

¹ Identification of nuclear recoils in a gas TPC with
² optical readout

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Abstract. The search for a novel technology able to detect and reconstruct nuclear recoil events in the keV energy range has become more and more important as long as vast regions of high mass WIMP-like Dark Matter candidate have been excluded. Gaseous Time Projection Chambers (TPC) with optical readout are very promising candidate combining the complete event information provided by the TPC technique to the high sensitivity and granularity of last generation scientific light sensors. A TPC with an amplification at the anode obtained with Gas Electron Multipliers (GEM) was tested at the Laboratori Nazionali di Frascati. Photons and neutrons from radioactive sources were employed to induce recoiling nuclei and electrons with kinetic energy in the range from 1 to few tens of keV. A He-CF₄ (60/40) gas mixture was used and the light produced during the multiplication in the GEM channels was acquired by a high position resolution and low noise scientific CMOS camera and a photomultiplier. A multi-stage pattern recognition algorithm based on an advanced clustering technique is presented here. A number of cluster shape observables are used to identify nuclear

41 recoils induced by neutrons originated from a AmBe source against X-ray ^{55}Fe photo-
 42 electrons. An efficiency of 18% to detect nuclear recoils with a 96% ^{55}Fe photo-electrons
 43 suppression with an energy of 5.6 keV is obtained. This makes this optically readout
 44 gas TPC a very promising candidate for future investigations of ultra-rare events as
 45 directional direct Dark Matter searches.

46 1. Introduction

47 The advent of a market of high position resolution and single photon light sensors can
 48 open new opportunity to investigate ultra-low rate phenomena as Dark Matter (DM)
 49 particle scattering on nuclei in a gaseous target.

50 The nature of DM is still one of the key issues to understand our Universe [1, 2].
 51 Different models predicts the existence of neutral particles with a mass of GeV or higher
 52 that would fill our Galaxy. They could interact with the nuclei present in ordinary
 53 matter producing highly ionizing nuclear recoils but with a kinetic energy as small
 54 as few keV. Moreover, given the motion of the Sun in the Milky Way towards the
 55 Cygnus constellation such nuclear recoils would exhibit a dipole angular distribution in
 56 a terrestrial detector. In this paper the use of a scientific CMOS camera to capture
 57 the light emitted by Gas Electron Multipliers (GEMs) in a Time Projection Chamber
 58 (TPC) device is described. The GEMs are located in the TPC gas volume at the anode
 59 position and are used to convert the ionization produced in the gas by the nuclear recoils
 60 into flashes of visible light. The emitted light and its spatial distribution is located in the
 61 detector geometry by using a clustering algorithm. Neutron and γ radiation emitted by
 62 radioactive sources are used to set in motion atomic electrons and nuclei, respectively, in
 63 the gas volume. Moreover, natural radiation as cosmic rays is leaving a trail of ionization
 64 in the gas.

65 All types of interactions produce distinctive patterns of light emission from the
 66 GEMs that can be reconstructed and analyzed. Therefore, nuclear recoils can be
 67 efficiently identified and separated from different kinds of background down to a few keV
 68 kinetic energy. The study of the optical readout of a TPC has been recently conducted
 69 with several small size prototypes (NITEC [3], ORANGE [4, 5], LEMON [6–8]) with
 70 various particle sources, in the context of the CYGNO project. In the following, the
 71 study of nuclear recoils excited by neutrons from an AmBe source and electron recoils
 72 from a ^{55}Fe source in the gas volume of the LEMON prototype is presented.

73 2. Experimental layout

74 A 7 liter active sensitive volume TPC (named LEMON) was employed to detect the
 75 particle recoils. A sketch (not to scale) of the detector setup is shown in Fig. 1 (left),
 76 while an image of the detector in the experimental area is shown in Fig. 1 (right). The
 77 sensitive volume where the ionization electrons are drifting features a $200 \times 240 \text{ mm}^2$
 78 elliptical field cage with a 200 mm distance between the anode and the cathode. The

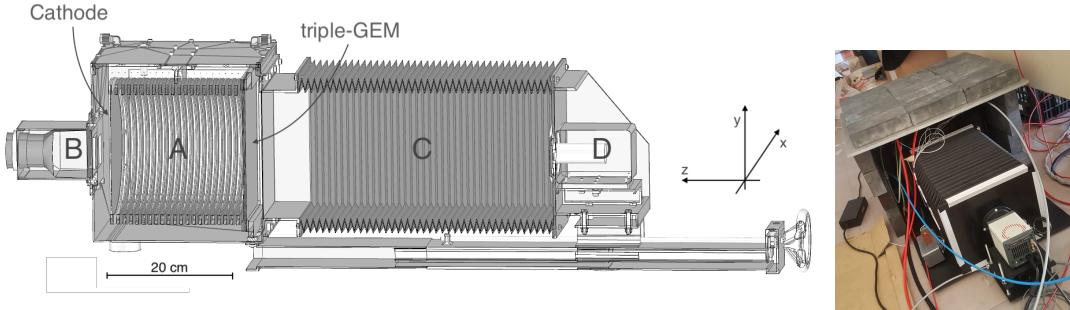


Figure 1. Left: the LEMON prototype with its 7 liter sensitive volume (A), the PMT (B), the adjustable bellow (C) and the sCMOS camera with its lens (D). Right: LEMON with the lead shield around the drift volume cage. The sCMOS camera (on the front) is looking at the GEMs through a blackened bellow.

79 anode side is instrumented with a $200 \times 240 \text{ mm}^2$ rectangular triple GEM structure.
 80 Standard LHCb-like [9] GEMs ($70 \mu\text{m}$ diameter holes and $140 \mu\text{m}$ pitch) were used with
 81 two 2 mm wide transfer gaps between them. The light emitted from the GEMs is
 82 detected with an ORCA-Flash 4.0 camera [10] through a $203 \times 254 \times 1 \text{ mm}^3$ transparent
 83 window and a bellow of adjustable length. This camera is positioned at a 52 cm distance
 84 from the outermost GEM layer and is based on a sCMOS sensor with high granularity
 85 (2048×2048 pixels), very low noise (around two photons per pixel), high sensitivity
 86 (70% quantum efficiency at 600 nm) and good linearity. This camera is instrumented
 87 with a Schneider lens (with an aperture $f/0.95$ and a focal length of 25 mm). The lens is
 88 placed at a distance $d = 50.6 \text{ cm}$ from the last GEM in order to obtain a de-magnification
 89 $\Delta = (d/f) - 1 = 19.25$ to image a surface $25.6 \times 25.6 \text{ cm}^2$ onto the $1.33 \times 1.33 \text{ cm}^2$ sensor.
 90 In this configuration, each pixel is therefore imaging an effective area of $125 \times 125 \mu\text{m}^2$
 91 of the GEM layer. The fraction of the light collected by the lens is evaluated [11] to be
 92 1.7×10^{-4} . A semi-transparent mesh was used as a cathode in order to collect light on
 93 that side also with a $50 \times 50 \text{ mm}^2$ *HZC Photonics XP3392* photomultiplier [12] (PMT)
 94 detecting light through a transparent $50 \times 50 \times 4 \text{ mm}^3$ fused silica window. More details
 95 can be found in Ref. [13].

96 A 5 cm thick lead shielding was mounted around the LEMON field cage to reduce
 97 the environmental natural radioactivity background. From the measurements of the
 98 GEM current with and without the lead shielding, a factor two reduction in the total
 99 ionization within the sensitive volume, very likely due to environmental radioactivity,
 100 was estimated.

101 3. Particle images in LEMON gas volume

102 The LEMON detector was operated in an overground location at Laboratori Nazionali
 103 di Frascati (LNF) with a He-CF₄ (60/40) gas mixture, the triple GEM system set at
 104 a voltage across the GEM sides of 460 V and an electric field between the GEM layers
 105 of 2.5 kV/cm . A six independent HV channels *CAEN A1257* module ensured stability

and monitored the bias currents with a precision of 20 nA. The gas mixture was kept at atmospheric pressure under continuous flow of about 200 cc/min and with the GEMs operated at 2.0×10^6 gain. The typical photon yield for this type of gas mixtures has been measured to be around 0.07 photons per avalanche electron [11, 14, 15]. The field cage was powered by a *CAEN N1570* [16], generating an electric field of 0.5 kV/cm.

The motion of particles within the gas mixtures was studied by means of different simulation tools. In particular, GARFIELD [17, 18] program was used to evaluate the transport properties for ionization electrons in the sensitive volume for an electric field of 500 V/cm.

Given the diffusion in the gas, ionization electrons produced at a distance z from the GEM will distribute over a region on the GEM surface, having a Gaussian transverse profile with a σ given by:

$$\sigma = \sqrt{\sigma_0^2 + D^2 \cdot z}, \quad (1)$$

where D is the transverse diffusion coefficient, calculated to be $140 \mu\text{m}/\sqrt{\text{cm}}$. The value of σ_0^2 was measured to be about $300 \mu\text{m}$ [19, 20]. Therefore, in average, a point-like ionization will result in a spot of 3–4 mm².

The expected effective ranges of electron and He-nucleus recoils were evaluated respectively with GEANT4 [21] and with SRIM [22] simulation programs. The recoil range estimated from simulation, as a function of the impinging particle kinetic energy, is shown in Fig. 2. These results show that:

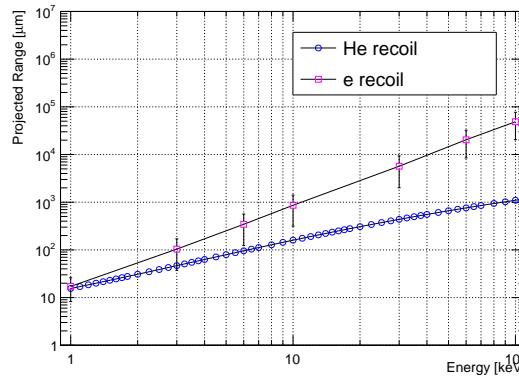


Figure 2. Average ranges for electron and He-nucleus recoils as a function of their kinetic energy. Range proiettato sulla direzione iniziale della traccia (parallela al piano delle GEM). Poco significativo. Spero che Giulia faccia un plot sul range 3D

- He-nuclei recoils have a sub-millimetre range up to energies of 100 keV and are thus expected to produce bright spots with sizes mainly dominated by diffusion;
- low energy (less than 10 keV) electron recoils are in general longer than He-nucleus recoils with same energy and are expected to produce less intense spot-like signals. For a kinetic energy of 10 keV, the electron range becomes longer than 1 mm and for few tens of keV, tracks of few cm are expected.

132 The sCMOS sensor was operated in continuous mode with a global exposure time
 133 of 30 ms. Typical images are shown in Fig. 3.

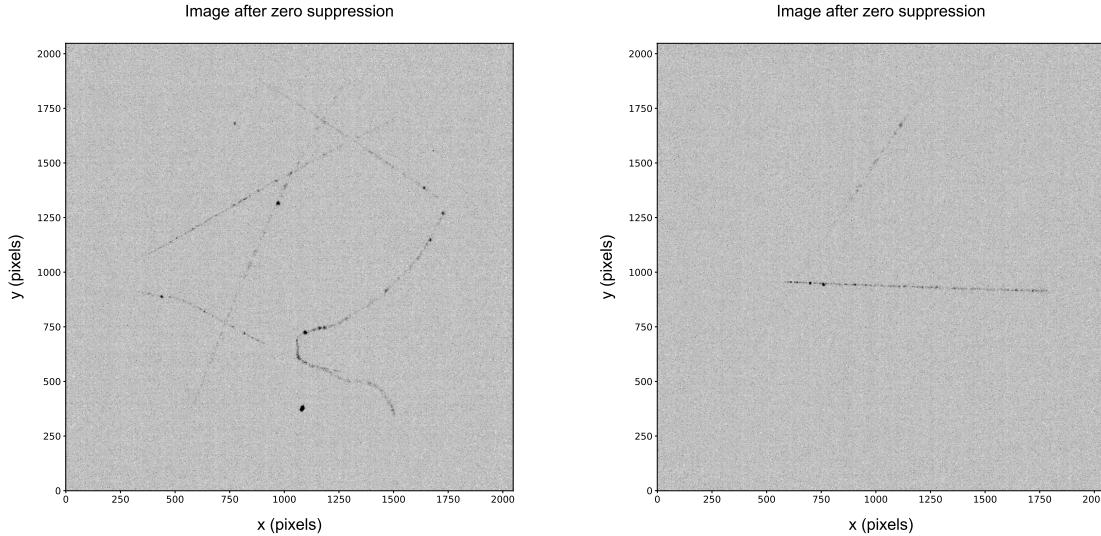


Figure 3. Two typical pictures taken with the sCMOS camera with a 30 ms exposure time. Left: cosmic tracks and natural radioactivity signals are present. Right: two long cosmic rays tracks are present, observed in a data taking run without any artificial source.

134 The PMT waveform was sent to a digitizer board with a sampling frequency of
 135 4 GS/s. The experiment trigger scheme is based on the PMT signal: if, during the
 136 exposure time window, this exhibits a peak exceeding a threshold of 80 mV, it is acquired
 137 in a time window of 25 μ s and the corresponding sCMOS image is stored. The digitizer
 138 is operated in single-event mode. No more than one signal is recorded in each sCMOS
 139 exposure time. Therefore, the PMT information was mainly exploited to select events
 140 with a cosmic ray track.

141 Several light spots are visible with different ionization patterns due to different
 142 types of particles interacting in the gas. Figure 3 (left) shows an image with typical
 143 long tracks from cosmic rays traveling through the full gas volume, where clusters of
 144 light with larger energy deposition are clearly visible, superimposed to radioactivity
 145 events likely due to natural origin. Figure 3 (right) shows an example of a cleaner event
 146 with one straight cosmic ray track, that can be used for energy calibration purposes.

147 Two different artificial radioactive sources were employed for testing and studying
 148 the detector responses.

149 A **neutron** source, based on a 3.5×10^3 MBq activity ^{241}Am source contained in a
 150 Beryllium capsule (AmBe) was placed at a distance of 50 cm from the sensitive volume
 151 side. Because of the interactions between α particles produced by the ^{241}Am and the
 152 Beryllium nuclei, the AmBe source isotropically emits:

- 153 • photons with an energy of 59 keV produced by ^{241}Am ;
 154 • neutrons with a kinetic energy mainly in a range 1–10 MeV
 155 • photons with an energy of 4.4 MeV produced along with neutrons in the interaction
 156 between α and Be nucleus.

157 The presence of a lead shield around the sensitive volume absorbed almost completely
 158 the 59 keV photon component. A small fraction of them reached the gas through small
 159 gaps accidentally present between the lead bricks.

160 A ^{55}Fe source emitting **X-rays** with a main energy peak at 5.9 keV. This is the
 161 standard candle for calibration and performance evaluation of LEMON, and its extensive
 162 use is documented in Ref. [23].

163 The events in Fig. 4 show images recorded with the same 30 ms exposure time,
 164 in presence of the two sources. The left panel shows an example of several light spots,
 165 characteristic of energy deposits due to ^{55}Fe low energy photons. The right panel shows
 166 a frame recorded in presence of the AmBe radioactive source: the short and bright
 167 track well visible in the center is very likely due to a nuclear recoil induced by a neutron
 scattering.

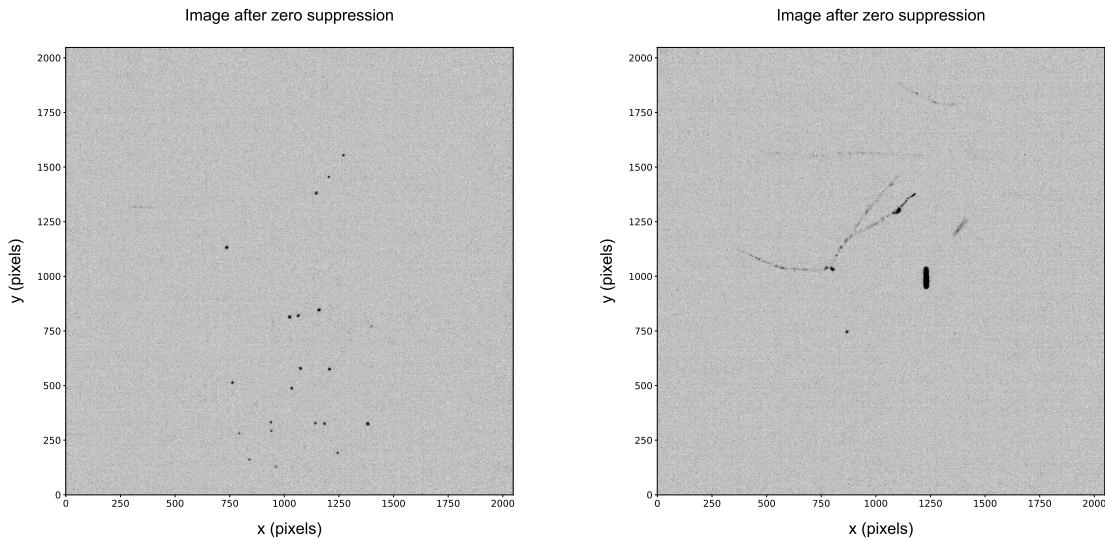


Figure 4. Two pictures taken with the sCMOS camera with a 30 ms exposure time. Left: picture taken in presence of ^{55}Fe radioactive source. Right: a nuclear recoil candidate is present, in an image with AmBe radioactive source, together with signals from natural radioactivity.

¹⁶⁹ **4. Cluster pattern recognition**

¹⁷⁰ The light produced in the multiplication process in the GEM and detected by the sCMOS
¹⁷¹ sensor is associated in clusters of neighboring pixels. This is done by following the trail
¹⁷² of energy deposition of the particle traveling through the gas of the sensitive volume.
¹⁷³ The deposited energy (that for stopped particles is equivalent to the total energy of the
¹⁷⁴ particle) is estimated by the amount of the light collected by the sensor. Therefore, it is
¹⁷⁵ of primary importance to have a reconstruction algorithm that includes all the camera
¹⁷⁶ pixels hit by the real photons originating from the energy deposits, while rejecting most
¹⁷⁷ of the electronic noise. This can either create fake clusters or, more likely, add pixels in
¹⁷⁸ the periphery of clusters of real photons, biasing the energy estimate.

¹⁷⁹ The energy reconstruction follows a three-steps procedure: the single-pixel noise
¹⁸⁰ suppression is briefly described in Section 4.1. This is followed by the proper clustering:
¹⁸¹ first the algorithm to form basic clusters from single small deposits is described in
¹⁸² Section 4.2, then the supercluster method, aiming to follow the full track pattern, and
¹⁸³ seeded by the basic clusters, is described in Section 4.3.

¹⁸⁴ The results of this paper are based on the properties of the reconstructed
¹⁸⁵ superclusters and are described in Section 5.

¹⁸⁶ *4.1. Noise suppression*

¹⁸⁷ The electronic noise of the sensor was estimated in data-taking runs acquired with the
¹⁸⁸ sensor in complete dark (*pedestal* runs). For each pixel, the pedestal was computed as
¹⁸⁹ the average of the counts over many frames, while the electronic noise was estimated as
¹⁹⁰ their standard deviation (SD). The distribution of the pixels SD is shown in Fig. 5. The
¹⁹¹ mode of this distribution is about 1.8 photons per pixels, but a tail is present, with pixels
¹⁹² having a noise of more than 5 photons per pixels. For such pixels, a very non-Gaussian
¹⁹³ distribution was observed, while for the pixels in the bulk of the distribution, the
¹⁹⁴ pedestal distribution followed a Gaussian shape. To form the pedestal-subtracted image,
¹⁹⁵ the pedestal mean μ_i was subtracted to the image for each i^{th} pixel. An initial noise
¹⁹⁶ suppression was applied by neglecting the pixels with counts less than $1.3 \times \text{SD}_i$. On such
¹⁹⁷ pedestal-subtracted zero-suppressed images an upper threshold was applied to reject hot
¹⁹⁸ pixels, which are more likely due to sensor instabilities than to energy deposition. These
¹⁹⁹ were found to be not malfunctioning pixels since they disappeared after a power cycle
²⁰⁰ of the camera: therefore a dynamic (run-by-run) suppression was needed. They were
²⁰¹ efficiently identified as high-intensity, isolated pixels, and distinguished by a true energy
²⁰² deposit, for which each pixel is surrounded by some other active pixels. A threshold
²⁰³ was applied on the ratio R_9 between the pixel and the average of the counts in a 3×3
²⁰⁴ pixels matrix surrounding it, and a minimum number of two pixels above noise in that
²⁰⁵ matrix was required to discriminate good from hot pixels.

²⁰⁶ The resolution of the resulting image was then reduced by forming *macro-pixels*, by
²⁰⁷ averaging the counts in 4×4 pixel matrices. This was needed to reduce the combinatorics
²⁰⁸ of the subsequent clustering algorithm to be executed in a reasonable time for each

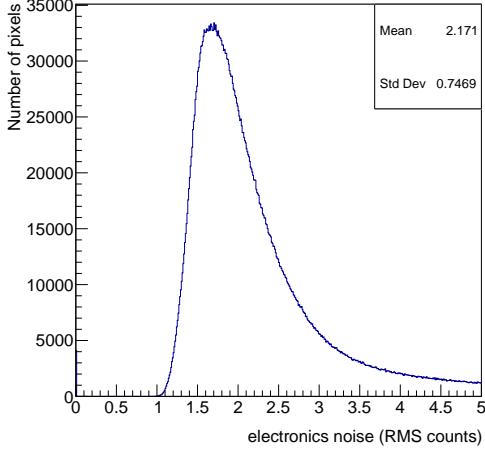


Figure 5. Distribution of the electronic noise of the sensor, estimated in images taken with sensor in complete dark, and evaluated as the SD of the distribution of the counts for each pixel.

209 image. On such 512×512 pixel map, a median filtering [24] was applied, as described in
 210 more details in Ref. [25]. The output image is passed to the basic clustering algorithm,
 211 described in the following.

212 *4.2. Basic clusters reconstruction*

213 The basic clustering algorithm, called IDBSCAN and described in details in Ref. [26],
 214 represents an evolution of the neighboring pixels clusters, called NNC, previously used
 215 to study the performances of the LEMON detector with ^{55}Fe radioactive source [23].
 216 It is briefly described also here, since it represents the seeding for the final clustering
 217 algorithm.

218 The energy deposition in the sensitive volume of the TPC was estimated from
 219 the two-dimensional (2D) projection on the $x-y$ axes of the light emitted in the
 220 multiplication process within the GEMs planes. The pattern showed a large variation,
 221 depending on the interacting particle. For events of ^{55}Fe calibration source, the signature
 222 of the typical 5.9 keV photons was a spot of few mm^2 with the exact size depending on the
 223 diffusion in the gas, i.e., on the distance from the anode along z of the energy deposition
 224 (see Fig. 4 left). Cosmic rays travel across the volume and leave a typical signature of
 225 a straight track, shown in Fig. 3 (right), but with several agglomerations with larger
 226 density along the path. Finally, natural radioactivity and the signal from nuclear recoils
 227 due to neutrons originated by the AmBe source showed an irregular pattern, sometimes
 228 curly, with several kinks along the path. Their track length and their size was found to
 229 depend a lot on the initial energy of the impinging neutron, and also on the mass of the
 230 recoiling nucleus.

231 Thus, the clustering algorithm needs to be flexible enough to efficiently reconstruct

a diverse set of patterns, from small round spots to long and kinky tracks. A first step of the clustering, called *seeding*, was used: it focused in the clustering of spot-like neighboring pixels. The method applied for the LEMON detector is an evolution of the classic DBSCAN algorithm [27]. This is a non-parametric, density-based clustering, which groups together pixels above threshold with many neighbors. Its distinctive characteristics making this method very suitable to the LEMON case is its ability to label as outliers, and so not to include in the clusters, pixels that lie isolated in low-density regions, i.e., pixels from electronic noise of the sensor surviving the zero suppression. The extension of DBSCAN used for LEMON data analysis consists in a larger phase space for the points that includes not only the $x-y$ plane, but also the number of photons in each pixel N_{ph} (i.e., the light intensity measured in each pixel).

To be as inclusive as possible, and since different interactions may have vastly different intensities, even varying along the track, the clustering procedure was iterated three times. First, the DBSCAN parameters were tuned to form clusters of dense (in $x-y$ dimension) and intense (in the N_{ph} dimension) pixels. The density in 3D was called *sparsity*. This step typically identifies either rare hot spots of the GEMs, or, efficiently, short nuclear recoils. The pixels belonging to the reconstructed clusters were then removed from the image, and the DBSCAN procedure was repeated, with looser sparsity parameters. The second iteration was tuned to efficiently reconstruct ^{55}Fe round spots and slices of tracks from nuclear recoils with lower intensity. It also collected the agglomerations with larger density along cosmic tracks, clearly visible in the example in Fig. 3 (right). A third iteration of DBSCAN with even looser parameters was finally executed, targeting faint portions of a cluster. These were especially used as a proxy for the characterization of clustered noisy pixels.

To be computationally viable, the IDBSCAN basic clustering was performed on the image with reduced resolution, 512×512 . In typical images this allows the basic clusters reconstruction to be run in approximately 1 s on an *Intel Xeon E5-2620 2.00 GHz* and 64 GB RAM. The reconstruction algorithm is implemented in PYTHON3 [28], and interfaced with the CERN ROOT6 v.6 [29].

Examples of clustered pixels in two cases are shown in Fig. 6. The left panel shows an example of clusters reconstructed on the low-resolution image of one event with ^{55}Fe source. Three spots are clearly visible: one, as typical for events with this calibration source with a moderate activity, is reconstructed by a single cluster of the second iteration. The other two are close enough that are merged in a single cluster of the same iteration. The right panel shows the outcome of the IDBSCAN algorithm on a longer track presumably from natural radioactivity and one possible short nuclear recoil. The nuclear recoil candidate is very dense, high-energetic, and isolated, and it is reconstructed as a single cluster in the first iteration. The long track shows several clusters with higher intensity. One of them has a large energy, and it is reconstructed as an isolated single iteration-1 cluster. The rest of the track is reconstructed by multiple iteration-2 clusters, which are split where the energy deposition has a minimum for too many pixels to be joined together in the same clusters. Events like these, which

274 are frequent for cosmic rays, natural radioactivity, but also signals from nuclear recoils
 275 with higher energy, justify the need of the subsequent step of the *superclustering*, which
 276 follows the track pattern without splitting it in parts. This is described in the following
 section.

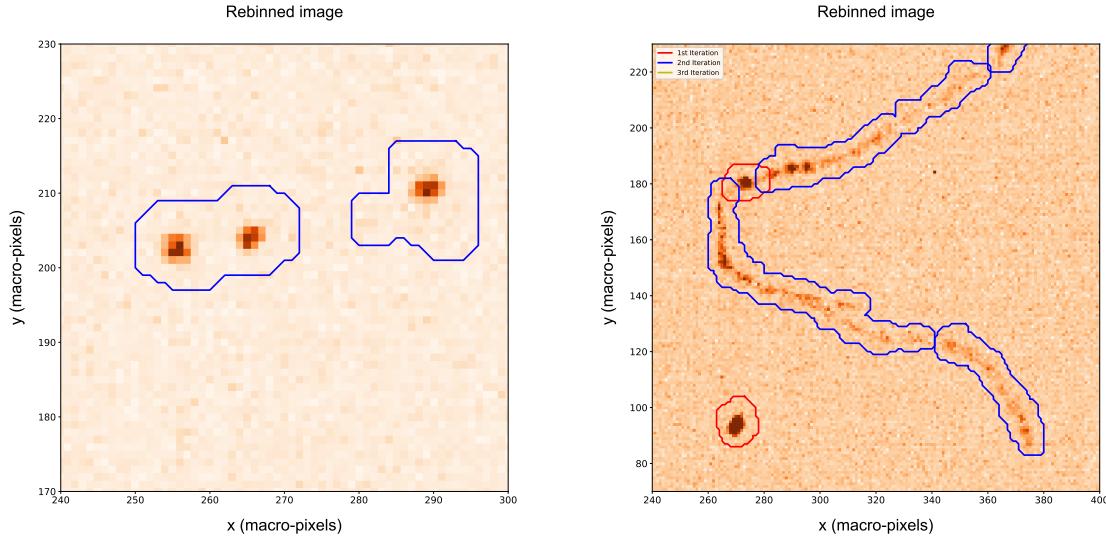


Figure 6. Basic clusters reconstructed with the IDBSCAN algorithm in the low resolution (512×512) image for two example events with very different patterns. Left: clusters on spots from ^{55}Fe source, two of which are merged together. Right: Track from natural radioactivity and a nuclear recoil candidate in an event with AmBe source. The long track is split in several basic clusters of different IDBSCAN iteration.

277

278 4.3. Superclusters reconstruction

279 The aim of the superclustering procedure is to collect the majority of the pixels belonging
 280 to a track which is long and, eventually, with an irregular pattern. The main limitation
 281 of IDBSCAN to follow a long track is mainly originated by the non uniform energy
 282 deposition along the path length. As can be clearly seen in Fig. 6 (right), or even in
 283 the example of a raw image of an event with two long cosmic rays in Fig. 3 (right),
 284 clusters with larger energy release are followed by regions along the path with a lower or
 285 even a zero release. These local minima are sometimes as large, in the 2D space, as the
 286 typical size of the ϵ parameter of DBSCAN [27]. Despite the low electronic noise of the
 287 ORCA-Flash 4.0 camera sensor, the energy releases in these local minima are similar
 288 in magnitude to the average single-pixel noise. The IDBSCAN is limited in connecting
 289 the full length of an extended path, because of two reasons. First, inflating ϵ parameter
 290 as much as needed to cover the areas of local minima conflicts with the need to reject
 291 noise around the cluster. The IDBSCAN parameters were optimized for the LEMON
 292 running conditions to collect most of the signals of $E \approx 5$ keV and to reject the typical
 293 noise of ≈ 1 photon per pixel. This avoids collecting extra noise in the cluster, biasing

the energy scale and worsening its resolution, and keeps the rate of fake clusters at a negligible level. This is studied in great detail in Ref. [26]. Second, the iterative nature of the algorithm with very different parameters for each iteration, each tuned for very different intensity, makes it convenient and efficient for a deposition of a fixed energy density (like the spots originating from the ^{55}Fe source), but not for the cases as in Fig. 6 (right), where the same track is split in several parts, with some of them in different iterations. This requires a method that can continuously follow the pattern of the track, profiting of the full resolution image, where the *gradients* of the energy deposition along the track trajectory are smaller than the ones in the transverse direction. Moreover, executing any of the most common clustering methods on the full 1024×1024 image is not manageable CPU-wise, due to the huge pixel combinatorics.

The procedure adopted for the final supercluster reconstruction in the LEMON detector started from defining the *interesting regions* in the image that may contain pixels from an energy deposit. These are identified by the basic cluster algorithm IDBSCAN previously described, which is applied on the 512×512 reduced-resolution image. In order to gather the peripheral pixels, especially along the track trajectory where breaks into small basic clusters may have happened, a window of 5×5 pixels is considered, around each pixel belonging to a macro-pixel clustered in a basic cluster. A full resolution image formed only by the interesting pixels passing the simple initial filtering described in Sec. 4.1 was created. The gradients of the intensity N_{ph} in such image were computed pixel-by-pixel to look for the edge region where the image turns from signal to noise-only:

$$||\nabla(N_{ph})|| = \sqrt{\left(\frac{\partial N_{ph}}{\partial x}\right)^2 + \left(\frac{\partial N_{ph}}{\partial y}\right)^2}, \quad (2)$$

while the gradient direction is given by:

$$\theta = \tan^{-1} \left(\frac{\partial N_{ph}}{\partial y} / \frac{\partial N_{ph}}{\partial x} \right). \quad (3)$$

In order to reduce the effect of the noise which makes the first derivatives in Eq. 2 to fluctuate, a Gaussian filter is applied, with a 5σ threshold, where σ is the SD of the intensities of the pixels considered.

The superclustering algorithm, applied on the filtered image, is an application of the *morphological geodesic active contours* [30,31], called GAC in the following. This method uses an active contour finding, widely used in computer vision, where the boundary curve \mathcal{C} of an object is detected by minimizing the *energy* E associated to \mathcal{C} :

$$E(\mathcal{C}) = \int_0^1 g(N_{ph})(\mathcal{C}(p)) \cdot |\mathcal{C}_p| dp, \quad (4)$$

where $ds = |\mathcal{C}_p| dp$ is the arc-length parameterization of the curve in the 2D space, and g is the stopping edge function, which allows to select the boundary of the cluster. In the GAC method used for the LEMON images, the g function is purely geometrical, and

uses the geodesics of the image, i.e., the local minimal distance path between points with the same gradient, defined before. The function $g(N_{ph})$ is given by:

$$g(N_{ph}) = \frac{1}{\sqrt{1 + \alpha |\nabla G_\sigma * N_{ph}|}}, \quad (5)$$

which is minimal in the edges of the image. The $G_\sigma * N_{ph}$ is the aforementioned 5σ Gaussian filter, and the parameter α , which regulates the strength of the filtering was tuned on typical LEMON images to be $\alpha = 100$.

This method was chosen because it allows to follow track patterns that may vary from convex to concave shape, eventually with kinks, e.g. in cases of δ -ray emissions. To improve the shrinking of the cluster boundary in the cases of tracks turning from concave to convex along their trail, the *balloon* force [31] is set to -1, in order to push the contour towards a border in the areas where the gradient is too small. A number of 300 iterations is used to evolve the supercluster contour.

The example track shown in Fig. 6 (right) after the basic clustering step, is shown again in full resolution, zoomed around the cluster, in Fig. 7 (left). The output of the superclustering with the GAC algorithm is shown on the right panel of the same figure. The splitting of the clustering, present after the basic cluster step, was recovered. The portions with high density and low density along the path of the energy deposition were joined together. Other three examples of superclustered images are shown in Fig. 8, in runs without any artificial radioactive source. The top left panel shows an example of a cosmic ray track fully reconstructed by the GAC superclustering, which also includes a δ -ray in the middle of the track length. The top right panel shows an example of curly track from a candidate of natural radioactivity interaction; bottom panel shows an example where both a cosmic ray and a curly track are present. In this case, the extremes of the long and straight track are still split, but this is much rarer than after the basic clustering, and it happens when the local minimal along the trajectories are compatible with noise-only for more than ≈ 1 cm.

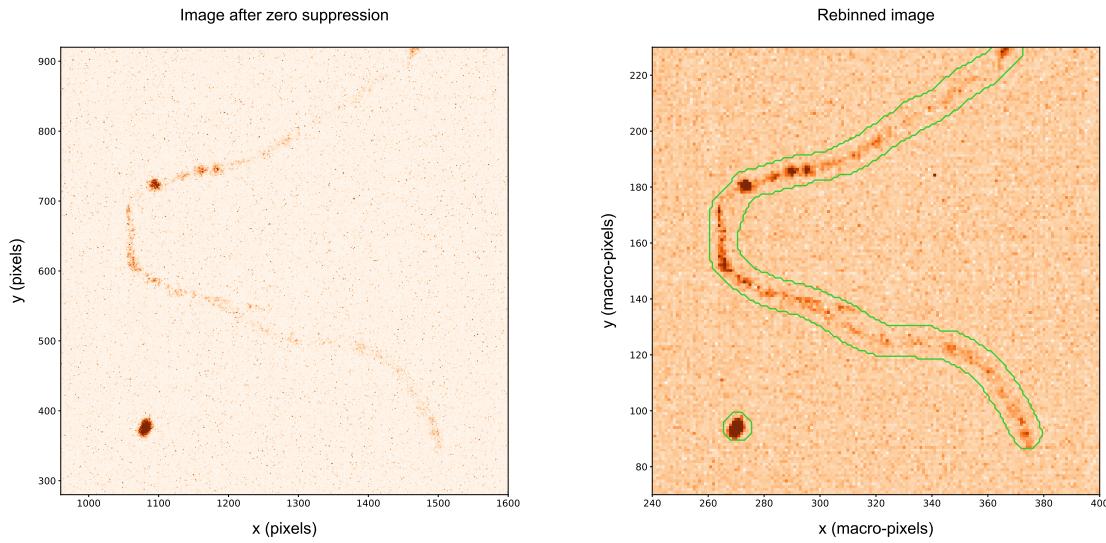


Figure 7. Left: zoom on the full-resolution image of a track candidate in a run with the AmBe radioactive source. Right: output of the superclustering on the rebinned image.

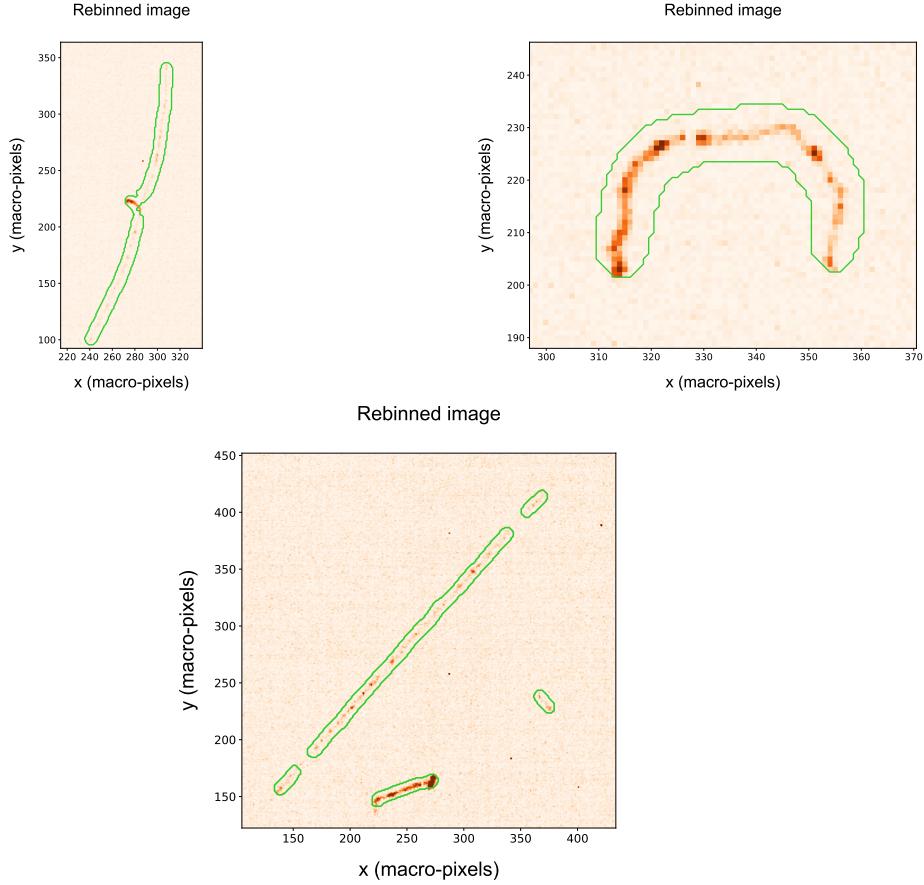


Figure 8. Superclusters reconstructed in a run without artificial radioactive sources. Top left: cosmic ray track fully reconstructed by the GAC superclustering. A δ -ray is included in the supercluster. Top right: curly track from a candidate of natural radioactivity interaction. Bottom: a cosmic ray with the extremes not joined to the main track, plus a curly track from natural radioactivity.

356 *4.4. Superclusters calibration*

357 The containment of the energy in the supercluster was verified with simulations
 358 performed with SRIM [22] of nuclear and electron recoils within the gas mixture of
 359 the LEMON detector. For both types of recoils, for the energy range of interest for
 360 DM search, e.g. $E < 10$ keV, when considering deposits without electronics noise and
 361 no diffusion in the gas, the peak of the $|E - E_{true}|/E_{true}$ is within 5%. Adding a
 362 Gaussian noise distribution with a mean equal to the one observed in the pedestal
 363 runs, and a diffusion following the parameterization in Eq. 1, the fraction of the true
 364 energy contained in the supercluster decreases to about 80%, as shown in Fig. 9. The
 365 distributions were obtained for nuclear recoils with $E = 6$ keV generated at the exact
 366 center of the LEMON detector. The mean and the Gaussian width of the peak are
 367 estimated by fitting the distributions with a Crystal Ball shape [32, 33], which includes
 368 a tail to consider a non-Gaussian asymmetric tail due to partial containment in the
 369 supercluster.

370 The decrease in the energy containment in the supercluster is due to the smearing
 371 of the 2D track pattern around the periphery of the cluster. This decreases the gradients
 372 in Eq. 2 around the edges, and so the supercluster can shrink more around the crest,
 373 loosing part of the tails that can be confused more easily with the noise. A more realistic
 374 noise description, and an improved diffusion model, based on the one measured in data
 375 is necessary to tune the supercluster parameters in simulation to recover part of the
 376 containment. Despite this, the resolution in presence of noise and diffusion is estimated
 377 in this simulated nuclear recoils with $E = 6$ keV to be around 4%. This energy resolution
 378 is expected to be very optimistic because the absence, in the simulation, of the dominant
 379 fluctuations of the GEM gain.

380 The absolute energy scale was then calibrated with the energy distribution measured
 381 in data with the ^{55}Fe source, which provides monochromatic photons of 5.9 keV, with
 382 the procedure described in Ref. [23]. The supercluster integral is defined as:

$$383 \quad I_{SC} = \sum_i^{cluster} N_i, \quad (6)$$

384 where N_i is the number of counts (photons) in the i^{th} pixel, and the sum runs over all
 385 the pixels of the supercluster. While to perform the basic- and super-clustering only
 386 pixels passing the zero suppression are considered, for the energy estimate in Eq. 6 all
 387 the pixels within the cluster contours are counted, eventually having negative N_i , after
 388 the pedestal subtraction. This is done to avoid a bias on the energy estimate. The
 389 distribution of I_{SC} , for a run taken in presence of ^{55}Fe source, is shown in Fig. 10. The
 390 position of the maximum in the single-spot distribution in runs with ^{55}Fe source allowed
 391 to calibrate the absolute energy scale of the LEMON detector. The energy resolution
 392 for the reconstructed GAC superclusters is about 18%, similar to the one that can be
 393 obtained with only the basic clustering step with IDBSCAN [26], and improving the one
 394 with the simple NNC algorithm previously used [23]. This value is still much larger
 395 than the one obtained with the simulation of nuclear recoils at the same energy, but an

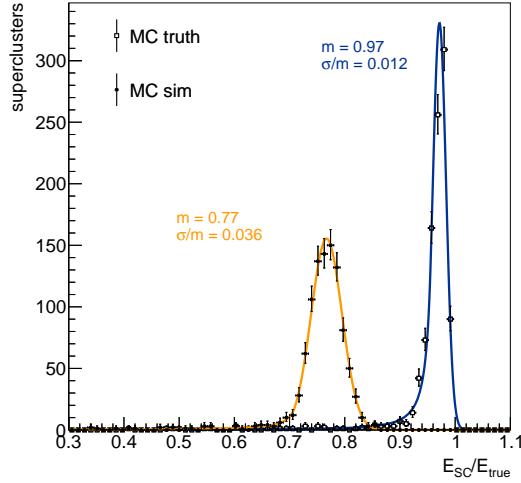


Figure 9. Distribution of the ratio of reconstructed supercluster energy, E , and the true energy of nuclear recoils $E_{true} = 6$ keV, generated in the center of LEMON and simulated with GEANT4 Monte Carlo (MC). The hollow points show the MC events generated without electronics noise and diffusion in the gas, while the filled circles represent MC events with both effects included. The curves represent parametric fits with a Crystal Ball function.

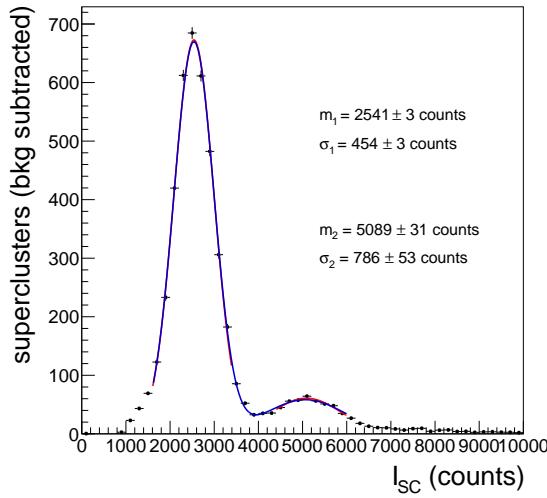


Figure 10. Distribution of the supercluster integral, before the absolute energy scale calibration is applied, in events with the ^{55}Fe source. Clearly visible is the large peak of a single spot, and, at around twice the energy, a broader peak for the case of two neighboring spots merged in a single supercluster.

396 improved noise and gas diffusion model, and a simulation of the gas gain fluctuations
 397 are needed to improve the data-MC agreement.

Using runs with this monochromatic, high rate source, positioned at different distances from the GEM planes, a decrease of the light response for lower distances from the GEM was observed. This effect is opposite to the expected behavior of a decreasing light yield at larger distances. Indeed, it is expected that during the drift along the z -direction the ionization charge undergoes a diffusion in the TPC gas and some electrons are removed by attachment to the gas molecule. Consequently some loss in the light collection may be expected. The opposite behavior, instead, is clearly observed. While this effect is currently under study in more detail, it was attributed to a possible saturation effect of the GEMs, especially in the third stage of multiplication, for which the charge density in one GEM hole is maximal. Under this hypothesis, an effective, empirical correction was developed, which relies on the charge density of a cluster from a ^{55}Fe deposit. The light density, δ , is defined as:

$$\delta = I_{SC}/n_p, \quad (7)$$

where n_p is the number of pixels passing the zero-suppression threshold (differently from the numerator, where all the pixels in the supercluster are considered). This effective calibration provides the absolute energy of a spot-like region similar to the ^{55}Fe ones, as a function of the supercluster density, δ : $E = c(\delta) \cdot I_{SC}$. In the hypothesis of saturation, the *local* density along the track is the parameter which regulates the magnitude of the effect, thus the correction has to be applied dynamically for slices of the supercluster having a size similar to the ^{55}Fe spots. This is achieved with the procedure described in the following.

First, the supercluster *skeleton*, i.e., the 1 pixel wide representation along the energy deposition path, is reconstructed. This is performed with a morphological thinning of the superclusters with the iterative algorithm from Ref. [34,35]. Second, a pruning of the obtained skeleton is done, to remove residual branches along the main pattern, using a hit-or-miss transform. The output of the *skeletonization* for the track of Fig. 7 is shown in Fig. 11. For the calibration procedure, the skeleton was followed, starting from one of the two end points, and circles having their center on a pixel of the skeleton and their radius equal to the average spot size of the ^{55}Fe clusters were defined. The local density δ_s of the slice s is computed, and its integral I_s is calibrated to an absolute energy through the effective correction $E_s = c(\delta_s) \cdot I_s$. The pixels of the supercluster used for the slice calibration are removed (including the skeleton ones), and the procedure is iterated, until having included all the pixels. The sum of the energies of all the slices is the estimate of the calibrated energy of the supercluster:

$$E_{SC} = \sum_s^{slices} E_s \quad (8)$$

As a closure test of this procedure, the calibrated energy of the superclusters reconstructed in the runs with the ^{55}Fe source is obtained. The value of the energy peak was obtained by fitting the distribution with the same function used in Fig. 10, and equals to $m_1 = 5.93 \pm 0.01$ keV, compatible with the expected value. The calibration procedure is an overkill for the case of the small ^{55}Fe spots, but it is necessary for very

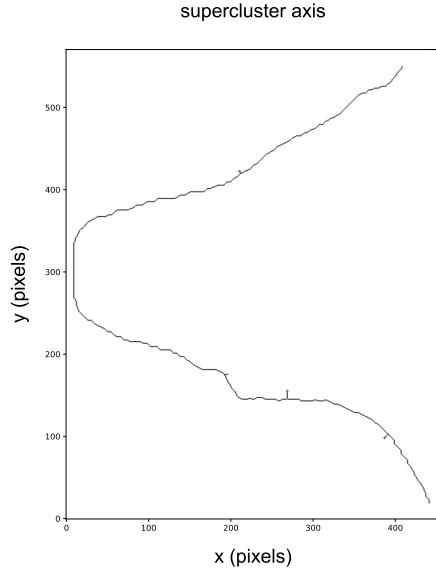


Figure 11. Output of the skeletonization and pruning of the branches for one example supercluster extended in space.

438 long cosmic ray tracks or even for medium-length superclusters from nuclear and electron
 439 recoils. The energy resolution worsen after the calibration ($\sigma_1 = 1.48 \pm 0.01$, i.e., 25%
 440 energy resolution), as a sign that the empiric correction is still suboptimal.

441 The skeletonization procedure provides a general method to estimate the track
 442 length (l_p), which is accurate both in the case of straight and curving track. In the
 443 case of straight tracks, the length extracted in this way coincides with the major axis
 444 estimated with a principal component analysis (PCA), described in the following section.
 445 For exactly round spots, the skeleton would collapse in the center of the cluster and the
 446 resulting length would be 1 pixel, but this completely symmetric case never happens in
 447 the considered samples.

448 5. Cluster shape observables

449 The interaction of different particles with the nuclei or the electrons in the gas of the
 450 TPC produce different patterns of the 2D projection of the initial 3D particle trajectory.
 451 These characteristics, to which we refer generically as “cluster shapes observables”, are
 452 useful to discriminate different ionizing particles. In particular, they were used to select
 453 a pure sample of nuclear recoil candidates produced by the interaction of the neutrons
 454 originating from the AmBe source and to identify various sources of backgrounds. The
 455 main cluster shape observables are described in the following:

- 456 • *projected length and width:* a singular value decomposition (SVD) on the $x \times y$
 457 matrix of the pixels belonging to the supercluster is performed. The eigenvectors
 458 found can be interpreted as the directions of the two axes of an ellipse in 2D. The

eigenvalues represent the magnitudes of its semiaxes: the major one is defined as *length*, l the minor one as *width*, w . These are well defined for elliptic clusters, or for long and straight tracks. The directions along the major and the minor axis are defined as *longitudinal* and *transverse* in the following. The longitudinal and transverse supercluster profiles, for the cosmic ray track candidates shown as an example in Fig. 8 (bottom) are shown in Fig. 12. The longitudinal profile shows the typical pattern of energy depositions in clusters, while the transverse profile, dominated by the diffusion in the gas, shows a Gaussian shape. It has to be noted that the cluster sizes represent only the projection of the 3D track in the TPC on the 2D $x-y$ plane;

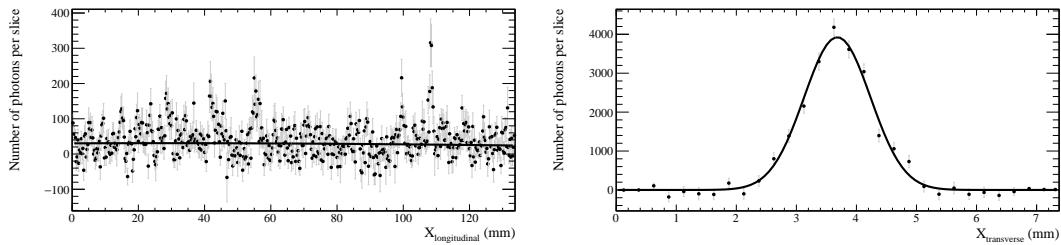


Figure 12. Supercluster profile in the longitudinal (top) or transverse (bottom) direction, for a long and straight cosmic ray track candidate shown in Fig. 8 (bottom). The longitudinal profile shows an energy deposition in sub-clusters, while the transverse direction shows the typical width of the diffusion in the gas. For the longitudinal profile, the line represent the average number of photons per slice. For the transverse profile, it represents a fit with a Gaussian PDF.

- *projected path length*: for curly and kinky tracks the values returned by the SVD of the supercluster are not an accurate estimates of their size. While the width is dominated by the diffusion, the length for patterns like the one shown in the example of Fig. 7 is ill-defined. In these cases, the path length, l_p , computed with the skeletonization procedure in Fig. 11 is used;
- *Gaussian width*: the original width of the track in the transverse direction is expected to be much lower than the observed width induced by the diffusion in the gas. Thus, as shown in Fig. 12 (right), the standard deviation, σ_{Gauss}^T , can estimated by a fit with a Gaussian probability density function (PDF);
- *slimness*: the ratio of the width over length, $\xi = w/l$, represents the aspect ratio of the cluster. It is very useful to discriminate between cosmic rays-induced background (long and thin) from low energy nuclear or electron recoils (more elliptical or round, as the ^{55}Fe spots);
- *integral*: the total number of photons detected by all the pixels gathered in the supercluster, I_{SC} , as defined in Eq. 6;
- *pixels over threshold*: the number of pixels in the supercluster passing the zero-suppression threshold, n_p ;

- 486 • *density*: the ratio δ of I_{SC} , divided by n_p , as defined in Eq. 7;
- 487 • *energy*: the calibrated energy, expressed in keV. The calibration method
488 simultaneously performs both the per-slice correction as a function of the local
489 δ , and the absolute energy scale calibration, which corrects the non perfect
490 containment of the cluster, using with ^{55}Fe source.

491 The projected supercluster path length, l_p , and Gaussian transverse size, σ_{Gauss}^T ,
492 are shown in Fig. 13, for data taken in different types of runs. During the data-taking
493 approximately 3000 frames were recorded in absence of any external artificial source (*no-*
494 *source* sample). In these frames the interaction of ultra-relativistic cosmic ray particles
495 (mostly muons) are clearly visible as very long clusters. Internal radioactivity of the
496 LEMON materials also contribute with several smaller size clusters. About 1500 frames
497 were acquired with the AmBe source, and approximately 10^4 calibration images with
498 ^{55}Fe source. In Fig. 13, as well as in the following ones showing other cluster properties,
499 the distributions obtained in runs without artificial radioactive sources are normalized
500 to the AmBe data total CMOS exposure time. For the data with ^{55}Fe source, since the
501 activity of the source is such to produce about 15 clusters/event, the data are scaled by a
502 factor one-tenth with respect to the AmBe exposure time for clearness. Considerations
503 about the trigger efficiency scale factor between data with and without an artificial
504 source are detailed later. The distributions in this section aim to show the different
505 cluster shape observables among the different kinds of events.

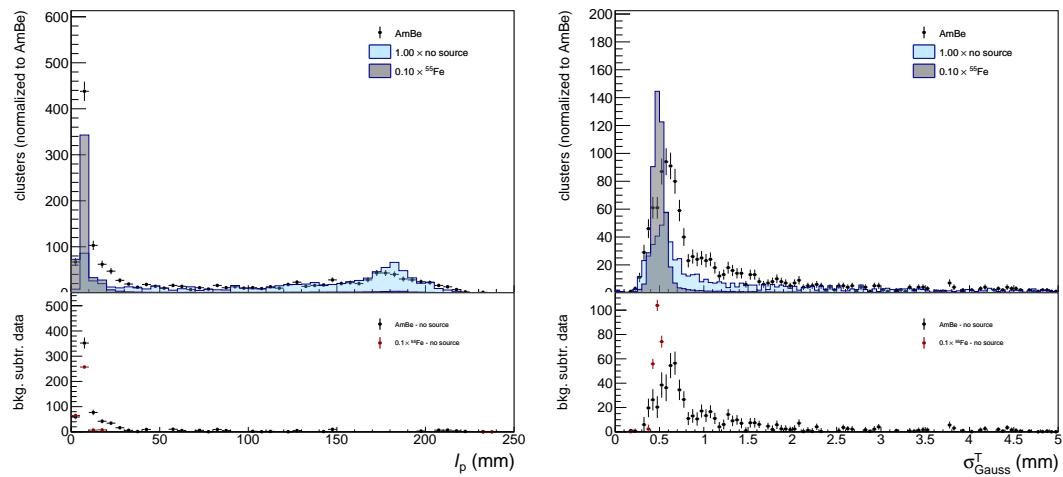


Figure 13. Supercluster sizes projected onto the $x-y$ plane. Left: longitudinal path length, l_p . Right: transverse Gaussian spread, σ_{Gauss}^T . Filled points represent data with AmBe source, dark gray (light blue) distribution represents data with ^{55}Fe source (no source). The normalization of data without any artificial source is scaled to the same exposure time of the AmBe one. For the data with ^{55}Fe source , a scaling factor of one tenth is applied for clearness, given the larger activity of this source.

506 As described in Sec. 2, each pixel images an area of $125 \times 125 \mu\text{m}^2$. Thus the cluster

507 sizes distributions show an average Gaussian width for the ^{55}Fe spots $\sigma_{Gauss}^T \approx 500 \mu\text{m}$
 508 (dominated by the diffusion in the gas), while it is larger, approximately $625 \mu\text{m}$, for
 509 data with AmBe source. The contribution of cosmic rays, present in all the data, is
 510 clearly visible in the data without any artificial radioactive source, corresponding to
 511 clusters with a length similar to the detector transverse size (22 cm).

512 Other observables are the slimness, ξ , and the light density, δ , shown in Fig. 14.
 513 The former is a useful handle to reject tracks from cosmic rays, which typically have a
 514 slim aspect ratio, i.e., low values of ξ , while the clusters from ^{55}Fe are almost round,
 515 with values of $\xi \approx 1$. Data with AmBe source, which contains a component of nuclear
 516 recoils, show a component of round spots, similar in size to the ones of ^{55}Fe , and a
 517 more elliptical component, with $0.4 < \xi < 0.8$ values. Finally, the light density, δ , is
 518 the variable expected to better discriminate among different candidates: cosmic rays
 519 induced background, electron recoils and nuclear recoil candidates. This is the variable
 520 used for the final particle identification.

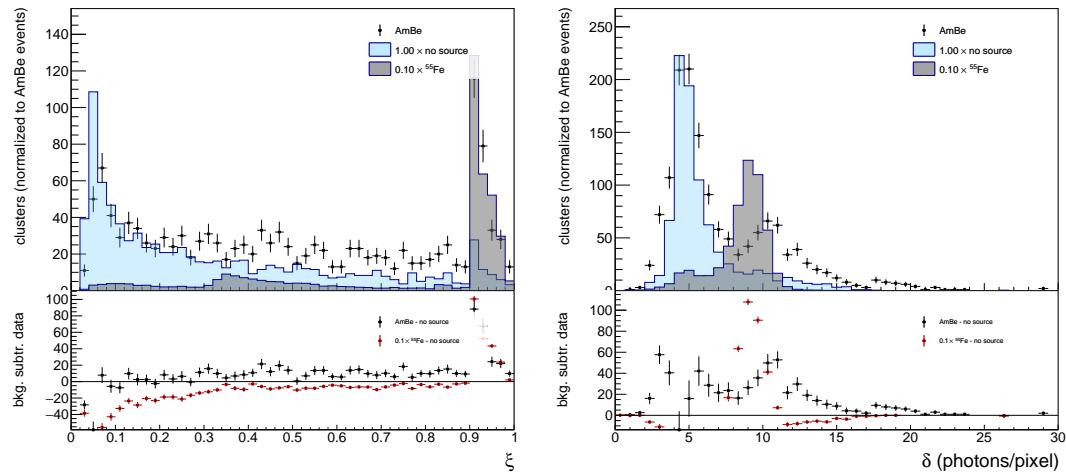


Figure 14. Supercluster variables. Left: slimness ξ ; right: light density δ . Filled points represent data with AmBe source, dark gray (light blue) distribution represents data with ^{55}Fe source (no source). The normalization of data without source is to the same exposure time of the AmBe one. For the data with ^{55}Fe , a scaling factor of one tenth is applied for clearness, given the larger activity of this source.

521 Finally, Fig. 15 shows the calibrated energy (E) spectrum for the reconstructed
 522 superclusters and the average projected $\frac{dE}{dl_p}$. The energy spectrum shows the $E = 5.9 \text{ keV}$
 523 for data with ^{55}Fe source, and a characteristic broad peak for cosmic rays tracks at
 524 around 60 keV . The distribution of the observed $\frac{dE}{dl_p}$ for the no-source sample and for the
 525 AmBe samples. The broadening of the distribution is mainly due to the specific energy
 526 loss fluctuation in the gas mixture of the cosmic ray particles. Its modal value, corrected
 527 for the effect of the angular distribution (an average inclination of 56° was measured from
 528 track reconstruction) is 2.5 keV/cm , in good agreement with the GARFIELD prediction
 529 of 2.3 keV/cm .

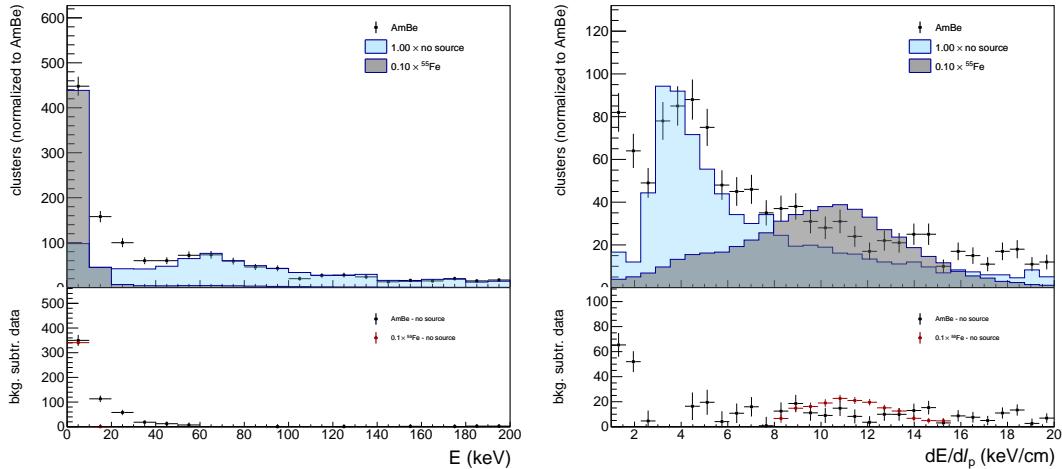


Figure 15. Supercluster calibrated energy spectrum (left) and their average $\frac{dE}{dl_p}$. Filled points represent data with AmBe source, dark gray (light blue) distribution represents data with ^{55}Fe source (no source). The normalization of data without source is to the same exposure time of the AmBe one. For the data with ^{55}Fe , a scaling factor of one tenth is applied for clearness, given the larger activity of this source.

530 5.1. Background normalization

531 The data with AmBe source, taken on the Earth surface, suffers from a large contribution
 532 of interactions of cosmic rays. The cluster shape observables provide a powerful handle
 533 to discriminate them from nuclear recoils candidates, but the small residual background
 534 needs to be statistically subtracted. The distributions shown earlier, where the different
 535 types of data are normalized to the same exposure time, demonstrate that the live-time
 536 normalization provides already a good estimate of the amount of cosmic rays in data
 537 with artificial radioactive sources. This approach does not account for a possible bias
 538 from the trigger, which is generated by the PMT signals, as described in Sec. 2. Indeed,
 539 in runs with the AmBe source, the PMT can trigger both on signals from neutron recoils
 540 or photons produced by the ^{241}Am , and on ubiquitous signals from cosmic rays, while
 541 in the sample without source only the latter is possible. This implies that, during the
 542 same exposure time, the probability to trigger on cosmic rays is lower in events with
 543 AmBe than in no-source events. The trigger efficiency scale factor, ε_{SF} , can be obtained
 544 as the ratio of the number of clusters selected in pure control samples of cosmic rays
 545 (CR) obtained on both types of runs:

$$546 \quad \varepsilon_{SF} = \frac{N_{CR}^{AmBe}}{N_{CR}^{no-source}}. \quad (9)$$

547 The CR control region is defined by selecting clusters with $l > 13\text{ cm}$, $\xi < 0.1$,
 548 $\sigma_{Gauss}^T < 6\text{ mm}$, having an energy within a range dominated by the cosmic rays
 549 contribution, $50 < E < 80\text{ keV}$. The selected clusters show small values of $\delta \approx 5$,
 550 well compatible with the small specific ionization of ultra-relativistic particles. This

sample is limited in statistics, but it is expected to be almost 100% pure. The scale factor obtained is $\varepsilon_{SF} = 0.75 \pm 0.02$.

In Fig. 16 the typical light density and polar angle (with respect the horizontal axis) distributions for long clusters of any energy, still dominated by cosmic rays, are shown for the AmBe and for the no-source sample, after having applied the ε_{SF} scale factor to the latter. Clusters with $\delta < 6$ are thus expected to be mostly coming from cosmic tracks, and they show indeed a polar angle which is shifted at values towards 90° .

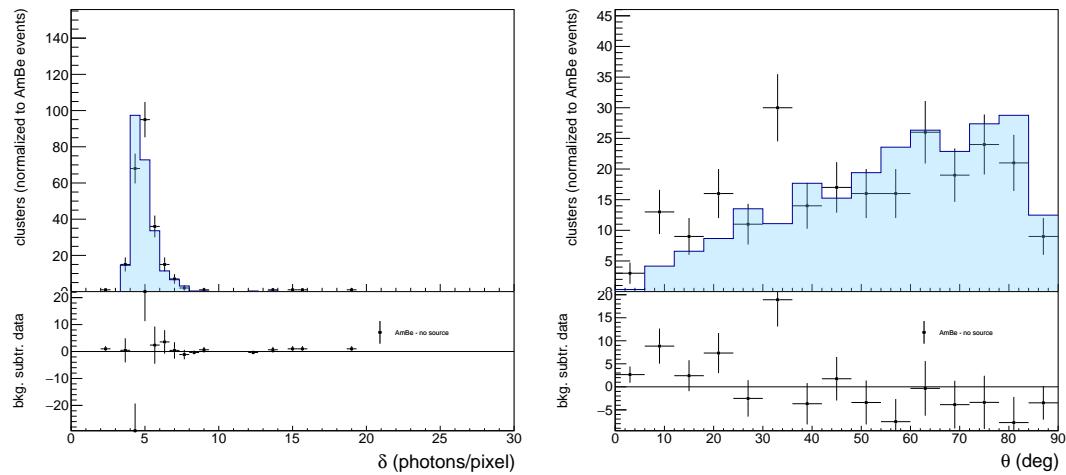


Figure 16. Supercluster light density δ (left) and polar angle (right) - with respect the horizontal axis - distributions for long clusters, dominated by cosmic rays tracks. Filled points represent data with AmBe source, light blue distribution represents data without any artificial source. The normalization of data without source is to the same exposure time of the AmBe one, accounting for the trigger scale factor ε_{SF} , as defined in the text.

559 6. Nuclear recoil identification results

560 The main observable to distinguish the signal of nuclear recoils from the various types
561 of background, is the energy density δ of the cluster.

562 6.1. Signal Preselection

563 To enhance the purity of the signal sample, a pre-selection was applied, prior to a tighter
564 selection on δ : clusters with $l_p > 6.3$ cm or $\xi < 0.3$ were rejected to primarily suppress
565 the contribution from cosmic rays. A further loose requirement $\delta > 5$ photons/pixel was
566 also applied to remove the residual cosmic rays background based on their low specific
567 ionization. Considering that the applied thresholds are very loose for nuclear recoils
568 with $E < 1$ MeV energies, as shown in Fig. 2, the preselection efficiency is assumed to

be 100%. For electron recoils it is estimated on the ^{55}Fe data sample, and is measured to be $\varepsilon_B^{\text{presel}} = 70\%$.

With this preselection, the distribution in the 2D plane $\delta - l_p$ is shown in Fig. 17 for AmBe source and no-source data and for the resulting background-subtracted AmBe data. The latter distribution shows a clear component of clusters with short length ($l_p \lesssim 1\text{ cm}$) and high density ($\delta \gtrsim 10$), expected from nuclear recoils deposits.

In addition, it shows a smaller component, also present only in the data with AmBe source, of clusters with a moderate track length, $1.5 \lesssim l_p \lesssim 3.0\text{ cm}$, and a lower energy density than the one characteristic of the nuclear recoils ($9 \lesssim \delta \lesssim 12$). Since the density is inversely proportional to the number of active pixels n_p , which is correlated to the track length, the almost linear decrease of δ as a function of l_p points to a component with fixed energy. The ^{241}Am is expected to produce photons with $E = 59\text{ keV}$. This hypothesis is verified by introducing an oblique selection in the $\delta - l_p$ plane: $|\delta - y| < 2$, where $y = 14 - p_l/50$, for the clusters with $120 < l_p < 250$ pixels, defining the control region PR . The obtained energy spectrum for these clusters is shown in Fig. 18, which indeed shows a maximum at $E = 60.9 \pm 3.6\text{ keV}$, within the expected resolution. These events are thus rejected from the nuclear recoils candidates by vetoing the PR phase space.

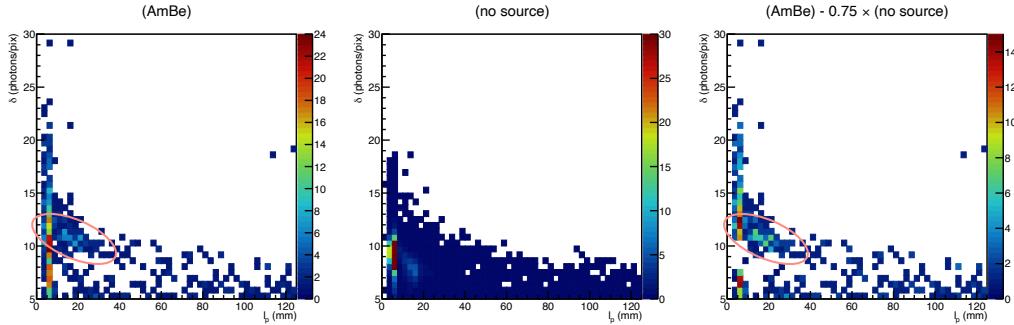


Figure 17. Supercluster light density δ versus length l_p , for data with AmBe source (left), data without any artificial source (middle), and the resulting background-subtracted AmBe data. The normalization of data without source is to the same exposure time of the AmBe one, accounting for the trigger scale factor ε_{SF} , as defined in the text.

587 6.2. PMT-based cosmic ray suppression

An independent information to the light detected by the sCMOS sensor of the camera is obtained from the PMT pulse, used to trigger the image shooting. For each image acquired, the corresponding PMT pulse waveform is recorded. Tracks from cosmic rays, which typically have a large angle with respect the cathode plane, as shown in Fig. 16 (right), show a broad waveform, characterized by the different arrival times of the several ionization clusters produced along the track at different z . Conversely, spot-like signals

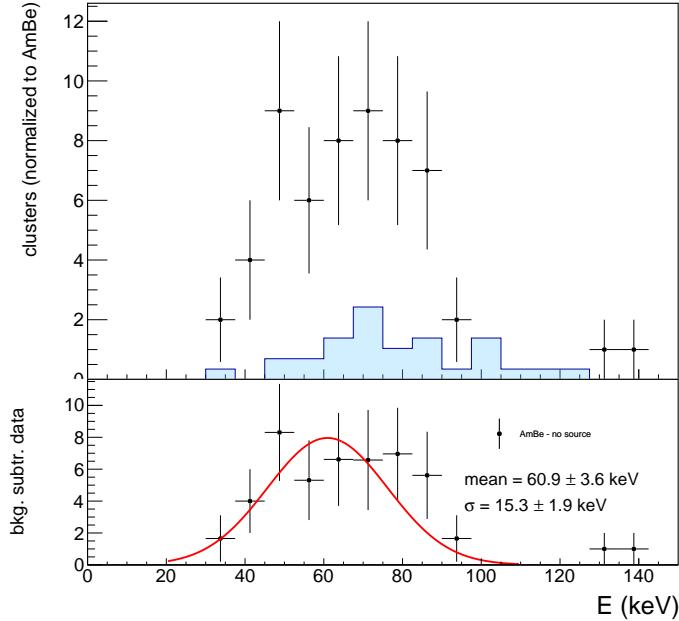


Figure 18. Calibrated energy spectrum for candidates in the control region PR , defined in the text. The background-subtracted distribution is fitted with a Gaussian PDF, which shows a mean value compatible with $E = 59$ keV originated from the ^{241}Am γ s interaction within the gas.

like ^{55}Fe deposits or nuclear recoils are characterized by a short pulse, as shown in Fig. 19.

The Time Over Threshold (TOT) of the PMT pulse was measured, and is shown in Fig. 20. It can be seen from the region around 270 ns, dominated by the cosmic rays also in the data with the AmBe source, that the trigger scale factor ε_{SF} also holds for the PMT event rate. As expected, spot-like clusters (in 3D) correspond to a short pulse in the PMT, while cosmic ray tracks have a much larger pulse. The contribution of cosmic ray tracks is clearly visible in the data with radioactive sources. A selection on this variable is helpful to further reject residual cosmic rays background present in the AmBe or ^{55}Fe data, in particular tracks which may have been split in multiple superclusters, like the case shown in Fig. 8 (bottom), and thus passing the above preselection on the cluster shapes. A selection $TOT < 250$ ns is then imposed. It has an efficiency of 98% on cluster candidates in AmBe data (after background subtraction), while it is only 80% efficient on data with ^{55}Fe source. The light density, and the energy spectrum, after the full preselection, is shown in Fig. 21.

6.3. Light density and ^{55}Fe events rejection

The light density distribution, after the above preselection and cosmic ray suppression, appear to be different among the data with AmBe source, data with ^{55}Fe source, and

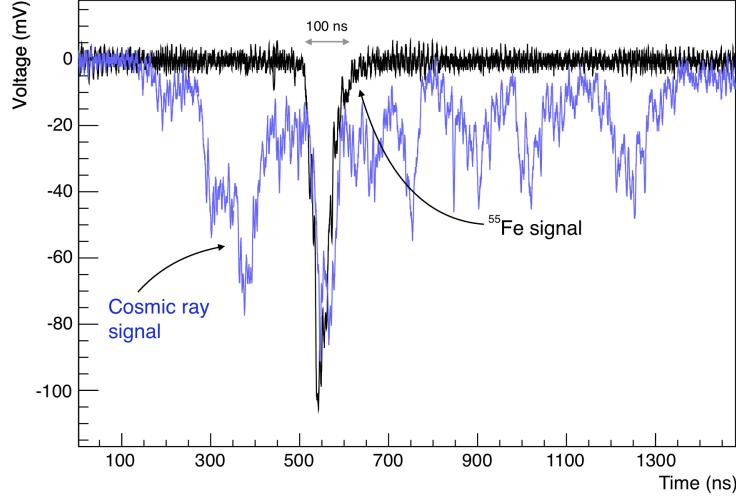


Figure 19. Example of two acquired waveforms: one short pulse recorded in presence of ^{55}Fe radioactive source, together with a long signal very likely due to a cosmic ray track.

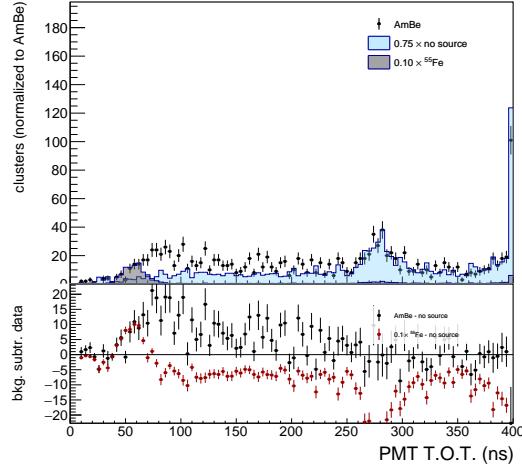


Figure 20. PMT waveform time over threshold (TOT). The last bin integrates all the events with $TOT > 400$ ns. Filled points represent data with AmBe source, dark gray (light blue) distribution represents data with ^{55}Fe source (no source). The normalization of data without source is to the same exposure time of the AmBe one, with trigger scale factor ε_{SF} applied. For the data with ^{55}Fe , a scaling factor of one tenth is applied for clearness, given the larger activity of this source.

612 data without any artificial source. The cosmic-background-subtracted distributions of
 613 δ in AmBe data and ^{55}Fe data, shown in the bottom panel of Fig. 21 (left), are used to
 614 evaluate a curve of electron recoils rejection $(1 - \varepsilon_B^\delta)$ as a function of signal efficiency (ε_S^δ) ,
 615 obtained varying the selection on δ . This is shown in Fig. 22. The same procedure could

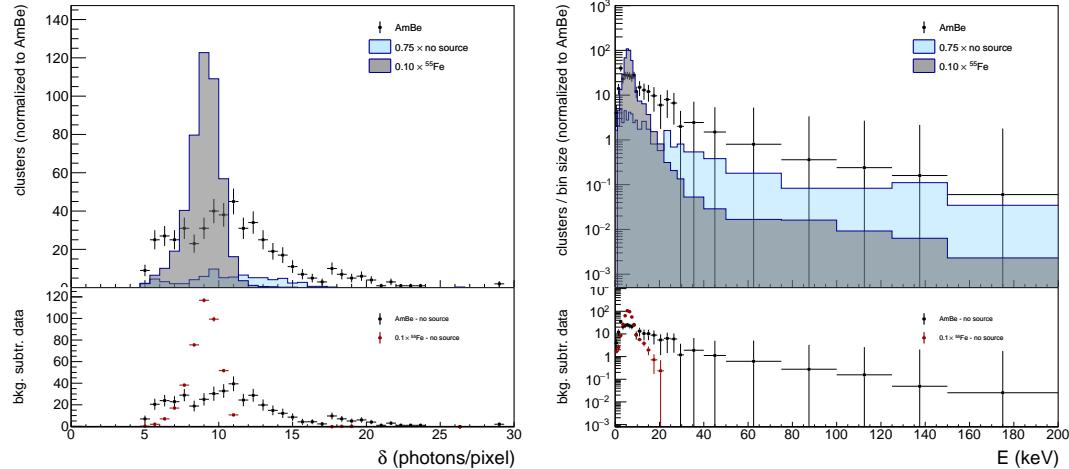


Figure 21. Supercluster light density δ (left) and calibrated energy E (right), after the preselection and cosmic ray suppression described in the text to select nuclear recoil candidates. Filled points represent data with AmBe source, dark gray (light blue) distribution represents data with ^{55}Fe source (no-source). The normalization of no-source data is to the same exposure time of the AmBe data, with the trigger scale factor ε_{SF} applied. For the data with ^{55}Fe , a scaling factor of one tenth is applied for clearness, given the larger activity of this source.

Table 1. Signal (nuclear recoils) and background (electron recoils) efficiency for two different selections on δ .

working point	Signal efficiency			Background efficiency		
	ε_S^{presel}	ε_S^δ	ε_S^{total}	ε_B^{presel}	ε_B^δ	ε_B^{total}
WP ₅₀	0.98	0.51	0.50	0.70	0.050	0.035
WP ₄₀	0.98	0.41	0.40	0.70	0.012	0.008

be applied to estimate the rejection factor against the cosmic ray induced background, but this is not shown because of the limited size of the no-source data. This kind of background will however be negligible when operating the detector underground. This is shown in Fig. 22. While this cut-based approach is minimalist, and could be improved by profiting of the correlations among δ and the observables used in the preselection in a more sophisticated multivariate analysis, it shows that a good rejection factor of electron recoils at $E = 5.9\text{ keV}$ can be obtained.

Table 1 shows then the full signal efficiency and electrons rejection factor for two example working points, WP₄₀ and WP₅₀, having 40% and 50% signal efficiency for the selection on δ . They correspond to a selection $\delta > 11$ and $\delta > 10$, respectively.

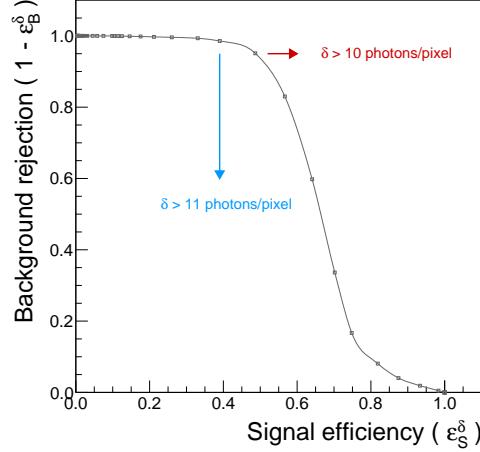


Figure 22. Background rejection as a function of the signal efficiency, varying the selection on the δ variable in data with either ^{55}Fe (background sample) or AmBe (signal sample) sources.

626 6.4. Signal Energy Spectrum and efficiency

627 The energy spectrum for the candidates with $\epsilon_S^{total} = 50\%$ in the AmBe sample is shown
 628 in Fig. 23 (left). With the full WP_{50} selection, the signal efficiency is computed for
 629 both the example working points in bins of energy. The electron recoil efficiency, ϵ_B^{total} ,
 630 represents a γ background efficiency at a fixed energy $E = 6\text{ keV}$, that is close to the
 631 ^{55}Fe emitted photon energy. For the WP_{50} , the efficiency for very low-energy recoils,
 632 $E = 6\text{ keV}$, is still 18%, dropping to almost zero at $E \lesssim 4\text{ keV}$.

633 Two candidate nuclear recoils images, fulfilling the WP_{50} selection (with a light
 634 density $\delta \gtrsim 10$ photons/pixels and with energies of 5.2 and 6.0 keV) are shown in
 635 Fig. 24. The displayed images are a portion of the full-resolution frame, after the
 636 pedestal subtraction.

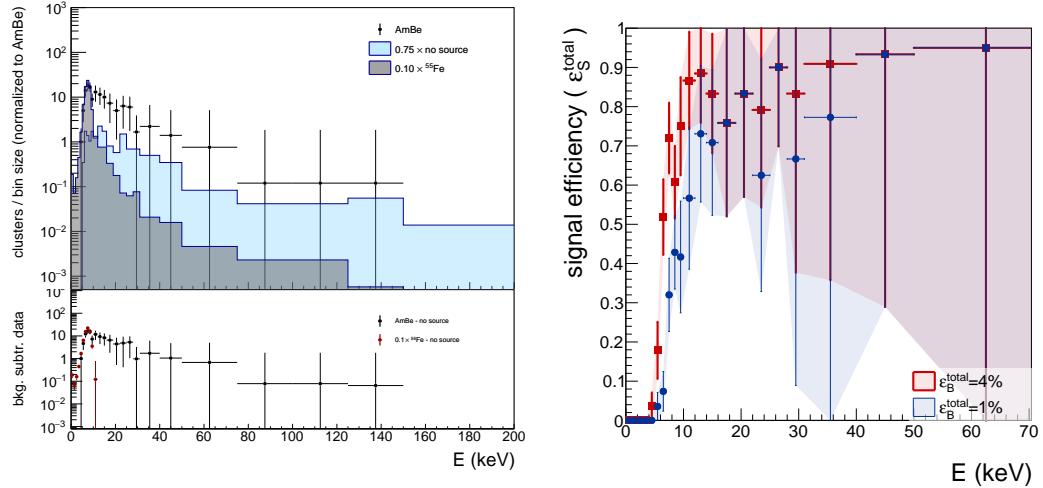


Figure 23. Left: supercluster calibrated energy E (left), after the full selection, which includes $\delta > 10$, 50% efficient on signal, to select nuclear recoil candidates. Filled points represent data with AmBe source, dark gray (light blue) distribution represents ^{55}Fe source (no-source) data. The normalization of no-source data is to the same exposure time of the AmBe data, with the trigger scale factor ε_{SF} applied. For the ^{55}Fe data, a scaling factor of one tenth is applied for clearness, given the larger activity of this source. Right: efficiency for nuclear recoil candidates as a function of energy, estimated on AmBe data, for two example selections, described in the text, having either 4% or 1% efficiency on electron recoils at $E = 6$ keV.

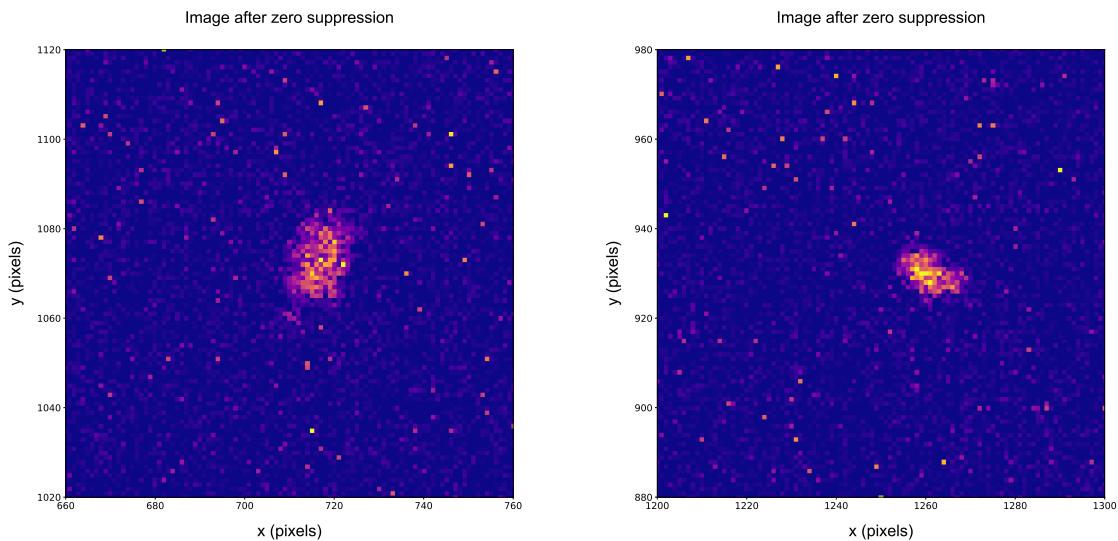


Figure 24. Examples of two nuclear recoil candidates, selected with the full selection, shown in a portion of 100×100 pixel matrix, after the zero suppression of the image. Left: a candidate with $E = 5.2$ keV and $\delta = 10.5$, right: a candidate with $E = 6.0$ keV and $\delta = 10$.

637 **7. Conclusion and outlook**

638 A method to efficiently identify recoiling nuclei after an elastic scattering with fast
 639 neutrons with an optically readout TPC was presented in this paper. A 7 liter prototype
 640 was employed by exposing its sensitive volume to two kinds of neutral particles in an
 641 overground location:

- 642 • photons with energy of 5.9 keV and 59 keV respectively provided by a radioactive
 643 source of ^{55}Fe and by one of ^{241}Am able to produce electron recoils with equal
 644 energy by means of photoelectric effect;
- 645 • neutrons with kinetic energy of few MeV produced by an AmBe source that can
 646 create nuclear recoils with kinetic energy lower than the neutron ones.

647 The high sensitivity of the adopted sCMOS optical sensor allowed a very good
 648 efficiency in detecting events with an energy released in gas even below 10 keV.

649 Moreover, the possibility of exploiting the topological information (shape, size and
 650 more) of clusters of emitted light permitted to develop algorithms able to reconstruct
 651 not only the total released energy, but also to identify the kind of the recoiling ionizing
 652 particles in the gas (either an electron or a nucleus). Cosmic ray long tracks are also
 653 clearly separated.

654 Because of their larger mass and electric charge, nuclear recoils are expected to
 655 release their energy by ionizing the gas molecules in few hundreds μm while the electrons
 656 are able to travel longer paths. For this reason, by exploiting the spatial distribution of
 657 the collected light, it was possible to identify 5.9 keV electron recoils with an efficiency
 658 of 96.5% (99.2%) against nuclear recoils by retaining a capability of detecting them with
 659 an efficiency of 50% (40%), averaged across the measured AmBe spectrum.

660 In average, nuclear recoils with a kinetic energy lower than 10 keV can be detected
 661 with an efficiency of about 14%.

662 The results obtained in the studies presented in this paper can be improved
 663 by means of more sophisticated analyses exploiting a multivariate approach, which
 664 combines a more complete topological information about the light distribution along
 665 the tracks. Additional enhancement of sensitivity can be achieved with a DAQ system
 666 collecting single PMT waveforms to be correlated with the track reconstructed in the
 667 sCMOS images.

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