Estudio de muones de rayos cósmicos con un detector Skipper-CCD

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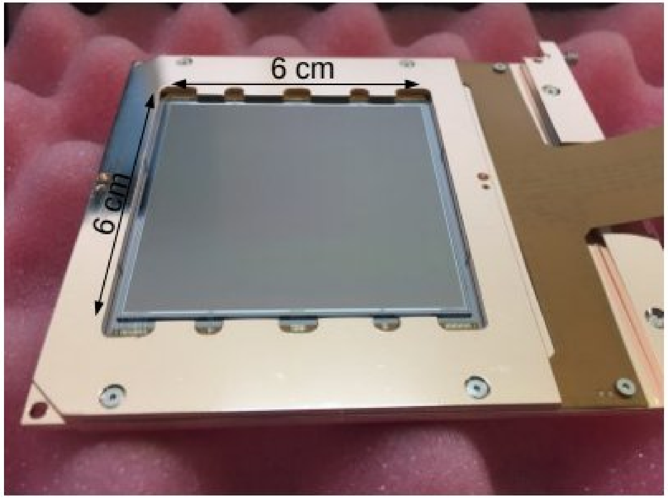
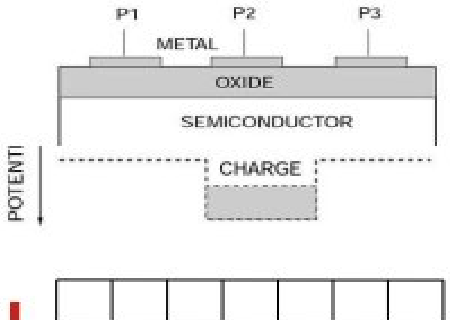
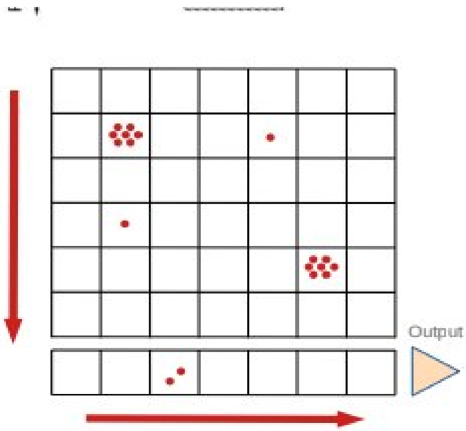
Content

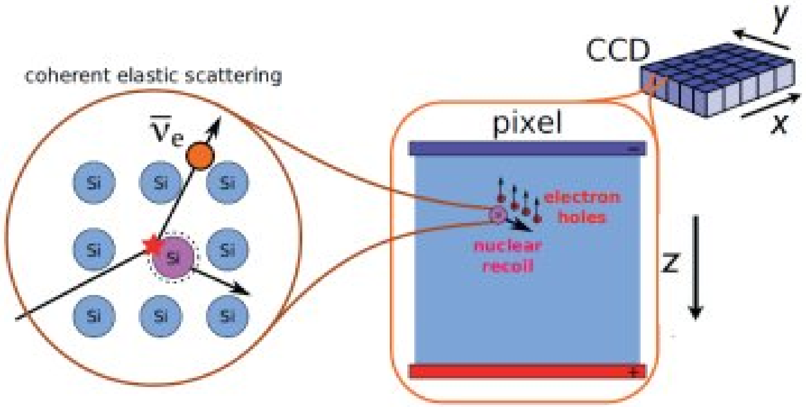
Standard Charge-Coupled Device (CCD)

- Array of MOS capacitors on a Si substrate. Can store images of energy depositions, producing e-h pairs, in pixels across the substrate area.
- An electric field drifts the carriers (holes) across the substrate to be collected near the surface in gate electrodes. After an that, the pixel charges are moved to an amplifier to be read out.
- Widely used in astronomical cameras but could be used as a **particle detector**.



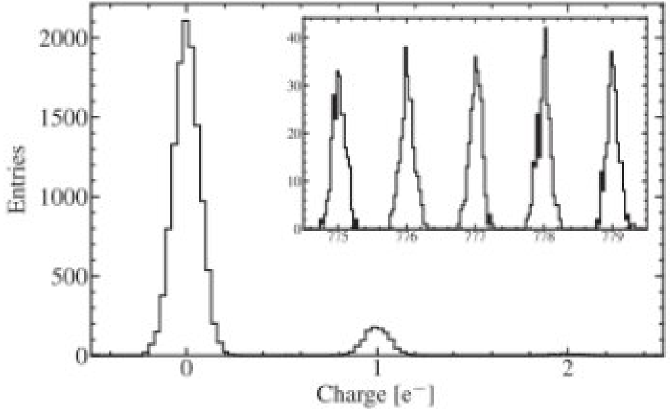


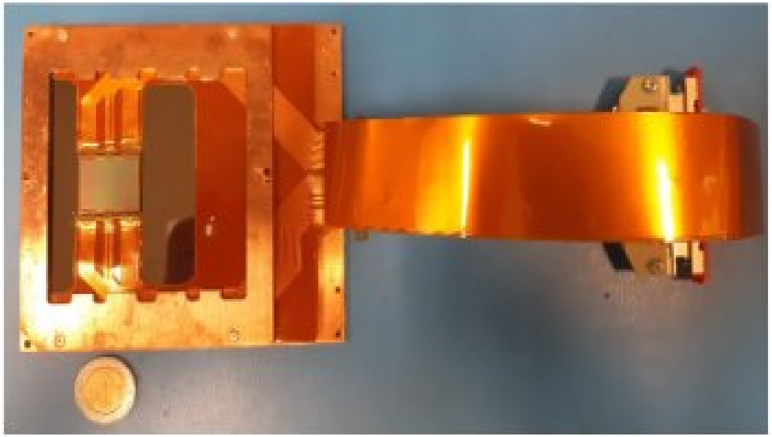




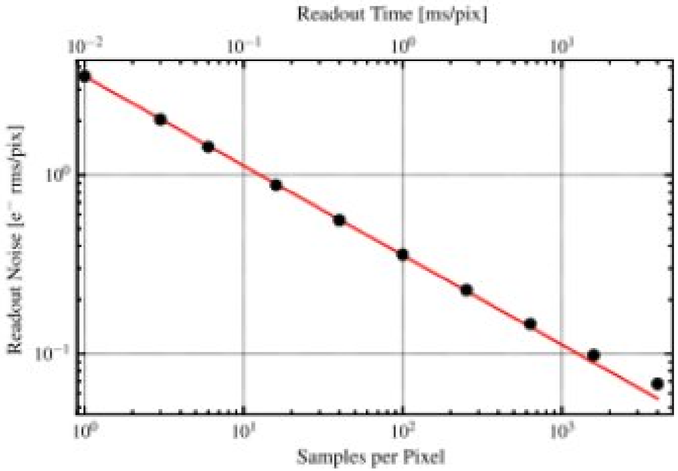
Skipper-CCD

- Identical to standard CCDs but **different readout stage.**
- Readout circuit modified to allows make **non-destructive** and **repeated charge measurement**, counting of individual ionization electrons, and **reduction of electronic noise** proportional to $\frac{1}{\sqrt{N_{samp}}}$
- Promising technology for **Dark Matter** and **neutrino** experiments (OSCURA, SENSEI, CONNIE) and other applications in fields such as quantum optics, astronomy or nuclear physics.



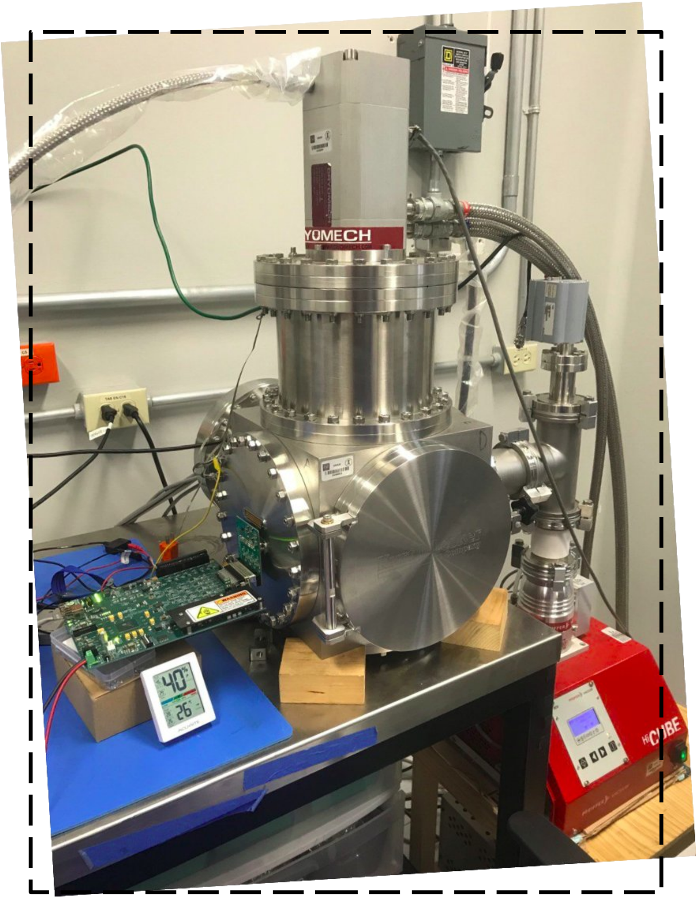


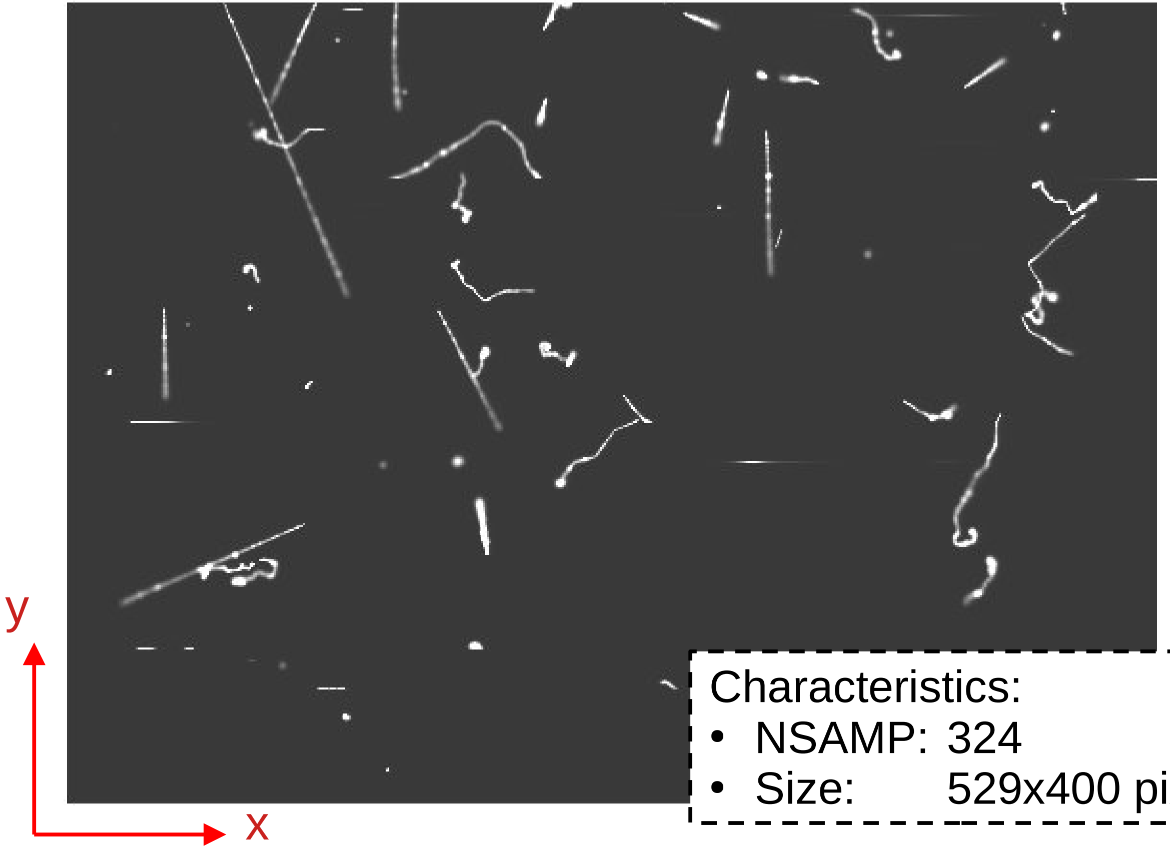
Skipper CCD from the ICN-UNAM



Skipper-CCD

The following image was obtained using the skipper-CCD of the ICN-UNAM detector laboratory.



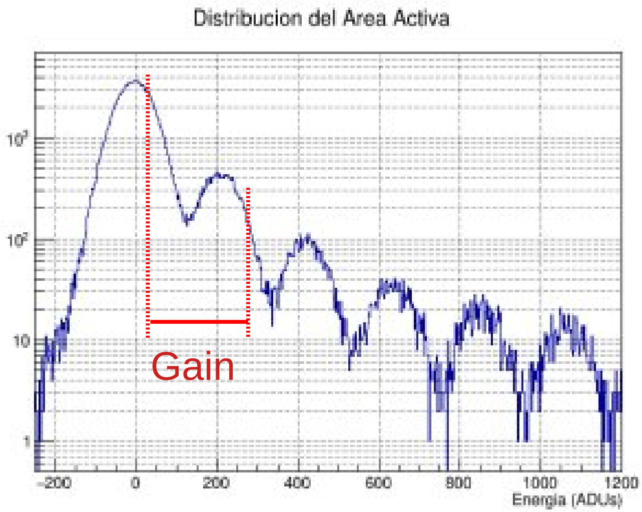


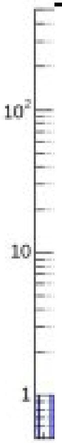
Characteristics:
- NSAMP: 324
- Size: 529x400 pix

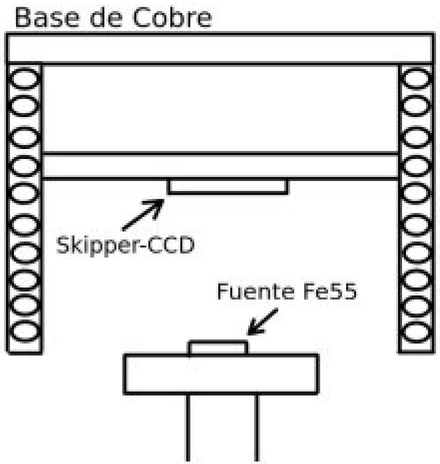
Calibration

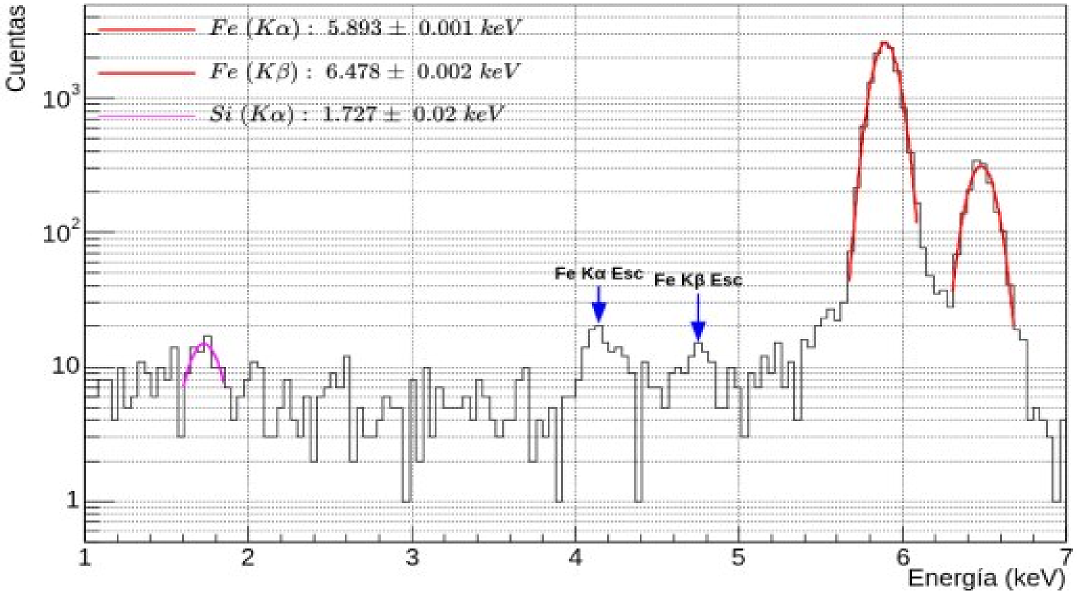
- Due to this sensor allow us counting individual ionization electrons, we can obtained an excellent energy calibration just using the pixel charge distribution. This is called **self calibration**.

- We used a Fe55 source to corroborate this **self calibration**. Below we can see its energy distribution.



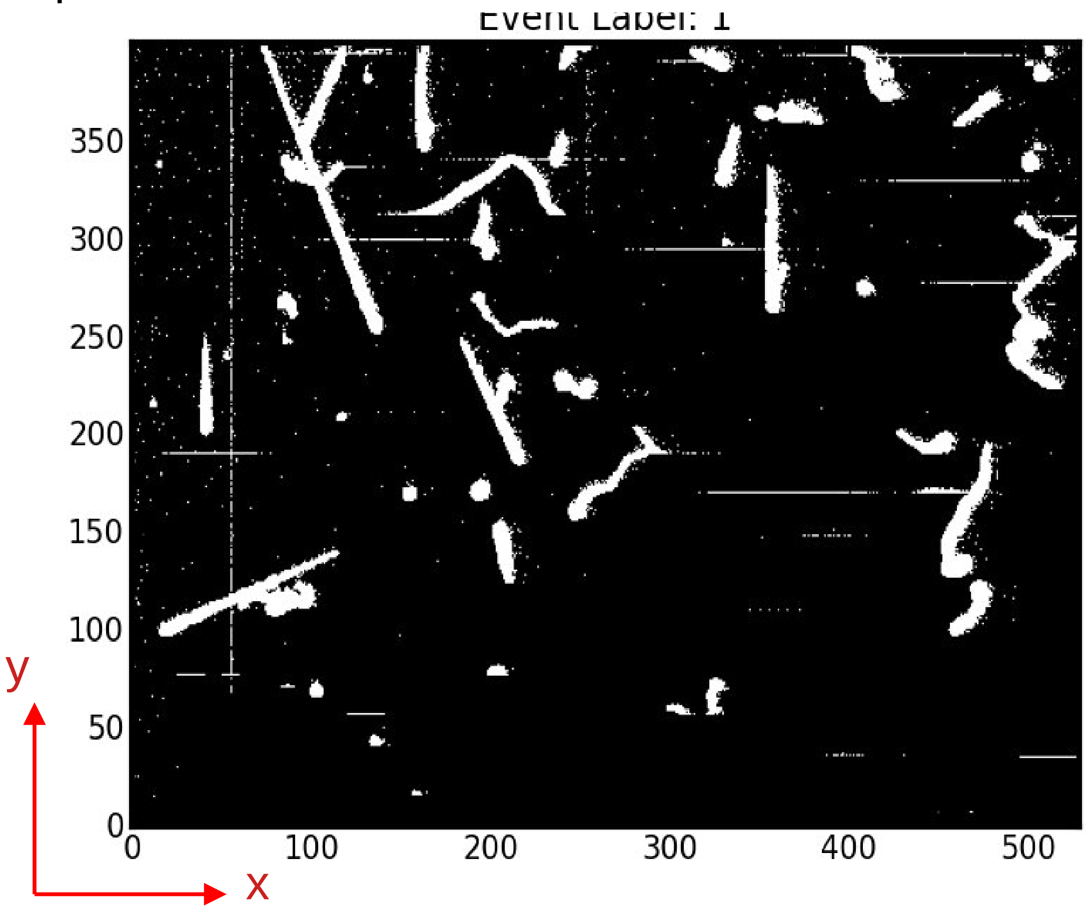






Clustering Process

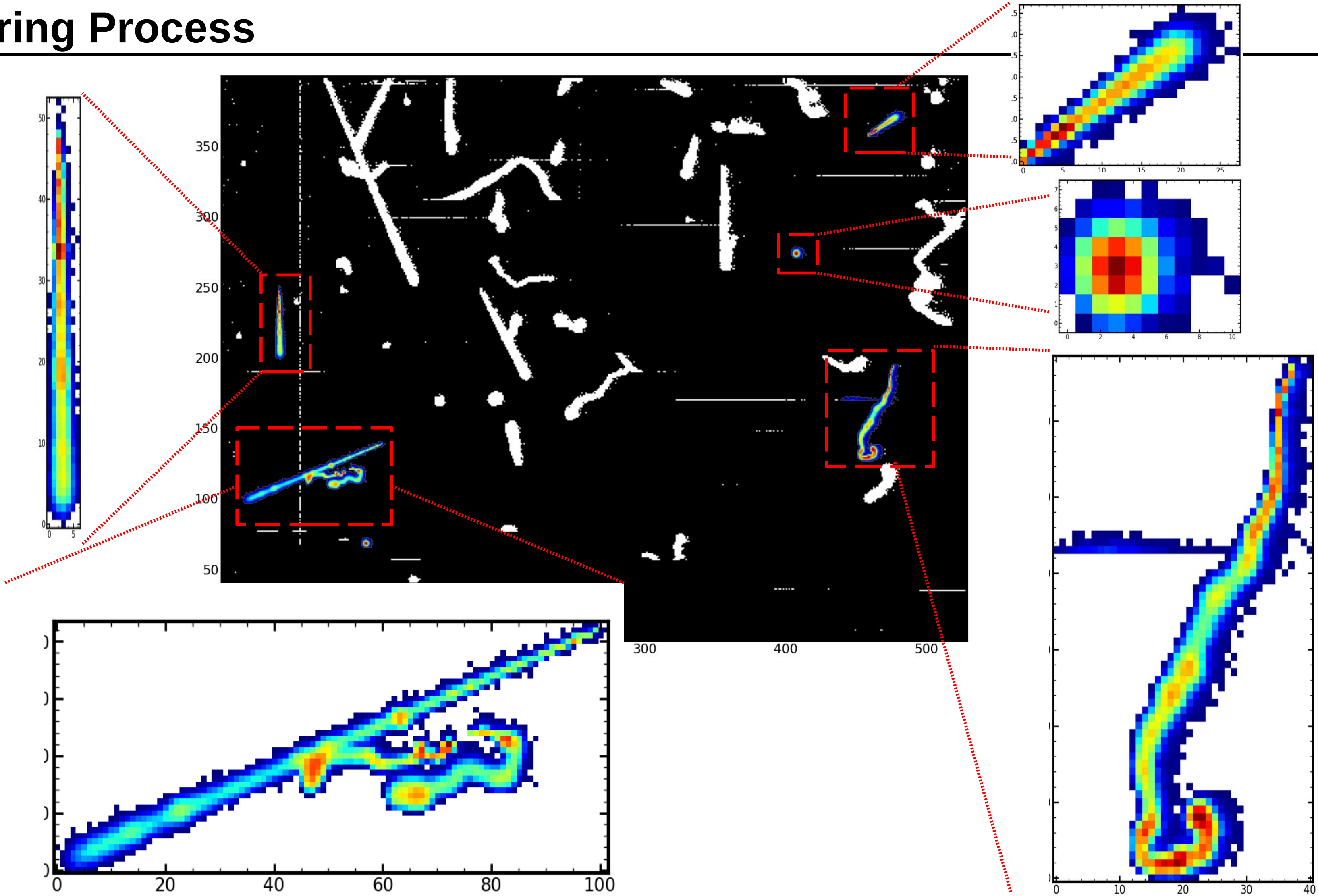
Using a simple algorithm based in Python that groups adjacent pixels with an higher energy than a established threshold we can **reconstruct the particle traces** and obtained the energy deposition distribution.



- Gain: 204.2 ADU/e-
- σ (noise): 0.27 e-

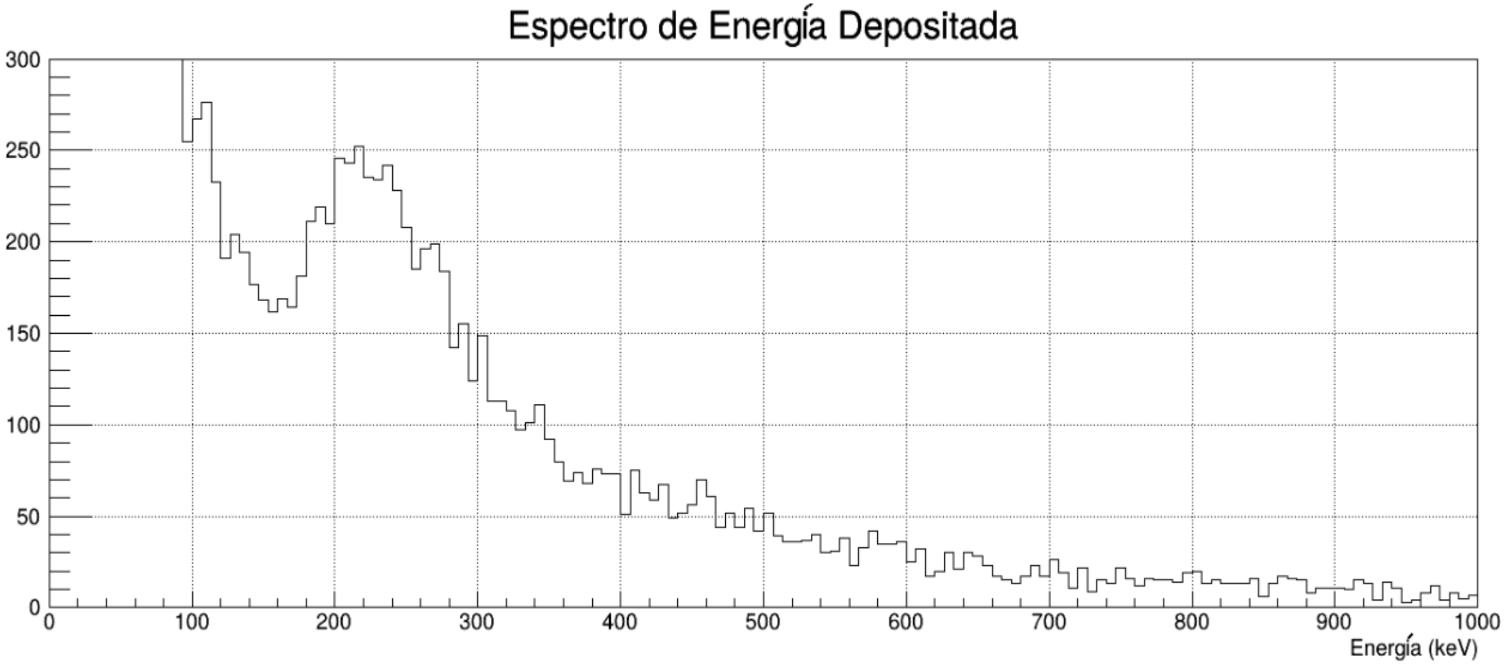
- We use a threshold of 3.5 e- (13σ)

Clustering Process



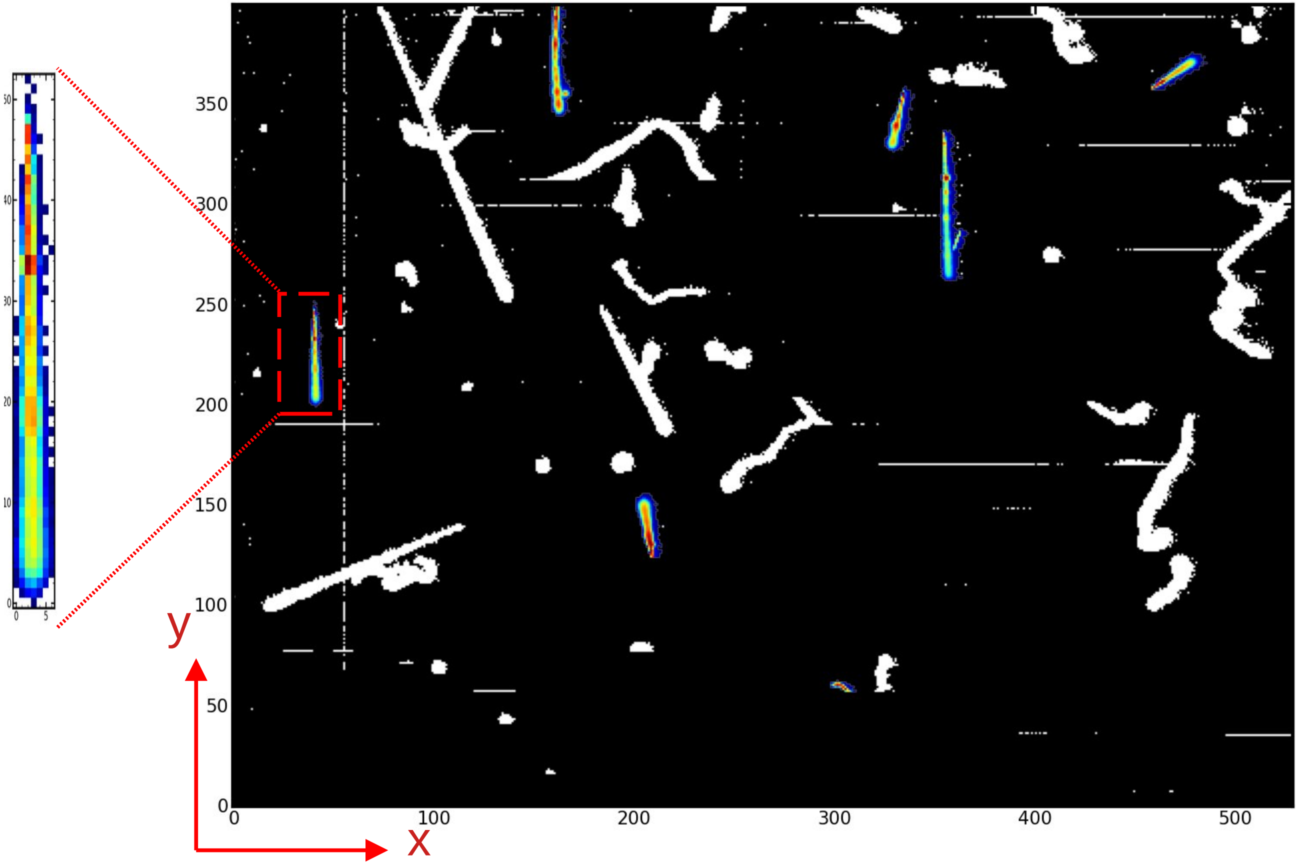
Clustering Process

The energy deposited distribution energy is shown below. The peak due to cosmogenic muons is clearly visible.



Muon Identification

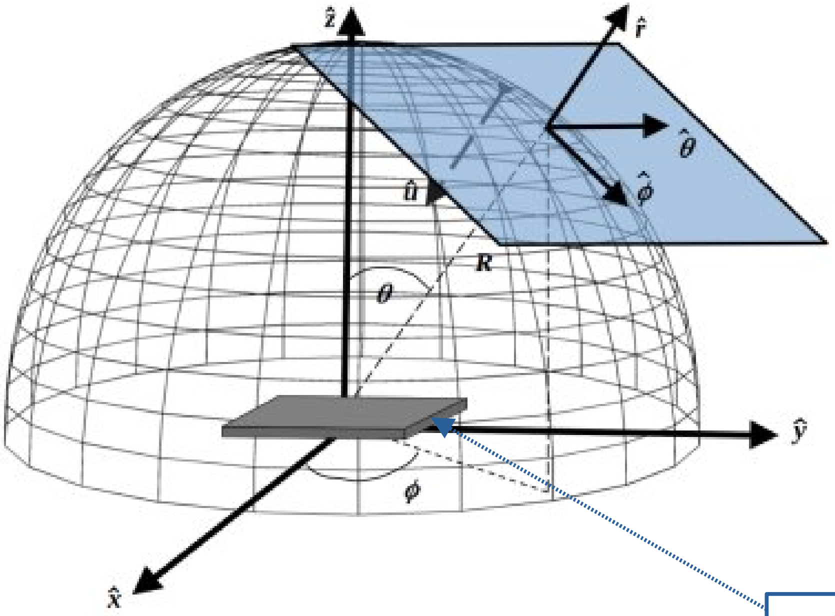
After that, we use the **ellipticity** and the **solidity** to identify the **muon traces**. We can obtain some properties like energy deposition, azimuthal and polar angle or the distance that traveled through the sensor. And we can identify **x & y parallel muons**.

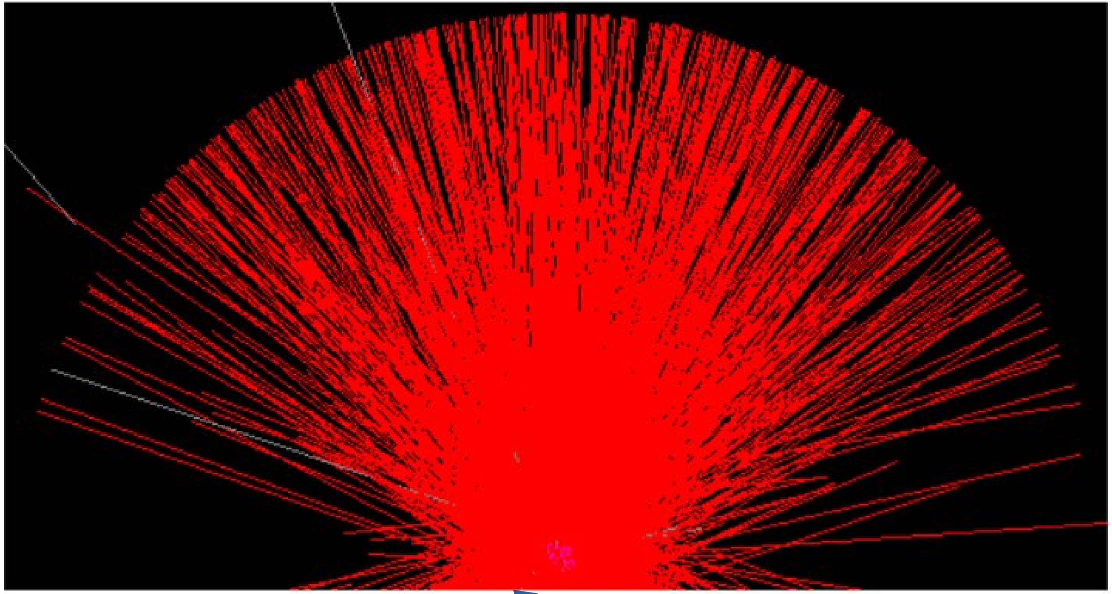


Monte Carlo Simulations

Two simulation were implemented: the first based in first principles using **Python** and **ROOT** and the second using **Geant4**. In both, that was implemented a **muon generator** using a **hemispherical model** centered in the sensor. The **Smith-Duller Distribution** was used to obtained the random kinetic energy of the muons.

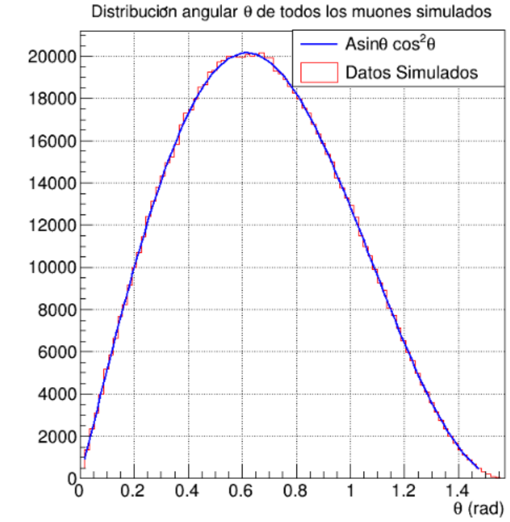
$$\Theta(\theta) \propto \sin\theta \cos^2\theta$$

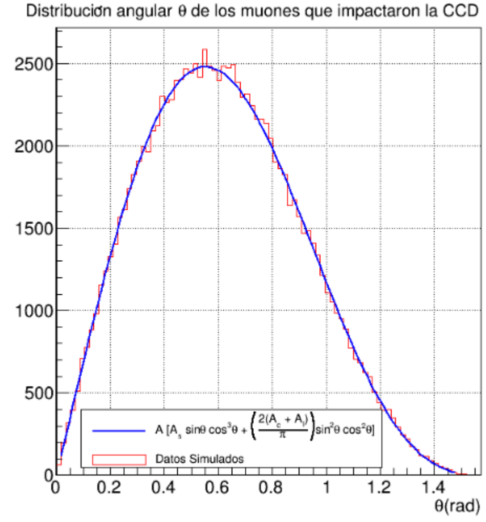


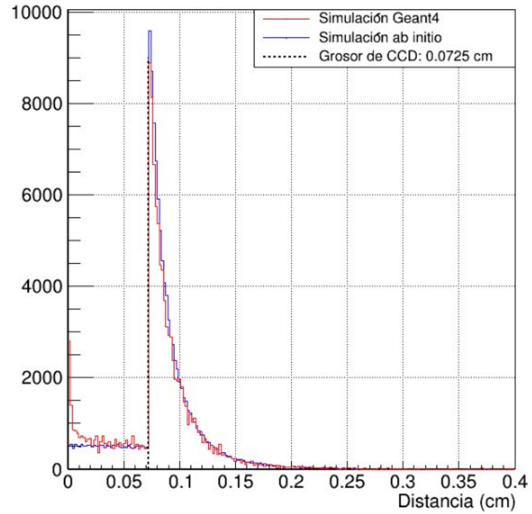


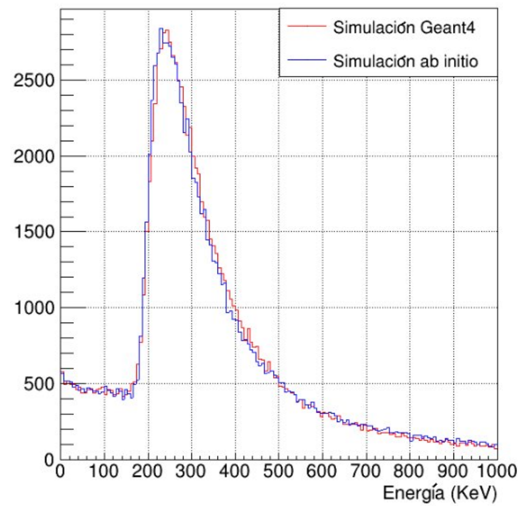
Skipper CCD

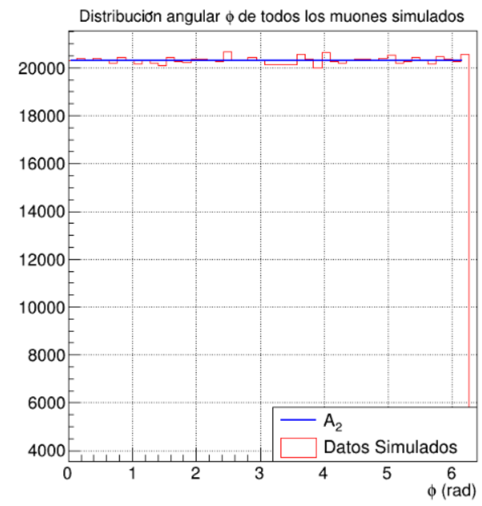
Monte Carlo Simulations

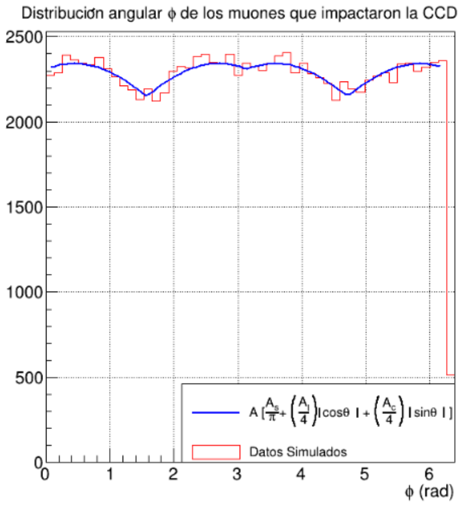


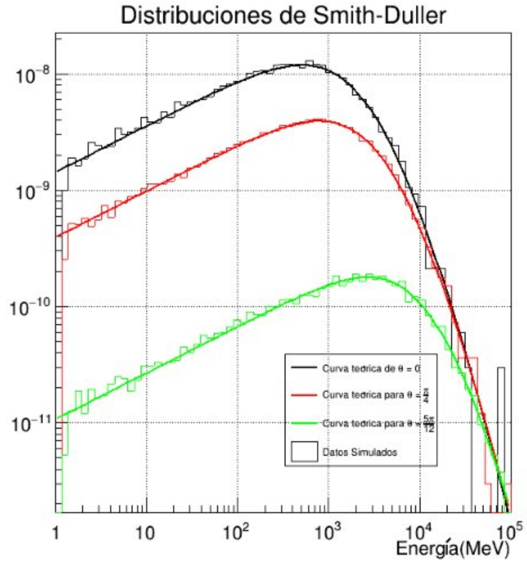


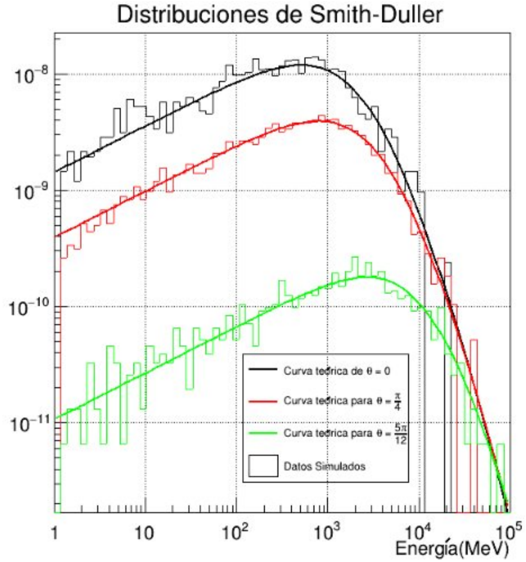






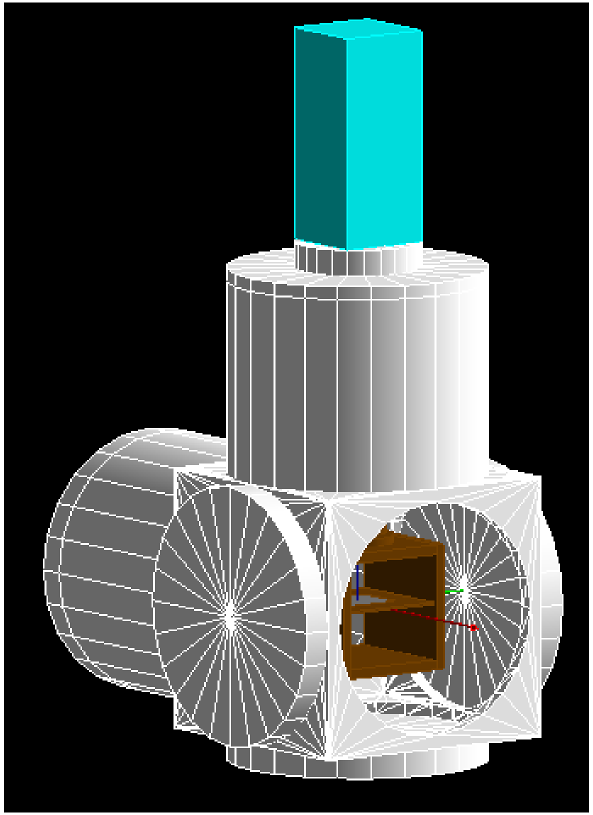


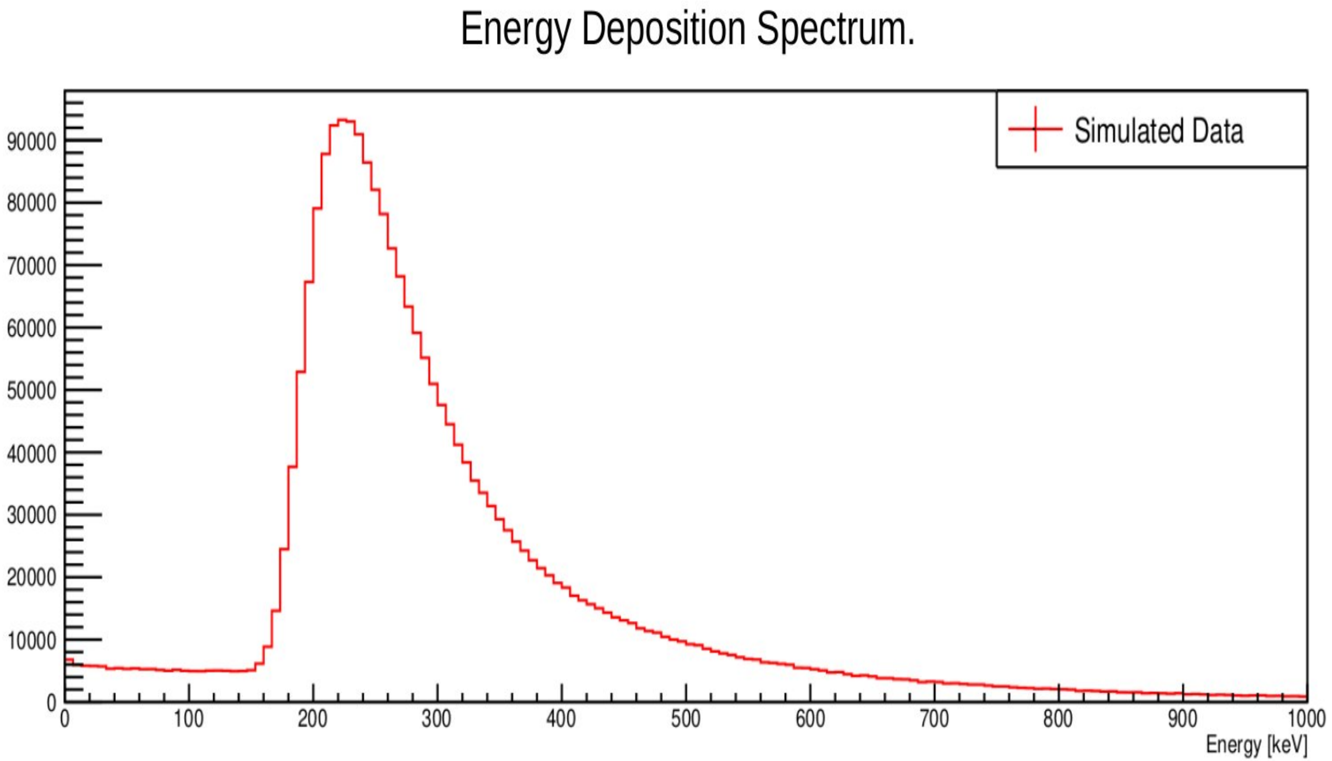




Monte Carlo Simulations

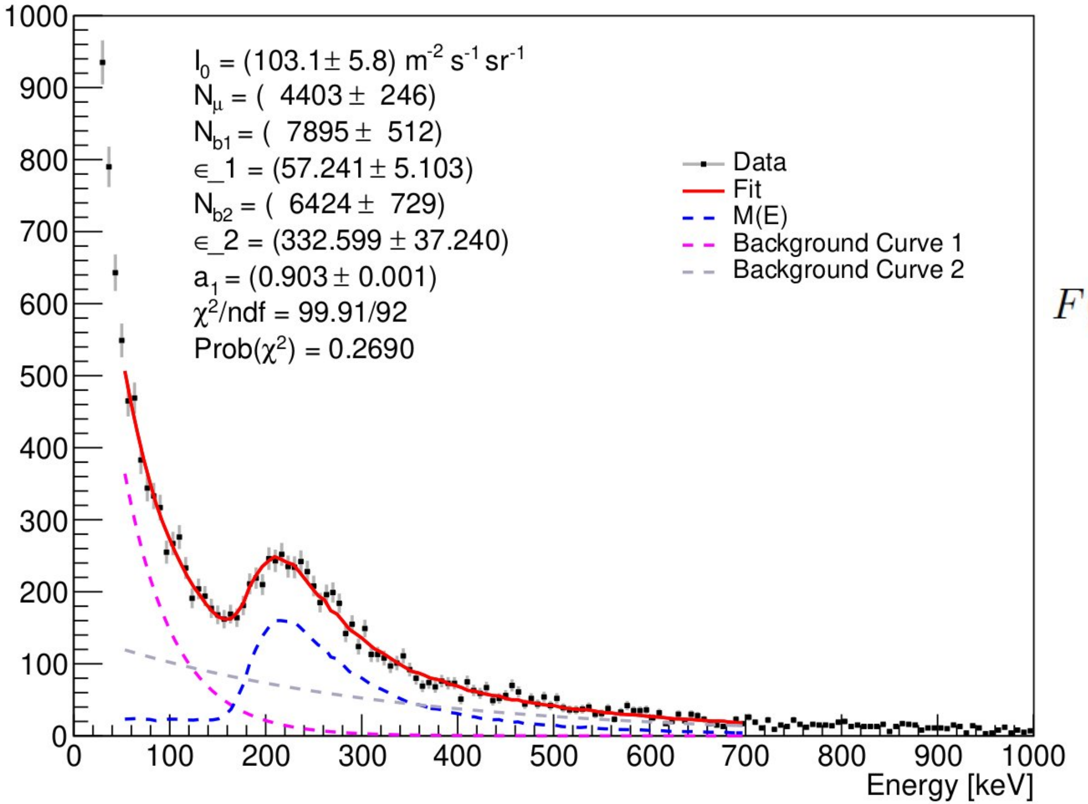
Then, a simulation of the complete experimental array was implemented in Geant4. From here we obtained the energy deposition distribution, M(E), that is shown below.





Calibration with Cosmogenic Muons

To model the energy distribution we use the simulated energy distribution **M(E)**, and two exponential curves as background. The fit is shown below.



$$\boxed{E = a_1 E_d}$$

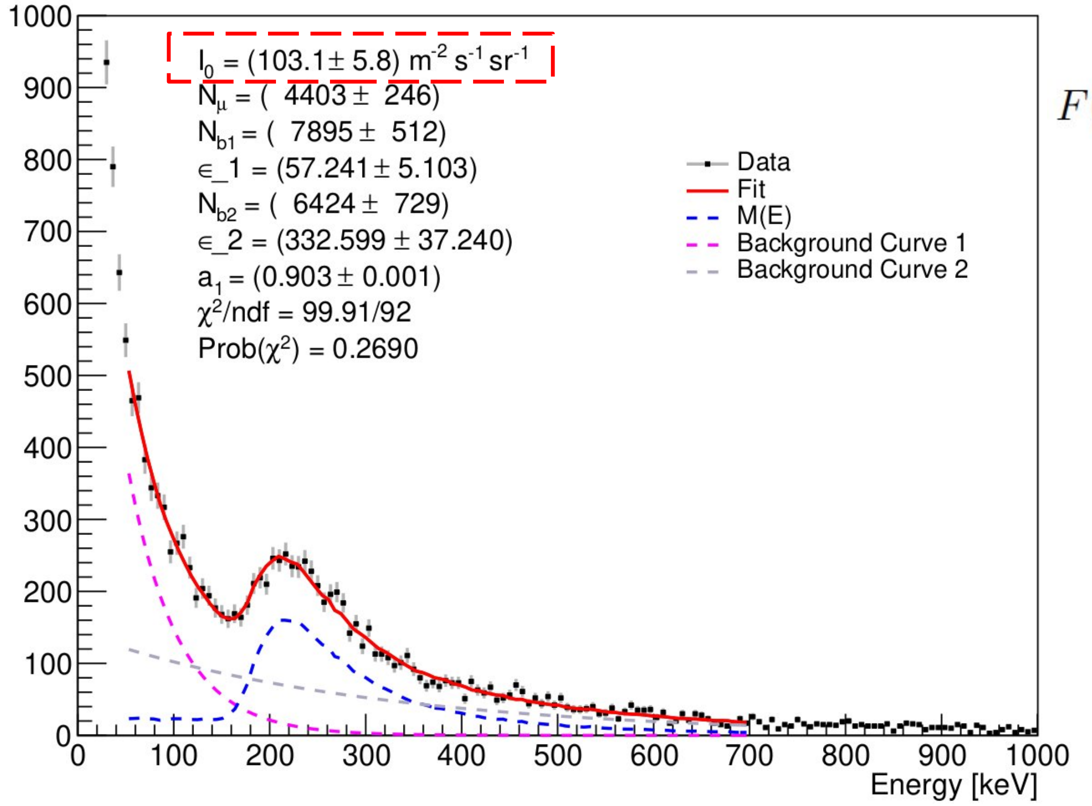
$$F(E) = \left(\frac{dE_d}{dE}\right) \cdot \left[N_\mu M(a_1 E_d) + \sum_{i=1}^{2} \frac{N_{b_i}}{\epsilon_i} \exp\left(-\frac{E_d}{\epsilon_i}\right)\right]$$

$$= \left(\frac{1}{a_1}\right) \cdot \left[N_\mu M(a_1 E_d) + \sum_{i=1}^{2} \frac{N_{b_i}}{\epsilon_i} \exp\left(-\frac{E_d}{\epsilon_i}\right)\right]$$

Calibration with Cosmogenic Muons

The vertical intensity of the muon flux (**I_0**) value was estimated at **103.1 ± 5.8** m^-2 s^-1 sr^-1. This is a preliminary result, but it is within an acceptable range of values.

$$\boxed{E = a_1 E_d}$$



$$F(E) = \left(\frac{dE_d}{dE}\right) \cdot \left[N_\mu M(a_1 E_d) + \sum_{i=1}^{2} \frac{N_{b_i}}{\epsilon_i} \exp\left(-\frac{E_d}{\epsilon_i}\right)\right]$$

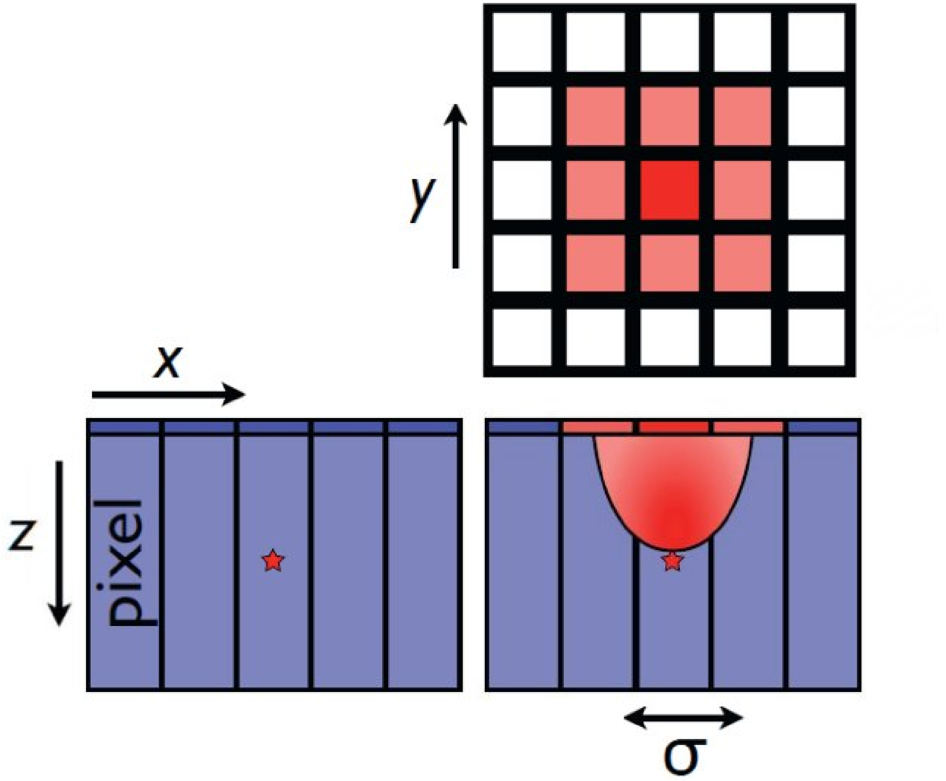
$$= \left(\frac{1}{a_1}\right) \cdot \left[N_\mu M(a_1 E_d) + \sum_{i=1}^{2} \frac{N_{b_i}}{\epsilon_i} \exp\left(-\frac{E_d}{\epsilon_i}\right)\right]$$

Range of values of I_0*
98.3 – 112.6 m^-2 s^-1 sr^-1

*From: Olmos Yáñez & Aguilar-Arevalo, NIM A [987, 164870] and Martínez Montiel, et al., EPJ Web Conf. [301, 04002]

Depth & Diffusion

To make a correct 3D reconstruction of the particles we have to obtained a relation between the energy diffusion and the depth where the deposition occurred.



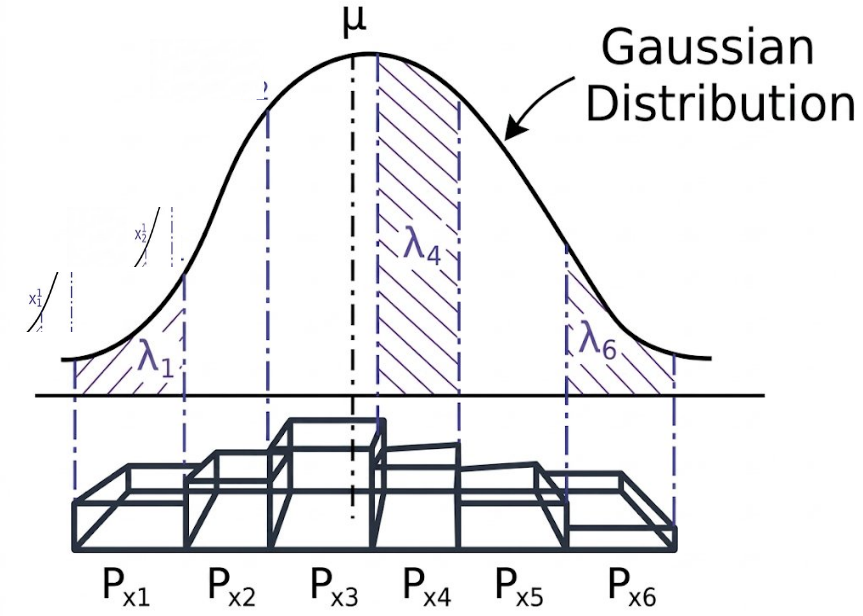
Size-to-depth Relation: The Binomial-Gaussian Model

A **binomial-Gaussian distribution** was used to obtain the size-to-depth relation. This model successfully decouples the diffusion effects from the readout noise. The free parameters **μ**, **σ_d**, and **QT** (total charge) are determined by **minimizing the negative log-likelihood function** shown below. This version is just for one dimension.

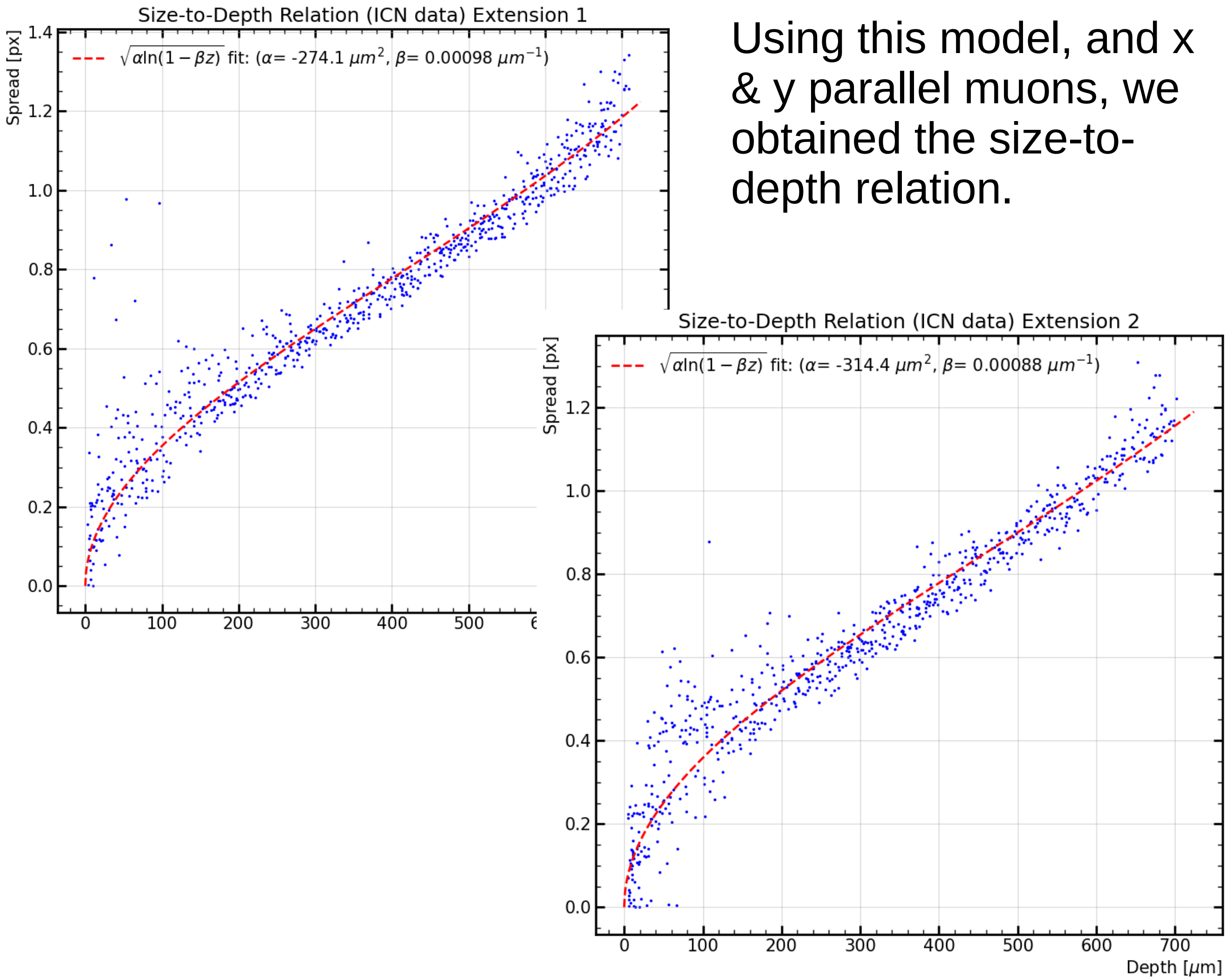
$$\mathcal{L}(\mu, \sigma_d, QT | \{q_{pix}^1, q_{pix}^2, ..., q_{pix}^{max}\}) = \prod_{i=0}^{i_{max}} \left(\sum_{k=0}^{QT} \left[\lambda_i^k (1-\lambda_i)^{QT-k} \right] \times \left[\frac{\exp\left(-\frac{(q_{pix}^i - k)^2}{2\sigma_n^2}\right)}{\sqrt{2\pi\sigma_n^2}} \right] \right)$$

Where:

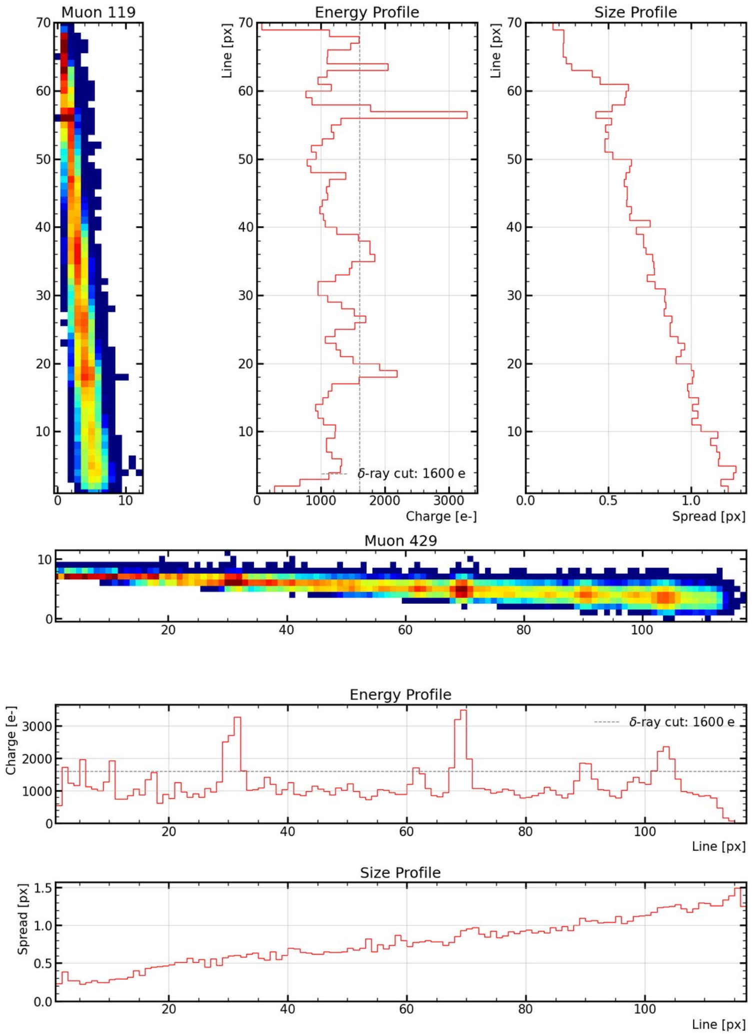
$$\lambda_i(x_1^i, x_2^i, \mu, \sigma_d) = \frac{1}{\sqrt{2\pi\sigma_d^2}} \int_{x_1^i}^{x_2^i} \exp\left(-\frac{(x-\mu)^2}{2\sigma_d^2}\right) \, dx$$



Size-to-depth Relation: The Binomial-Gaussian Model

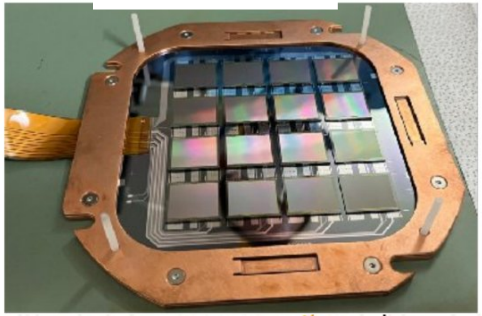


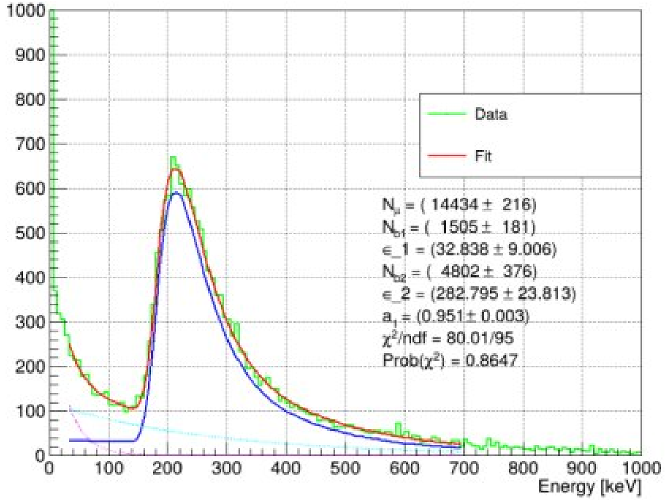
Using this model, and x & y parallel muons, we obtained the size-to-depth relation.

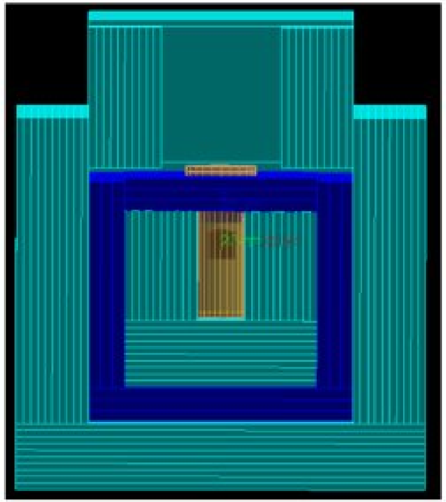


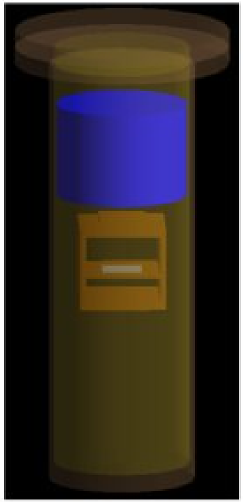
Future Work

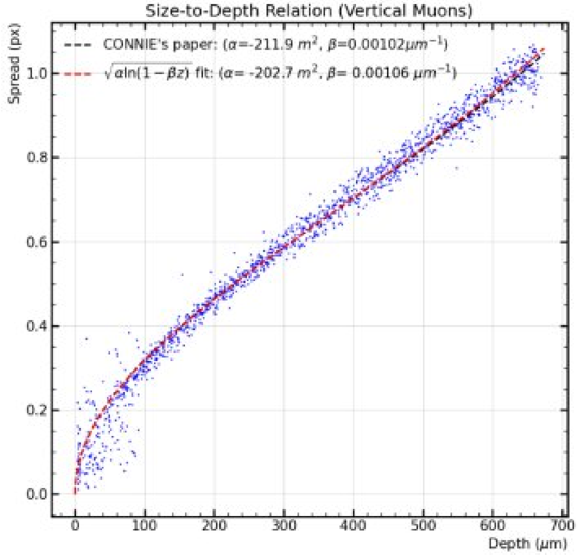
We've implemented the same processes in the international experiment called **COherent Neutrino-Nucleus Interaction Experiment** (**CONNIE**) located in Rio de Janeiro, Brazil, and we're going to start implemented in the new **Multi-Chip Module (MCM)**.











Conclusions

- Skipper-CCD successfully operating at the detectors’ laboratory in the ICN-UNAM. Achieved **sub-electron noise** (0.27 e-) performance.
- .Cross checked Skipper CCD self calibration with an Fe55 x-ray source..
- Geant4 simulation implemented to study calibration with cosmogenic muons.
- Calibration consistent with Fe55 required a **0.90 scaling** between data and simulation.
- The **vertical intensity of the muon flux** was estimated at **103.1 ± 5.8** m^-2 s^-1 sr^-1 . Consistent with previus measuremnts
- Size-to-depth relation obtained with the **x and y-parallel muons** using a **Binomial-Gaussian model.**
- This work is been implemented to the CONNIE experiment with Multi-Chip Module.

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- Dr. Gabriel Zapata (DGAPA)
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- Dr. Jaime Octavio Guerra Pulido (FC-UNAM)
- Dr. José A. Herrera Lara

Thank you for your attention!

Backups

Estimation of I_0

To estimate vertical intensity of the muon flux (I 0) the expression shown below was used.

$$I_0^{est} = I_0^{aux} \left(\frac{n_\mu}{n_{\mu_{sim}}} \right) \left(\frac{T_{sim}}{T_{exp}} \right) \frac{1}{eff}$$

Where

- N_Tsim: total number of simulated muons
- n_mu: # of muons under the fit.
- n_mu_sim: # of muons that hit the sensor.
- T_exp: experimental time (taken from the images)
- T_sim: simulated time (this is obtained from other expression)
- Eff: efficiency of the sensor
- Plane side length (l): length of the plane side that was used in the simulation

Estimation of I_0

The term $= I_0^{aux} \left(\frac{}{n} \right.$ is an auxiliary value, but it doesn’t affect the estimation. To calculate the T_sim, the value N_Tsim was divided by the next expression. This expression is just the integral of the CCD frontal face.

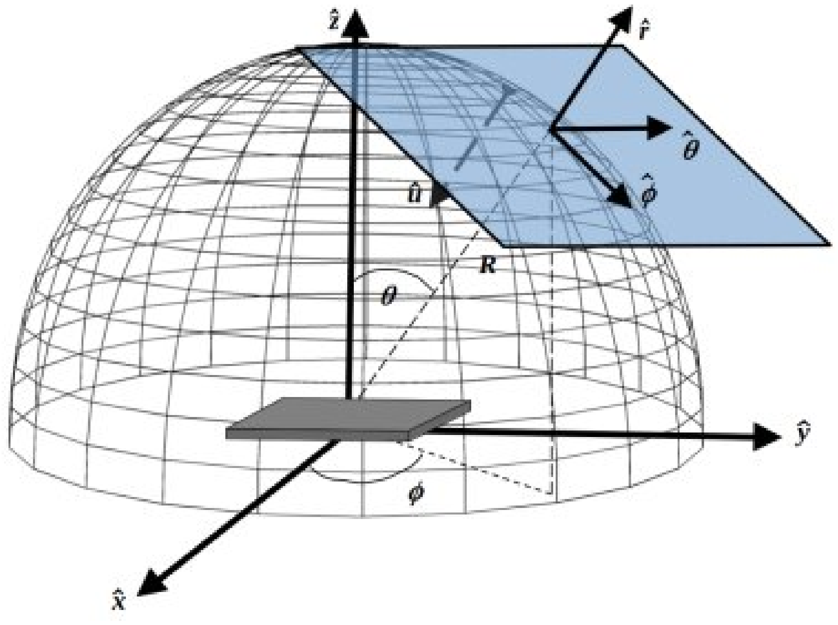
$$\frac{dN}{dt} = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} \int_A I_0 \cos^2\theta \cos\theta \sin\theta \; d\theta d\phi dA = \frac{2\pi}{3} l^2 I_0^{aux}$$

Using a I_0^aux value of 101.2 m^-2 s^-2 sr^-1, and a plane side length of 0.03 m, we obtained that

dN/dt ≈ 0.190758 s^-1 sr^-1.

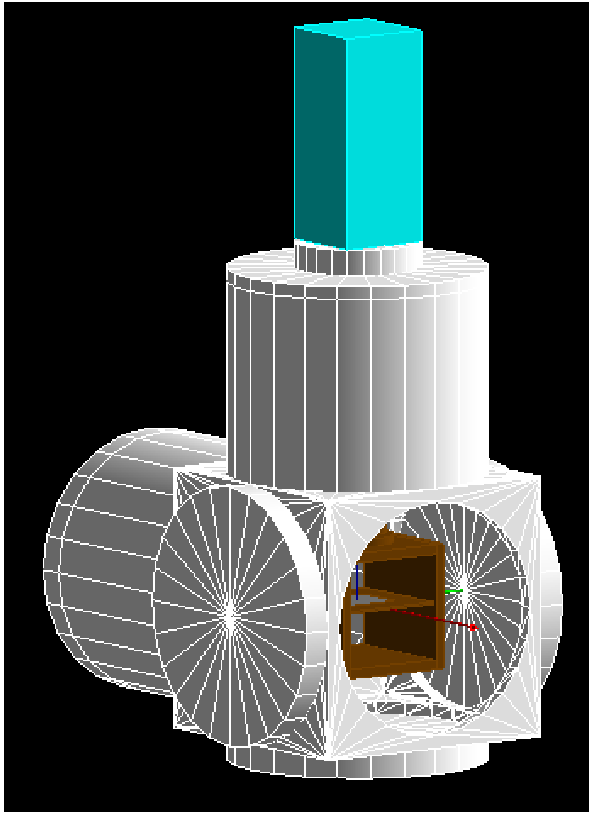
And finally we need to calculate:

$$T_{sim} = \frac{N_{Tsim}}{dN/dt}$$



Estimation of I_0

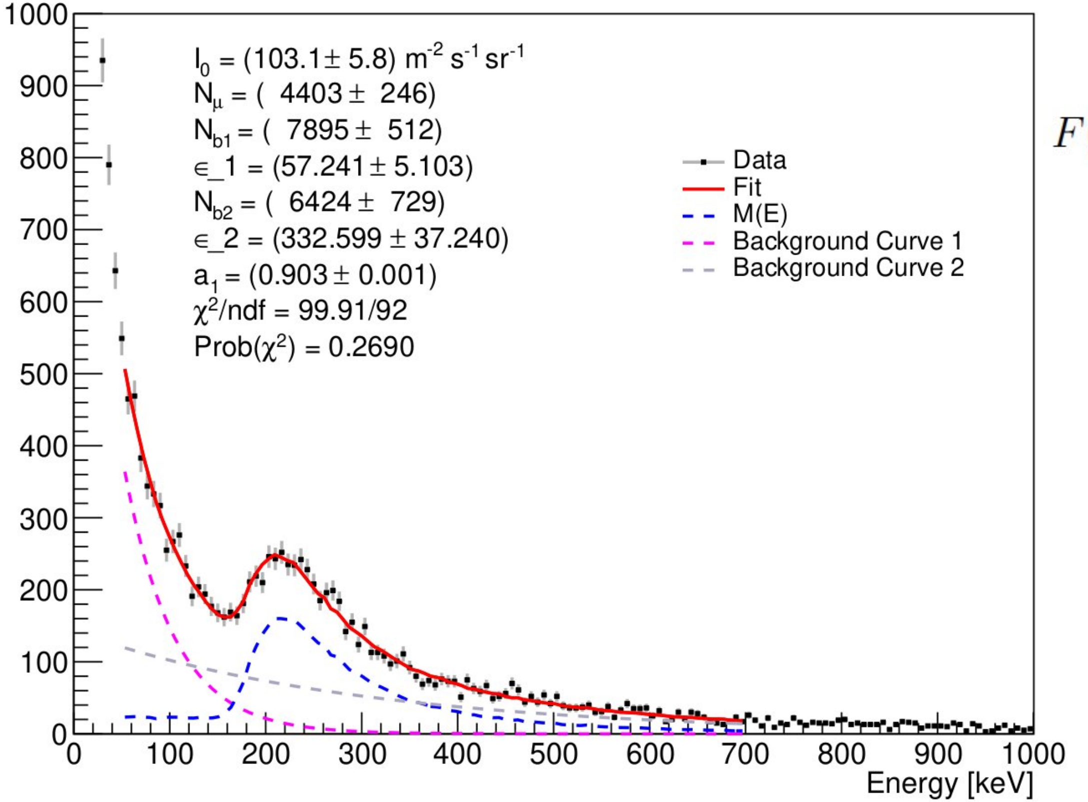
Using the latest version of the simulation, the I_0 was estimated. We use the next parameters for the expressions:



- N_Tsim: 5 millions of muons
- n_mu_sim: 137,157 muons
- T_exp: 825,914 s ≈ 229.42 hrs ≈ 9.56 days
- Plane side: 3.0 cm ≈ 0.03 m
- T_sim: 26,211,288.39 s ≈ 7,290.9 h ≈ 303.4 days
- Eff: 100% (= 1.0)

Estimation of I_0

The fit of the curve F(E) is shown below. From this, we obtained **n_mu = 4403** muons. Finally, the I_0 was estimated at **103.1 ± 5.8** m^-2 s^-1 sr^-1.



$$\boxed{E = a_1 E_d}$$

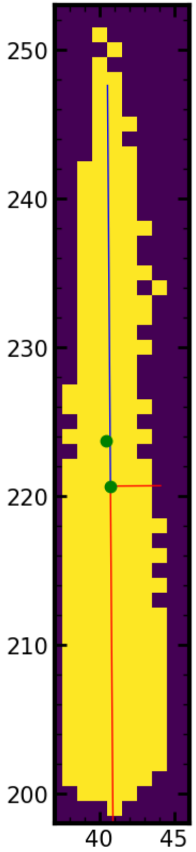
$$F(E) = \left(\frac{dE_d}{dE}\right) \cdot \left[N_\mu M(a_1 E_d) + \sum_{i=1}^{2} \frac{N_{b_i}}{\epsilon_i} \exp\left(-\frac{E_d}{\epsilon_i}\right)\right]$$

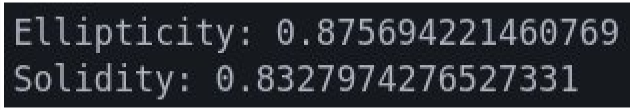
$$= \left(\frac{1}{a_1}\right) \cdot \left[N_\mu M(a_1 E_d) + \sum_{i=1}^{2} \frac{N_{b_i}}{\epsilon_i} \exp\left(-\frac{E_d}{\epsilon_i}\right)\right]$$

$$I_0^{est} = I_0^{aux} \left(\frac{n_\mu}{n_{\mu_{sim}}}\right) \left(\frac{T_{sim}}{T_{exp}}\right) \frac{1}{eff}$$

Muon Detection Algorithm

The principal parameters that we use are the **ellipticity** and the **solidity**. The first one is to measure how long the cluster is, and the second one is to measure how compact it is; both are between 0 and 1. We use a threshold of 0.65 for both.





Solidity examples.