3D RECONSTRUCTION AND CALORIMETRY WITH CODED APERTURE MASKS STATUS

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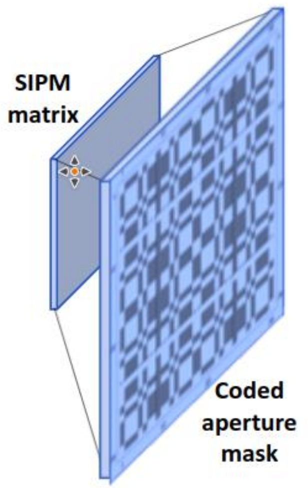
DUNE Italia collaboration meeting - LNF
8/11/2022

3D RECONSTRUCTION WITH CODED APERTURE MASKS



Coded aperture mask techniques were developed as the evolution of a single pinhole camera

Matrix of multiple pinholes to improve light collection and reduce exposure time

Image formed on sensor is the superimposition of multiple pinhole images.

Advantages:

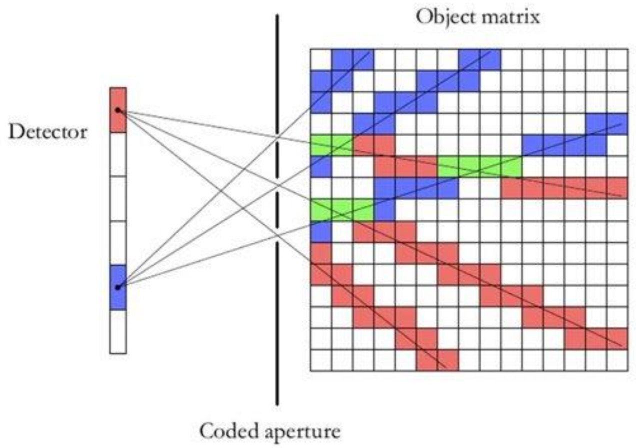
- Good light transmission (50%)
- Good depth of field
- Small required volume

Detailed description of Hadamard masks and deconvolution methods:
Eur. Phys. J. C 81 (11) 1011 (2021)

Readout system with SiPM matrixes coupled with coded aperture masks.

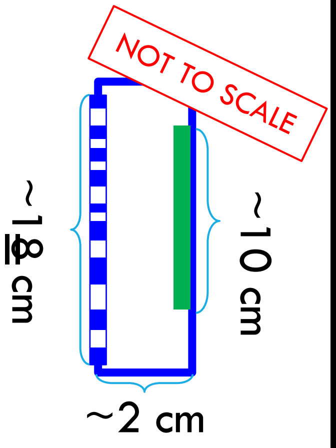
The custom **reconstruction algorithm** produces a **3D map of the deposited energy**:

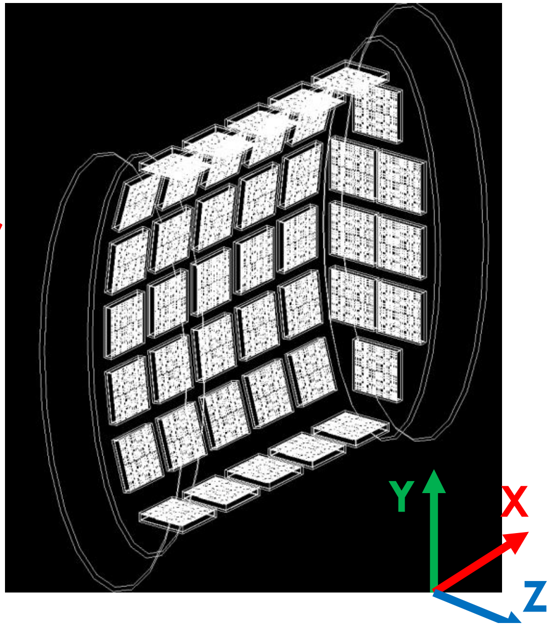
- measured incident photons are propagated back into the LAr volume with an appropriate weight assigned to voxels.
- This weight represents the Bayesian probability of the voxel to be a source of the detected photons.
- A score in the segmented reconstruction volume is calculated by adding these weights.

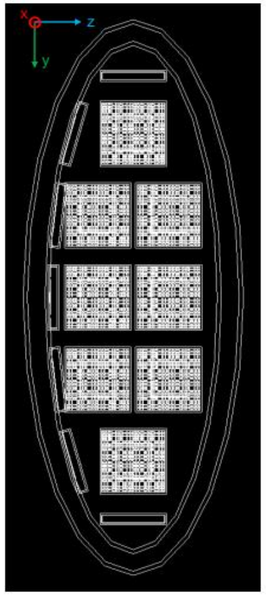


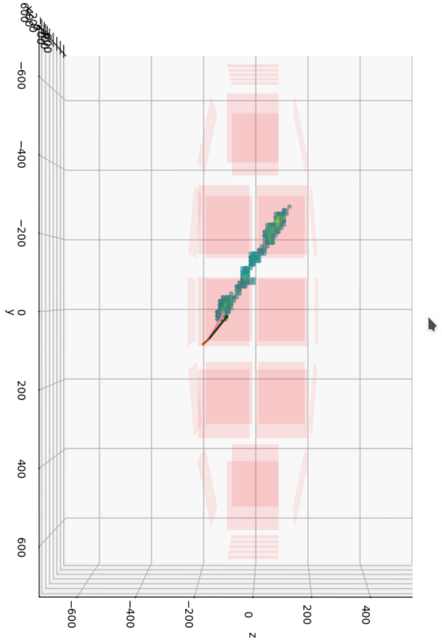
RECONSTRUCTED NEUTRINO EVENTS IN GRAIN

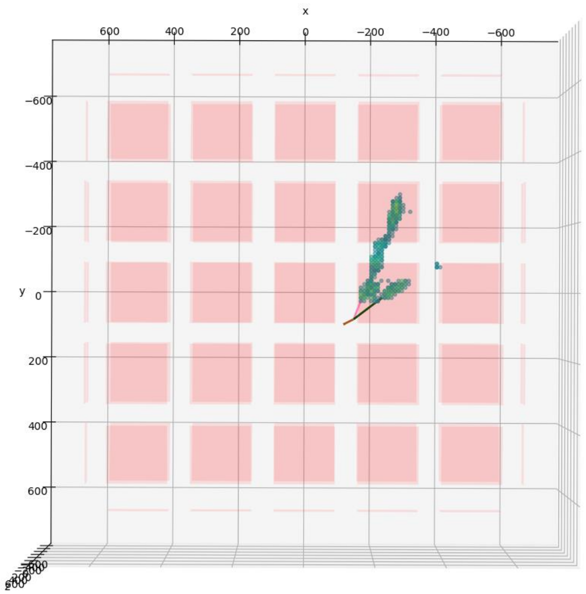
- Simulated GRAIN geometry: x, y, z = 130 x 146 x 48 cm3
- 76 cameras, covering most of the available surface:
  - 25 cameras on each curved (YX) face arranged in a 5x5 grid
  - 5 cameras on top/bottom
  - 8 cameras on each side (YZ) face
- 32x32 matrix sensors, 3.2 mm pixels and 25% QE with full electronics simulation
- 2x2 mosaic rank 31 Hadamard pattern, mask pitch 2.91 mm

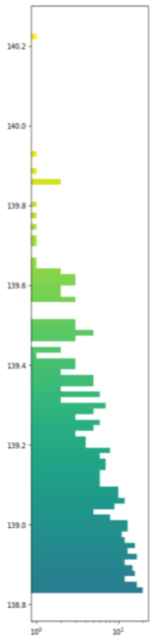


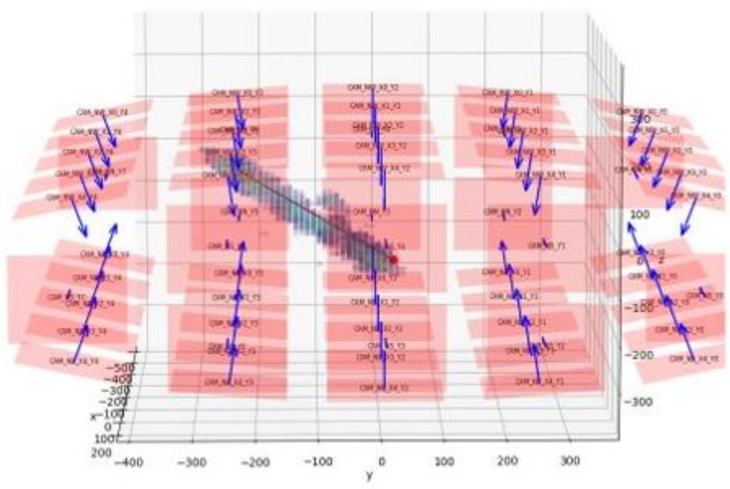








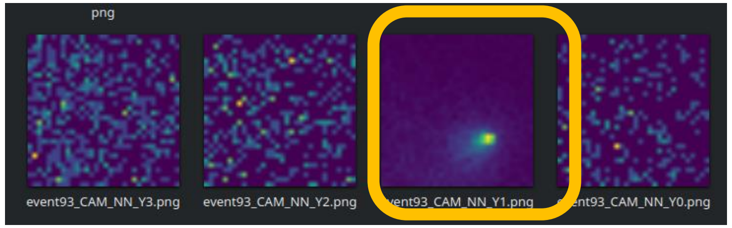




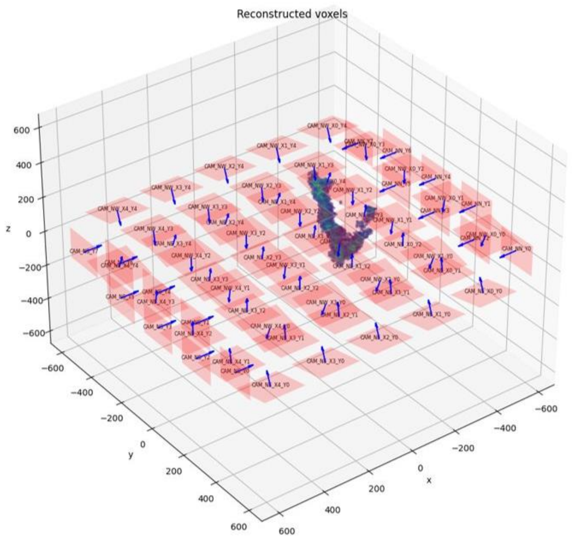
CHALLENGES

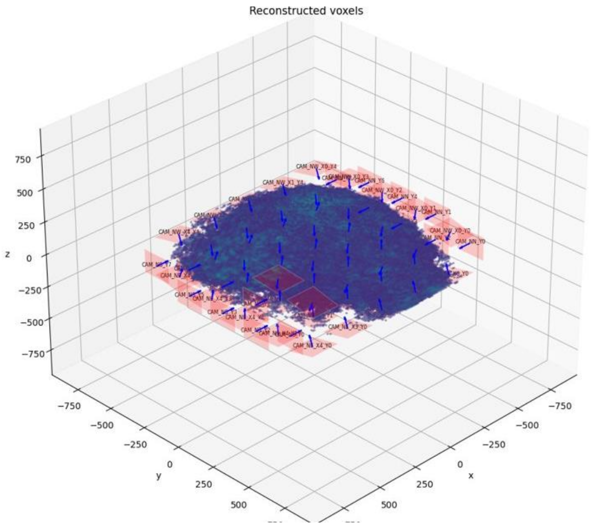
1. Computationally heavy – parallel implementation on GPU, weights are geometry dependent and can be precomputed once and stored.

2. Particles may cross a camera, producing photons between the SiPM matrix and the mask, “blinding” them. A Method based on Convolutional Neural Networks to be developed to classify blind camera and remove them from reconstruction.



3. Low contrast between signal and background voxels:





Same event neutrino event, voxel selection amplitude cuts:

(1) 98.5% of max value

(2) 95.5 % of max value

ITERATIVE ALGORITHM

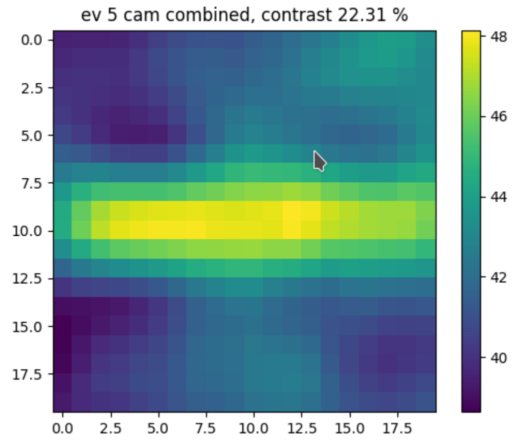
Iterative algorithm based on Maximum Likelihood Expectation Maximization:

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

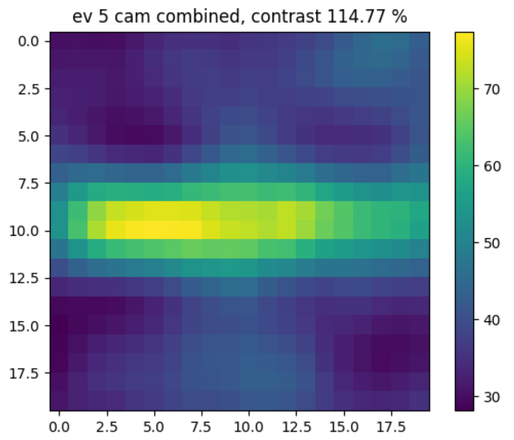
- λ_j^k activity density of voxel j at iteration k
- $p(j,s)$ probability of a photon originated in voxel j is detected by pixel s
- H_s detected photon on pixel s

Contrast improvement

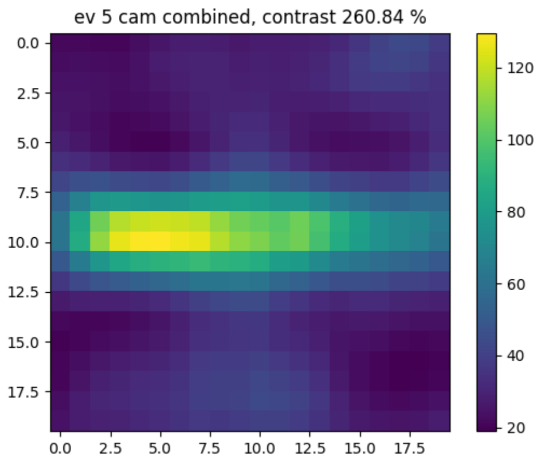
1 Iteration

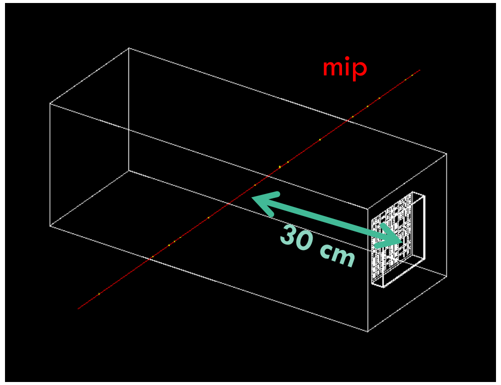


5 Iterations

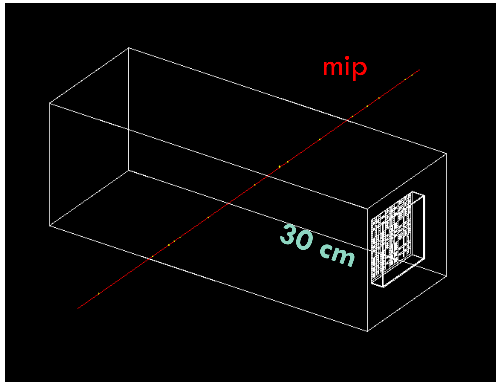


10 Iterations



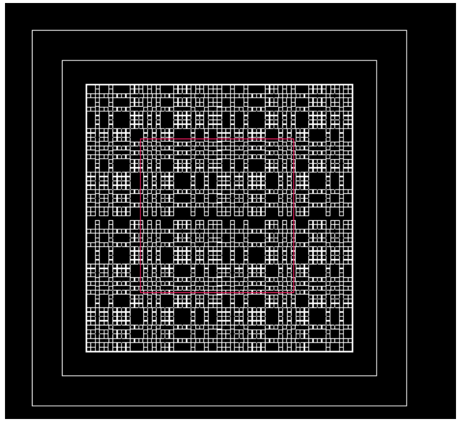


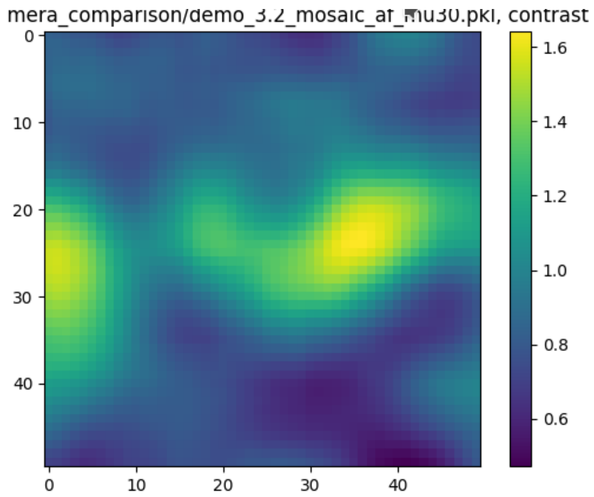
CAMERAS COMPARISON



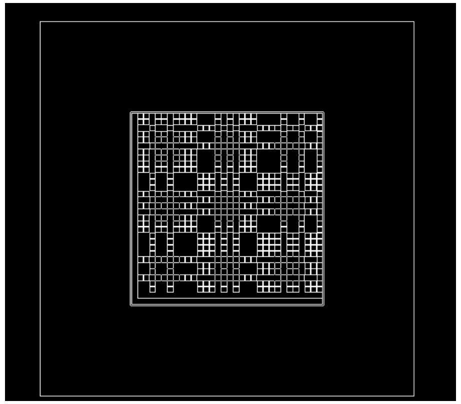
Performance comparison of different mask sizes and ranks with Hadamard pattern

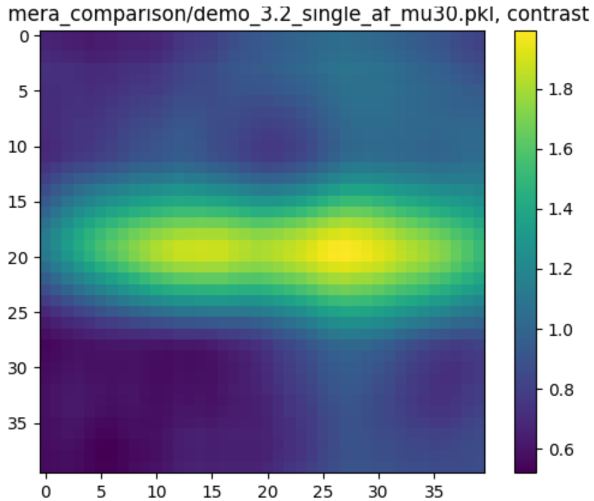
GRAIN mosaic
2x2 masks rank 31



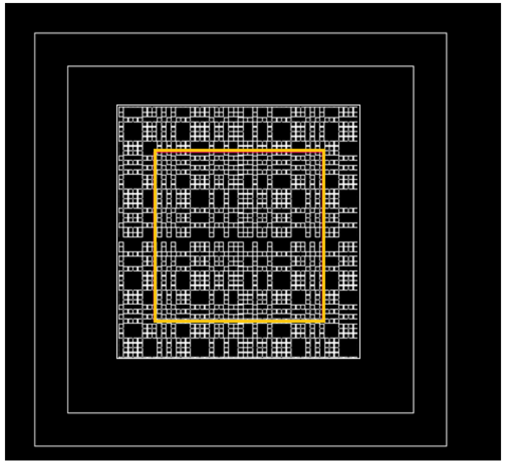


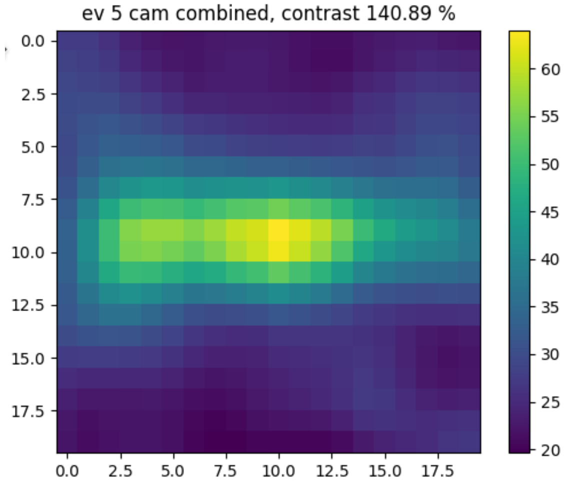
mask rank **31**
Mask size = sensor matrix





mask rank **43**

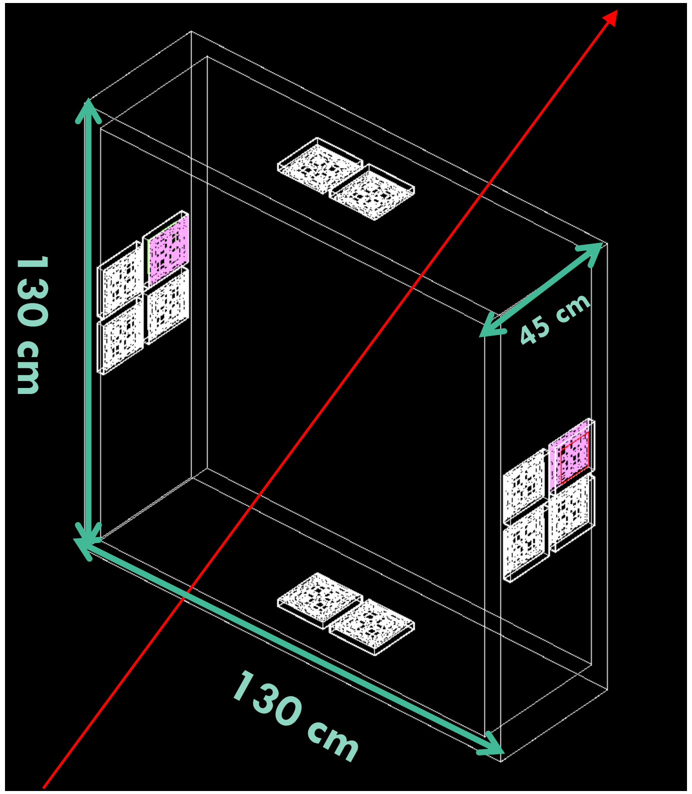


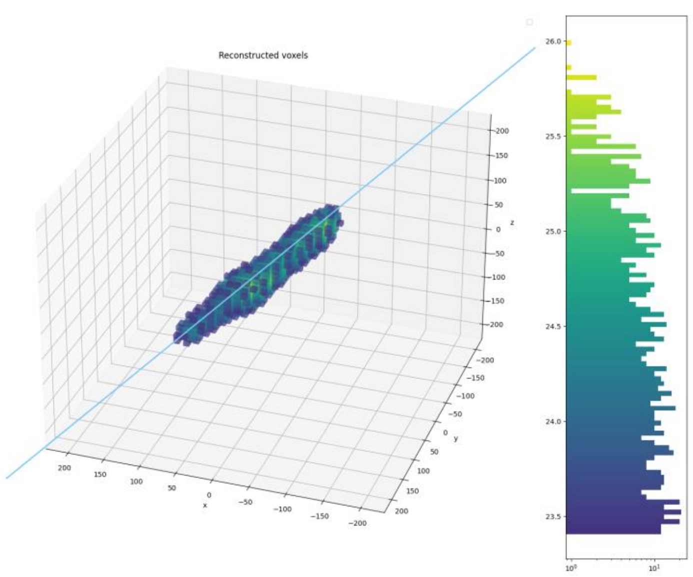


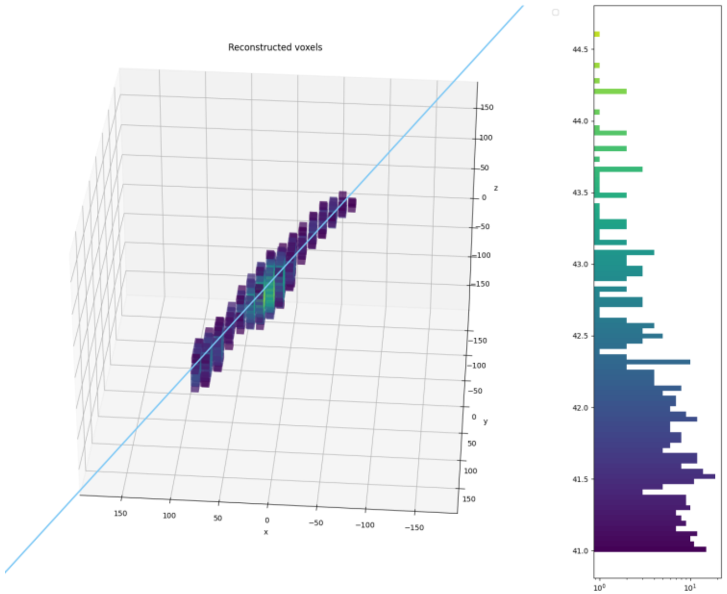
MIPS SIMULATION IN GRAIN SIMPLIFIED GEOMETRY

- Simplified geometry with 2x2 cameras placed on cryostat sides and a single camera row on top and bottom, 130 cm apart
- Diagonal muons ~3 GeV simulated through volume center
- 5 iteration of MLEM algorithm
- Time window for photon collection = 200 ns, 25% PDE

- With rank 31 and rank 43 masks track reconstruction is possible
- Track ~ 6-8 voxels width →local principal curves algorithm







Next step:
Tracks and nu events GRAIN geometry with full coverage of side walls

ENERGY RECONSTRUCTION IN GRAIN

After isolating the contribution of each event from the background of the previous events (see V. Pia's talk), we want to Reconstruct the deposited energy in GRAIN from the total number of detected photons

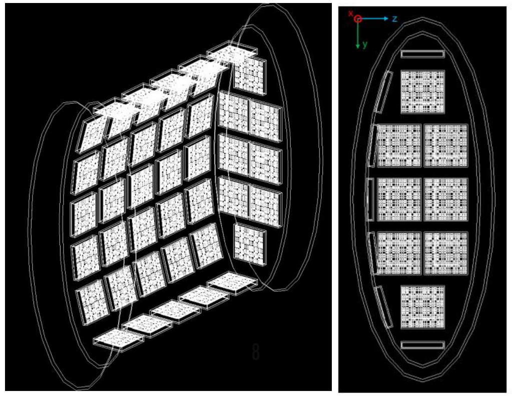
Obtain a calibration coefficient to estimate the total deposited energy from the number of the detected photons.

Challenges:

- Space dependence
  - Same events in different positions inside GRAIN generate a different number of photons.
- Large number of events required
  - Long computational time

Solution:

- Different coefficients for different volume region
  → 1/8 of GRAIN volume divided in 5x5x5 cm voxels
- Reduce light yield
- Fast detector response



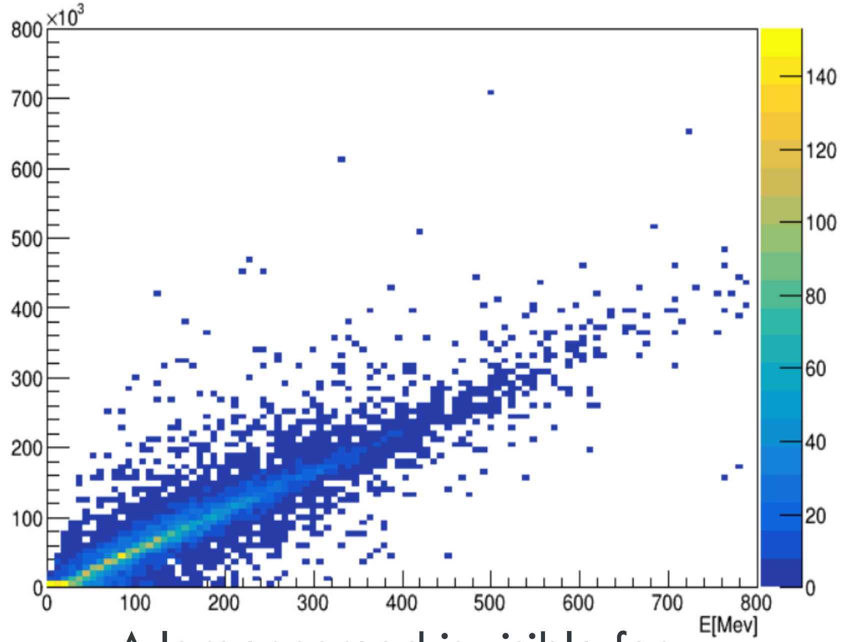
N.B. Calorimetry studies performed with mosaic cameras and full wall coverage

UNIFORM/CENTRAL VOXEL COMPARISON

A comparison between neutrino events with vertex in the central voxel and a uniform distribution in GRAIN volume was made to check whether or not the space dependence complication is real.

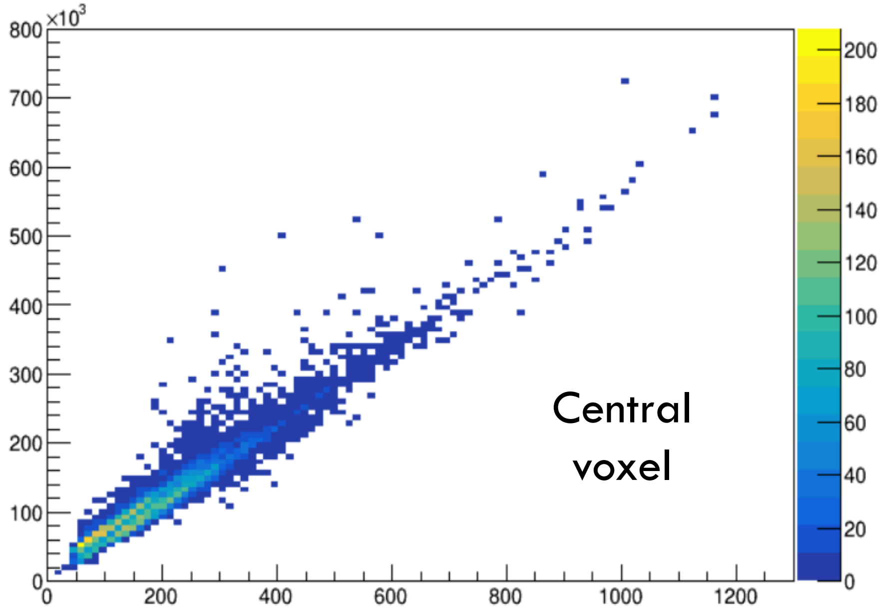
Sample:
10k ν_{μ} CCQE

Detected photons for **numu CCQE interaction**
Vs
Deposited energy (from EDepSim)



A larger spread is visible for the uniformly distributed events.

Detected photons for **numu CCQE interaction**
Vs
Deposited energy (from EDepSim)

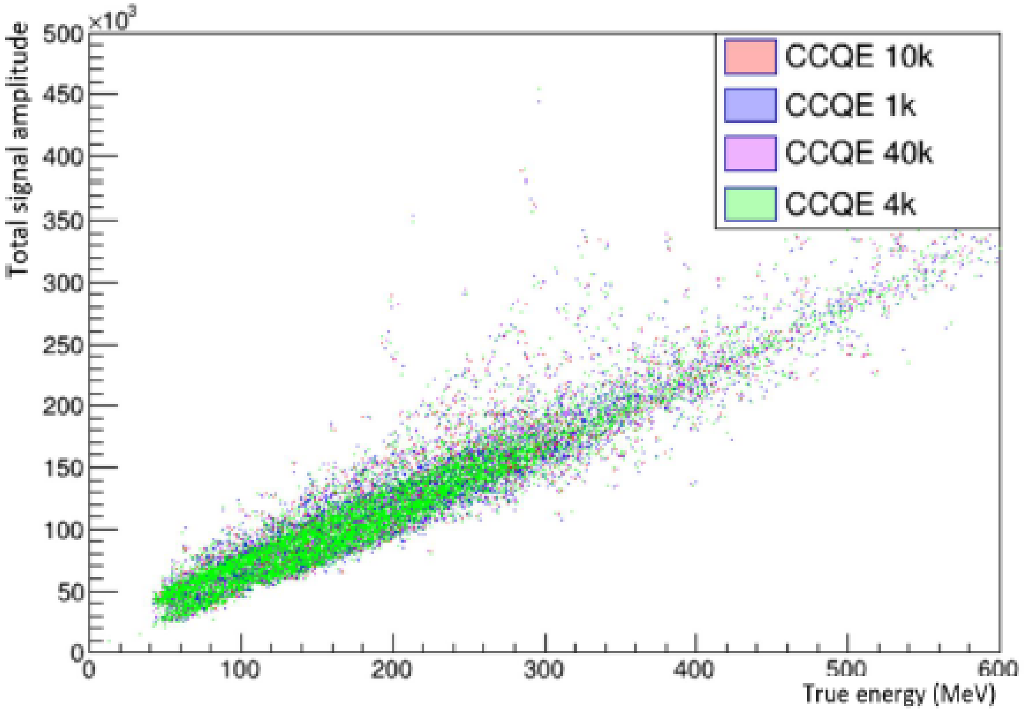


The calibration must be performed on a local scale.

REDUCED LIGHT YELD + FAST RESPONSE VALIDATION

Light yield reduction

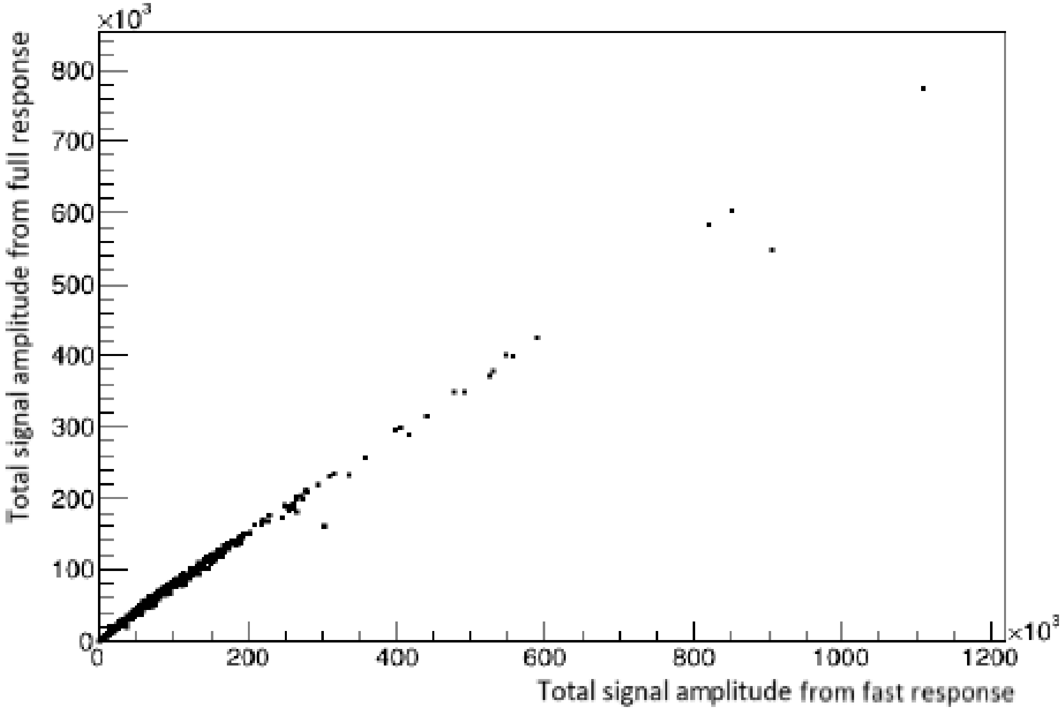
Good proportionality has been found in the number of detected photons for different light yields of **10k photons/MeV scaled to 40k photons/MeV**



Fast vs Full response simulations

Linear correspondence between the two simulations has been found

- Light yield = 10k photons/MeV



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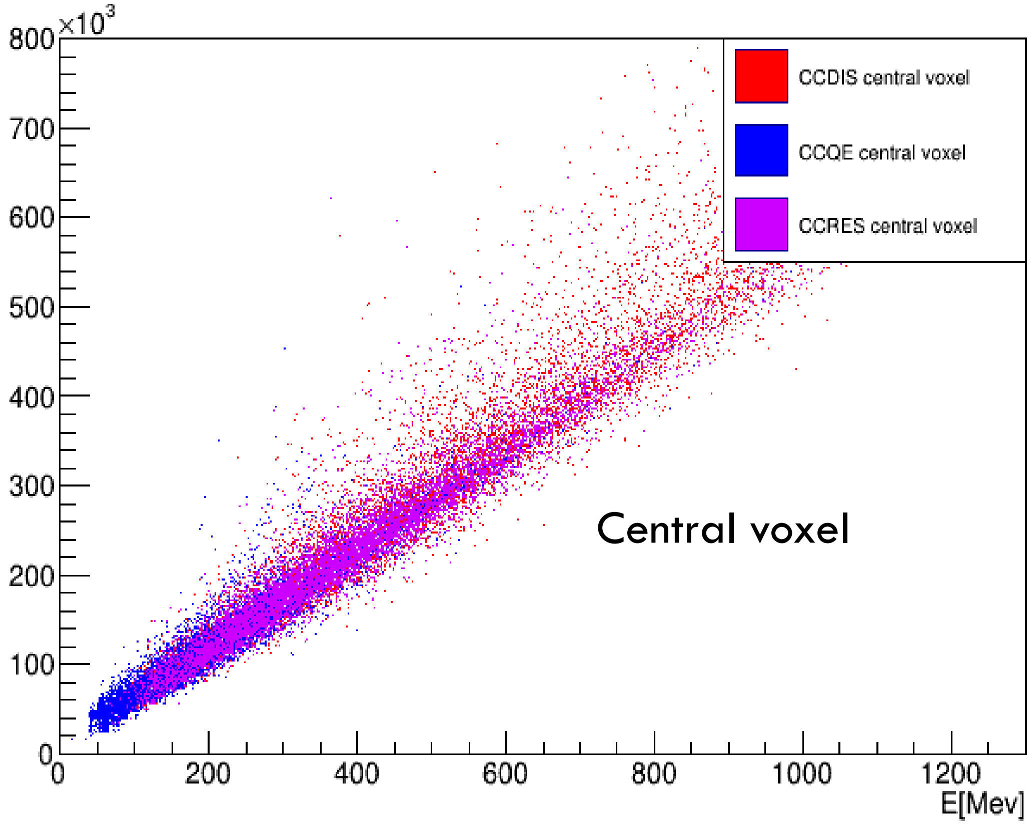
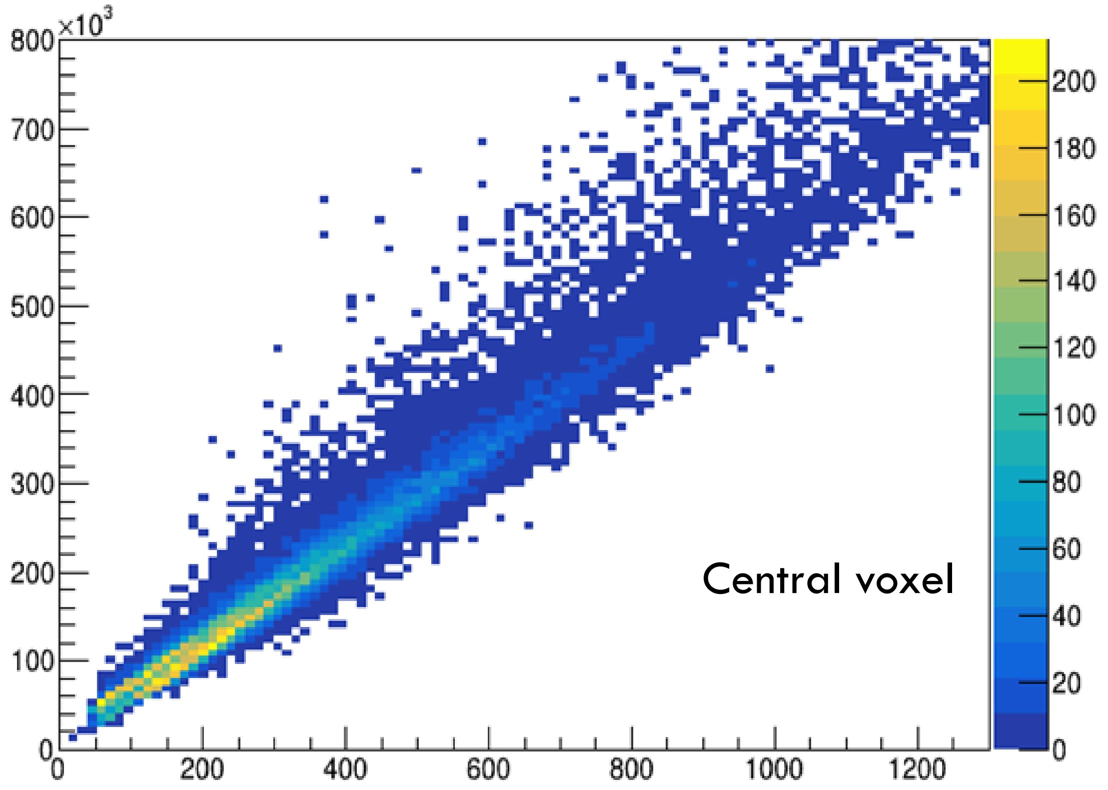
CENTRAL VOXEL EVENTS

Samples:
10k ν_μCCQE
10k ν_μCCDIS
10k ν_μCCRES

Detected photons for **different numu interaction types**
Vs
Deposited energy (from EDepSim)

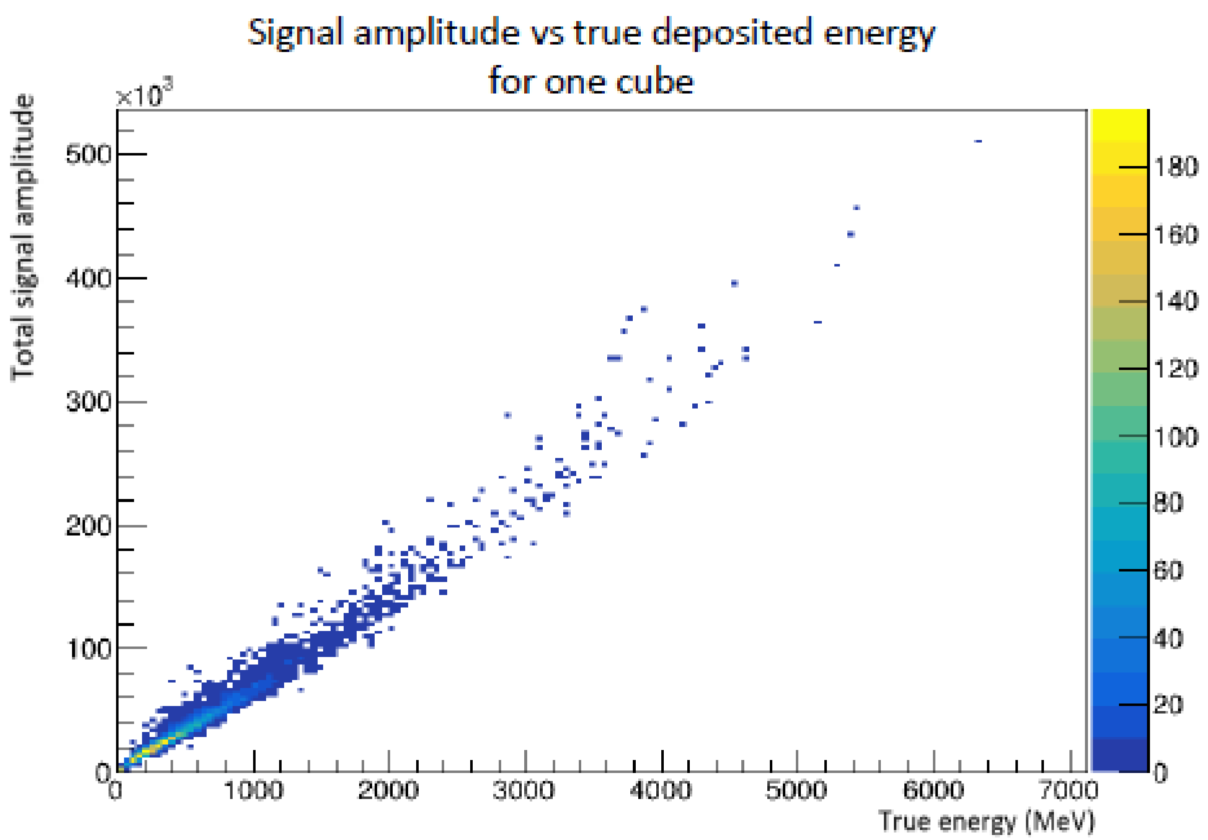


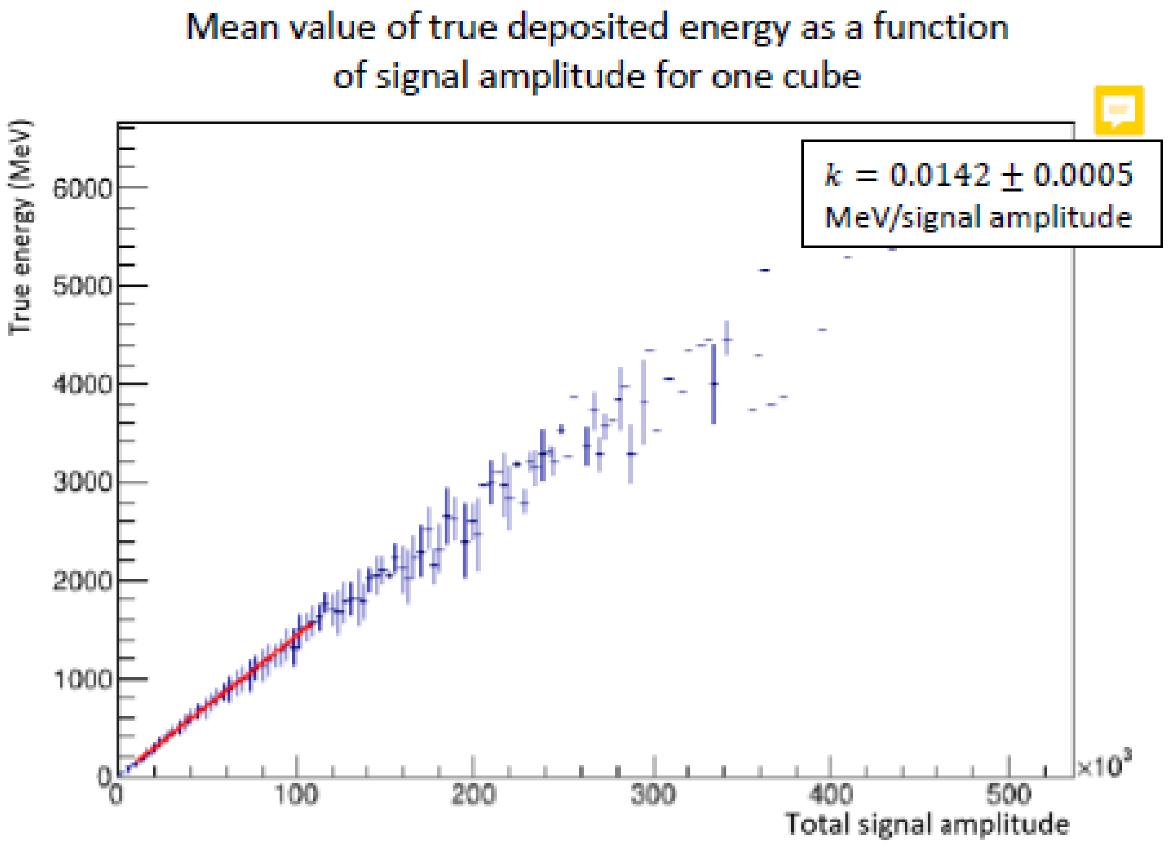
Detected photons for **different numu interaction types**
Vs
Deposited energy (from EDepSim)



RECONSTRUCTED ENERGY RESOLUTION

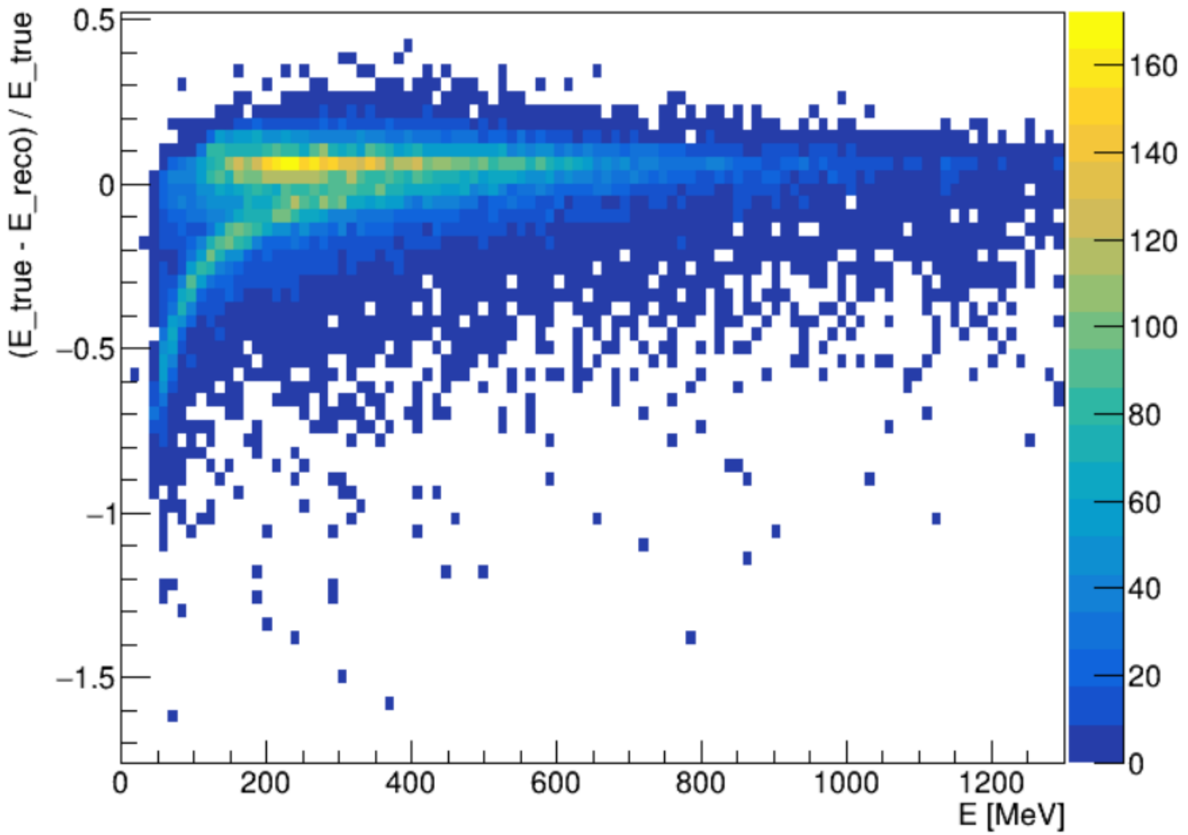
The calibration coefficient can be used to estimate the deposited energy of an event from the total number of detected photons.

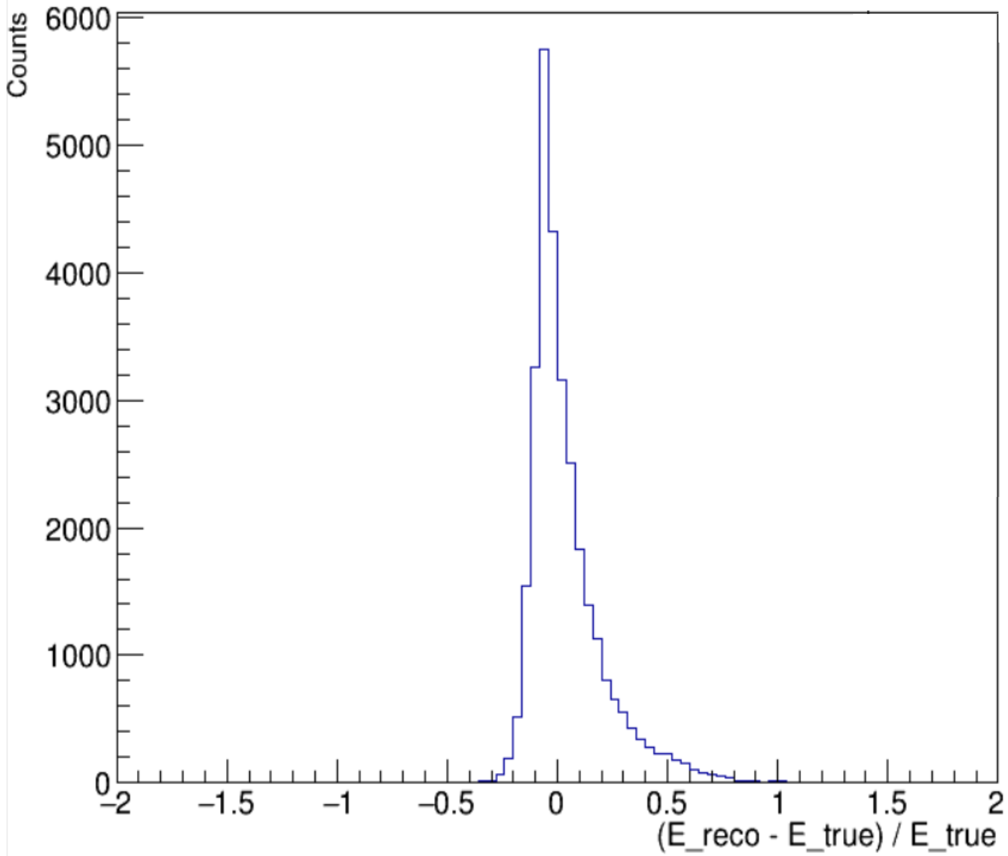




RECONSTRUCTED ENERGY RESOLUTION

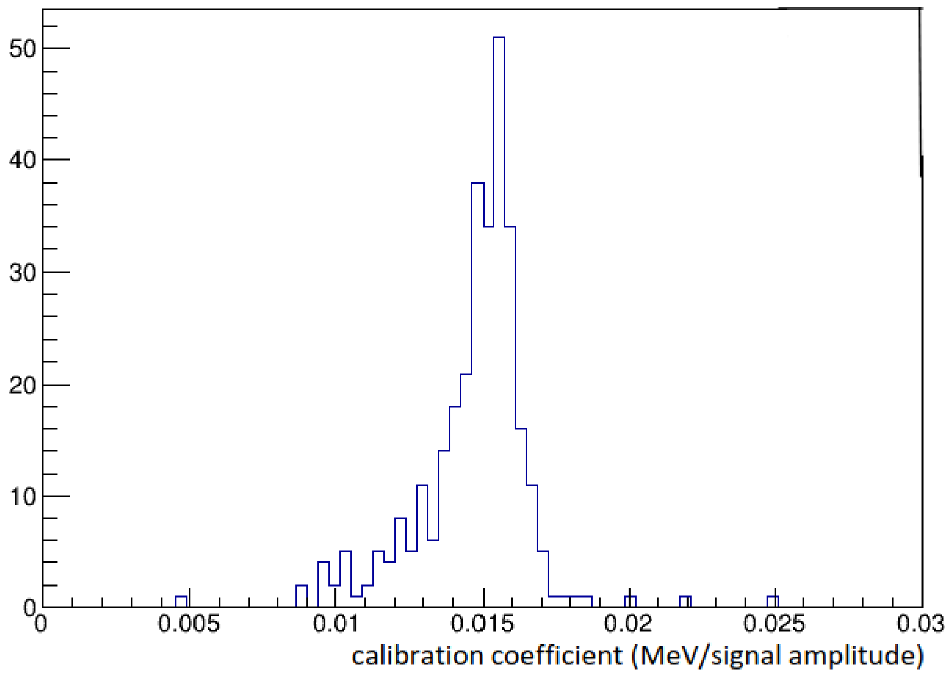
$\frac{|E_{true}-E_{reco}|}{E_{true}}$ for each simulated event as a function of the true deposited energy





CALIBRATED ENERGY RESOLUTION

Cube calibration coefficient distribution:



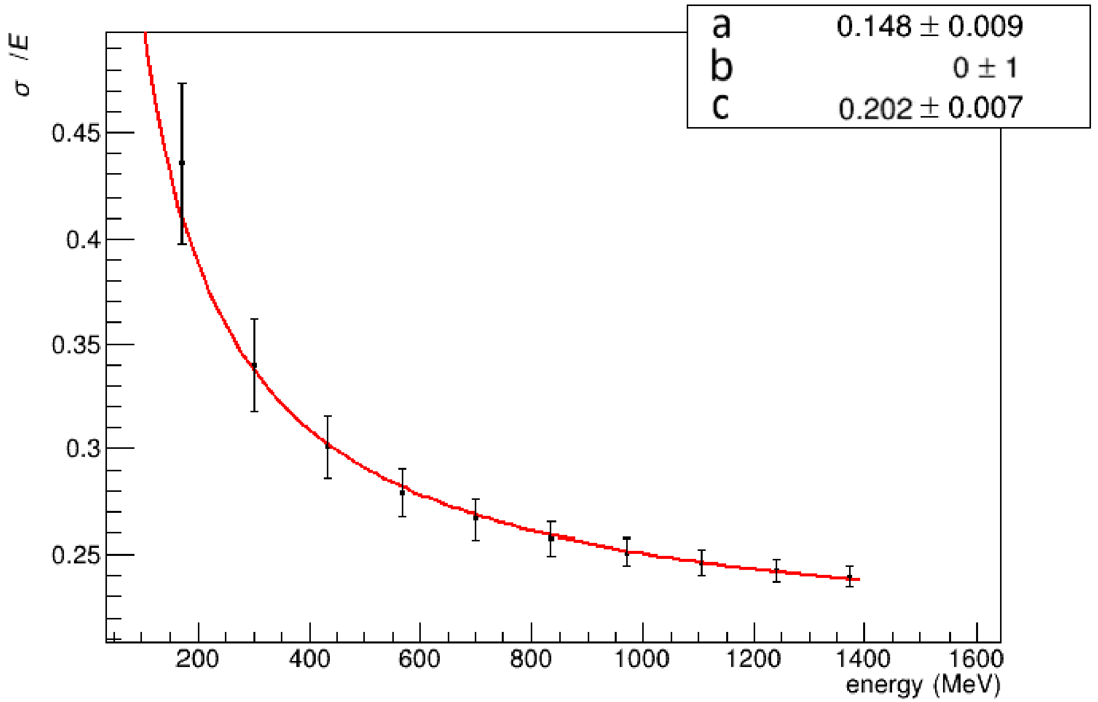
$$k_{mean} = 0{,}015\ MeV/signal\ amplitude$$
$$RMS = 0{,}002\ MeV/signal\ amplitude$$

$$RMS/k = 13\%$$

This allows to estimate an overall **energy resolution using** $\boldsymbol{kmean}$

The energy resolution of each cube has been computed fitting the points with the function

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



Data sample
1M simulated events
(NC + CC)

$$\frac{\sigma}{E} = \frac{15\%}{\sqrt{E}} \oplus 20\%$$

F. Chiapponi

CONCLUSIONS

3D RECONSTRUCTION:

- Improved 3D algorithm with Maximum likelihood expectation maximization
- Cameras with mosaic masks, chosen for 2D deconvolution techniques, are not ideal for 3D algorithm, various masks dimensions are being investigated
- Currently MLEM algorithm is able to reconstruct MIP tracks in GRAIN with similar performances to first algorithm, but using only cameras on sides and top/bottom (~30-40k channels)

CALORIMETRY:

- Computed calibration coefficient for 5 cm side voxels
- First estimate of Energy resolution for GRAIN: $\frac{\sigma}{E} = \frac{15\%}{\sqrt{E}} \oplus 20\%$

BACKUP SLIDES

ML – EM 3D RECO ALGORITHM

H_s numero di hit nel pixel s

$$f(H_s|\lambda_s) = e^{-[\lambda s]} \frac{[\lambda_s]^{H_s}}{H_s\,!} \quad \text{where} \quad [\lambda_s] = \sum_j \lambda_j\, p(j,s)$$

- λ_j unknown activity density to be estimated from measured data
- *p(j,s)* probability of a photon originated in voxel j is detected by pixel s

Log-likelihood maximization

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

k = iteration number

$\lambda_j^0 = 1$

OLD ALGORITHM

λ_j = voxel score

V = photon originated in voxel j

S = photon detected by sensor s

$$\lambda_j = \frac{1}{\sum_s p(s|v)} \cdot \sum_s H_s \cdot p(v|s)$$

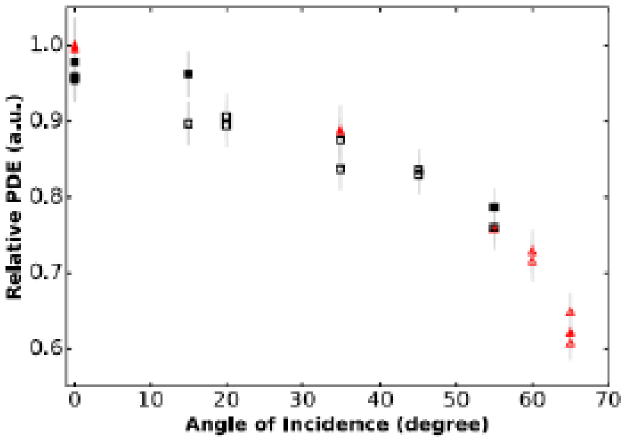
$$p(v|s) = \frac{p(s|v)\ \cdot p(v)}{p(s)} \qquad p(s) = \sum_j p(s|v) \cdot p(v)$$

$$p(v) = prior = 1$$

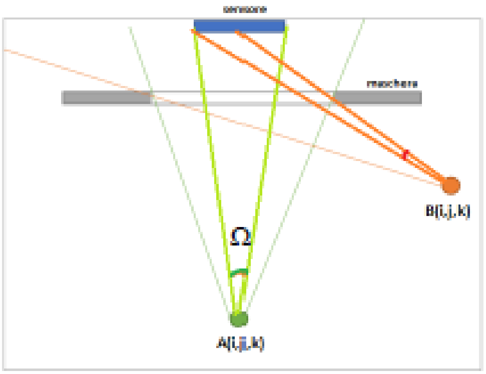
$P(sens \mid vox)$

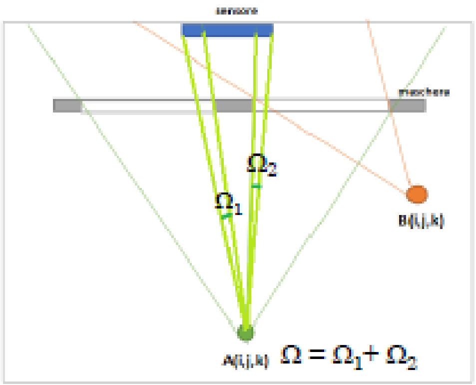
$P(sens \mid vox) = P\ geometry \cdot P\ attenuation \cdot P\ detection$

- $P\ geometry = \Omega / 4\pi$ oppure $A_{visibile}/A_{sens}$
  - Ω : angolo solido sotteso dall'area del sensore (c,s) che si vede attraverso i fori della maschera dal centro del voxel (i,j,k)
  - A : area del sensore (c,s) che si vede attraverso i fori della maschera dal voxel (i,j,k)
- $P\ attenuation = e^{-d/\lambda\, att}$
  - d: distanza(centro sensore, centro voxel)
  - $\lambda\, att$: lunghezza di attenuazione
- $P\ detection$ → la PDE di un SiPM dipende anche dall'angolo di incidenza del fotone (non ancora implementato nella simulazione)



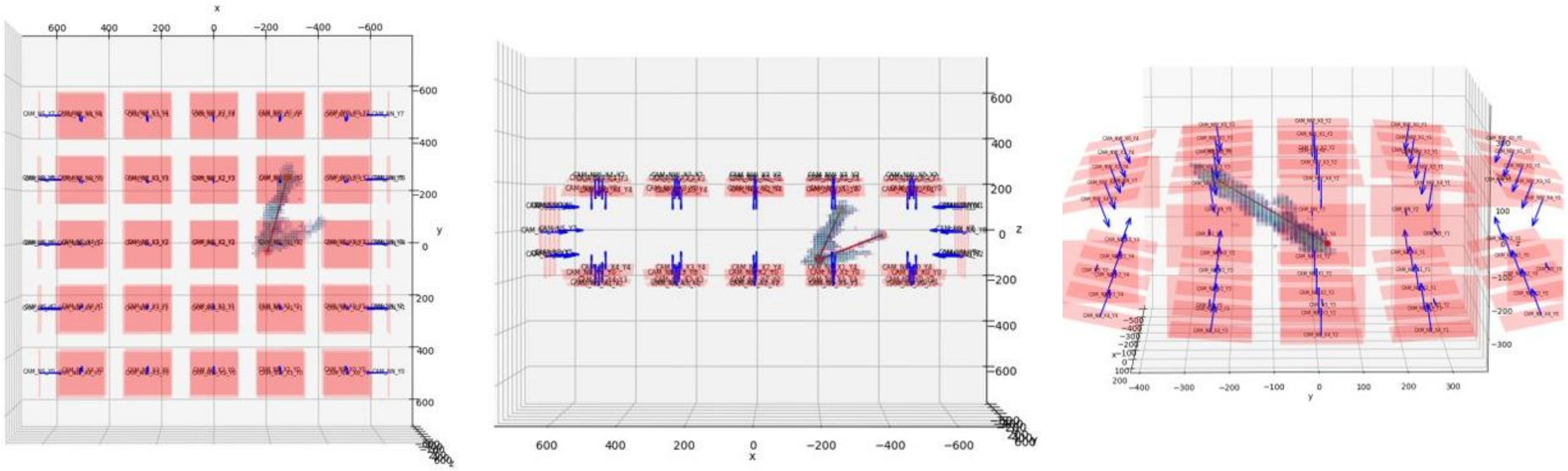
Nakarmi P. et al. *"Reflectivity and PDE of VUV4 Hamamatsu SiPMs in liquid xenon"* https://arxiv.org/pdf/1910.06438.pdf





A few events

V. Cicero



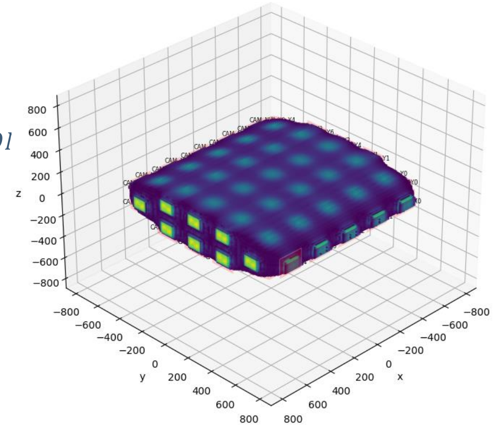
Solid angle distribution

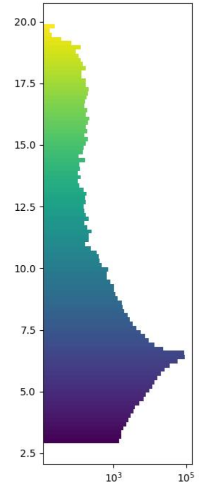
For a given event, in the i-th voxel:

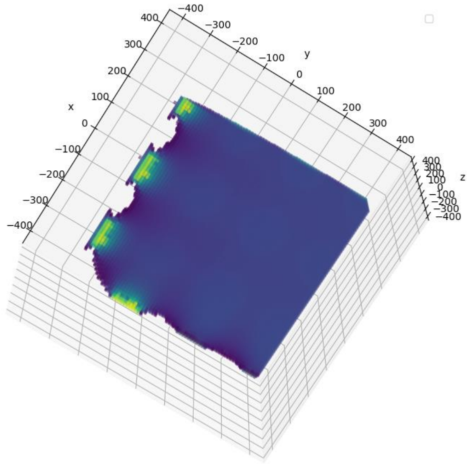
$$N^{i}_{photons} = \alpha^{i}_{QE}\alpha^{i}_{GEOl}$$

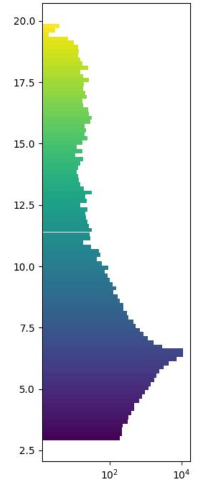
Where:

- $i = 1, \dots, n_{VOXELS}$
- N_0 = number of photons emitted isotropically in a single voxel
- α^{i}_{QE} = quantum efficiency → **KNOWN**
- α^{i}_{GEOM} = geometrical acceptance → analytically **ESTIMATED**
- $N^{i}_{photons}$ = total number of photons collected in the image from that voxel –



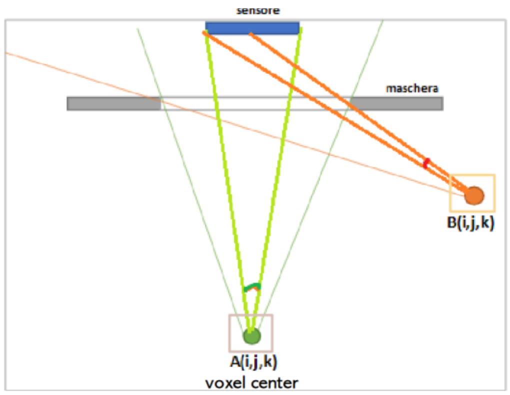






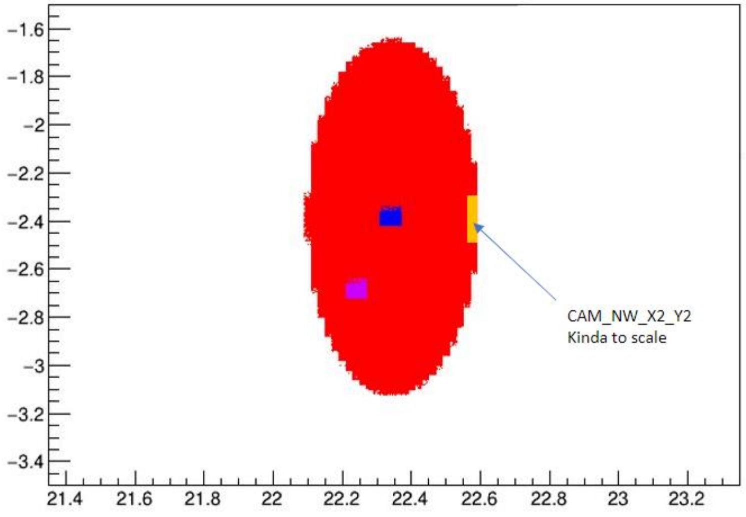
Log scale

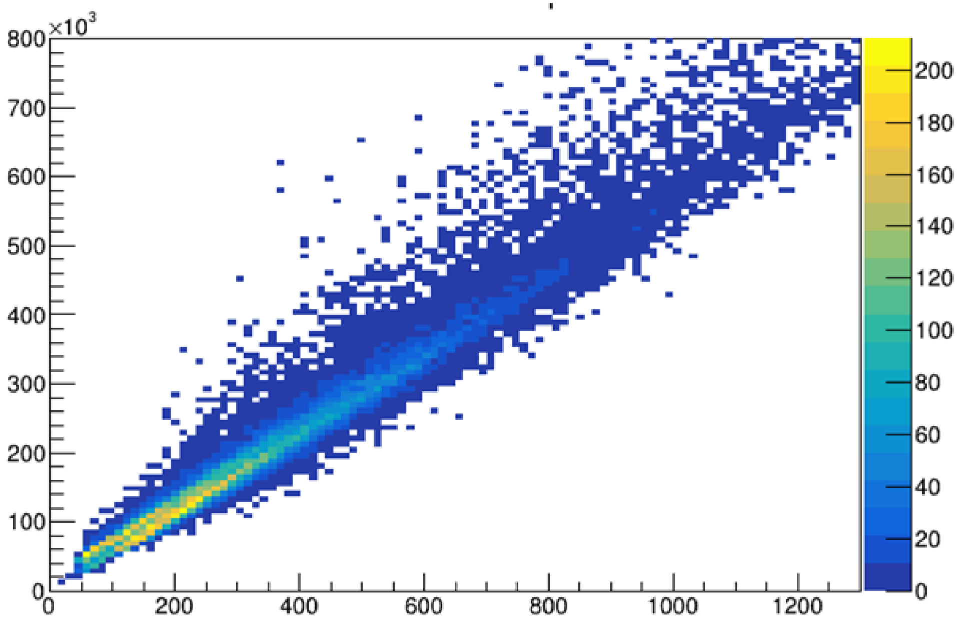
Both simulated voxels are in the *almost* uniform region of α^{i}_{GEOM}.

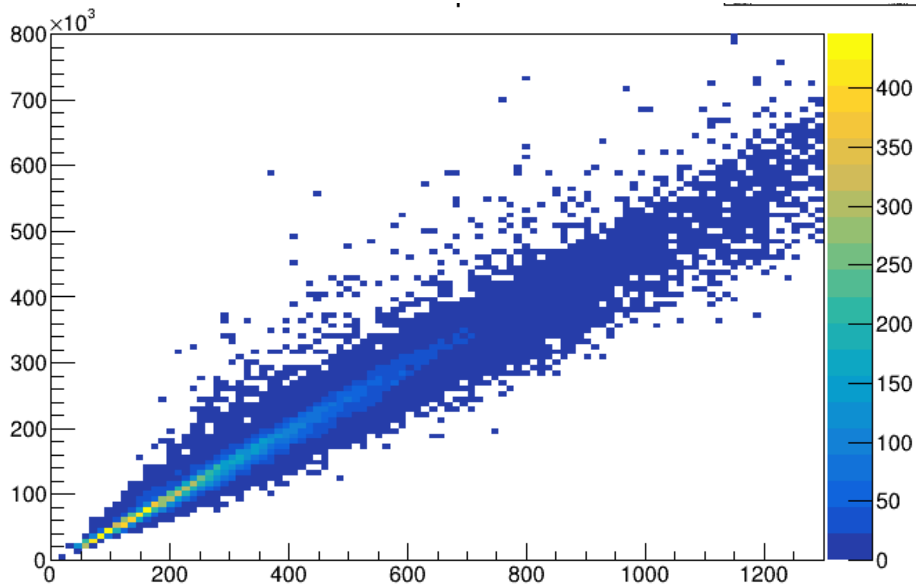


Blind cameras

- Due to the distribution of the masks, the events in the central region often blind a camera. This camera gives a much larger number of detected photons.







Samples:
10k ν_μCCQE
10k ν_μCCDIS
10k ν_μCCRES

Reconstructed energy resolution