Optics and reconstruction with Coded Aperture masks

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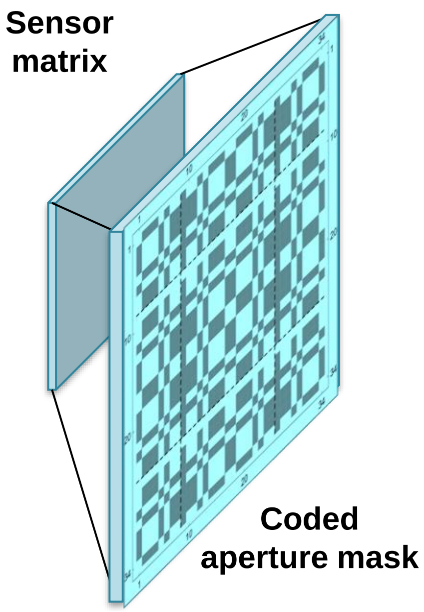
CSN1 Review of SAND

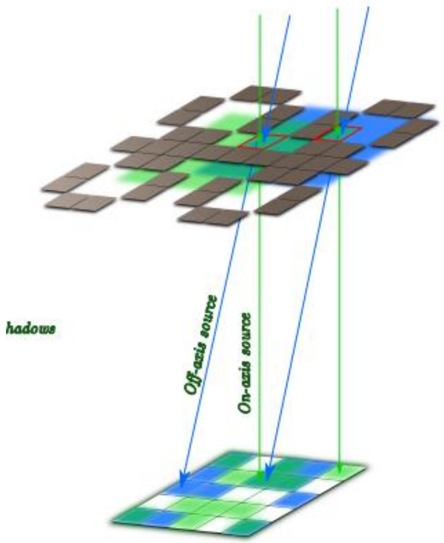
11/07/2024

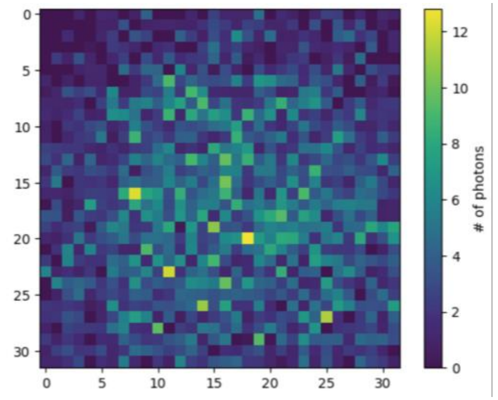
Coded aperture (CA) imaging



- A Coded aperture mask is a thin sheet of opaque material with a well-defined pattern of holes placed at a fixed distance from a sensor plane.
- conceptually the evolution of a single pinhole camera
  - A matrix of multiple pinholes improves light collection
- Advantages:
  - Light transmission (depends on mask pattern/holes size, usually ~50%)
  - Compact design
  - Robust and easy to build

concept





The image formed on the sensor is the superimposition of multiple pinhole images

Reconstruction with CA masks

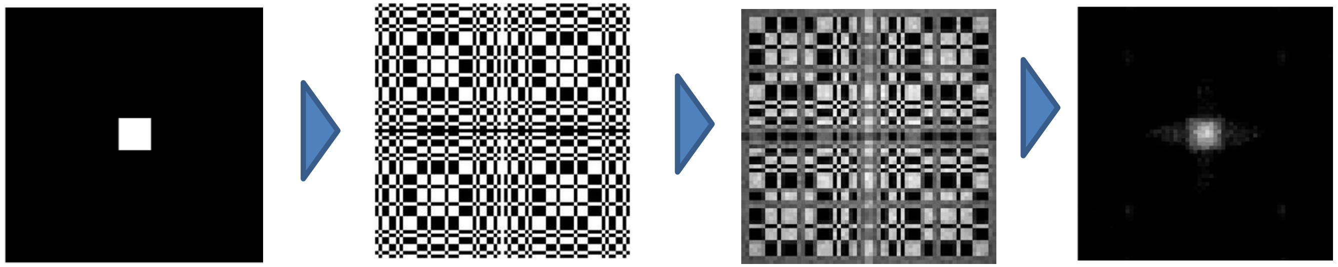
- For **FAR field** imaging (e.g. Astrophysics applications):
  - the original image can be obtained with a **deconvolution** process where the decoding matrix is derived from the mask pattern

$$O'(x,y) = I\,(x,y) \otimes H\,(x,y)$$

Source — detected image — Decoding matrix

$$M(x,y) \otimes H(x,y) = \delta(x,y)$$

mask



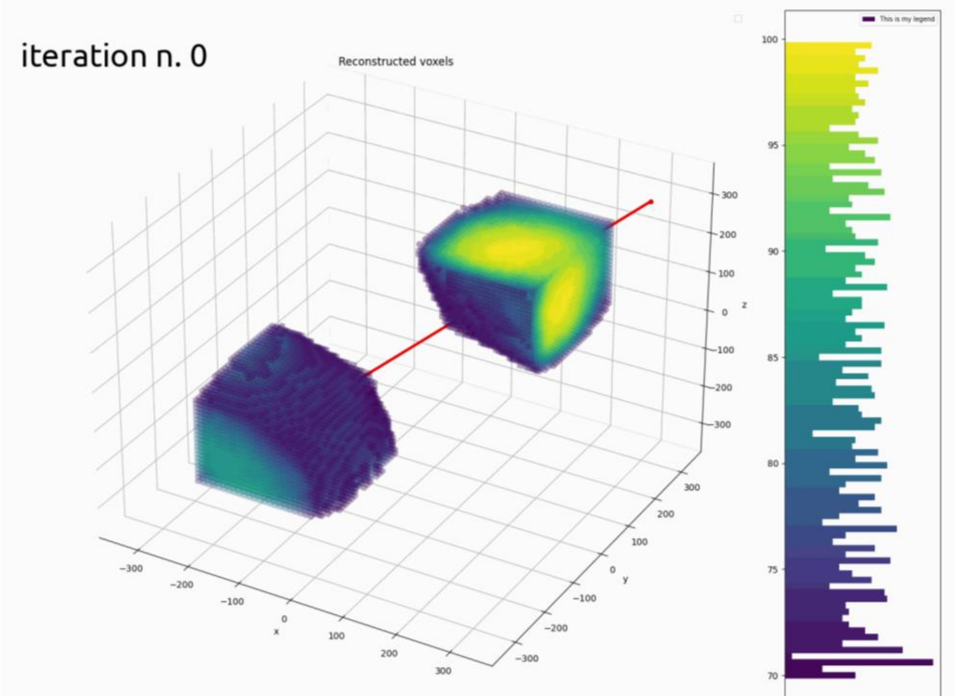
Source — Mask pattern — Encoded image — Reconstructed image

- for **NEAR field** imaging (i.e. GRAIN scale) and low light yields:
  - more complex and computationally intensive algorithms are typically implemented

  (Filtered Back Projection, **Maximum Likelihood Expectation Maximization** algorithms…)

GRAIN Reconstruction algorithm

- Directly reconstructs in 3D dimensions the initial photon source distribution in a segmented volume (voxels)
- Combines information of multiple cameras at once
- **Maximum Likelihood Expectation Maximization** (MLEM) algorithm:
    - iteratively converges to the photon source distribution that maximizes the likelihood of detecting the observed images
- Implemented for execution on (multiple) GPUs



GRAIN Reconstruction algorithm

- Photon counting is described by a Poissonian pdf:

$$f\,(H_s|[\lambda_s]) = e^{-[\lambda_s]}\,\frac{[\lambda_s]^{H_s}}{H_s\,!}$$

$$[\lambda_s] = \sum_j \lambda_j\, p(j,s)$$

H_s number of detected photons by sensor *s*

$[\lambda_s]$ detected photons expectation value

λ_j unknown photon emission in voxel ***j***

p(j,s) probability of a photon that originated in voxel *j* is detected by pixel *s*

- Likelihood for all sensors:

$$\prod_s e^{-[\lambda_s]}\,\frac{[\lambda_s]^{H_s}}{H_s\,!}$$

maximization

Reconstruction algorithm:

$$\lambda_j^{k+1} = \frac{\lambda_j^k}{\sum_s p(j,s)} \cdot \sum_s \frac{H_s \cdot p(j,s)}{\sum_j p(j,s)\cdot \lambda_j^k}$$

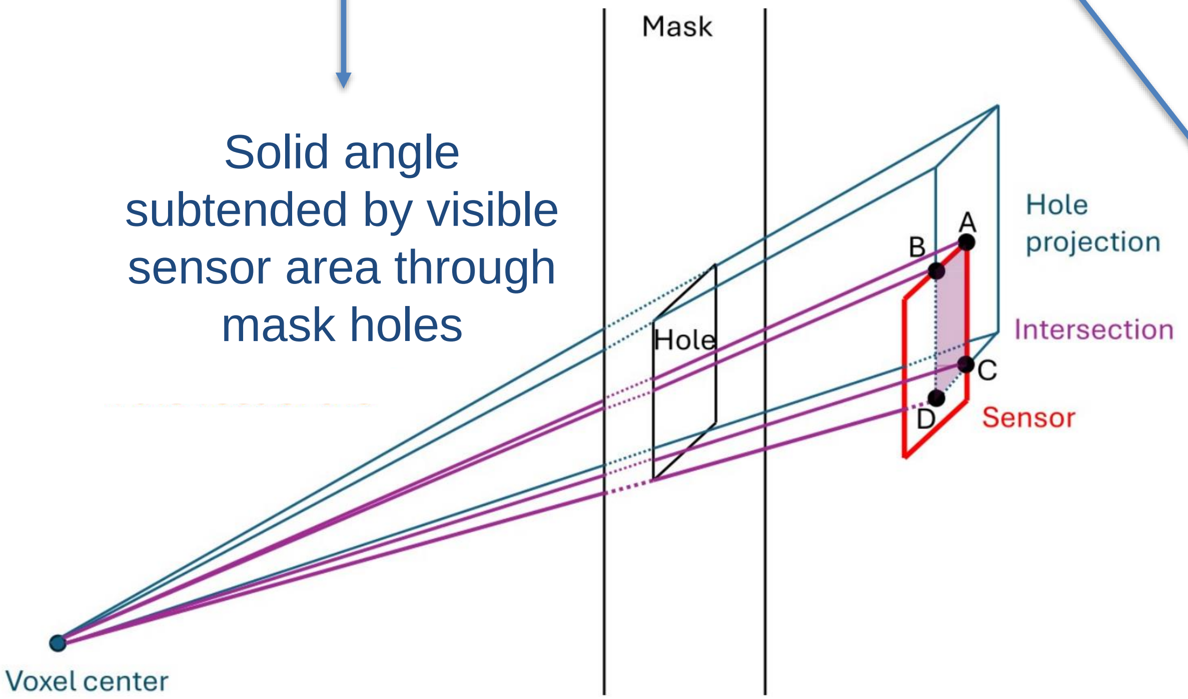
k iteration number

GRAIN reconstruction algorithm

The algorithm key element is the accurate computation of **p(j,s)**

$$p\,(j,s) = P\,geometry\,(j,s) * P\,LAr\,(j,s) * P\,sensor\,(s)$$

Solid angle subtended by visible sensor area through mask holes



Sensor Photon Detection Efficiency

Photon absorption in LAr
Depends on distance between voxel and sensor

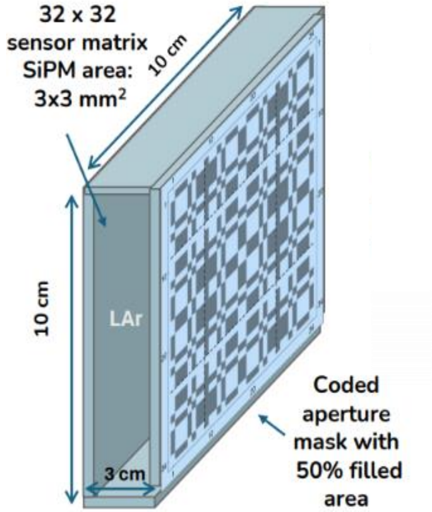
GRAIN CA imaging system

- **Sensor matrix:**
  - 32 x 32 Silicon Photomultipliers (SiPM)
  - SiPM active area: 3x3 mm^2

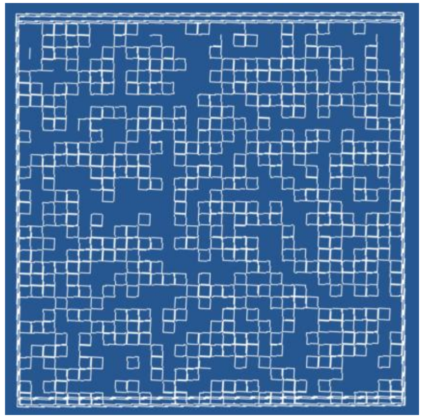
- 60 cameras in GRAIN
- covering elliptic sides + bottom and top rows

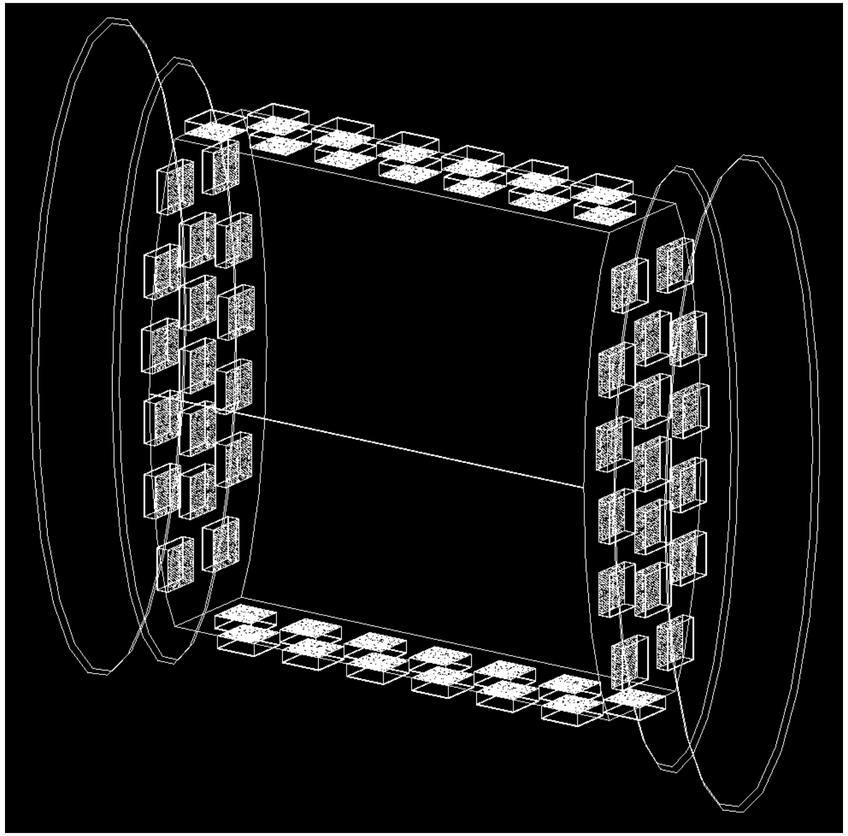
- **Coded aperture mask**:
  - Random uniform pattern of holes
  - Holes aligned to SiPMs, area: 3x3 mm^2
  - Distance from sensors: 3 cm

Camera design was optimized with simulations in simplified geometry

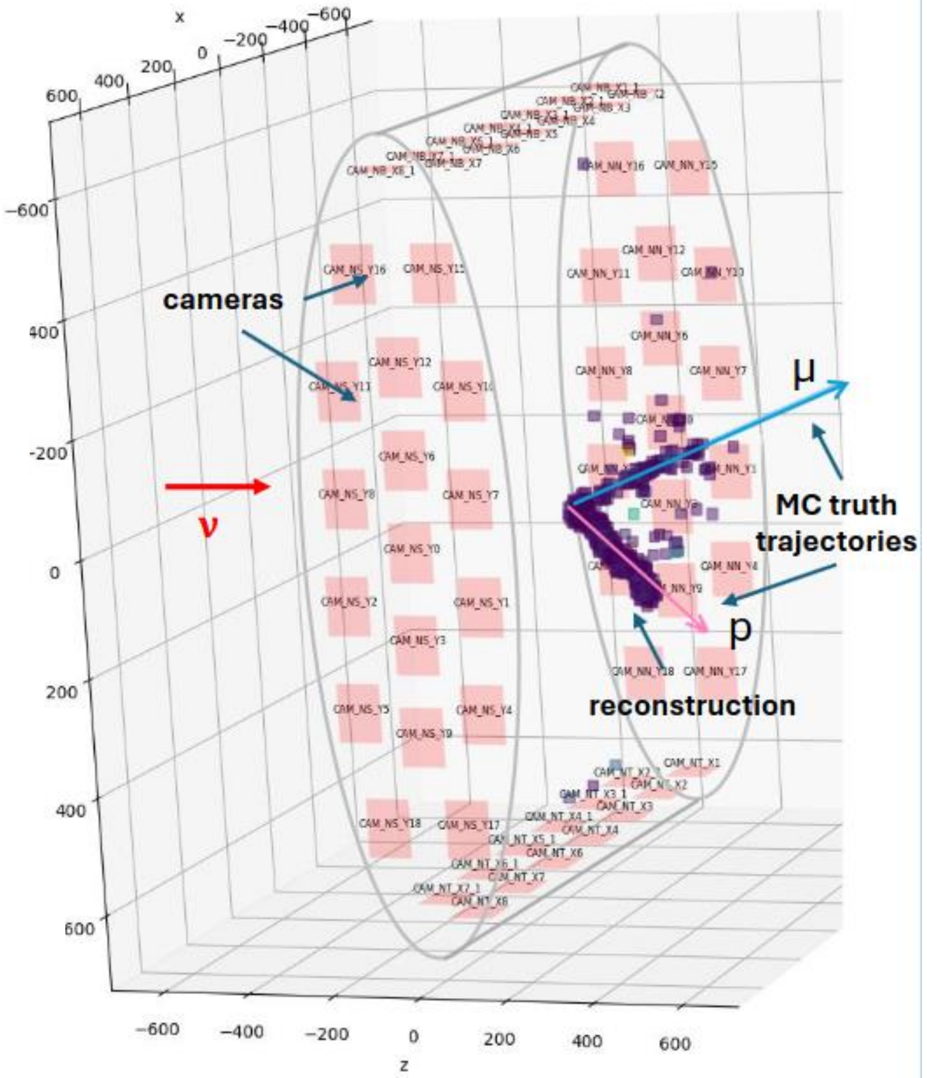


Mask pattern





Example of reconstructed neutrino event



***ν* – Ar Charged Current Quasi-Elastic scattering**

Reconstruction:

- 12 mm voxel size
- 200 algorithm iterations
- Shown voxels with estimated photon emission ~> 5% of max value

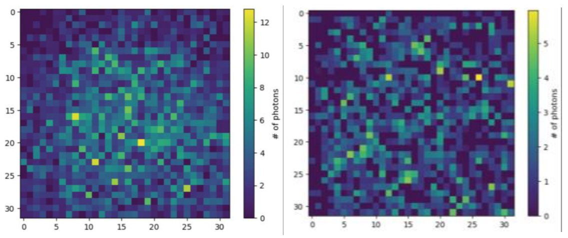
Simulation and reconstruction chain

Event generation (Genie) → **Energy deposits simulation (Edep-sim)** → **Propagation of optical photons in LAr simulation (GEANT4)** → **Detector response simulation**

→ **3D MLEM reconstruction** → **Track finding and fitting** → 3D tracks

→ **Calorimetry** → 3D tracks

Camera images



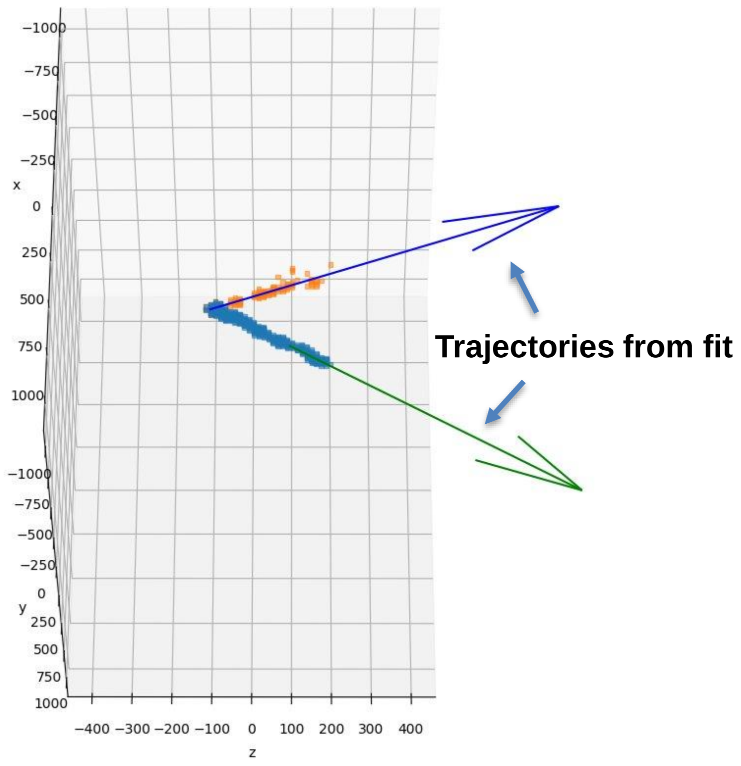
3D tracks:

- Start/end direction
- Containment in GRAIN
- Matching with tracker
- Energy deposited

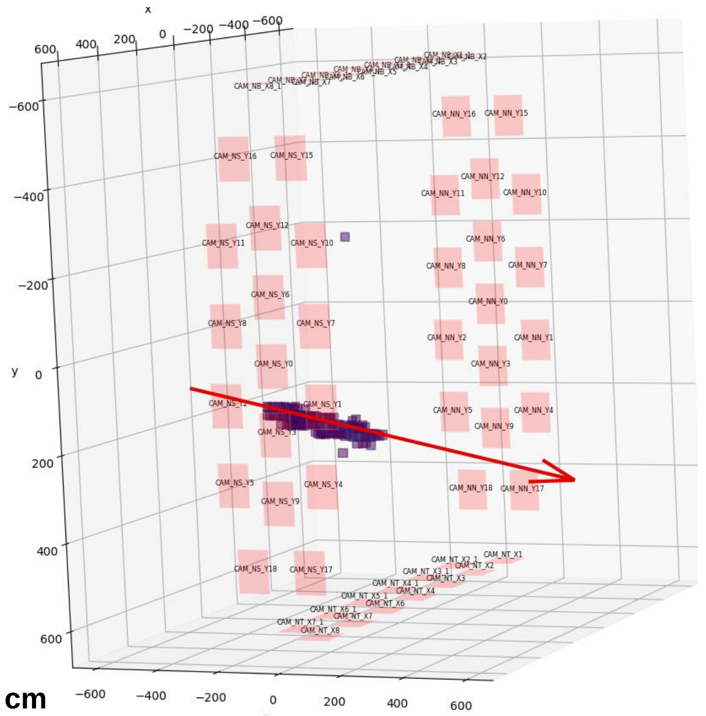
Reconstruction analysis

Development of analysis tools for the Coded Aperture Masks 3D reconstruction is in progress.

- **Analysis steps**:
  - Thresholding
  - Track finding:
    - Weighted 3D Hough transform for lines
    - match voxels to track seeds
  - Track fitting:
    - minimization of squared distance weighted with voxel scores



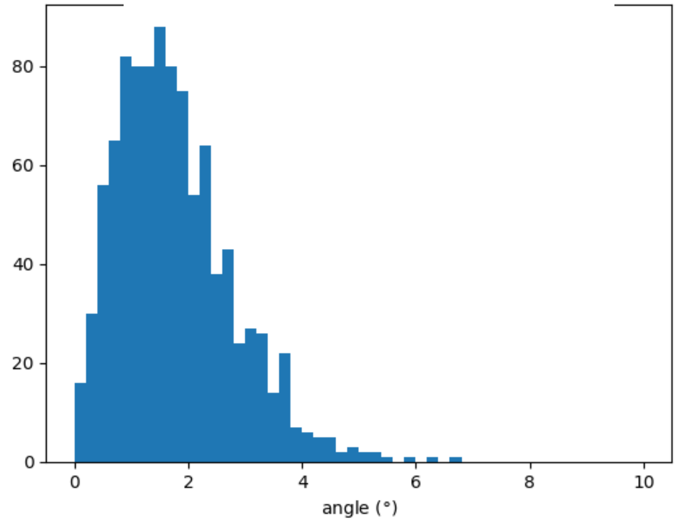
Muon reconstruction in GRAIN



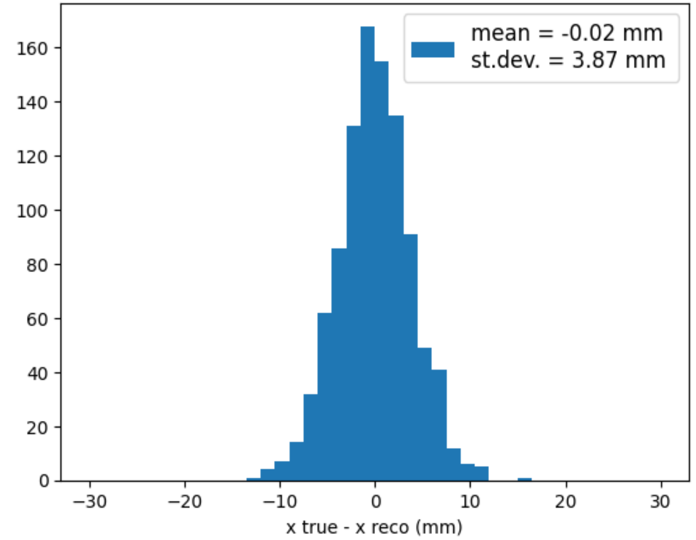
Simulated sample:
- 1k muons crossing GRAIN along z
- Origin position: ([-30, + 30], [-30, + 30], -50) cm
- Direction: θ = [160, 180], φ = [0, 360]
- Energy = (1 ± 0.3) GeV

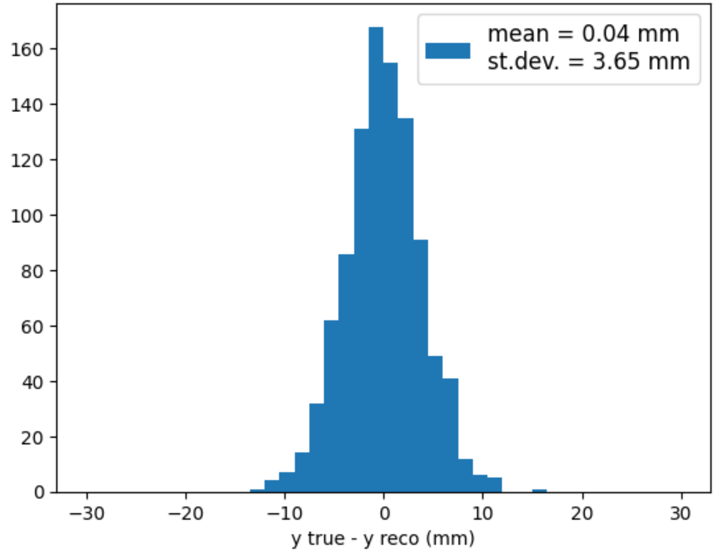
Reconstruction:
- Voxels size = 18 mm
- Iterations = 200
- Reconstruction time: ~ 3.5 min / event

Angle between MC and reconstructed track direction



Track position residuals at z = 0 cm



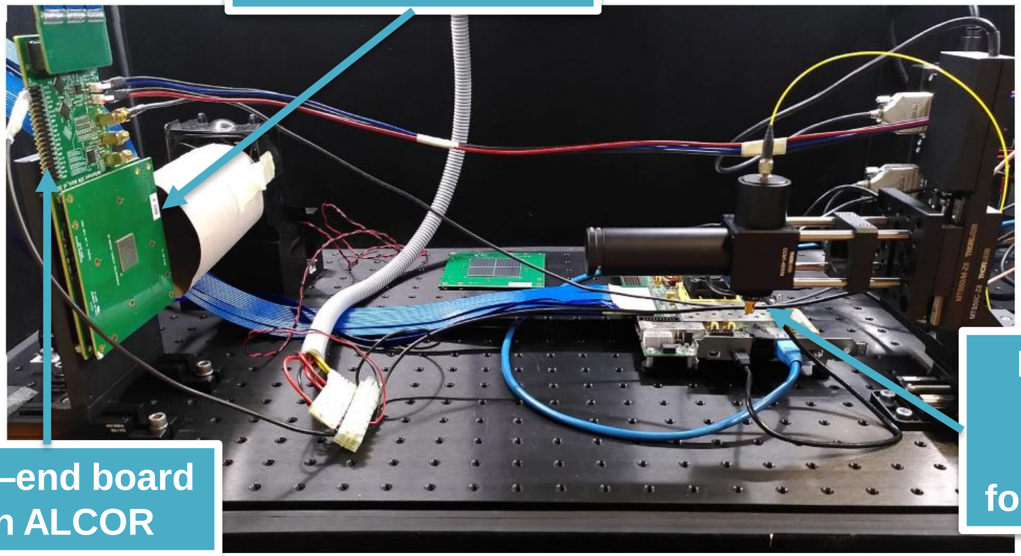


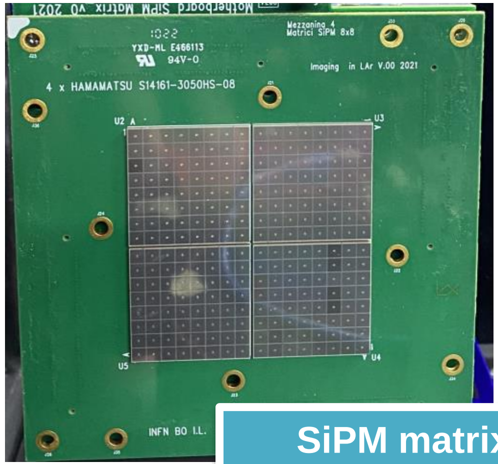
Camera prototype

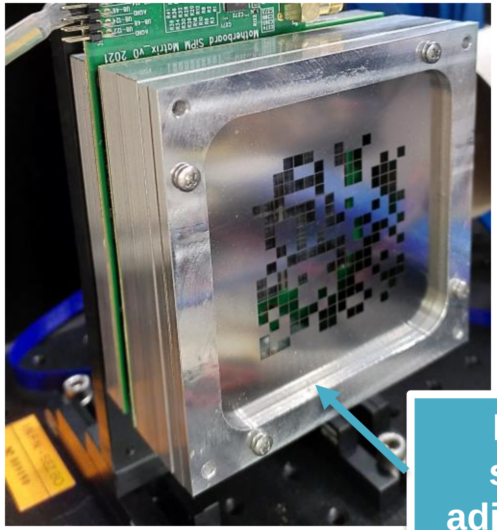
- Built 2 camera prototypes:
  - 16 x 16 SiPM matrix
  - SiPM area 3x3 mm^2
  - Mask: stainless steel sheet 120 um thick, laser cut

- Front end electronics with 8 ALCOR ASIC
- DAQ with a Xilinx FPGA board

- to be tested in LAr at ARTIC facility at Genoa with cosmic rays







Conclusion

- A tracking and calorimetry system for GRAIN based on the imaging of LAr scintillation light is being designed
- A “camera” of GRAIN imaging system will be based on matrices of SiPM coupled either to VUV lenses or **Coded Aperture masks**
- For the CA system we implemented a MLEM algorithm that directly reconstructs the event in 3D, with GPU acceleration
- First CA camera prototypes with 16 x 16 pixels have been built and will be tested in LAr in the incoming months.