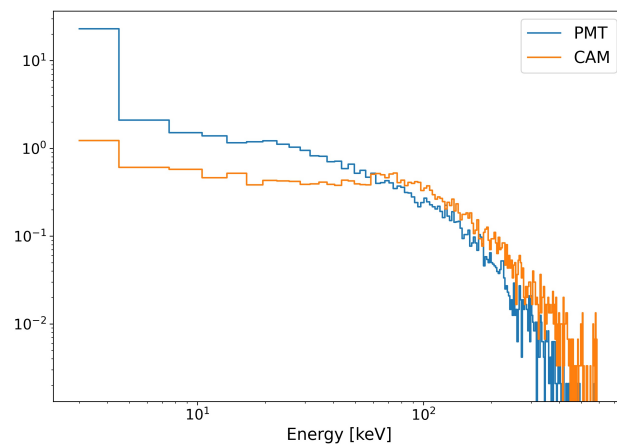


Figure 3.15. Energy spectrum as reconstructed by the PMTs algorithm and relative comparison with the one provided by the camera. Picture from [76]. Distributions normalized to the same lifetime.

What emerges from this first study is that we have an underestimation of high energy tracks and, on the other hand, a greater number of low energy events. Looking at this comparison, however, one must take in account the differences between the two devices. While the camera acquires only tracks corresponding to activated lines, PMTs collect all the signals over a certain energy threshold with an efficiency, assumed, of 100%. A more rigorous comparison will involve the MC simulation of the PMTs acquisition.

3.4 Combined PMTs and camera analysis

3.4.1 PMT spatial reconstruction

Regarding the PMT spatial abilities, we start a new type of strategy that adopts both the reconstruction algorithms. The camera has a significantly higher level of accuracy and precision in identifying the position of clusters on the GEM plane compared to the PMTs. Therefore, we can use the camera's results as a reference to validate the PMT reconstruction.

This validation is carried out in two ways. First, we check if the PMT reconstruction can produce the typical spatial distribution pattern of the iron spots, similar to what the camera achieves. To do this, the algorithm was applied only to waveform belonging to a calibration run and presenting one single peak². The result is shown in Fig. 3.16

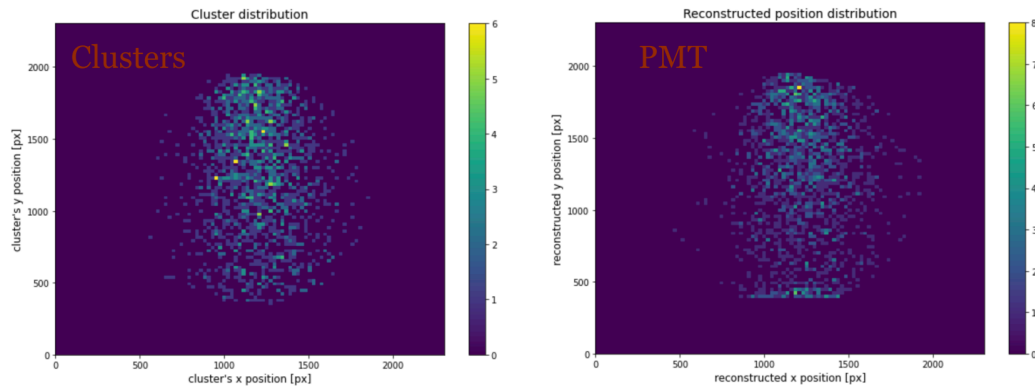


Figure 3.16. Spatial distribution of the iron spots as reconstructed by the camera and the PMTs. The typical "shower" shape appears in both cases.

The resulting distribution from the PMT reconstruction appears to have a similar shape and exponential profile as the one provided by the camera. However, an unexpected overpopulation is reconstructed in the lower side of the plane and its origin is still under debate. A possible cause is identified in the stringent constraints assumed during the Bayesian process that forbid a reconstruction of the event outside the GEM plane.

A second, and much more quantitative, analysis is the evaluation of the distance

²Same selection adopted for the longitudinal diffusion 3.3.1

between the guess given by the PMTs and the one from the camera. For each picture only the iron spots are considered (using the usual cuts Tab. 3.3) and each PMT position was associated to the closest cluster. The result is shown in Fig. 3.17 and good performances come out: 99.7% of the fit process converged giving the 37% within 1 cm from the assigned cluster and 73% within 2 cm. It is a promising result since the main goal is not to achieve the spatial definition of the camera but a good reconstruction of the tracks position. In the context of cluster-WF association, 2 cm is already a good performance since the low pile up rate of the underground campaign.

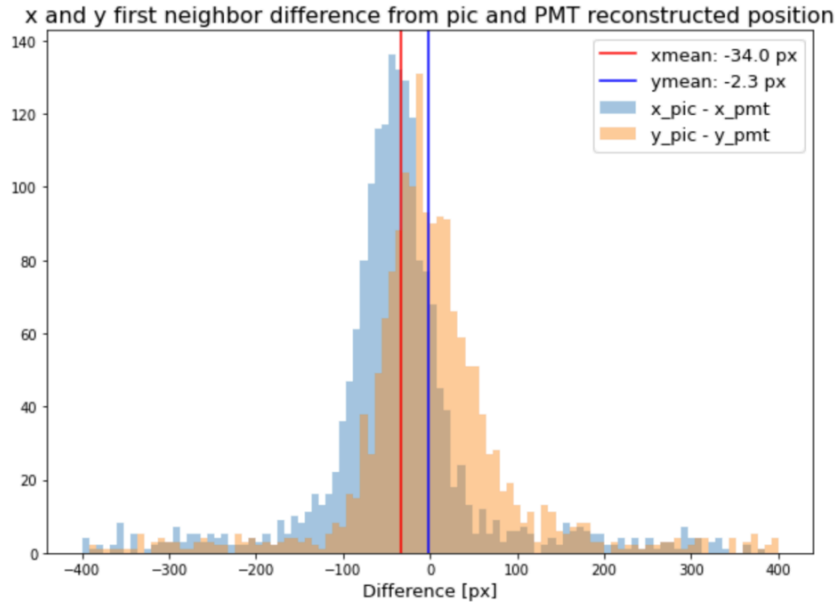


Figure 3.17. Distribution of the x and y distance of the iron spots reconstructed by the PMTs and by the camera. The association is made through a first neighbor criterion.

For the reconstruction of long tracks a slicing technique is required for the same reasons of sec. 3.3.1. However, in this case a different sampling strategy is adopted (Fig. 3.18). Motivated by the fact that tracks are composed of separated ionization clusters, for each waveform all the peaks are identified and the integration is performed in small windows around them.

In details:

- All the waveforms are smoothed performing their moving average in a window of 5 samples;
- All the peaks of the waveforms are identified through the `peak_finder` tool of the package `scipy.signal`;
- Only the peaks with a correspondence in at least another channel are considered (MAJORITY 2 logic);
- An integration in a 50 sample window is performed around each peak and the Bayesian inference is applied;

- To each reconstructed point, the relative z coordinate is associated knowing the drift velocity in the gas mixture and the temporal tag of the examined peak.

Even though this peak-finder algorithm is robust, there still doesn't exist a complete study on the performance of the *reco* algorithm on long tracks. Nevertheless I conclude this section showing two promising examples of what the code was able to do in some specific cases in Fig. 3.19.

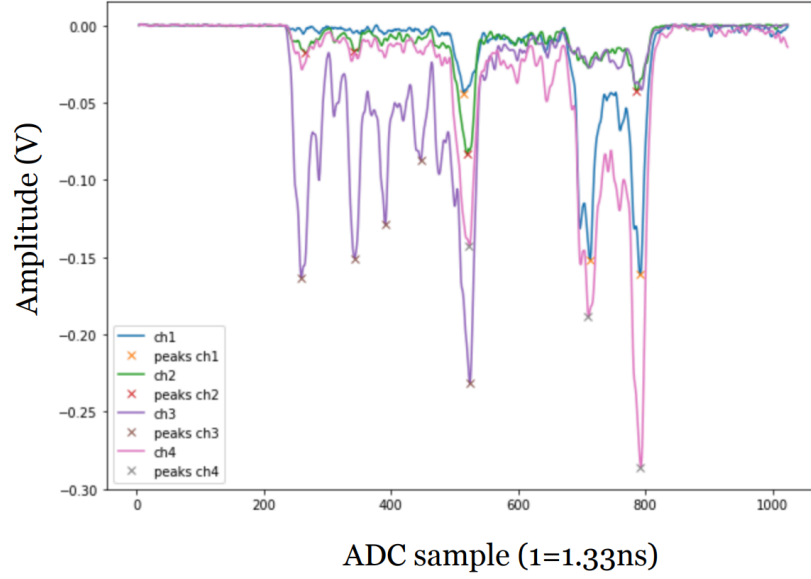


Figure 3.18. Example of long track smoothed by the moving average algorithm and with the peaks identified by the code explained in this section.

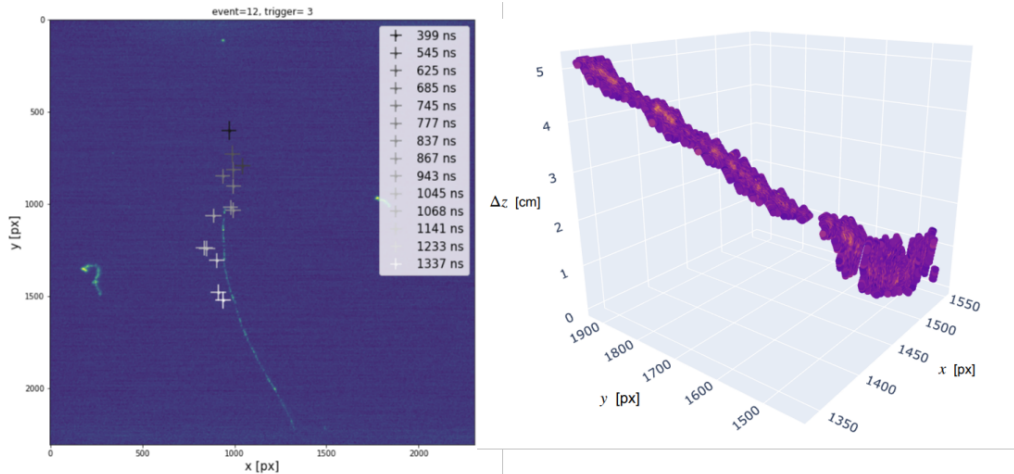


Figure 3.19. Two cherry events explaining the main goal of the PMT reconstruction. On the left the nice reconstruction of a truck and the relative temporal information. On the right another well reconstructed straight track presented in a 3-dimensional plot.

3.4.2 Investigation of the light scaling law in PMT Reconstruction

In Section 2.3.4, I discussed the physics behind the reconstruction algorithm employed for the four PMTs of LIME. During this discussion, a fundamental question emerged on why the expected scaling of light intensity with distance was a cubic law, whereas experimental observations suggest a fourth-power law.

In light of this experimental evidence, this latter dependence is adopted and good performances from the reconstruction code appears. Nevertheless, the scaling law must be understood. In this section I present a theoretical study primarily based on geometrical considerations. Then I discuss an experimental evaluation performed *in situ* on the LIME RUN 2 data.

Geometrically expected behavior

The reason of third scaling power is purely geometrical. In Sec. 2.3.4 I assumed the ionization cluster on the GEM plane to be point-like. However, considering the real dimensions of the source doesn't change the expected behavior.

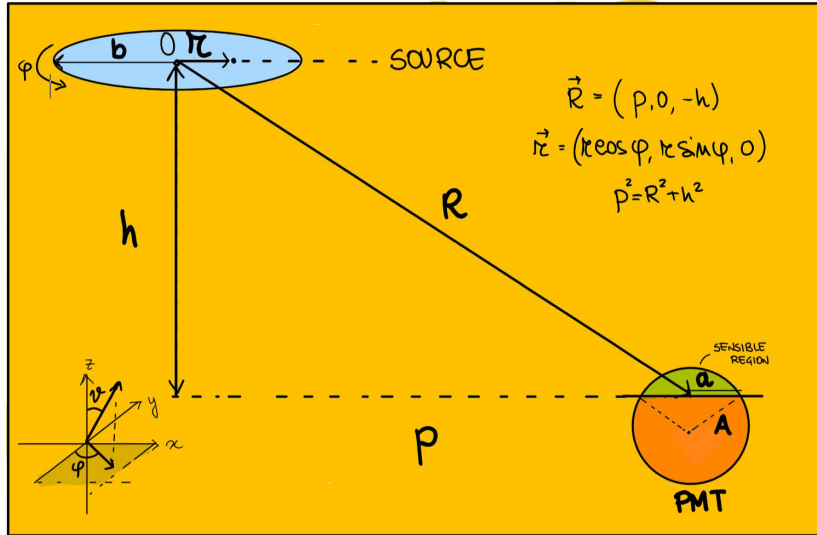


Figure 3.20. Sketch of the distances relating the light source on the GEM plane to the PMT devices. On the right the coordinates of the vectors.

Taking Fig. 3.20 as reference, the effect of an extended source is provided by integrating over all its points:

$$L \propto \int_0^b dr \int_0^{2\pi} d\phi \frac{r}{|\vec{R} - \vec{r}|^3} = \int_0^b dr \int_0^{2\pi} d\phi \frac{r}{(R^2 + r^2 - 2pr \cos \phi)^{3/2}} \quad (3.7)$$

The integration is performed numerically by Mathematica and, in Fig. 3.21, the resulting dependence of light from R is presented³. The expected behavior is still a cubic one.

³The adopted parameters are: $h = 19$ cm and $b = 1$ cm.

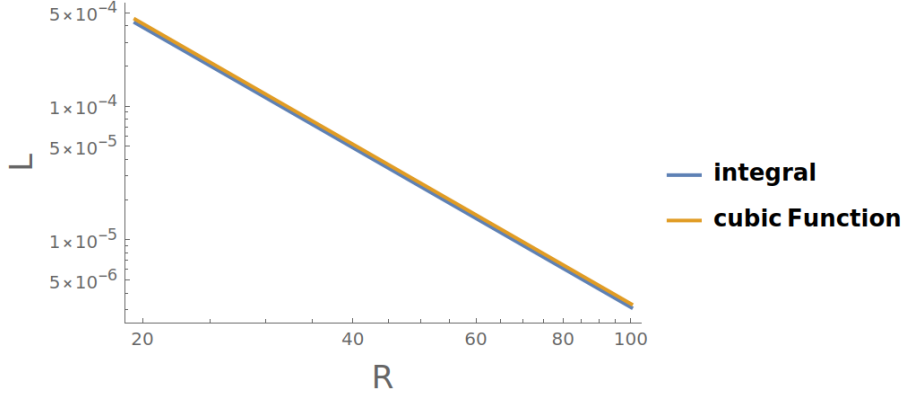


Figure 3.21. Dependence of the light intensity on R as resulting from the numerical integration discussed in the paragraph. The size of the cluster is taken in account and the dependence is still cubic.

Again the same possibility is investigated but with the employment of MC simulation performed by a Python code and a hit-or-miss strategy. Referring to Fig. 3.20 the idea is to scan all the possible distances p between the PMT and the source and, for each of those cases, create $N \times M$ lines with a point on the source and direction randomly generated. If a line intersects the PMT hence it is a count, otherwise not. Considering all the number of counts in function of the distance R we obtain a measure of the L dependence. The advantage of a numerical simulation respect to theoretical evaluation of Eq. 3.7 is that allows to add some details in the geometry in a much easier way.

The details are the following:

- p_{max} is the maximum horizontal distance allowed, s is the length of the single step adopted in the p -scan, b is the dimension of the source;
- For each value of p and for each point on the source, we generate $N \times M$ lines. Here, M represents the number of points considered on the source, and N is the number of lines considered for each of these points;
- The origin $\vec{r}$ of the lines on the source is chosen in a systematic way: only in the direction parallel to $\vec{p}$, from $-b$ to b . Actually the point is always generated at the origin O and what changes is that the PMT is not considered anymore positioned in $\vec{R}$ but in $\vec{R} - \vec{r}$;
- The line direction is randomly generated following a uniform distribution in ϕ and in $\cos(\theta)$
- From the datasheet of the PMTs [62], the photocathode can be sketched as a cap and the equation ruling the line-sphere intersection is considered:

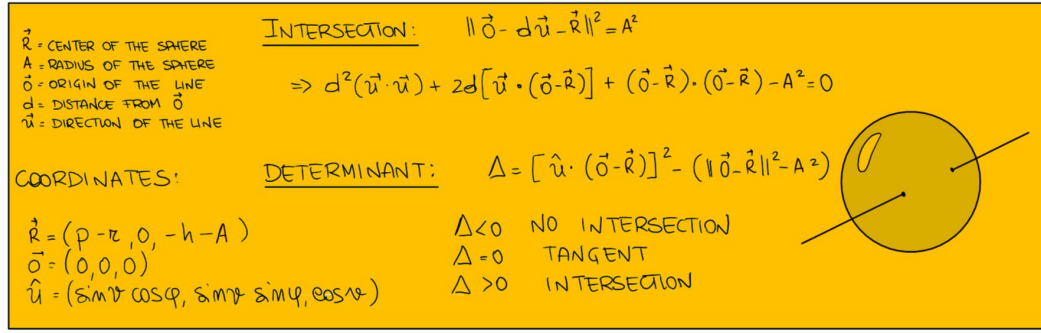


Figure 3.22. Summary table of the algebra concerning the intersection between a line and a sphere. The same labels of the section are used.

The condition that the PMT detects the signal is the positivity of the determinant. Because I consider a cap, another condition is added to the z position of the hitting point:

$$\vec{R} \cdot \hat{u}_z > z + A - \sqrt{A^2 - a^2} \quad (3.8)$$

- The counts with same p , even if with different $\vec{r}$, are summed together and the dependence on R is shown in Fig. 3.23.

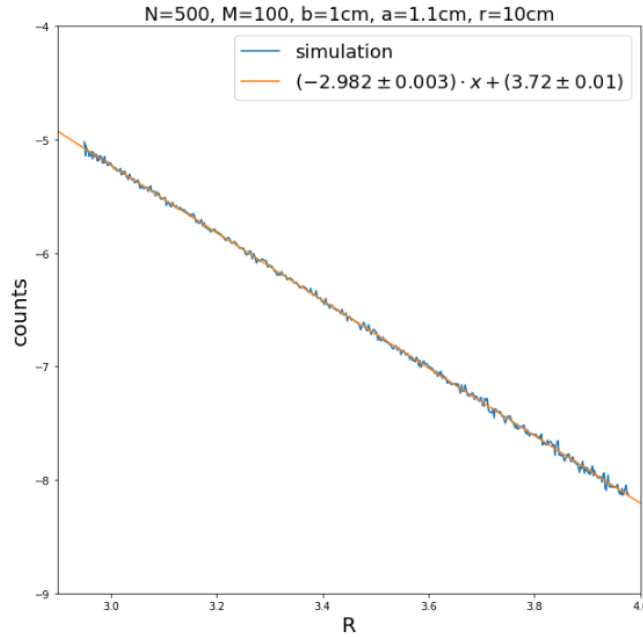


Figure 3.23. Dependence of the light intensity on R as resulting from the numerical simulation performed in the paragraph. The size of the cluster b is considered and the best fit, revealing a cubic dependence, is shown.

In conclusion, both the studies conducted do not provide any geometrical justification for adopting a fourth-power law. Through the simulation, other tests have been carried on considering some details of the PMTs structure. I have considered the effect

of the faceplate surrounding the photocathode and a non perfect convexity of the cap. Nevertheless, no considerable deviation from a cubic law has emerged. Therefore, we face two possibilities: either a new experimental analysis supports a cubic behavior, or we must explore other physical factors beyond geometry. One potential avenue for further investigation is the optical aspect of the scaling, considering the different media encountered by light before it reaches the detector. This could be a promising area to explore. In the next section, I will introduce a new approach for experimental measurement of the scaling power, which will help us gain a better understanding of this phenomenon.

Determination of the scaling law with an *in situ* measurement

The experimental strategy adopted in this study consists of achieving the scaling power α knowing the position of the tracks in the plane because supplied by the camera reco. In this context, the problem of associating a cluster to the relative WFs arises, since the PMT algorithm itself has the final goal to produce the association. The answer comes from the fact that, at the price of losing a lot of valid events, sometimes a cluster is unequivocally linked to only one PMTs event.

With this in mind, a clean data-set of iron events (because they are really common, spot-like and we know how to select them) is generated in a two step recipe:

- From all the pictures I select only the ones with just an iron spot through the usual selection Tab. [3.3](#)
- From all the surviving pictures, I select only the ones that present just a iron-like PMTs event as in sec. [3.3.1](#)

With a mean value of **3** valid events for run, a clean dataset of **306** elements is produced for the analysis and an example of the effects of the selection is shown in Fig. [3.24](#).

Once the data-set is available, the relation:

$$\frac{L_i}{\text{sc_integral}} = C_i \frac{L}{R_i^\alpha} \quad (3.9)$$

can be checked in a double logarithm representation:

$$\log\left(\frac{L_i}{C_i \cdot \text{sc_integral}}\right) = \log(L) - \alpha \cdot \log(R_i) \quad (3.10)$$

The reason for the double logarithm scale is because it requires a linear fit instead of a more complex non-linear regression: alpha is the angular coefficient of the line to be fitted. Note that the following consideration have to be taken in account:

- The index i runs over the 4 PMT channels.
- As mentioned in sec [2.2.1](#), the conditions of the experiment weren't the same along all the periods of data taking. We express this stability referring to the light yield (LY), i.e. the ratio of the number of scintillation photons to

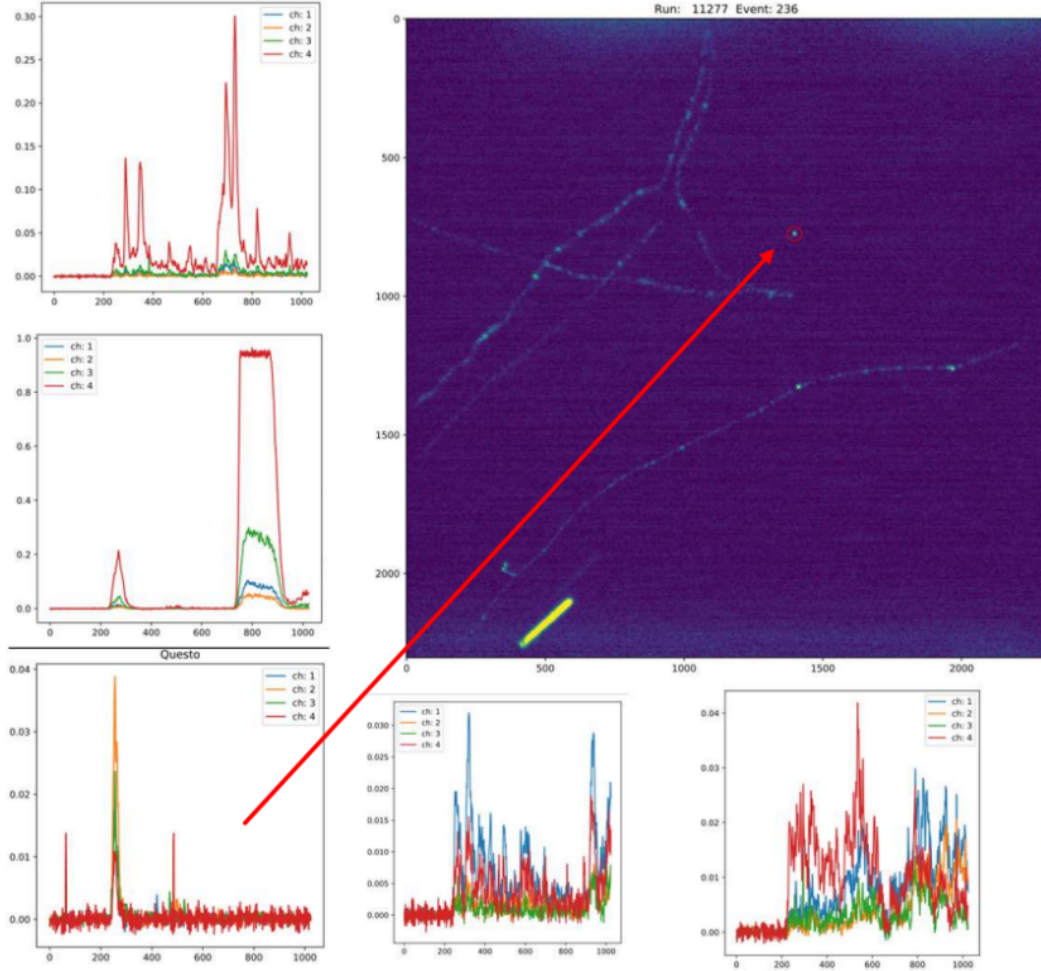


Figure 3.24. An example of event passing the clean data-set conditions. Even though multiple clusters and waveforms are collected, only one possible iron association can be performed and it enters the data-set.

the energy release of the tracks. The runs considered (because of the large number of samples needed for the fit) all belong to RUN 2 and for this reason presents different LY and, hence, different L of Eq. 3.9. This means that all the selected events couldn't be used together for the inference process if the normalization for `sc_integral` wasn't applied. In the assumption that the LY for PMTs scales exactly as for the camera, that *reco* variable normalizes all the data to a common scale.

- The position of the cluster comes from the camera *reco* and must be reported in the PMT frame using the rotation:

$$\begin{aligned} x_{PMT}[cm] &= (y_{PH} + 170) [px] / 0.0152 \\ y_{PMT}[cm] &= (x_{PH} + 180) [px] / 0.0152 \end{aligned} \quad (3.11)$$

- The position of the four PMTs in the camera view is given by the sketch in

Fig. 3.25

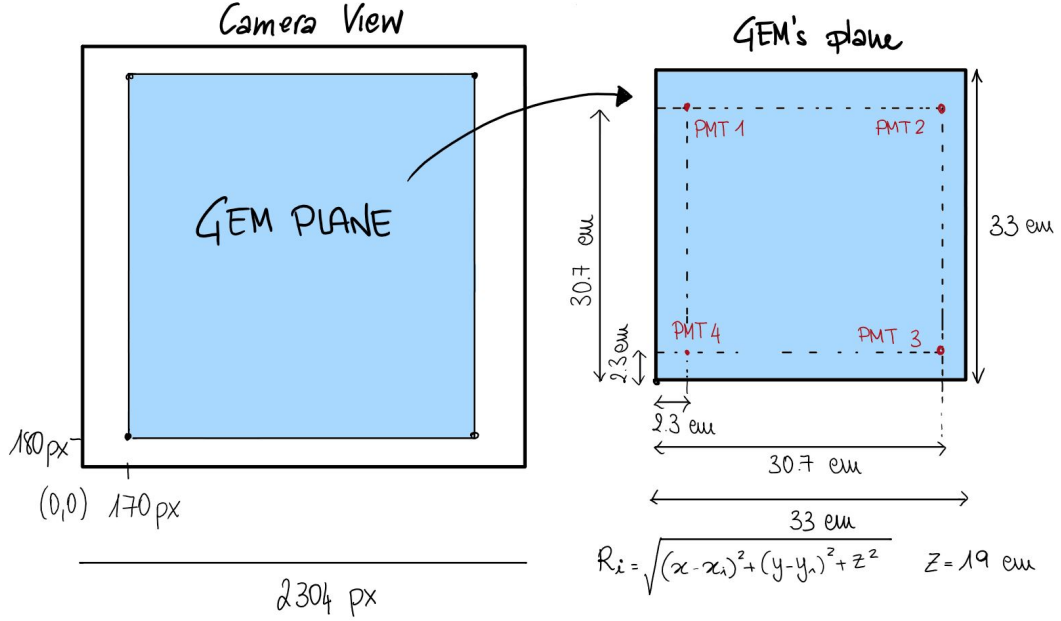


Figure 3.25. Sketch of the position of the four PMTs with respect to the camera view and the GEM plane.

The alpha extrapolation is performed with the function `curve_fit` from the Python library `scipy.optimize` and the data with the best fit are plotted in Fig. 3.27 and Fig. 3.28. The former is the fit for the 4 channel independently while the latter considers all the 4 PMTs together. On the lower side of both figures, the distances of the points from the best fit are plotted together with their distribution⁴. The inferred coefficients are listed in Tab. 3.8. In Fig. 3.26, the spatial distribution of the clean dataset respect to the four PMTs.

	α	$\log(L)$
channel 1	(-4.24 ± 0.08)	(18.7 ± 0.6)
channel 2	(-4.14 ± 0.07)	(17.9 ± 0.6)
channel 3	(-4.42 ± 0.06)	(20.6 ± 0.5)
channel 4	(-4.36 ± 0.08)	(20.2 ± 0.6)
combined	(-4.01 ± 0.06)	(17.3 ± 0.5)

Table 3.8. Value of the power α and luminosity L as inferred by the four PMTs. Also the combination of data is considered.

The final outcome is that, again, an effective scaling of $\alpha = 4$ emerges, in particular from the fit in Fig. 3.28. However, looking to the distances from the best fit, a

⁴Due to the fact that these distances are not normalized for the uncertainties of the points, they don't represent the residuals of the fit.

systematic deviation from the assumed model appears. The conclusion is that a fourth power represents a good effective parameter for the LIME prototype but a more complex behavior could emerge during the scaling of the CYGNO project.

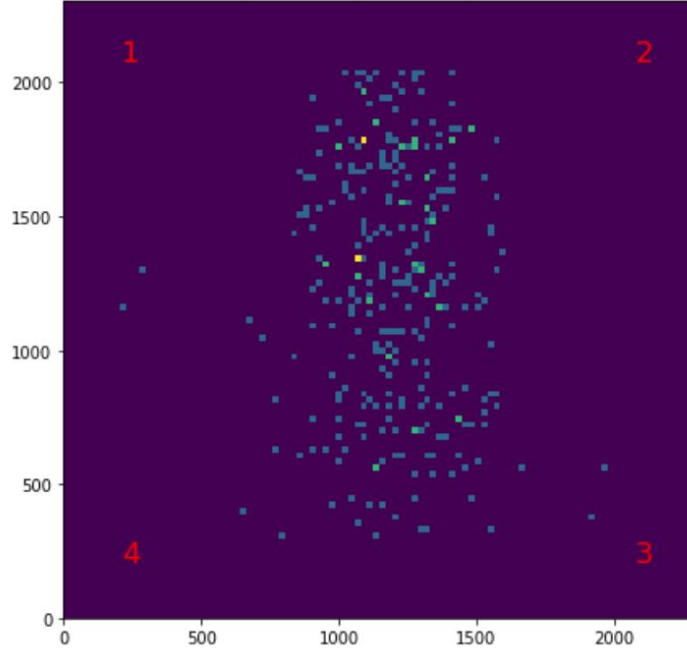


Figure 3.26. Spatial distribution of the events in the clean dataset. The number refers to the position of the four PMTs in the picture.

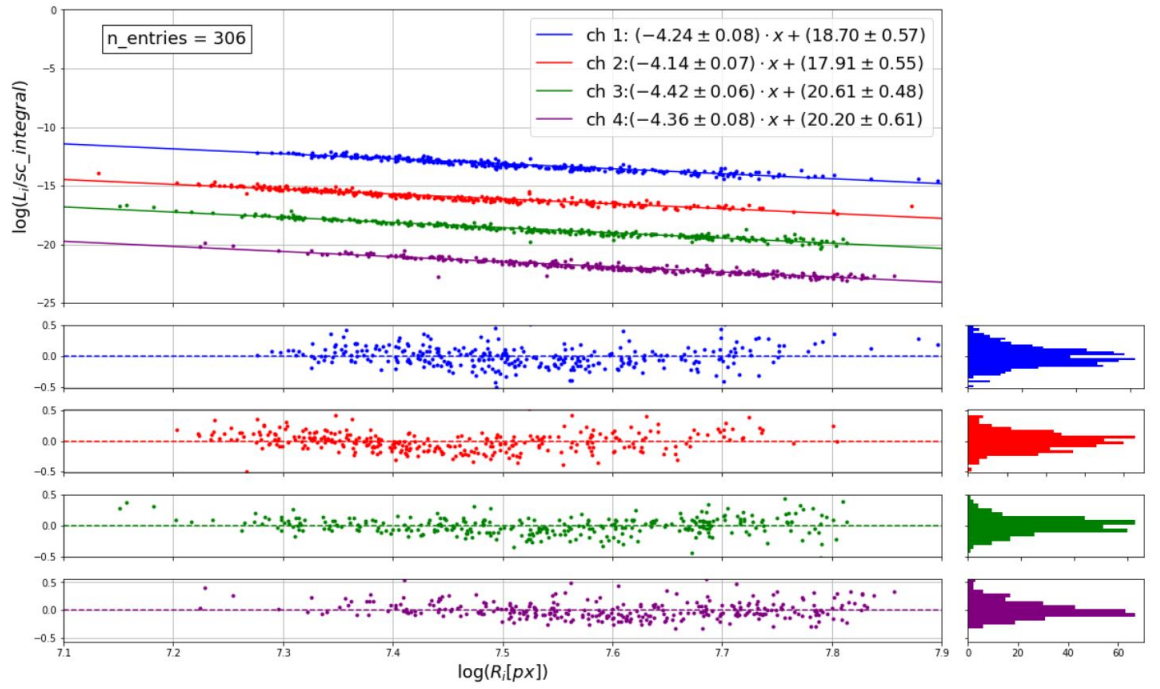


Figure 3.27. Best fit and relative residuals of the alpha power law in double log scale for the four PMTs

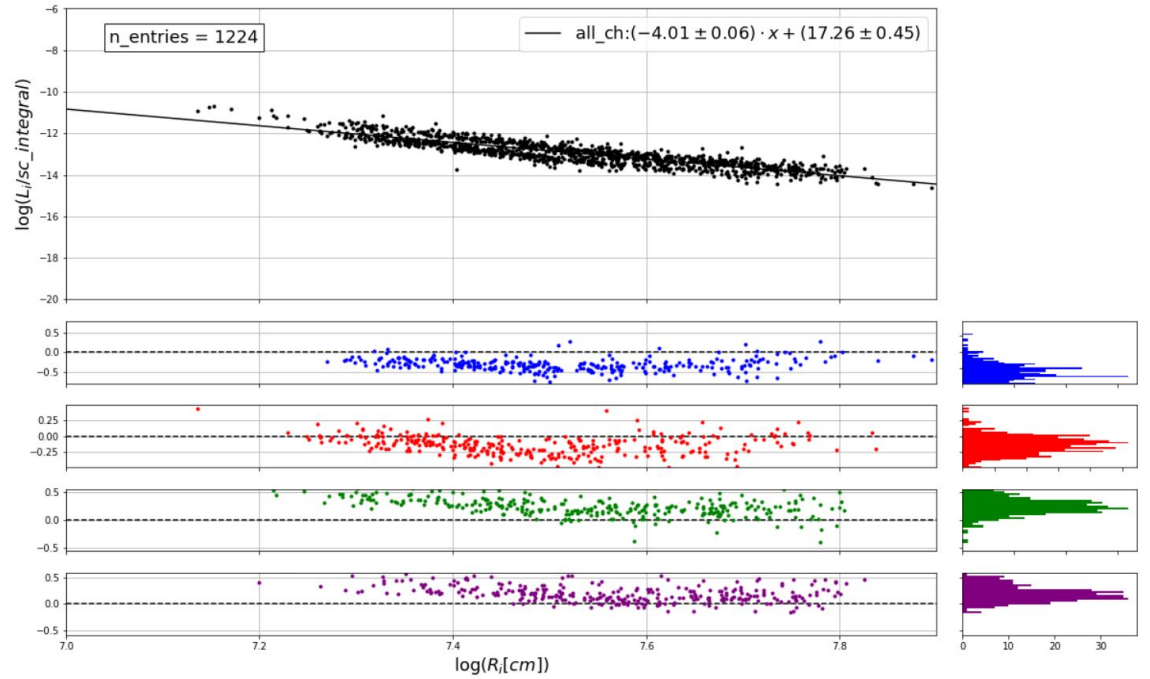


Figure 3.28. Best fit and relative residuals of the alpha power law in double log scale for the four PMTs combined

Chapter 4

Analysis of the AmBe RUN 3 dataset

The distinction between electronic recoil (ER) and nuclear recoil (NR) events is a fundamental ability in the context of dark matter research, as the latter are potentially enhanced by WIMP-nucleus interactions (see Sec. 1.3). The CYGNO project aims to achieve discrimination between these two signatures through the different ionization processes that characterize them. In this chapter, I provide some insights based on the reconstructed variables of the camera algorithm with the goal of identifying some preliminary potential quality cuts. In the first part, I discuss considerations based on the linear energy density of the reconstructed clusters during the RUN 2 configuration. This analysis reveals distinctions between tracks of different natures but does not point to an effective discrimination between ER and NR events. Regarding this, a data acquisition in presence of an external Americium-beryllium (AmBe) source emerges as an excellent opportunity to develop a preliminary analysis aiming for separating NR from ER induced events. In the second part of the chapter I discuss this AmBe campaign with the aim to visualize a signal excess induced by the high NR event rate.

4.1 The linear energy density variable

While presenting the CYGNO project, I emphasized how it means to achieve a discrimination between ERs and NRs by looking at the energy density of the tracks. In this section I delve into a preliminary analysis based on such a discrimination strategy using the camera reconstructed variables.

The data considered come from background runs in RUN 2 configuration. In Tab. 4.1 I resume some general information about the analyzed dataset and in Tab. 4.2 I list some cuts needed to clean them from spurious events. Those cuts aim to remove, from the dataset, random fake clusters and avoid tracks passing through the sensor noisy bands (Sec. 2.3.1).

runs[from,to]	n. pictures	tot. reco. events	clean reco. events	iron calib. run
[11590,11711]	45909	122100	40716	11956

Table 4.1. Main information about the background runs analyzed in the section. By "tot. reco. events" I mean the total number of reconstructed events; by "clean reco. events" the number of survived events after the cuts of Tab. 4.2 "iron calib. run" refers to the run adopted for the energy calibration.

cut	motivation
$sc_rms > 6$	it cuts fake clusters
$R(sc_xmean, sc_ymean) < 900$	it avoids the sensor noisy bands
$(sc_xmin > 200) \ \& \ (sc_max < 2100)$	it avoids the sensor noisy bands

Table 4.2. Sensor noise removal cuts. 0.152 is the conversion factor from px to mm and $R()$ states for radius centered in the middle of the GEM plane.

The plot displayed in Fig. 4.1 represents what I term a **linear energy density diagram**, i.e. a 2D histogram that correlates two camera reconstruction variables:

- **x axis:** the variable `sc_integral` converted in keV
- **y axis:** `sc_integral/sc_length` expressed in keV/mm that represents the linear energy density of a track along its direction of motion.

The conversion in keV and mm is performed through an iron calibration run and the usual factor 0.152 mm/px. Three bands appear and in the following I consider them separately with the aim to understand by which type of tracks they are populated. The selection is applied, through the lines indicated in Fig. 4.1, as:

- **Region_1:** the points between the blue and the orange lines;
- **Region_2:** the points between the green and the orange lines but over the red one;
- **Region_3:** the points between the red and the green lines.

Region_1

In Fig. 4.2 I show 5 cluster examples belonging to the first band, with an iron spot for a visual comparison. The hypothesis that emerges about their nature is that they are events on the CMOS camera, i.e. traces originated from the direct interaction of real particles with the sensor. The main argument in favor of such interpretation is that these events appears in pedestal runs with a rate consistent with the data runs. Being the GEMs off, no signal from the TPC can reasonably reach the camera and the origin of the track must be the sensor itself.

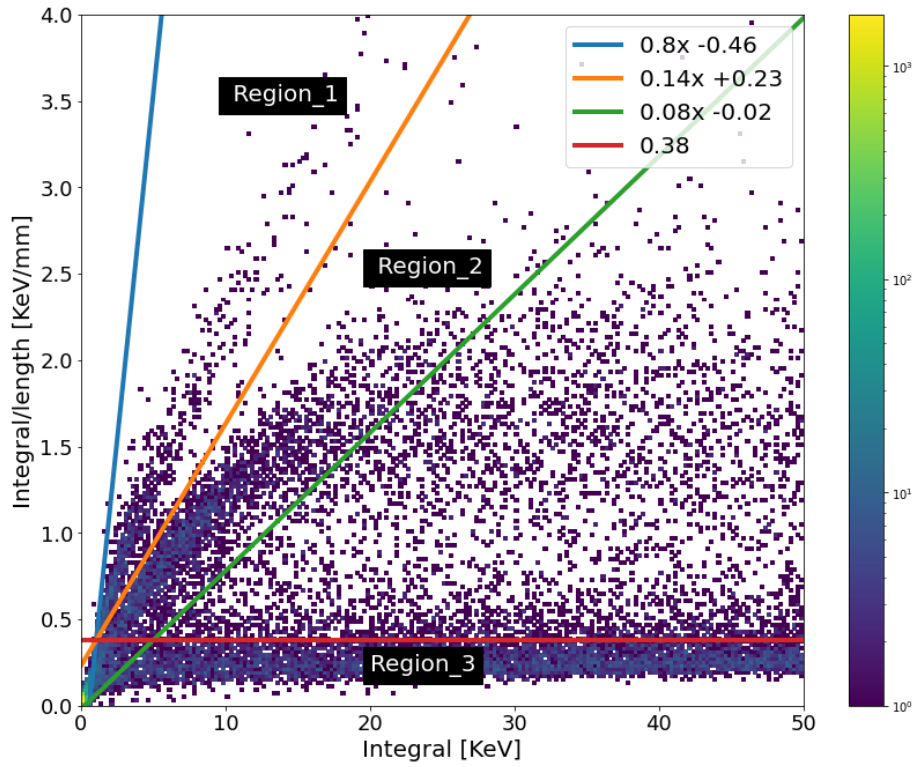


Figure 4.1. linear energy density diagram as reconstructed by the camera. Three bands appear and they are selected through the colored lines in the plot.

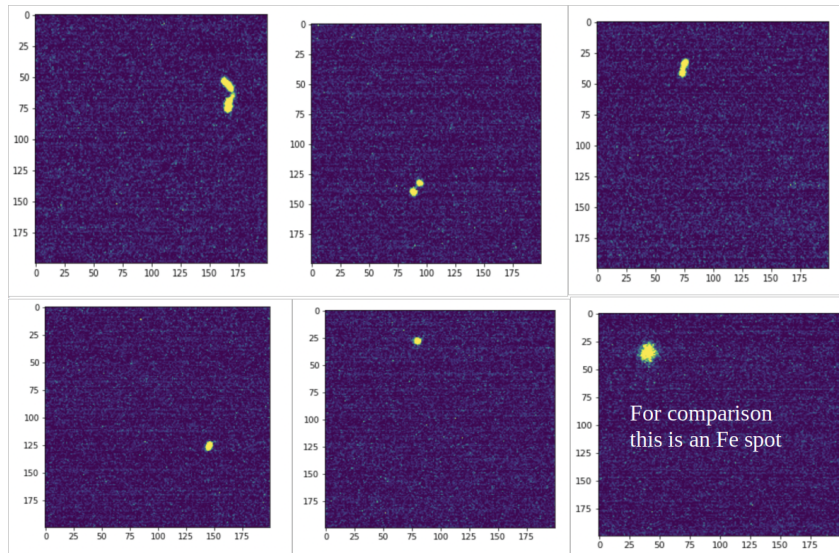


Figure 4.2. Example of clusters belonging to the Region_1 and comparison with an iron spot.

In Fig. [4.3](#) I show how the entire Region_1 can be mostly excluded by requiring the condition $0.152 \cdot \text{sc_tgausssigma} > 0.5 \text{ mm}$. The events on the sensor don't

diffuse in the gas and this justifies why a minimum value on the transverse dimension removes most of them. All in all the real effects of such cut must be fully understood and, until now, the possibility of deleting very localized real events is not excluded.

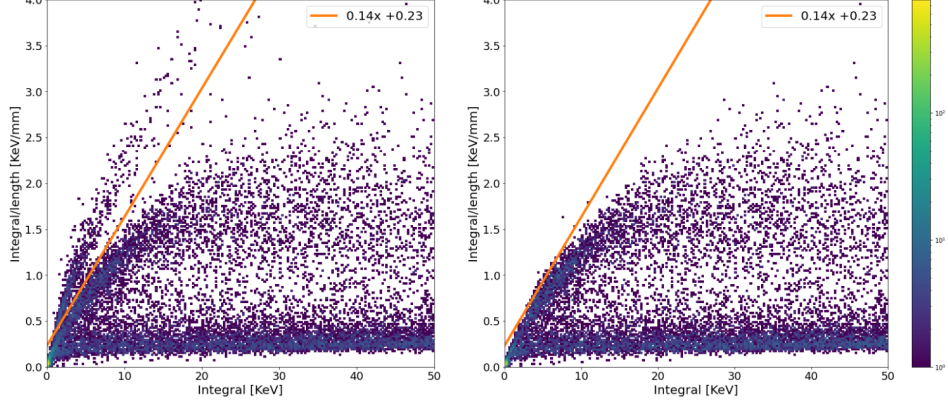


Figure 4.3. From the left to the right the effect of the cut $0.152 \cdot \text{sc_tgausssigma} > 0.5$ on the background dataset. The events on the Region_1 mostly disappear supporting the hypothesis of events on the sensor.

Region_3

Let's consider the lower region before the central one. It appears as a region of tracks that, despite the value of their energy, have always the same density and we believe they are mostly MIP (Minimum Ionizing Particles). In support of this hypothesis, 300 eV/mm is the expected energy release by a MIP in the CYGNO gas mixture (Sec. 2.1.3) and this value is perfectly consistent with the energy loss of the tracks belonging to the region considered. In Fig. 4.4, an example of track with the correspondent WF.

Region_2

Finally, let's consider the last remaining region. In sec. 2.5 I presented a study on the linearity response of LIME through the measure of different X-ray radioactive sources. The photons emitted by those sources generate ERs in the gas mixture due to electromagnetic interactions and in Fig. 4.5 I show the linear energy density diagram in each case. This plot reveals a consistent pattern in each source run: an excess is consistently observed in Region_2 compared to the Background case. Furthermore, this excess shifts along the spectrum as the energy of the generated X-rays increases. Consequently, the delineation of ERs band comes out.

The outcome of this section is the fact that the linear density variable is indeed able to differentiate various particle signatures (events on the CMOS, MIP, ERs) but no evidence of a fourth region of NRs has been observed. A possible reason of such missing evidence can be related to the low event occurrence of NR signals. Simulations estimate a NR event rate of $2 \cdot 10^{-3}$ Hz that corresponds, given the number of picture considered, to ~ 30 evn, the 0.07% of the total reconstructed clean dataset.

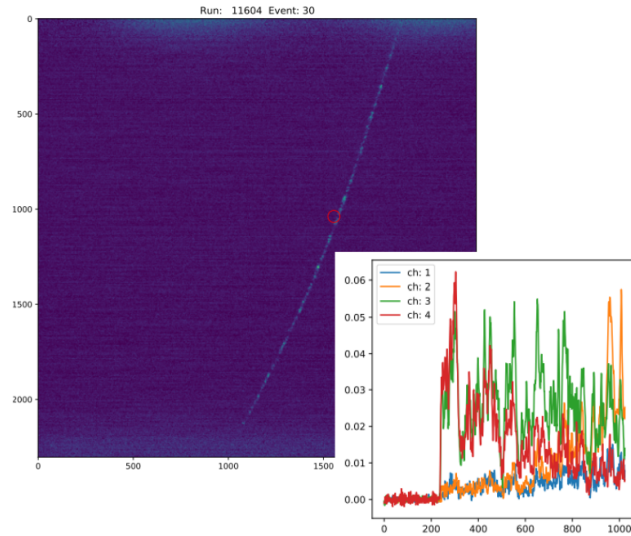


Figure 4.4. Example of a candidate belonging to the Region_3. It appears as a long track traveling the entire detector and with a constant luminosity along the path.

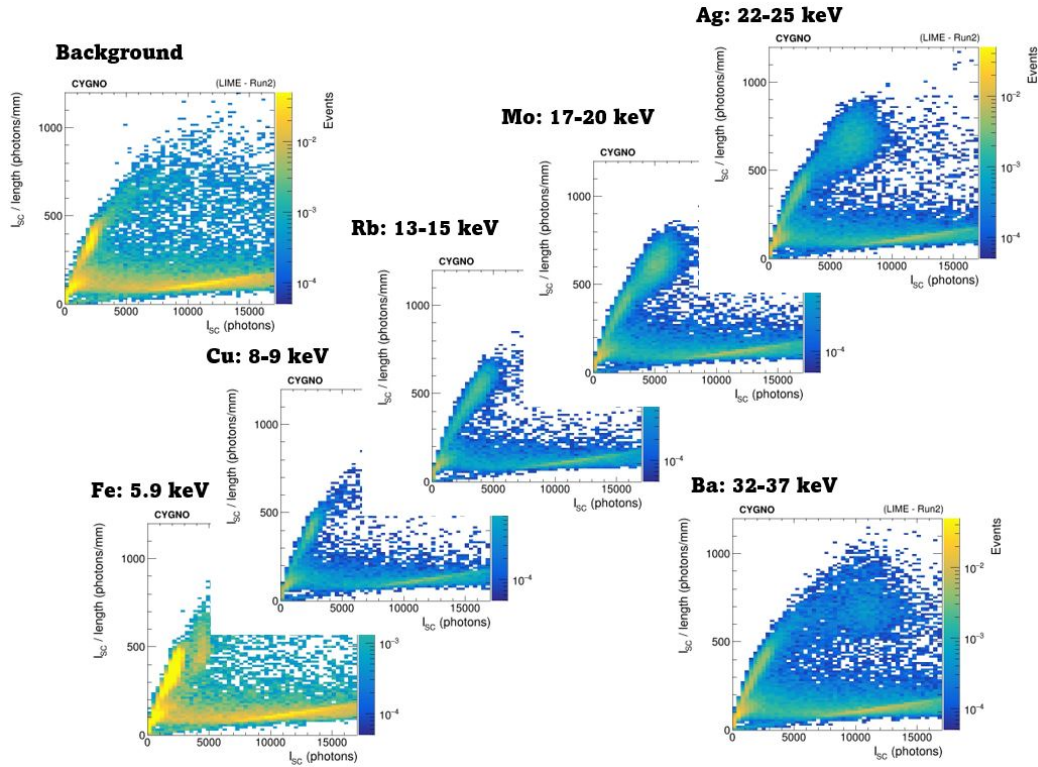


Figure 4.5. Linear energy density diagrams for the X-ray scan presented in Sec. 2.5. The Region_2 appears mostly populated by the ERs induced by the external photons and a corresponding growing in energy appears.

4.2 AmBe runs at LNGS

4.2.1 Analysis strategy and overview

The AmBe campaign conducted during the underground commissioning at LNGS, in the RUN 3 configuration, presents a valuable opportunity to gain insights into how NR events manifest within the LIME detector. Datasets collected with a high rate of induced NR events may reveal an excess in the relative linear energy density diagram, suggesting some initial selection cuts to isolate the NR events. In the following sections, I will outline my contribution to the analysis of the AmBe data. This analysis is based on a direct comparison between the reconstructed variables of background runs and AmBe runs. However, it's important to notice that this comparison is not entirely straightforward due to certain issues that emerged during the campaign. Firstly, the data-taking period was shortened to just 3 days out of the planned 10 days due to a critical error in the gas system. As a result, a stable LY was not available, necessitating the application of energy corrections when considering variables proportional to `sc_integral`. Additionally, a different choice of filters between the background and AmBe runs led to an environmental-radioactive contamination in the former case compared to the latter. Despite these challenges, this analysis yields a list of selection cuts that can be applied as a result of the AmBe data evaluation.

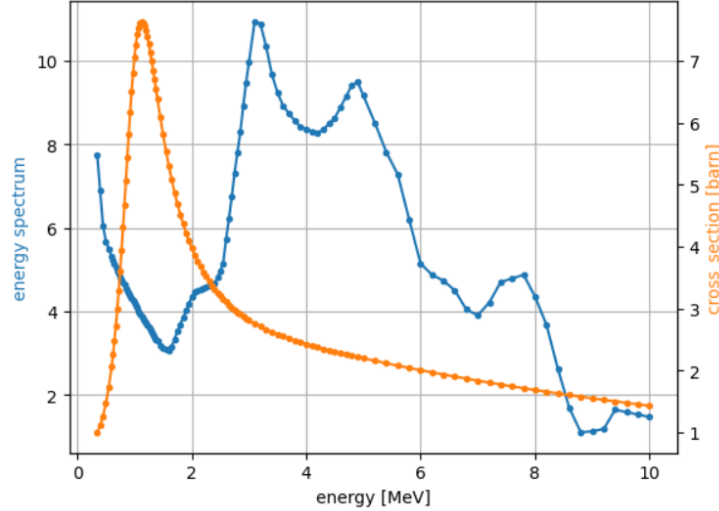
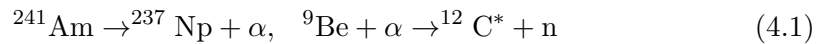


Figure 4.6. In orange the cross section of neutrons in helium; in blue the energy spectrum of the neutrons emitted by an Americium-beryllium source.

4.2.2 Expected event rate

Americium-beryllium is a radioactive neutron source that exhibits several emission channels. This leads to the emission of neutrons with different kinetic energies accompanied by γ -ray emission. The reaction chain consists of:



subsequently, the excited carbon nuclei decay through a γ -photon emission. During the underground AmBe data taking, the source was supplied by Laboratori Nazionali del Gran Sasso (LNGS) with an activity $I = 200$ neutrons/s. The spectrum of emission consists of an isotropically production of:

- photons with an energy of 59 keV by ^{241}Am . The presence of the copper shielding in RUN 3 configuration has the effect of mostly absorb all such photons;
- neutrons with a continuous spectrum of kinetic energy in the range $1 \div 10$ MeV (Fig. 4.6);
- photons with an energy of 4.4 MeV produced by the relaxation of the first excited state of carbon;

Knowing the intensity and the energy spectra $g(E)$ of the source and the differential cross section of neutrons σ_E interacting with He (reported in Fig. 4.6) we can evaluate the expected rate of NR events in LIME:

$$R_C = \left(\frac{N_T \cdot \sigma}{A \cdot t} \right) \cdot N_P = \left(I \cdot \epsilon_\Omega \right) \left(\int \sigma_E \cdot g(E) dE \right) \frac{\rho N_A l}{M_A} \quad (4.2)$$

Here N_A stands for the Avocadro constant, M_A for the molar mass of helium, ϵ_Ω stands for the geometrical acceptance due to the collimation of the source, while l is the active length of the detector. The adopted values are $\epsilon_\Omega = 0.5$ and $l = 33$ cm, so the rate evaluation can be performed¹:

$$R_C = 0.23 \text{ evn/s} \quad (4.3)$$

This analysis is a simplistic evaluation that assumes only the interaction of the neutrons with helium nuclei and doesn't take into account the 10 cm of copper shielding of the detector. A more reliable value is the one given by the simulation:

$$R_C = 0.15 \text{ evn/s} \quad (4.4)$$

two order of magnitude bigger than the Bkg case.

The main information about the AmBe and the background runs are listed in Tab. 4.3. The usual cuts adopted to avoid fake clusters and tracks passing through the sensor noisy bands are applied to both the dataset (Tab. 4.2). In addition, the row condition $0.152 \cdot \text{sc_tgausssigma} > 0.5$ mm is imposed to delete the events on the sensor.

4.2.3 Preliminary corrections

During the AmBe campaign, the working conditions of the experiment (like the internal pressure, humidity, ecc...) weren't stable, resulting in a LY variation. In

¹The numerical integral is evaluated by mean of the composite trapezoidal rule through the function `scipy.integrate.trapz`

	runs	n. pictures	tot. reco. events	clean reco. events	starting	ending
Bkg	560	47692	4678802	52618	28-07-2023	02-08-2023
AmBe	414	35979	3484657	39678	02-08-2023	04-08-2023

Table 4.3. Table summarizing the key aspect of the Bkg and AmBe dataset considered in the section. By "tot. reco. events" I mean the total number of reconstructed events; by "clean reco. events" the number of survived events after the cuts discussed in the section. "starting" and "ending" state for the beginning and the conclusion dates of the runs considered.

Fig. 4.7, I present its evaluation per run. All future analyses between reconstructed variables, dependent from the LY, are corrected by this calibration.

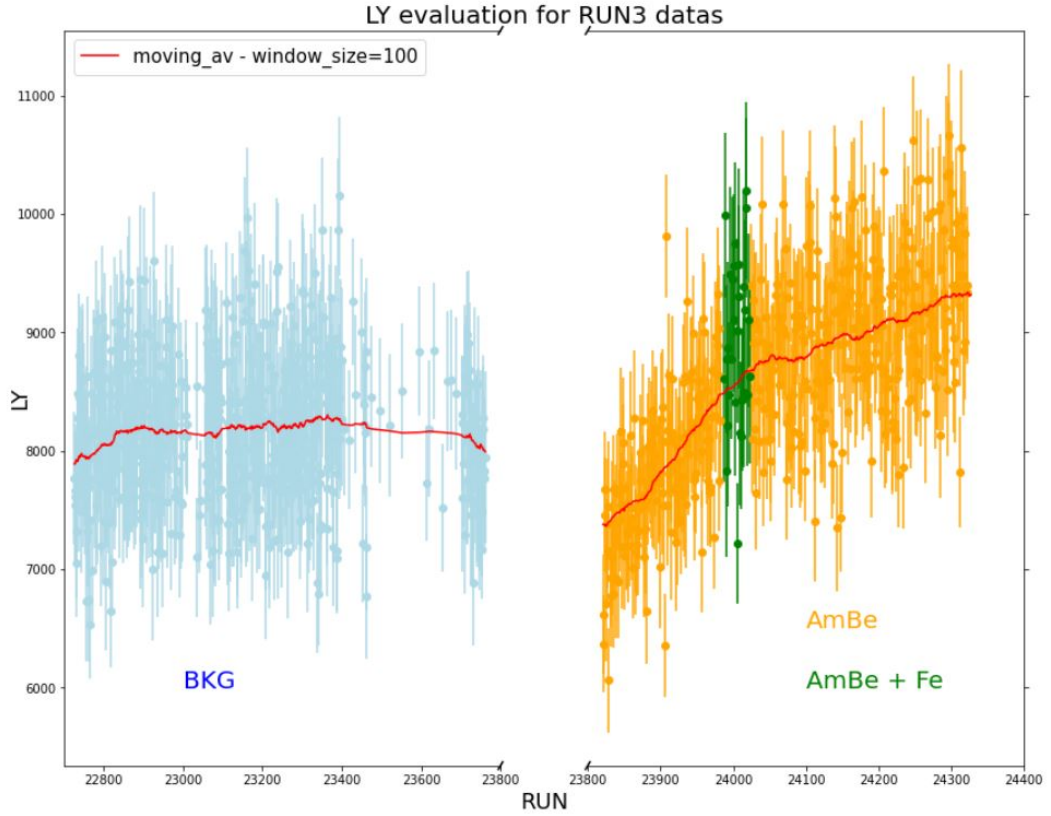


Figure 4.7. LY evaluation for the bkg and AmBe data considered in the section. In red, the moving average of the points in a window of 100 runs.

The first comparison involving reconstructed variables regards the calibrated energy spectrum plotted in Fig. 4.8. The two distributions (and this will regard all the histograms in the chapter) are normalized to the same lifetime. The counts in each bin of the background histograms are normalized through the value:

$$\text{norm_counts}_i = \text{counts}_i \times \frac{\# \text{ pictures}_{AmBe}}{\# \text{ pictures}_i} \quad (4.5)$$

where i is the source considered.

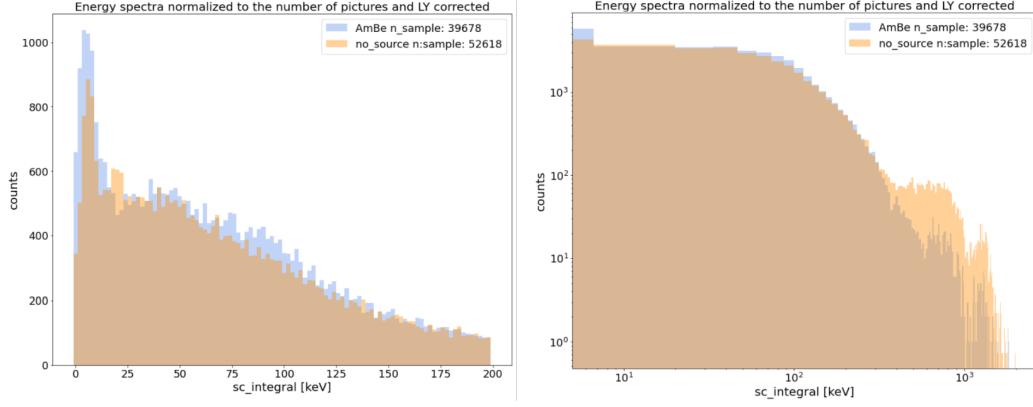


Figure 4.8. Un-cut energy spectrum of bkg and AmBe runs. The data are corrected for the different LY and are normalized to the same lifetime.

As expected, some excesses in AmBe data emerges, and they will be considered in the next section. More surprisingly a peak around 20 keV (clearly in the plot on the left) and an excess at $\mathcal{O}(\text{MeV})$ (plot on the right) come out in the background data. The two data-taking (no source and AmBe) were taken with few hours of distance with the same shielding configuration so such a discrepancy was unexpected. A possible origin is under investigation by the collaboration and some guesses refers to a different choice of filters and a different re-circulation flux in the two cases. All in all, the cuts listed in Tab. 4.4, once applied to both data-sets, are able to identify and remove the two excesses. A rigorous study on the efficiency of those cuts is ongoing and, up to now, the effect on the NR events is unknown. In Fig. 4.9 the energy spectrum after the selection.

cut	effect
$\text{sc_corr_int}/\text{sc_nhits} < 0.03$	cut on high energy excess
$\text{sc_tgausssigma} > 8$	cuts on 20 keV excess
$\text{sc_corr_int}/\text{sc_nhits} > 0.02$	
$\text{sc_corr_int}/\text{sc_nhits} < 0.01$	
$\text{sc_tgaussamp} < -\text{sc_size} + 4200$	

Table 4.4. List of cuts adopted to take care of the excesses appearing in the background data. The first one regards the high energy excess while the others regard the peak around 20 keV.

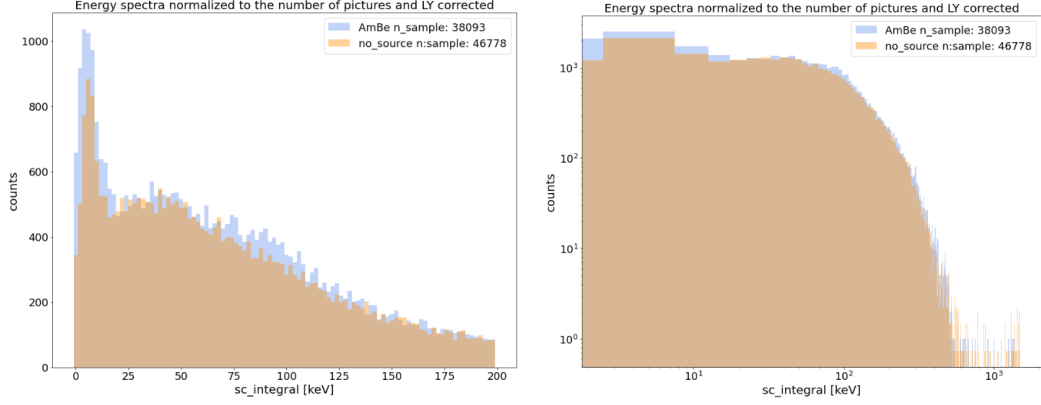


Figure 4.9. Cutted energy spectrum of bkg and AmBe runs. The data are corrected for the different LY and are normalized to the same lifetime.

4.2.4 AmBe-background comparison

The main peak in AmBe energy spectrum is at 3 MeV (Fig. 4.6) and a neutron of such energy produces a nuclear recoil of average energy:

$$\langle R \rangle_\theta = \frac{\mu^2}{m_{He}} v^2 \quad (4.6)$$

In the approximation of non-relativistic velocity and considering a quenching factor of 30%, we obtain a typical energy release of ~ 300 keV. In Sec. 2.1.3 I presented the relation between the 3D length of a NR as function of it's energy. For the value under consideration, a track of length about $\mathcal{O}(1 \text{ mm} \div \text{cm})$ can be extrapolated from the picture. Although it is a qualitative calculation, what emerges is that a NR selection can be achieve by some considerations of the size of the clusters. In Fig 4.10 I show the comparison between the variables `sc_length` and `sc_width/sc_length` for the AmBe and *bkg* runs. An excess in the former dataset appears for short and round clusters and this condition is also consistent with the procedure advanced at the beginning of the section. For this reason, the first two cuts listed in Tab. 4.5 are applied to both datasets. In addition, they remove the 4 MeV photons from AmBe and the long cosmic, returning a cleaner sample of data.

cut	effect
$0.152 \cdot \text{sc_length} < 20 \text{ mm}$	cut on short tracks
$\text{sc_width}/\text{sc_length} > 0.7$	selection of quite round clusters
$\text{delta} > 0.02 \text{ keV/px}$	selection of high density tracks

Table 4.5. Table of NR cuts identified during the bkg-AmBe comparison.

Once applied the cuts on the cluster size, the remaining data are compared through

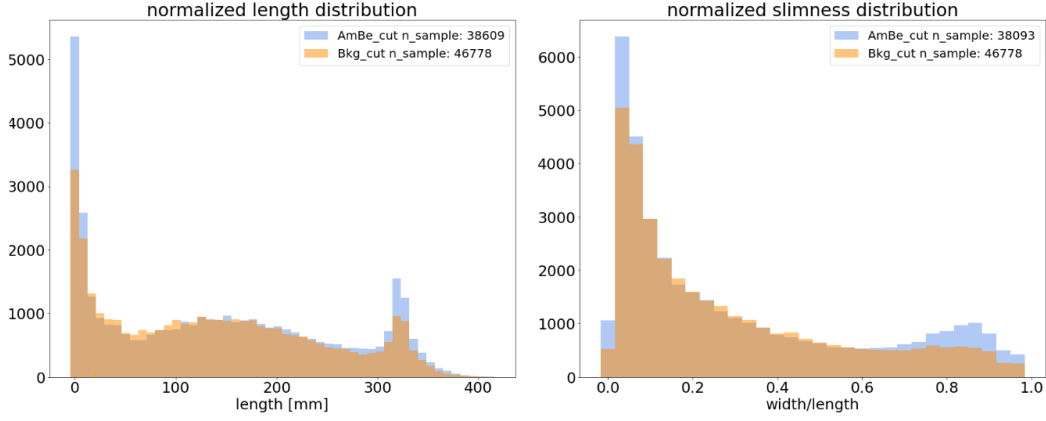


Figure 4.10. Comparison of the distribution of the variables `sc_length` and `sc_width/sc_length` for the AmBe and bkg runs. Normalized to the same lifetime.

the variable `delta` defined as:

$$\text{delta} = \frac{\text{sc_integral}}{\text{sc_nhits}} \quad (4.7)$$

Again, the original strategy of a density selection comes out and the best cut, suggested by the compared histograms in Fig. 4.11, is the one reported in the last row of Tab. 4.5. The final selected data, from both datasets, are plotted in Fig 4.12 adopting the linear energy density diagram. As we can see from the top of the picture, an excess in the Region_2 of the diagram appears in the AmBe runs and the found selection populates exactly this band. In the bottom part I outline in red the events selected as NRs candidates.

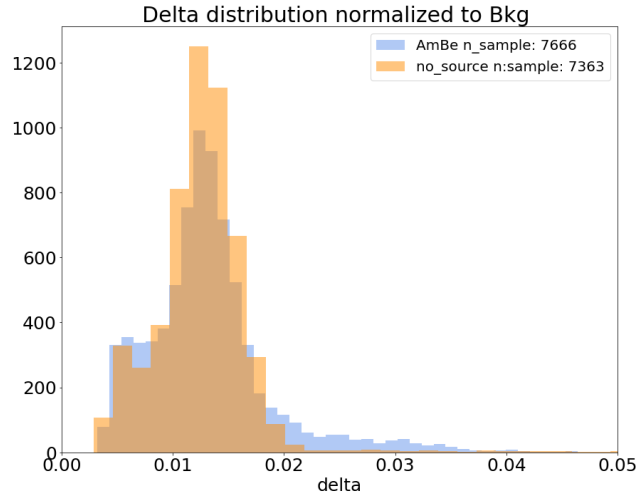


Figure 4.11. Comparison of the delta distribution between AmBe and bkg runs. Normalized to the same lifetime.

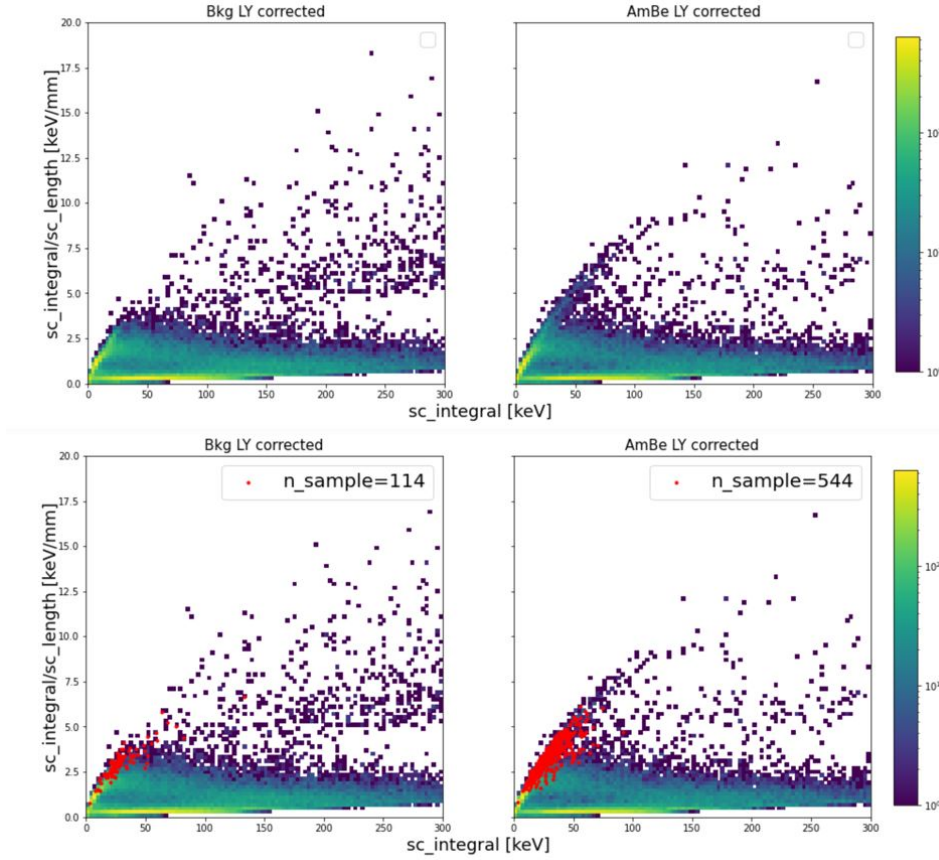


Figure 4.12. At the top, the linear energy density diagram for bkg and AmBe datasets; in the lower side the same plot but with the selected NR clusters outline in red.

4.2.5 A feedback from MC simulation

A valuable feedback about the quality of the selection identified in this chapter can be achieved by means of the MC simulation of the detector. We can apply the camera reconstruction algorithm to the simulated events after the digitization step and, consequently, compare with the actual data. This is a standard strategy and in this section I provide an initial comparison. However, it's important to note that the digitization step of the simulation is still in its preliminary stage, and therefore, no conclusive results can be drawn at this time.

In Fig. 4.13 I present the comparison between the energy spectra of:

- the AmBe data after the application of the clean cuts of Tab. 4.4;
- the sum of Background data (after the application of the clean cuts of Tab. 4.4) and the simulation of only AmBe source.

Both are obtained by the distribution of the variable `sc_integral` converted in keV. This conversion is operated for the data as explained in this chapter. For the simulation, instead, a calibration constant is derived by the MC truth energy.

The comparison shows a good shape agreement between the two spectra, hinting to

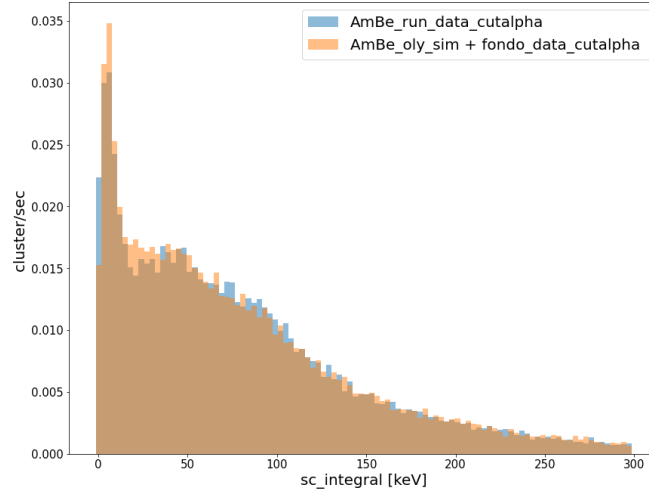


Figure 4.13. Energy spectra, given by the variable `sc_integral` converted in keV, of AmBe data and the sum of Bkg data and AmBe source simulated.

a consistent application of the selection cuts.

Indeed they are applied to both datasets and the result is shown in Fig. 4.14. Here the linear energy density diagram of AmBe data is plotted with the simulated NR events superimposed. What emerges is that NR events populate the Region_2 as anticipated by the data analysis and the event selection is able to identify $\sim 15\%$ of the total amount of NR events. In Fig. 4.15 I present a summarizing plot that shows the cluster of a NR candidate event and of an ER event (from iron) of similar energy. From this picture, a difference in energy density between the two signatures is visible also by eye.

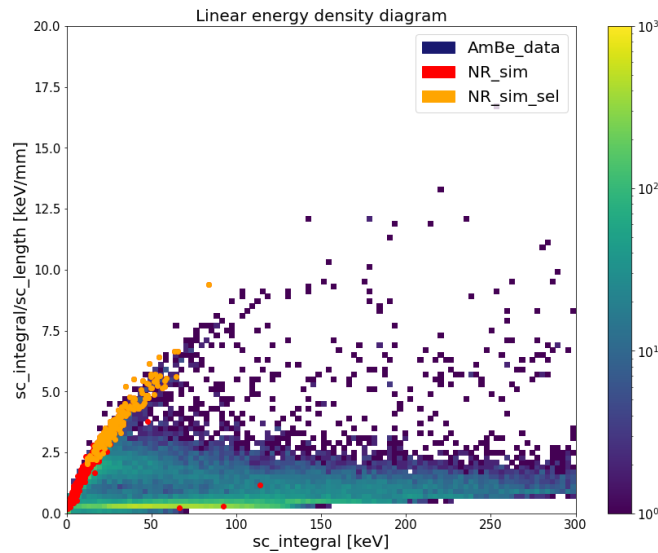


Figure 4.14. Linear energy density diagram of AmBe data with the simulated NR events (red points) superimposed. The orange dots represent the NR simulated events that passes the selection presented in this chapter.

4.2.6 Conclusions

The AmBe campaign conducted during the underground commissioning at LNGS provides a valuable opportunity to gain insights into how NR events manifest in the LIME detector. Building on a previous AmBe campaign conducted with the LEMON prototype of the CYGNO experiment [55], we have identified an initial set of selection criteria to isolate NR events. The effectiveness of these selection cuts will be assessed through MC simulations together with other possible reconstruction variables correlations.

Regarding the CYGNO strategy of achieving a ER/NR discrimination through the energy density variable, the effects of GEM's saturation and diffusion must be taken into account. These two effects have been extensively studied within the LIME prototype and in particular, for ^{55}Fe spots, a preliminary correction has been developed. However, for NR events the precise impact of these two effects needs further characterization yet. Both affect the energy density variable, posing constraints on its ability to effectively differentiate NR from ER events.

In response to these challenges, the CYGNO collaboration is pursuing two strategies to correct for saturation and diffusion. One approach involves identifying a corrective factor based on the z-coordinate once the cluster's position in the detector is determined. However, both the camera and the PMTs require a reconstruction analysis to infer the absolute z-position of a track, and this strategy is still under development. Nonetheless, promising results have been observed in iron spots, as detailed in reference [59].

Another strategy involves considering the effect of saturation and diffusion in the digitization process of MC simulations. Although this procedure is already part of the digitization algorithm, the saturation model used as input is currently in a preliminary stage of development.

In summary, this analysis of AmBe campaign represent a first characterization of the LIME response to NR events. However further investigation are essential for enhancing our understanding of LIME ability to differentiate between NR and ER events.

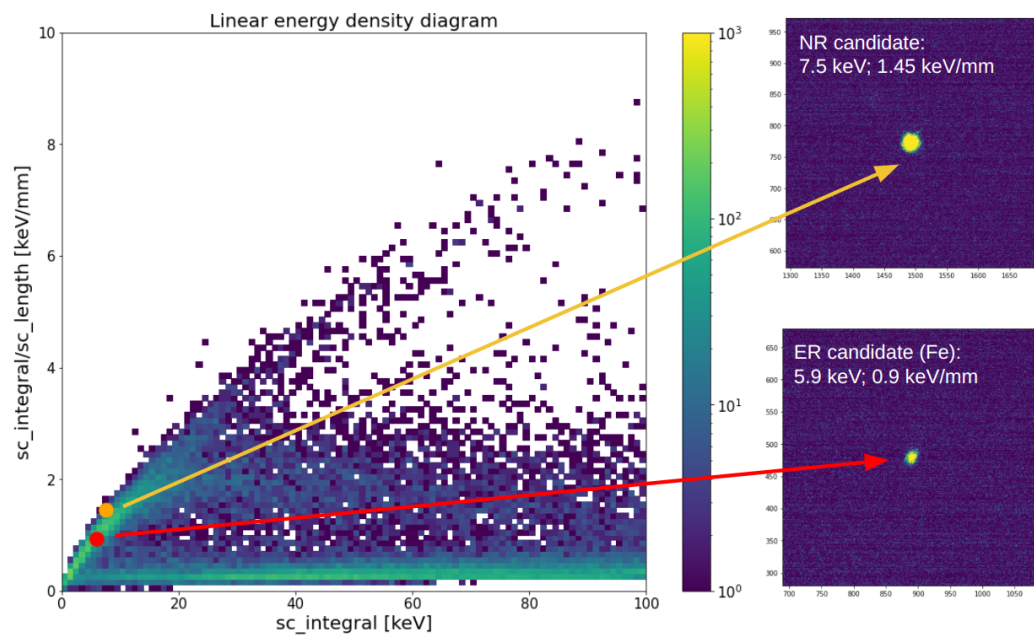


Figure 4.15. Picture of a NR candidate event and an ER event (from iron) and relative position in the linear energy density diagram. They have a similar energy but the energy density suggests a different nature of the two interactions.

Chapter 5

Conclusions

The CYGNO project is an emerging experiment with a forward-looking approach within the field of Dark Matter research. Its primary objective is to explore the still mostly-unknown $\mathcal{O}(\text{GeV})$ DM mass range through an innovative experimental setup employing optical readout and GEM amplification technologies. Furthermore, it aims to achieve a sensible directional capability able to detect a daily modulation of the DM signal. Currently, the CYGNO experiment is conducting the underground commissioning of its actual prototype: the Long Image ModuLE (LIME). During my thesis project, I had the opportunity to actively participate to such an underground campaign giving my contribution to most of its aspects.

With regard to the crucial task of validating the CYGNO experimental approach, I conducted an analysis focused on both longitudinal and transverse diffusion, as assessed by the two optical devices employed in the experiment. The results of this analysis exhibited a high degree of consistency with the expected behavior, thereby confirming a thorough understanding of the physics underlying the gas mixture chosen by the collaboration. This achievement advances future robust MC simulation of the signal interactions within the TPC of LIME.

From the point of view of characterizing the reconstruction algorithms, I curated a clean dataset of events for which the position on the GEM plane was conferred by the camera algorithm. This dataset enabled an *in-situ* investigation of the PMTs reconstruction algorithms and, to a good approximation, validated the assumed model employed during the campaign. In addition, I developed a MC simulation able to take in account all the structural details of the LIME prototype, with the scope of identifying a geometrical understanding of such adopted model.

Finally I delved into the challenging task of separating ER from NR events. In pursuit of this goal, I initially conducted an analysis of background runs based on the linear density variable discrimination. Although no definitive separation between ER and NR events was evident, this analysis provided valuable insights into the goal of characterizing the composition of the intrinsic background signal observed in LIME. In a dedicated campaign involving an external AmBe source, instead, I derived some preliminary selection criteria for the recoils induced by the produced neutrons. Although the developed selection must be verified with a MC simulation, it reproduces events belonging to an excess in the linear energy density diagram observed in the AmBe data in comparison to the background signal.

Appendix A

The drift of Electrons in Gases

In this appendix, I discuss the drift of electrons and ions within gases, which is a crucial component of Time Projection Chambers (TPCs) as outlined in the reference [77]. I begin by examining the underlying principles at the microscopic level, with a primary focus on electron drift, which is particularly pertinent to my thesis project. For a more comprehensive exploration of ion motion within a drift chamber, I recommend referring to the work cited in [57], which also directly pertains to the CYGNO experiment. The primary objective of this chapter is to provide the fundamental theoretical concepts necessary for comprehending the characteristics of a drift chamber.

A.1 The microscopic picture

An electron that drifts through a gas is continuously scattered by the gas molecules during its motion in the direction of the anode. In the assumption of isotropic scatters, after a collision the electron loses any preferential direction and adds, to its randomly oriented velocity c , an extra velocity u defined as:

$$u = \frac{eE}{m}\tau \quad (\text{A.1})$$

Here τ is the average time elapsed between two consecutive collisions and u appears macroscopically as a drift velocity. Due to the successive collisions, the electron loses some of its energy but it's also accelerated by the electric field and a balance is reached. On a path of length x , the number of collisions N_c is $x/\tau u$ and on each of these events there is an average fractional loss λ of the energy ϵ . The equation is indeed:

$$eEx = N_c \lambda \epsilon = \frac{x}{\tau u} \lambda \epsilon \quad (\text{A.2})$$

Knowing the energy of an electron

$$\epsilon = \frac{1}{2}mc^2 \quad (\text{A.3})$$

and the relation between τ and the cross section of the collisions

$$\frac{1}{\tau} = N\sigma c \quad (\text{A.4})$$

one reaches the dependence of the drift velocity from the drift field:

$$u^2 = \frac{e}{m} \frac{E}{n} \sqrt{\frac{\lambda(\epsilon)}{2\sigma^2(\epsilon)}} \quad (\text{A.5})$$

Note that both λ and σ depend on the energy of the particle and this has an effect of the functional dependence of u from E . In addition, the drift velocity explicitly depends on the reduced field E/n implying a role of the gas pressure too. In figure [A.1](#) I present an example of drift velocity as a function of the drift field. The Ramsauer peak, clearly visible for CH_4 and C_2H_4 , is due to a quantum effect that acts on the cross-section σ .

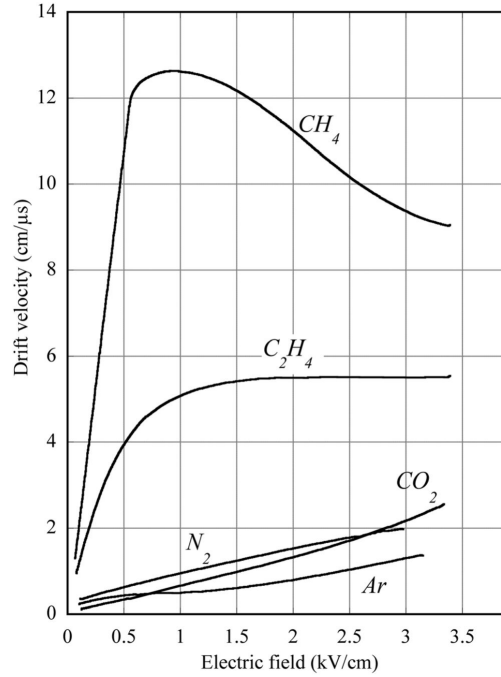


Figure A.1. Drift velocity in function of the drift field for some pure gasses at Normal Pressure Conditions (NPC). Picture from [\[56\]](#).

A.2 Diffusion

As the electrons are scattered on the gas molecules, their direction of motion can deviate isotropically in all directions resulting in a Gaussian density distribution:

$$n = \left(\frac{1}{\sqrt{4\pi Dt}} \right)^3 \cdot \exp \left(\frac{-r^2}{4Dt} \right) \quad (\text{A.6})$$

where $r = x^2 + y^2 + (z - ut)^2$.

D is the diffusion coefficient of the distribution and can be related to the drift variables by means of a microscopic analysis.

Let $\hat{x}$ be the direction for which I'm interested in the diffusion (Fig. A.2). Hence every movement l_i is projected on that axis as $x_i = l_i \cos(\theta_i)$ and I'm interested on the variance of the variable

$$X = \sum_{i=0}^{N_c} x_i \quad (\text{A.7})$$

The free mean path variable l_i follows an exponential distribution $g(l_i) = \frac{1}{l_0} e^{-l_i/l_0}$, with $l_0 = c\tau$, while $\cos(\theta_i)$ a uniform one. The variance can be evaluated by means of the following steps:

$$\begin{aligned} \langle X^2 \rangle &= \int \left(\sum_{i=0}^{N_c} x_i \right)^2 \prod_{k=0}^{N_c} \left(\frac{1}{l_0} e^{-l_k/l_0} dl_k \right) \left(\frac{1}{2} d\cos(\theta_k) \right) \\ &= N_c \left(\int_0^\infty l_k^2 \frac{1}{l_0} e^{-l_k/l_0} dl_k \right) \left(\int_{-1}^1 \frac{1}{2} \cos^2(\theta_k) d\cos(\theta_k) \right) \\ &= N_c \cdot \frac{1}{2} \cdot \frac{2}{3} \cdot 2l_0^2 = \frac{2t}{3\tau} l_0^2 \end{aligned} \quad (\text{A.8})$$

Note that only the terms proportional to l_k^2 have been considered because of the sign of the integral. In the final step, I have considered the relation $N_c = t/\tau$

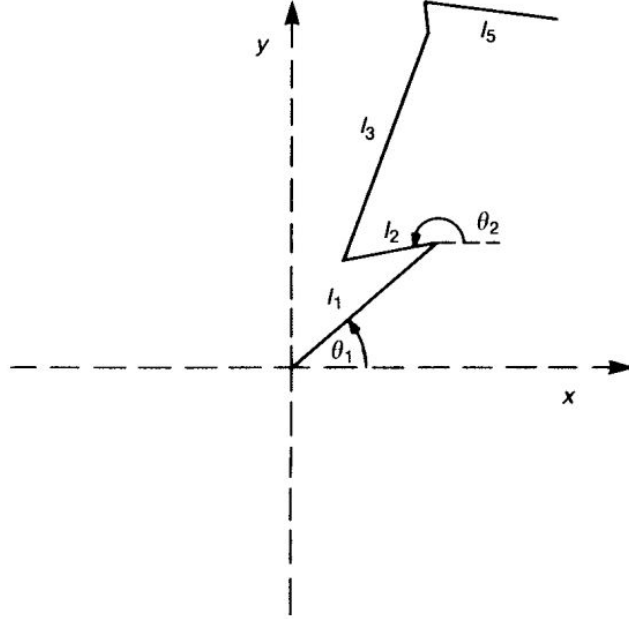


Figure A.2. Path of an electron in a drift chamber with the reference frame adopted in section. For each step the angle of scattering and the length of the segment is indicated

The part of the variance proportional to $2t$ is the diffusion coefficient

$$D = \frac{l_0^2}{3\tau} = \frac{2\epsilon}{3m} \tau \quad (\text{A.9})$$

To summarize, the diffusion width $\sigma_x = \sqrt{\langle X^2 \rangle}$ of an electron cloud which has travelled for a time t (or over a distance L) has the form

$$\sigma_x = \sqrt{\sigma_0^2 + 2Dt} = \sqrt{\sigma_0^2 + \frac{2D}{u}L} = \sqrt{\sigma_0^2 + f^2L} \quad (\text{A.10})$$

where σ_0 is the initial width of the electronic cloud¹. The factor f is introduced because adopted as diffusion coefficient during the thesis, differently from what assumed until now.

I conclude the section highlighting the adopted assumption of an isotropic diffusion writing down the formula A.6. In 1967, Wagner et al. [78] discovered an anisotropy: the diffusion coefficient has a tensorial structure with different values along the direction perpendicular to the drift field respect to the one parallel to it.

¹In a real life experiment σ_0 mostly refers to the spatial sensibility of the detector

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