STUDY OF A NOVEL VUV-IMAGING SYSTEM IN LIQUID ARGON FOR NEUTRINO OSCILLATION EXPERIMENTS

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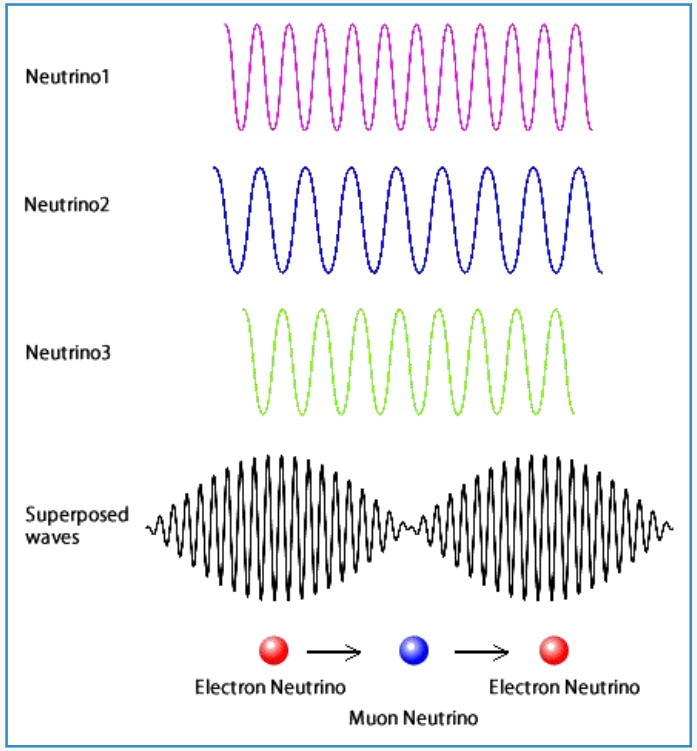
NEUTRINO MIXING AND OSCILLATION

Neutrino oscillations are an *in-flight* change of flavour and are a consequence of the neutrino mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$U = PMNS\ matrix$



Oscillation phenomenon is the proof of a non-zero neutrino mass and that the Standard Model must be extended.

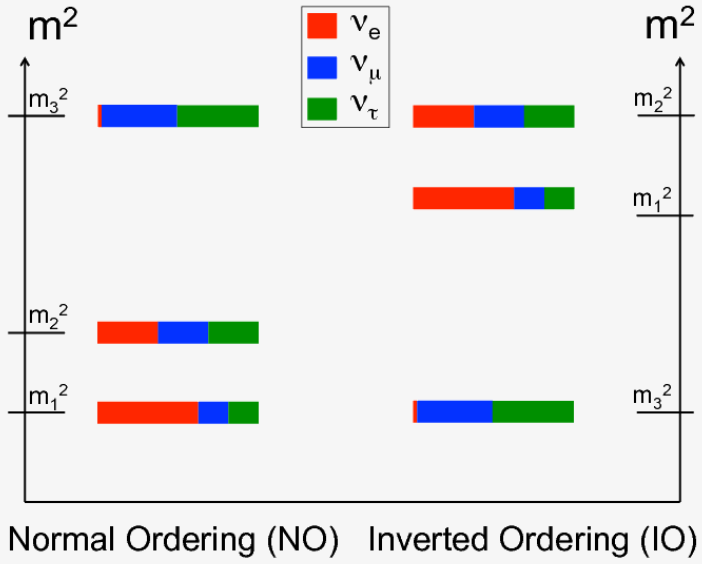
Some parameters are still unknown: δ_{CP}, $\mathrm{sign}(\Delta m^2_{23})$

↓

Possible answers to open questions

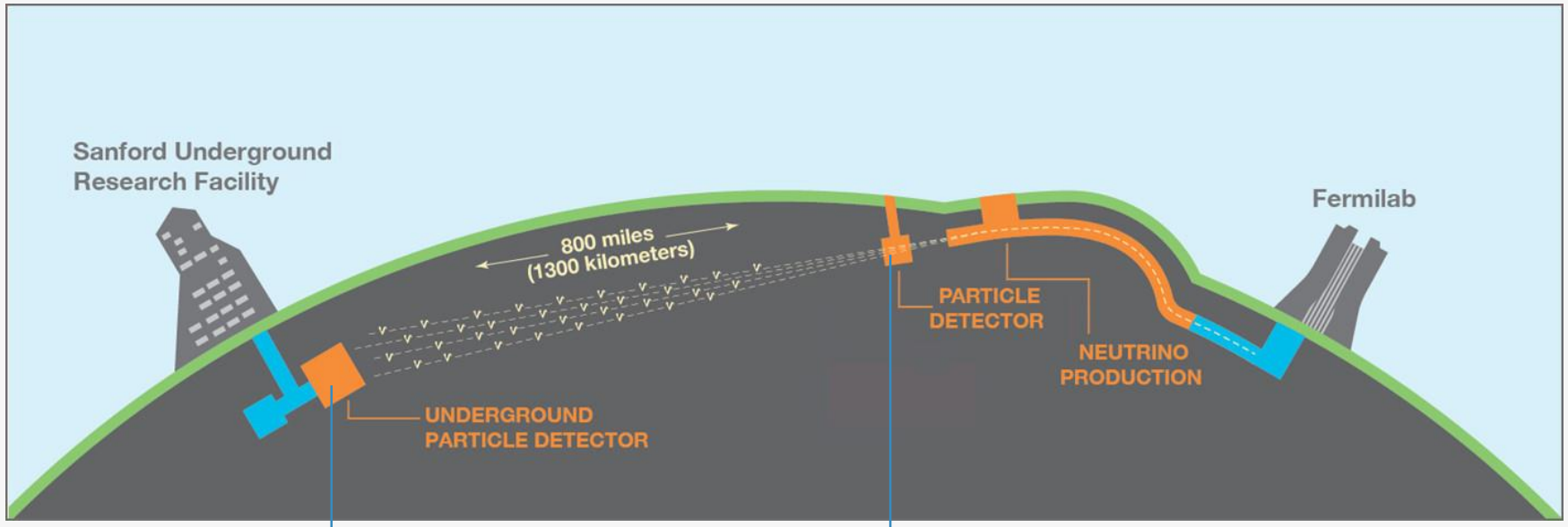
↓

Studied by several experiments



Deep Underground Neutrino Experiment - DUNE

Dual-site long-baseline neutrino experiment for CP-violation and mass ordering measurements.



Far Detector

- 1300 km from the source
- Multi kiloton LArTPC
- neutrino oscillation measurements

Near Detector

- few hundred meters from the source
- on- and off-axis detectors
- constraints on systematic

DUNE EXPERIMENT

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * D_{\nu_e}^{far}(E_\nu, E_{rec}) dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * D_{\nu_\mu}^{near}(E_\nu, E_{rec}) dE_\nu}$$

Near Detector requirements :

- Flux measurements ($\nu/\bar{\nu}$ and flavour discrimination) → Magnetic field
- Able to work in high intensity particle flux → Fast time response
- ν/Ar cross section measurements → Same Far Detector material

Far Detector LArTPC could not be the best solution due to the slow time response. →

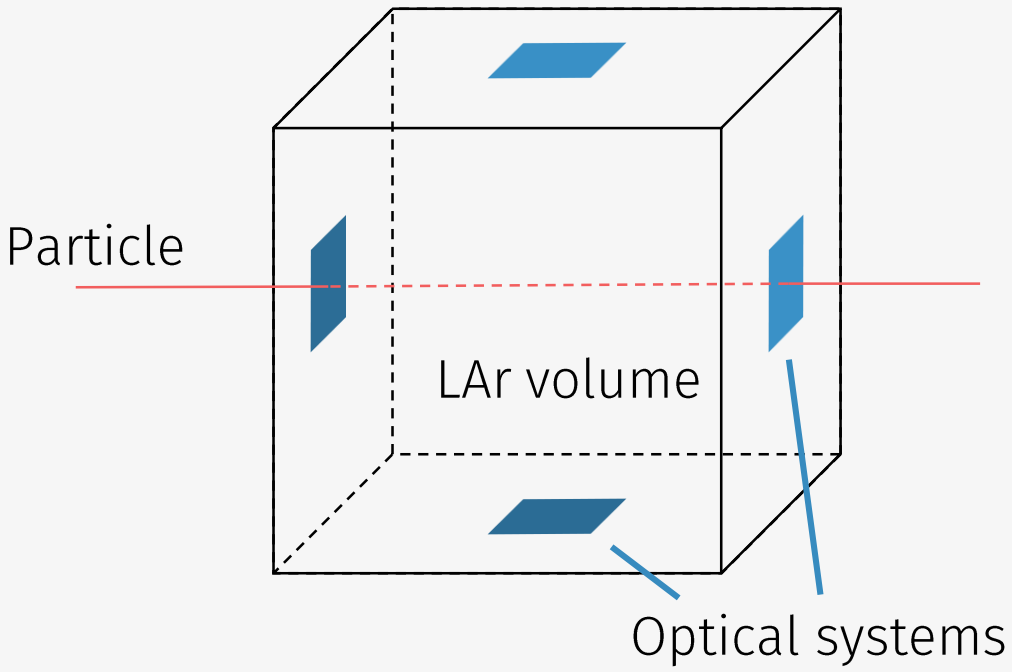
INNOVATIVE DETECTION TECHNIQUE AT THE NEAR DETECTOR

INNOVATIVE DETECTOR CONCEPT

Exploit only the scintillation light emitted in a cube of LAr to provide the spatial reconstruction of the events.

An Optical system able to collect the light and a fast segmented photon detector (SiPM matrix) are needed.

Perform a complete 3D reconstruction of the event from 2D picture of the tracks.



Liquid Argon

40000 photons/MeV (MIP particles)

Fast Component time: 7 ns

Intensity peak @ 128 nm

Attenuation length $\mathcal{O}(1\ \mathrm{m})$

Optical system requirements

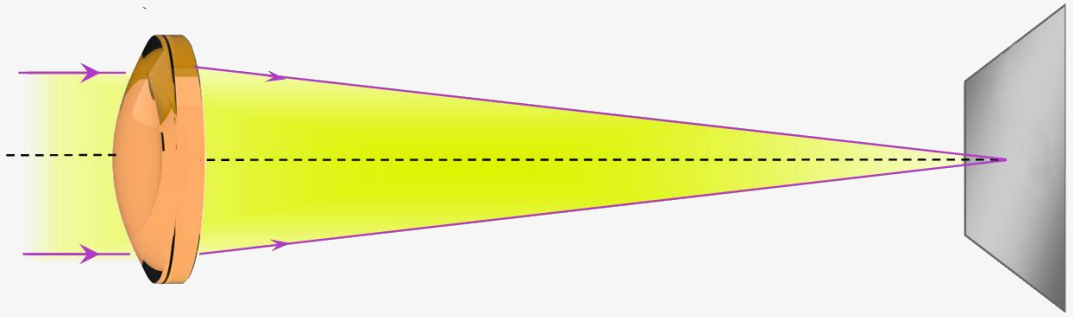
High efficiency @ 128 nm

Large depth of field

Cryogenic temperature

DETECTOR CONCEPT

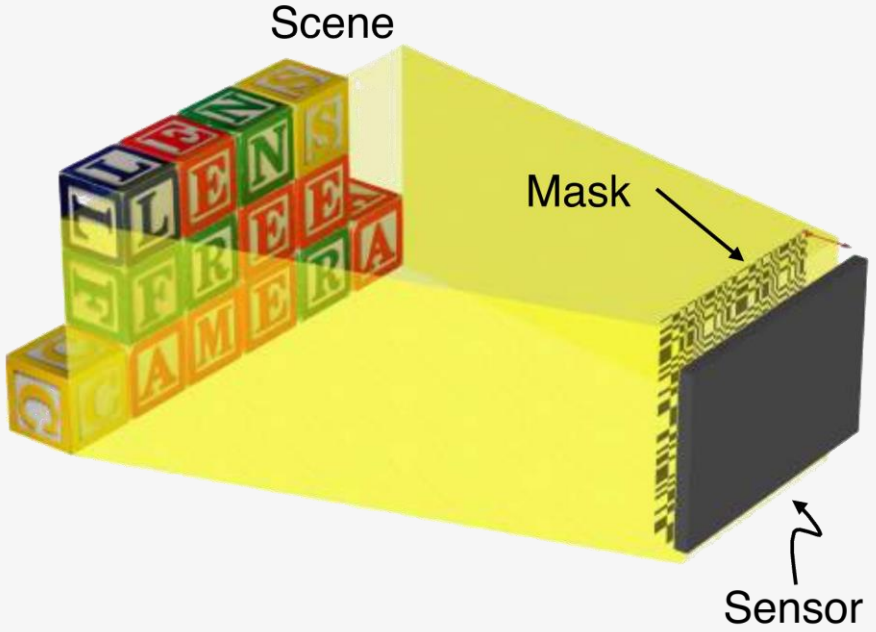
Usually, optical systems are made using lenses and mirrors.



Lens

- Low transmission efficiency @ 128 nm
- Small Depth of Field
- Small Field of View

A possible alternative is the Coded Aperture Technique

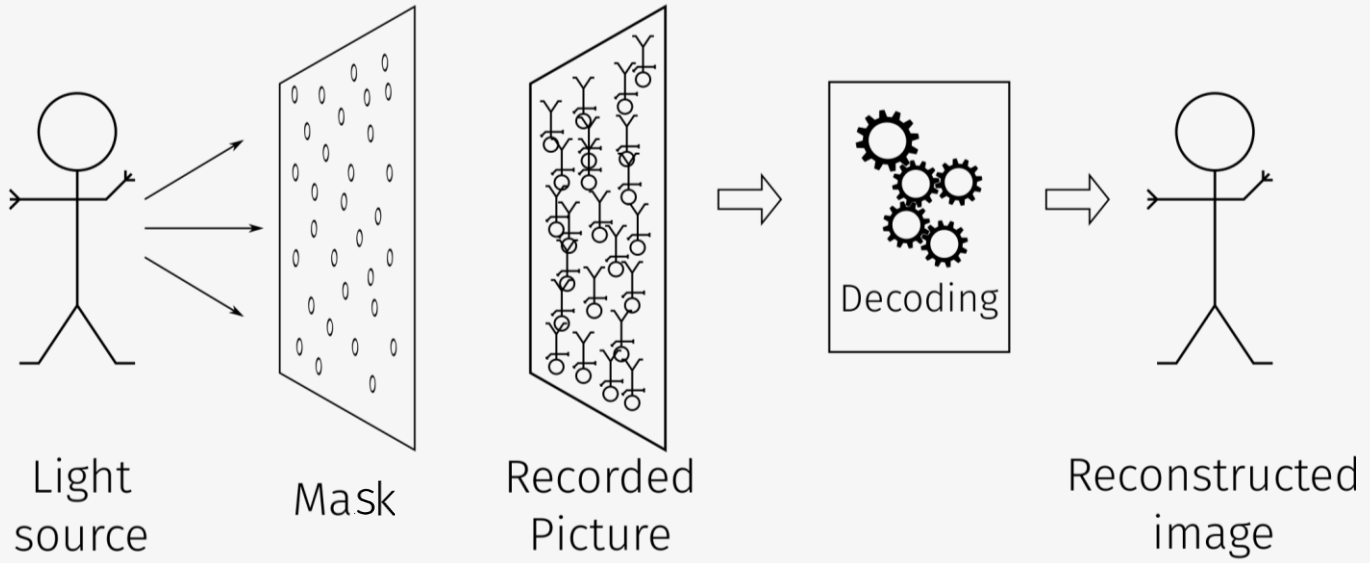


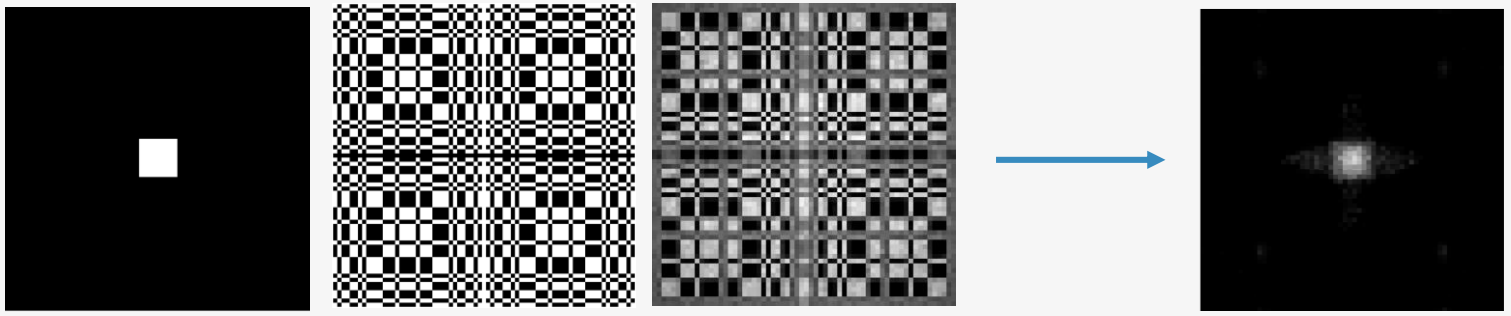
- High luminosity lens
- Constant transmission efficiency
- Infinite Depth of Field
- Large Field of View

CODED APERTURE TECHNIQUE

It is an extension of the pinhole camera, where multiple holes are used instead of one.

Specific patterns (mask) allow to decode the sensor response and obtain the initial image.





PARAMETERS OPTIMIZATION

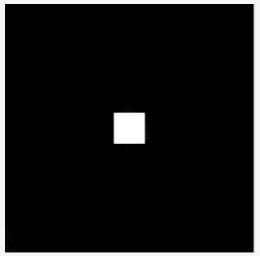
First step of this work is the systems study and the optimization.

The feasibility is studied with a simple optical simulation of a light source using both lenses and masks.

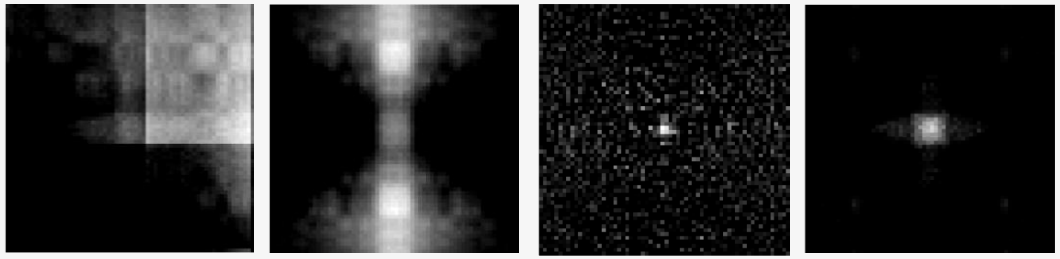
Starting point constrained from the hardware.

- Coded Aperture
  - Pixel size: 2.4 mm
    - Box size: 350 mm
    - Working distance: 95 mm
    - Mask pitch: 2.28 mm
    - Mask-sensor distance: 5 mm
    - 37x37 pixel grid
- Lens
  - Working distance: 40 mm

ARTIFACTS

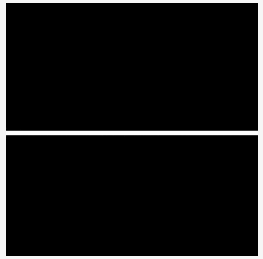


Original

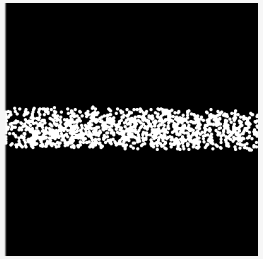


Reconstructed

OPTIMIZE THE BLUR



Original



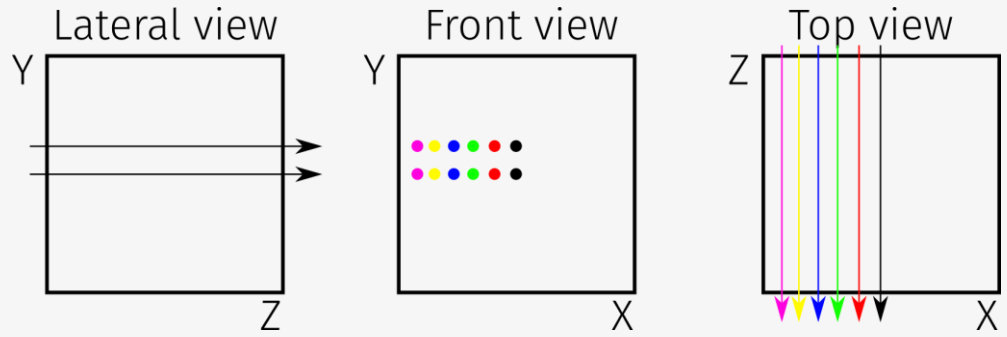
Reconstructed

TRACKS SIMULATION

In the second step of my work, Geant4 toolkit is used to simulate particles crossing the box.

Different beams simulated to study the feasibility :

- Every 25 mm
- Different position from the optical axis
- 1 GeV muons for beam



Geant4 used to simulate the emission and propagation of the scintillation light.

The output is the number of photons collected by each pixel sensor.

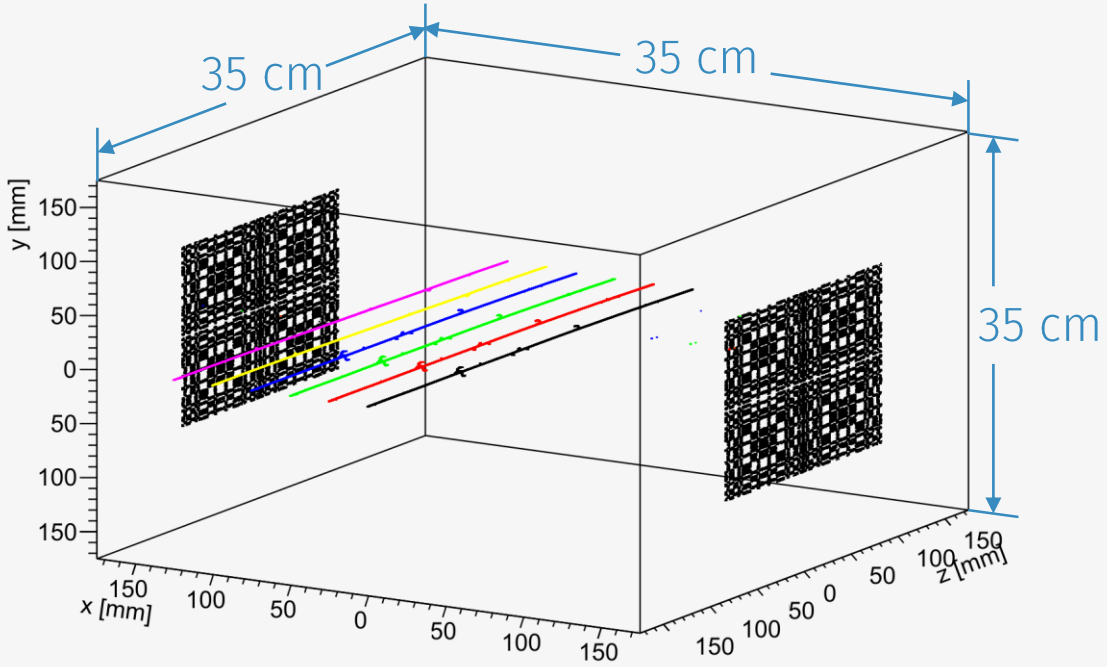
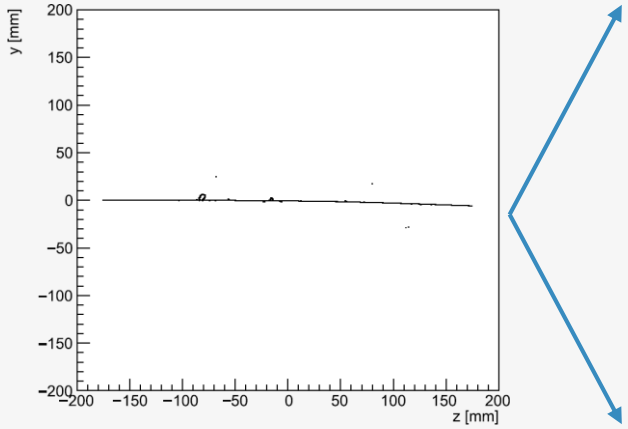


IMAGE RECONSTRUCTION

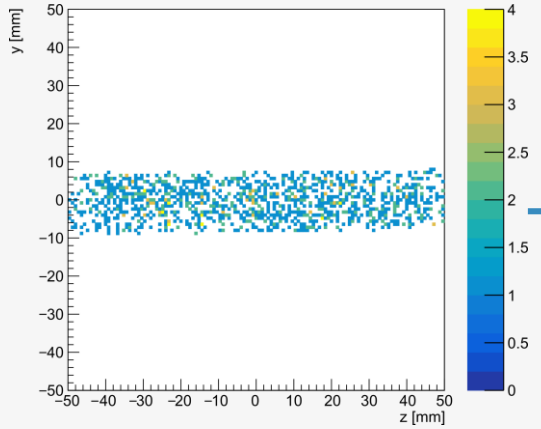
Using the sensor response, the final images for both lens and mask are obtained.

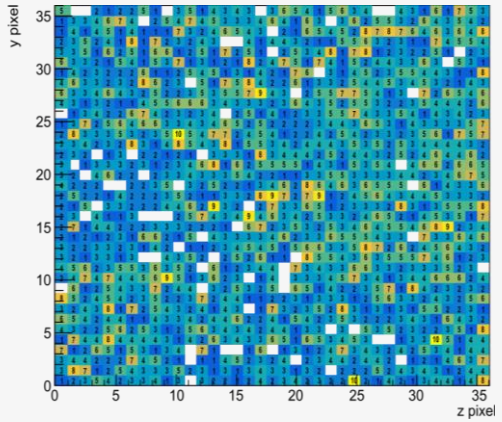


Simulated track

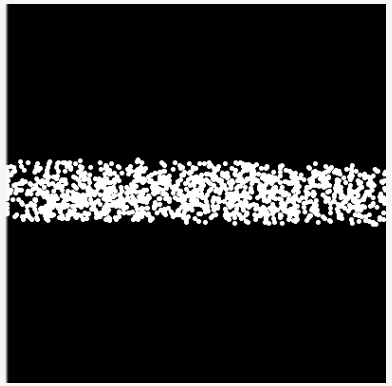
LENS

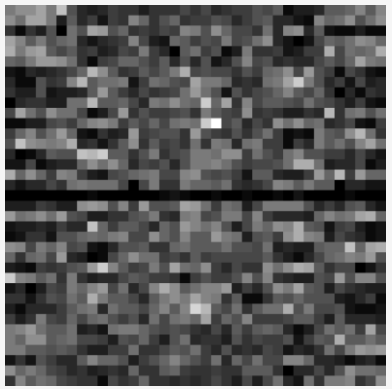
MASK



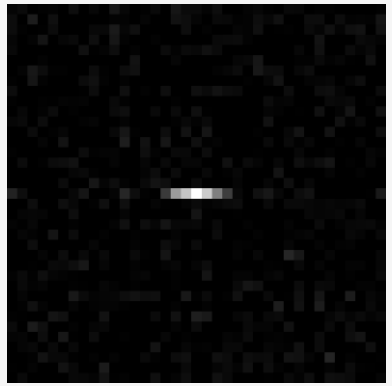


Sensor response





Gray level



Reconstructed image

ANALYSIS - MASK

Two different analyses are performed with the mask results: image quality and track reconstruction capability.

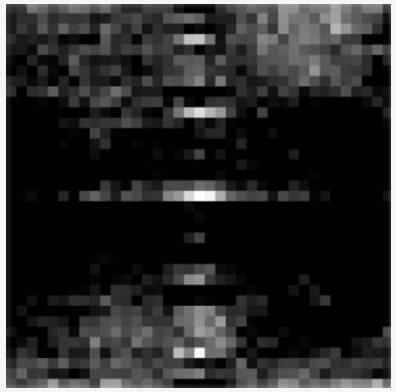
IMAGE QUALITY

Performed measuring the Manhattan Distance between reconstructed and true image.

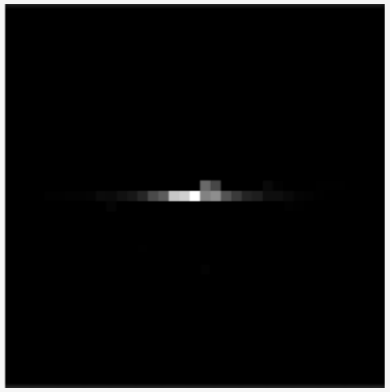
$$d(x,y) = \sum_{i}^{N} |x(i) - y(i)|$$

$N = \text{n. pixels}$

Reconstructed (x)



True image (y)



TRACK IDENTIFICATION

Performed using a track finding algorithm and comparing the measured slope and intercept with the expected ones.

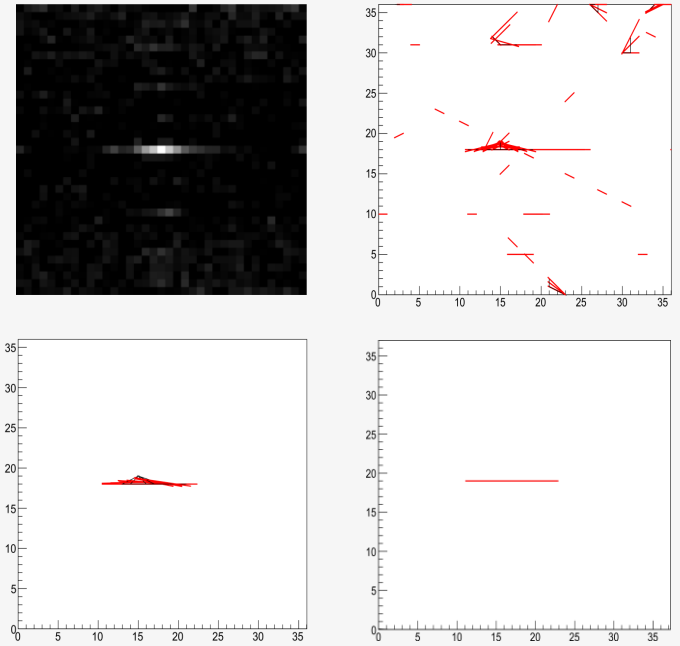
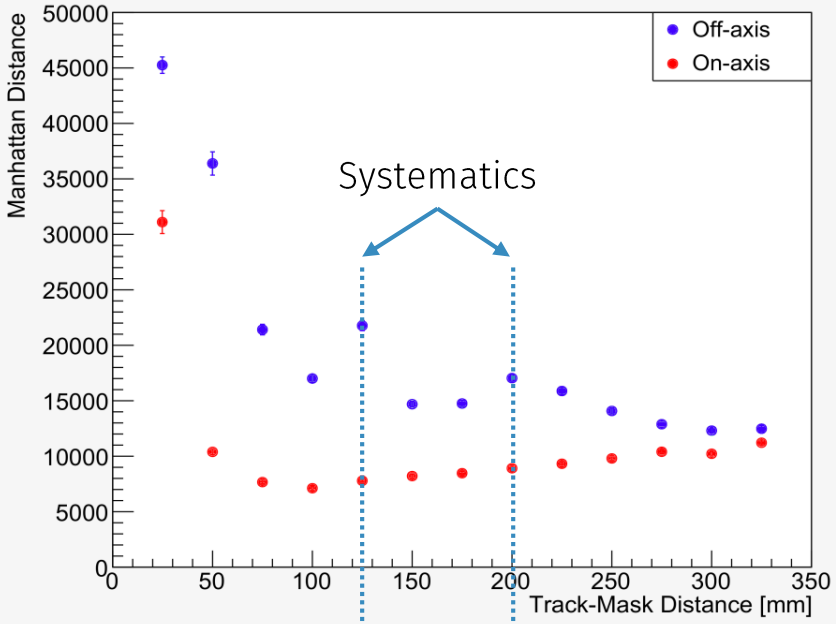
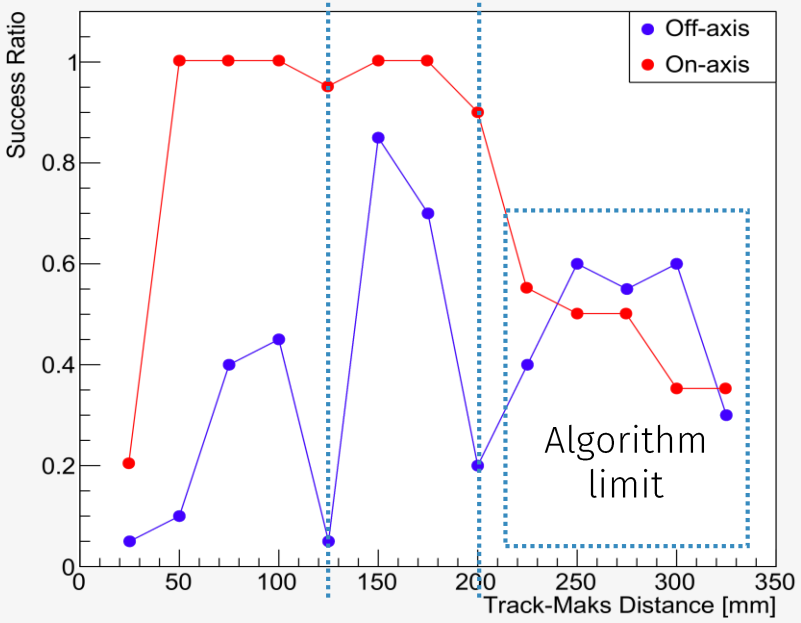


IMAGE QUALITY



TRACK IDENTIFICATION



The image quality plot represents the mean value of the 20 events for each configuration.

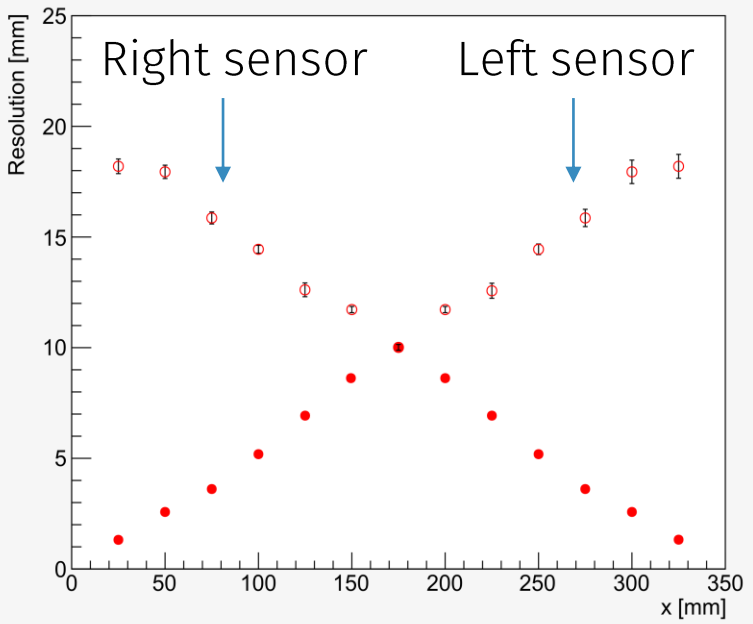
The shape of the distribution is due to the presence of the artifacts.

A track is successfully identified if it lies entirely on the expected pixels of the source image.

The identified tracks are used to measure the detector resolution:

$$res = \frac{\lambda}{\sqrt{12}\sqrt{N}} \qquad \lambda = pixel/mm\ conversion\ factor \qquad N = number\ of\ points\ in\ a\ track$$

RESOLUTION



ANALYSIS - LENS

Lens analysis was performed measuring the Circle of Confusion to extimate the distance of the tracks from the lens.

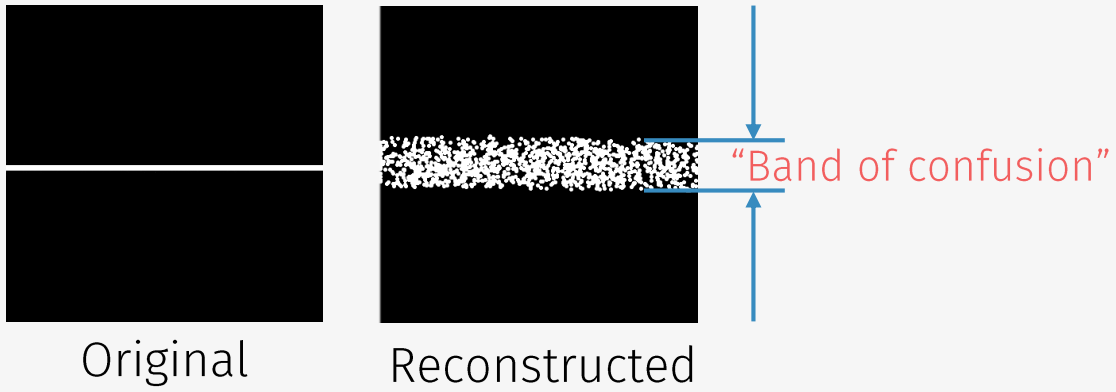
CIRCLE OF CONFUSION

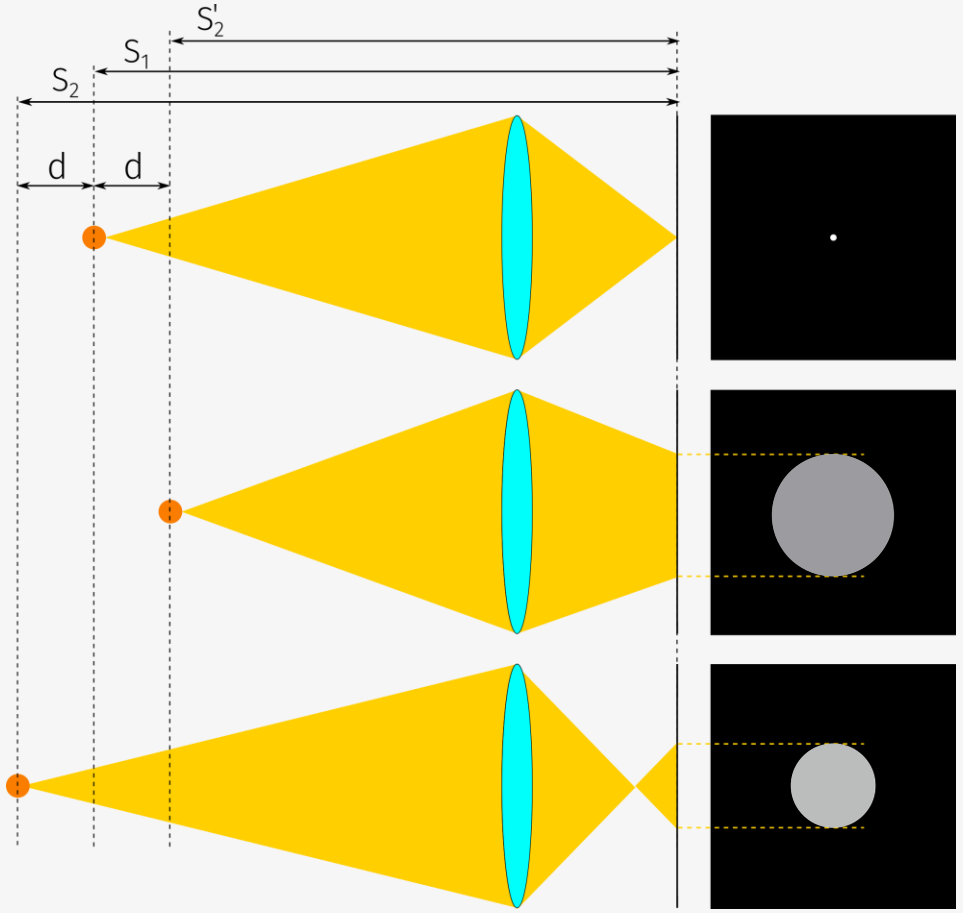
$$c = A\frac{|S_2 - S_1|}{S_2}\frac{f}{S_1 - f}$$

$c = CoC\ diameter$ $A = lens\ diameter$

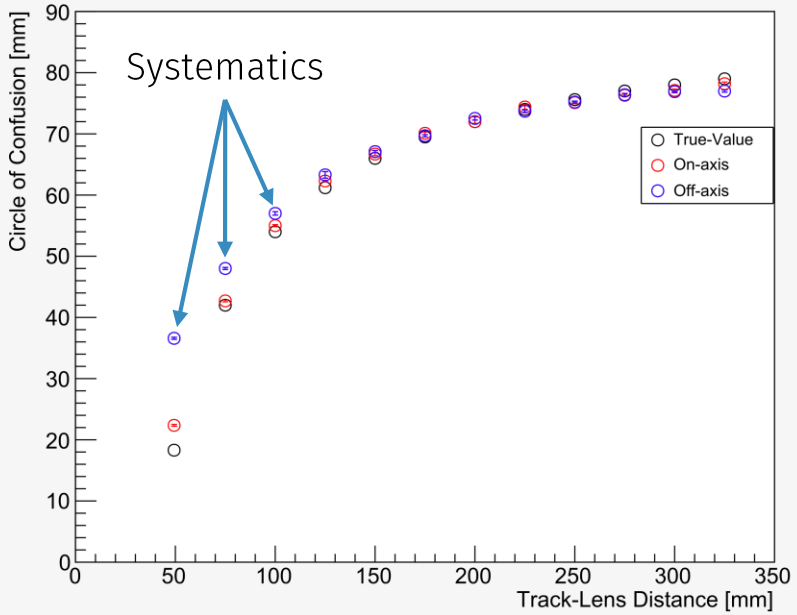
$S_1 = focused\ distance$ $f = focal\ lenght$

$S_2 = source\ distance$



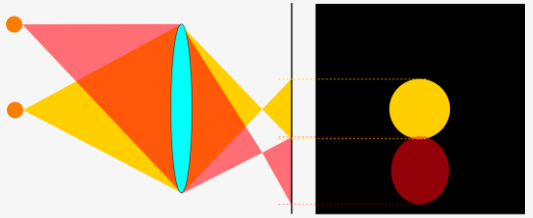


CIRCLE OF CONFUSION



The Circle of Confusion plot represents the mean value of the 20 events for each configuration.

Systematics are due the different size of the CoC for the off-axis tracks.

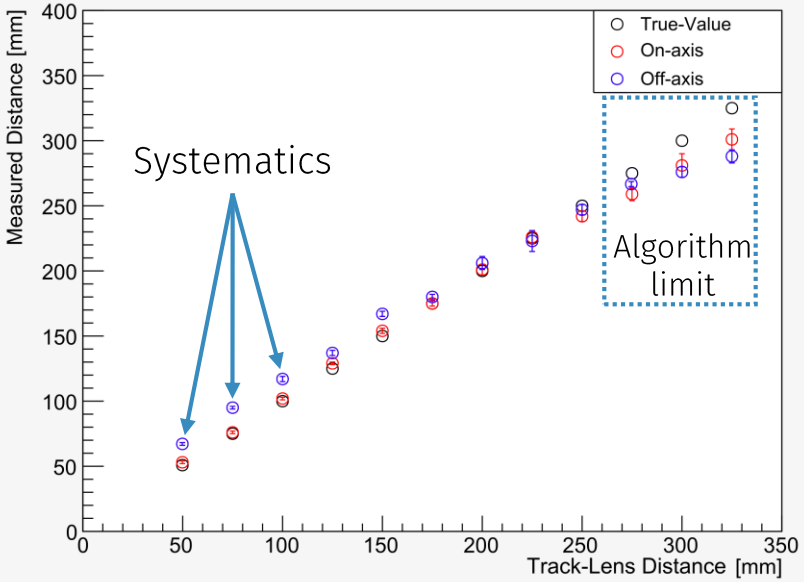


The algorithm can be modified to improve the result for the farther configurations.

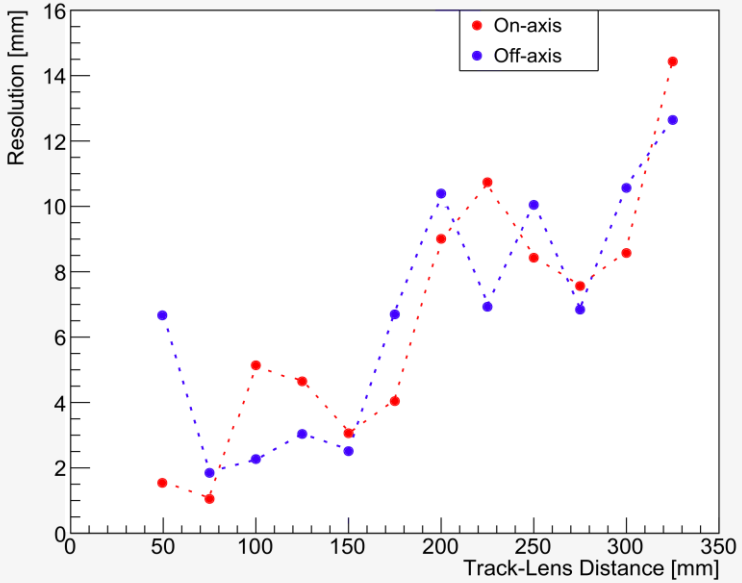
The measured distances are used to estimate the detector resolution.

$$res = RMS \qquad RMS = dis(X_{rec} - X_{true})$$

TRACK DISTANCE



RESOLUTION



CONCLUSIONS AND PERSPECTIVES

CONTEXT

- Innovative detection technique exploiting only Argon scintillation light to perform a 3D event reconstruction in the DUNE experiment.
- Preliminary study of the Coded Camera Technique to evaluate advantages and disadvantages compared to lenses.

THESIS WORK

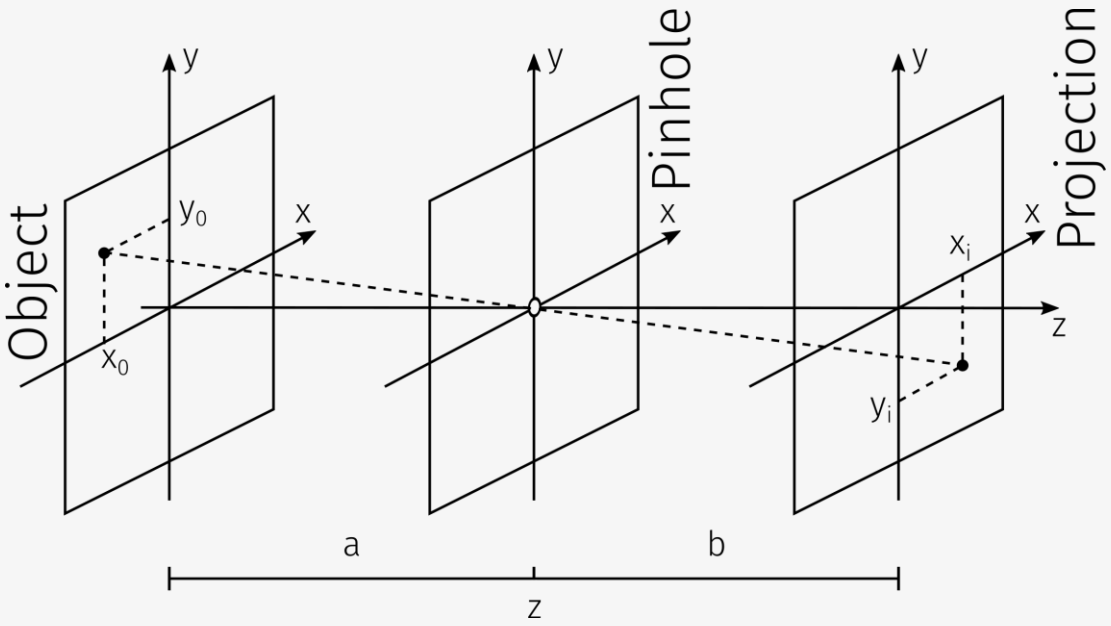
- Feasibility study on the detector concept.
- Reconstruction of the particle tracks and analysis of performances using both lenses and masks.
- Measurements of the detector resolution using both the optical systems: [2, 10] mm for [5, 18] cm distance respectively.

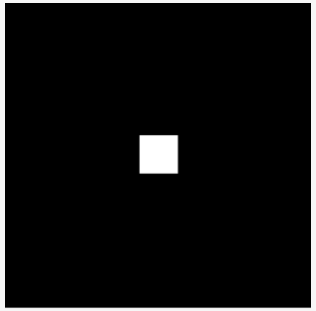
PERSPECTIVES

- Possible improvements using stereo projections.
- Exploiting the simulation results to build a detector prototype.

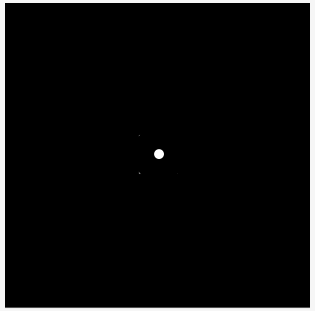
BACKUP

PINHOLE

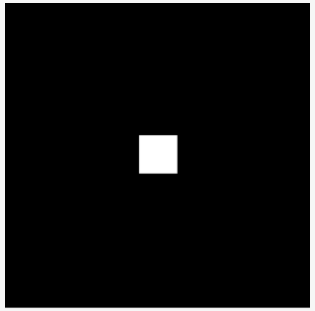




Light source



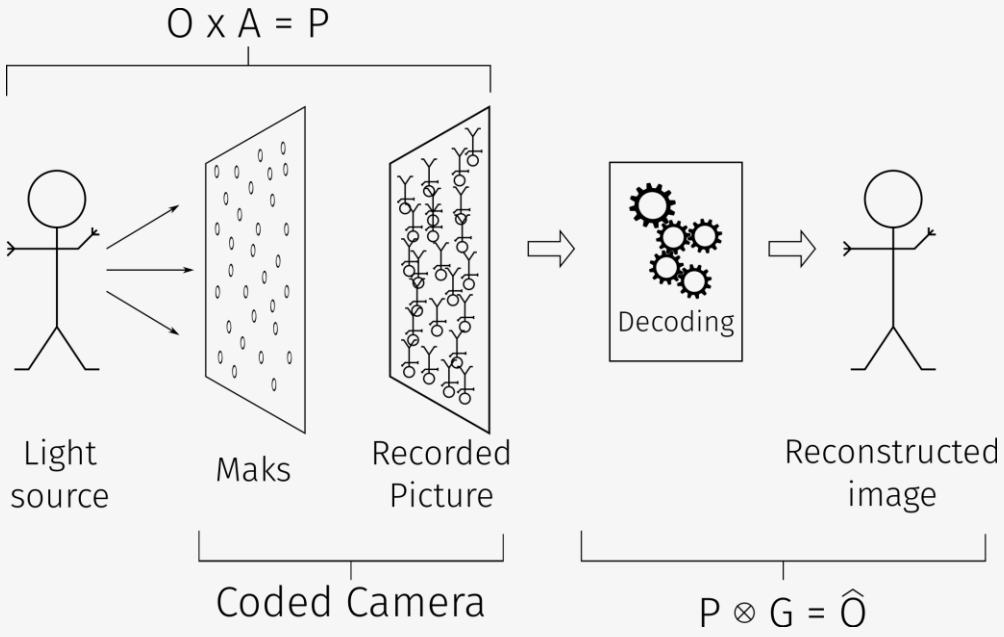
Pinhole



Recorded/ reconstructed image

CODED APERTURE

$$\hat{O} = P \otimes G = (O \times A) \otimes G$$



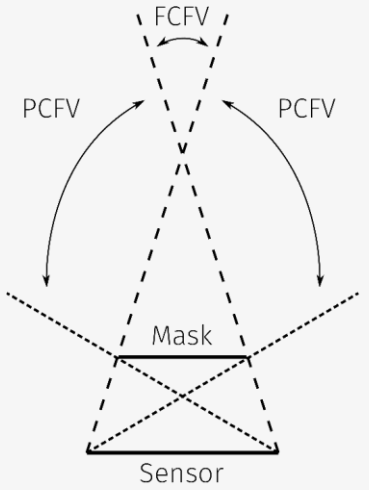
Mask

$$A_{ij} = \begin{cases} 0 \text{ if } i = 0 \\ 1 \text{ if } j = 0, i \neq 0 \\ 1 \text{ if } C_i^r C_j^s = +1 \\ 0 \text{ otherwise} \end{cases}$$

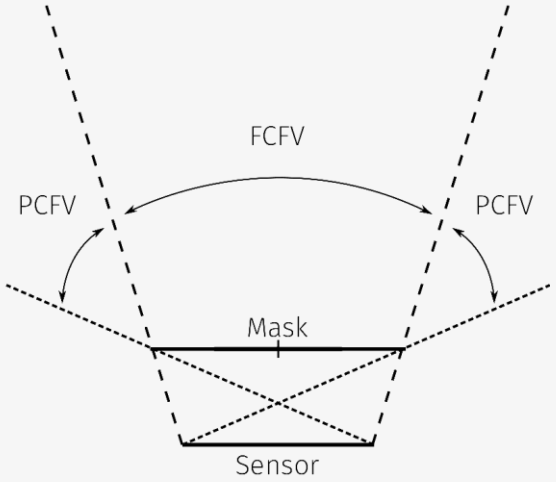
Kernel

$$G_{ij} = \begin{cases} 1 \text{ if } i + j = 0 \\ 1 \text{ if } A_{ij} = 1, i + j \neq 0 \\ -1 \text{ if } A_{ij} = 0, i + j \neq 0 \end{cases}$$

$$C_i^r = \begin{cases} +1 \text{ if } i \text{ is a quadratic residue modulo } r \\ -1 \text{ otherwise} \end{cases}$$



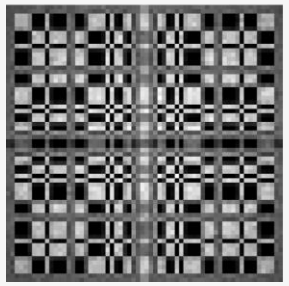
(a)



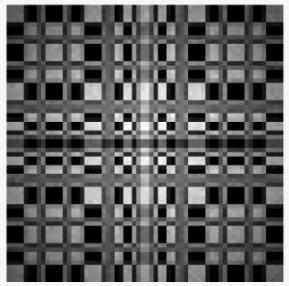
(b)

NEAR FIELD ARTIFACTS

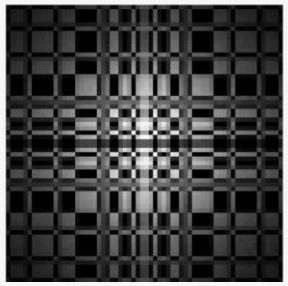
a = 20 cm



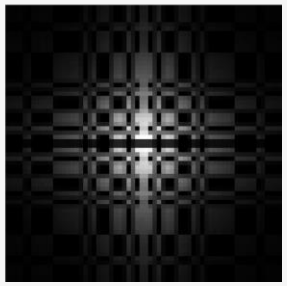
a = 10 cm



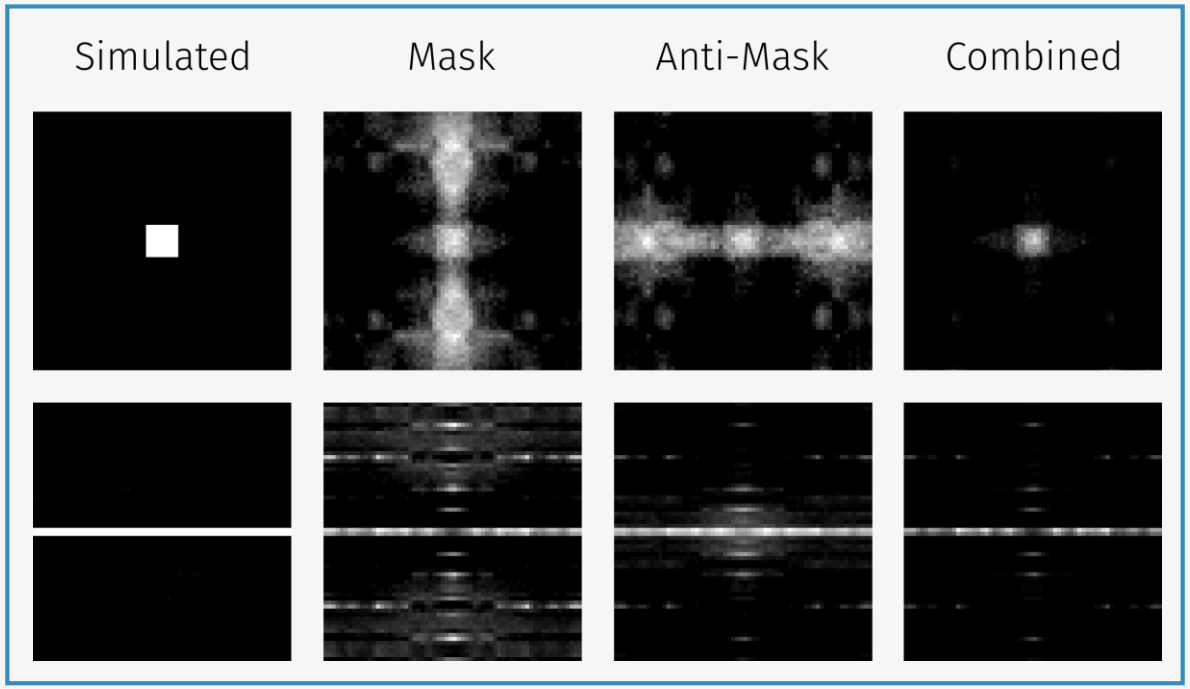
a = 5 cm



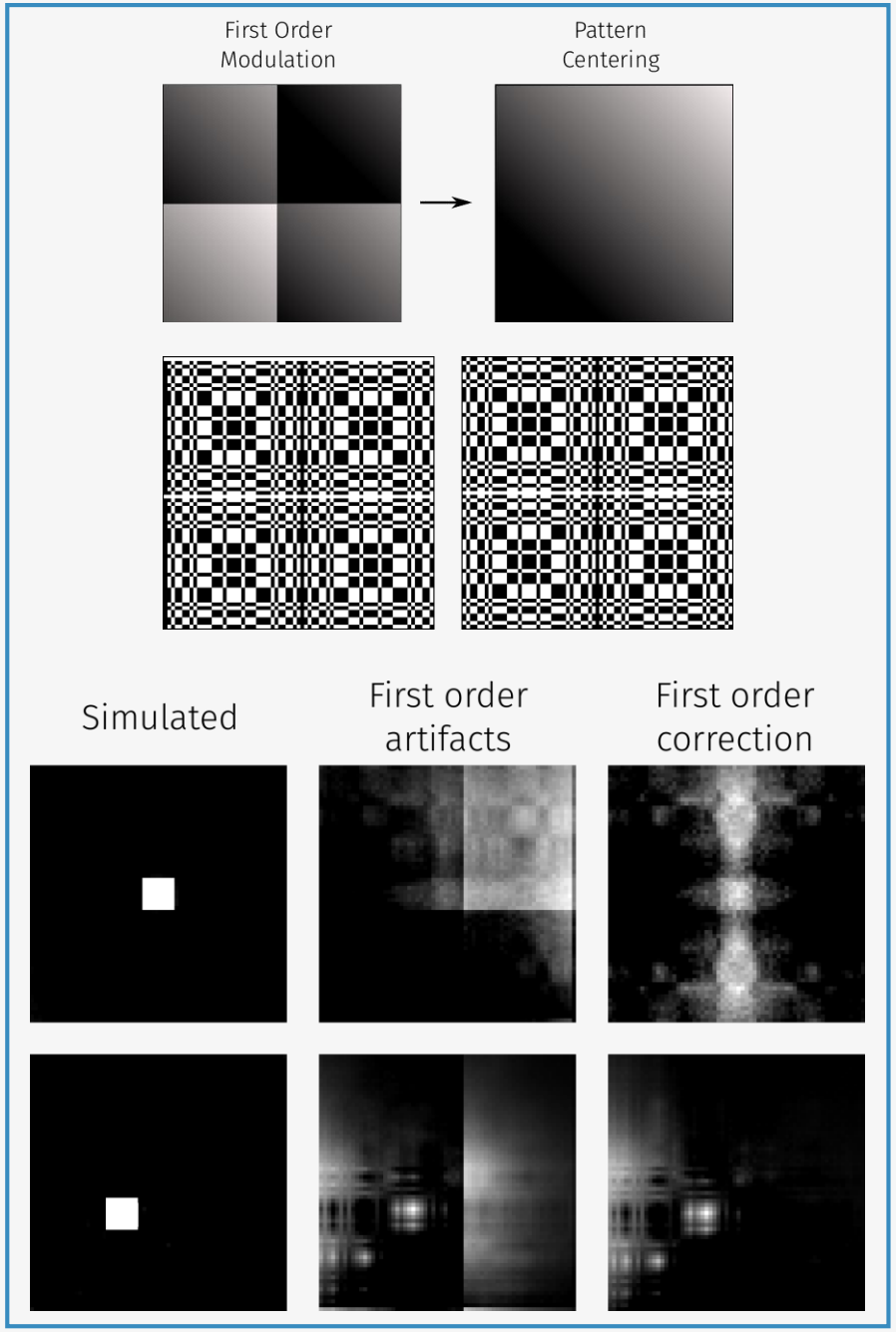
a = 2 cm



SECOND ORDER

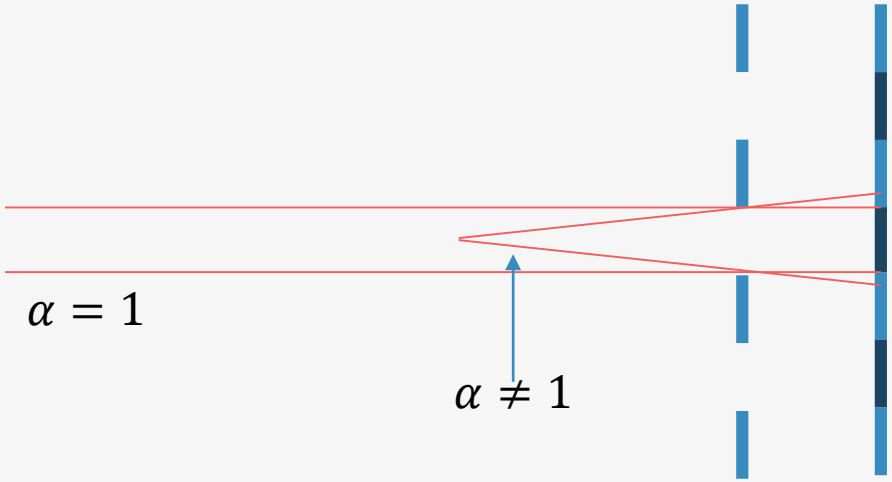


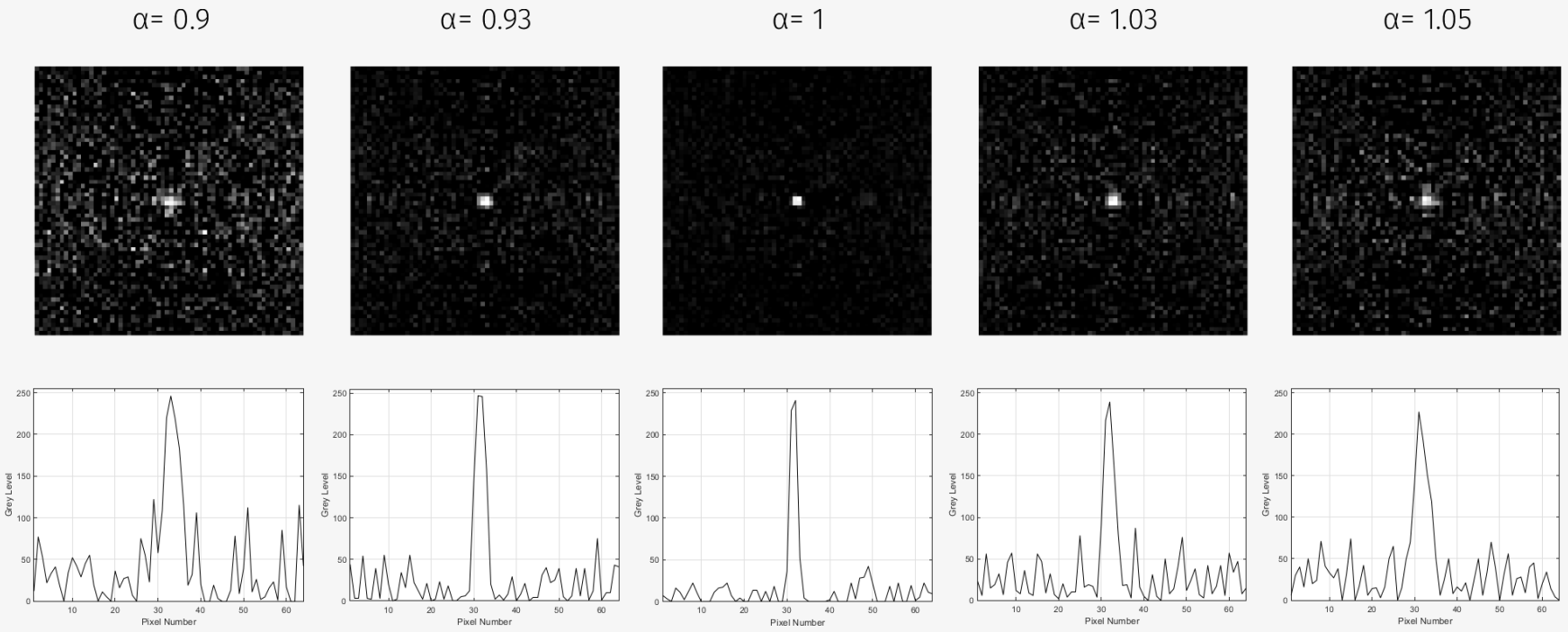
FIRST ORDER



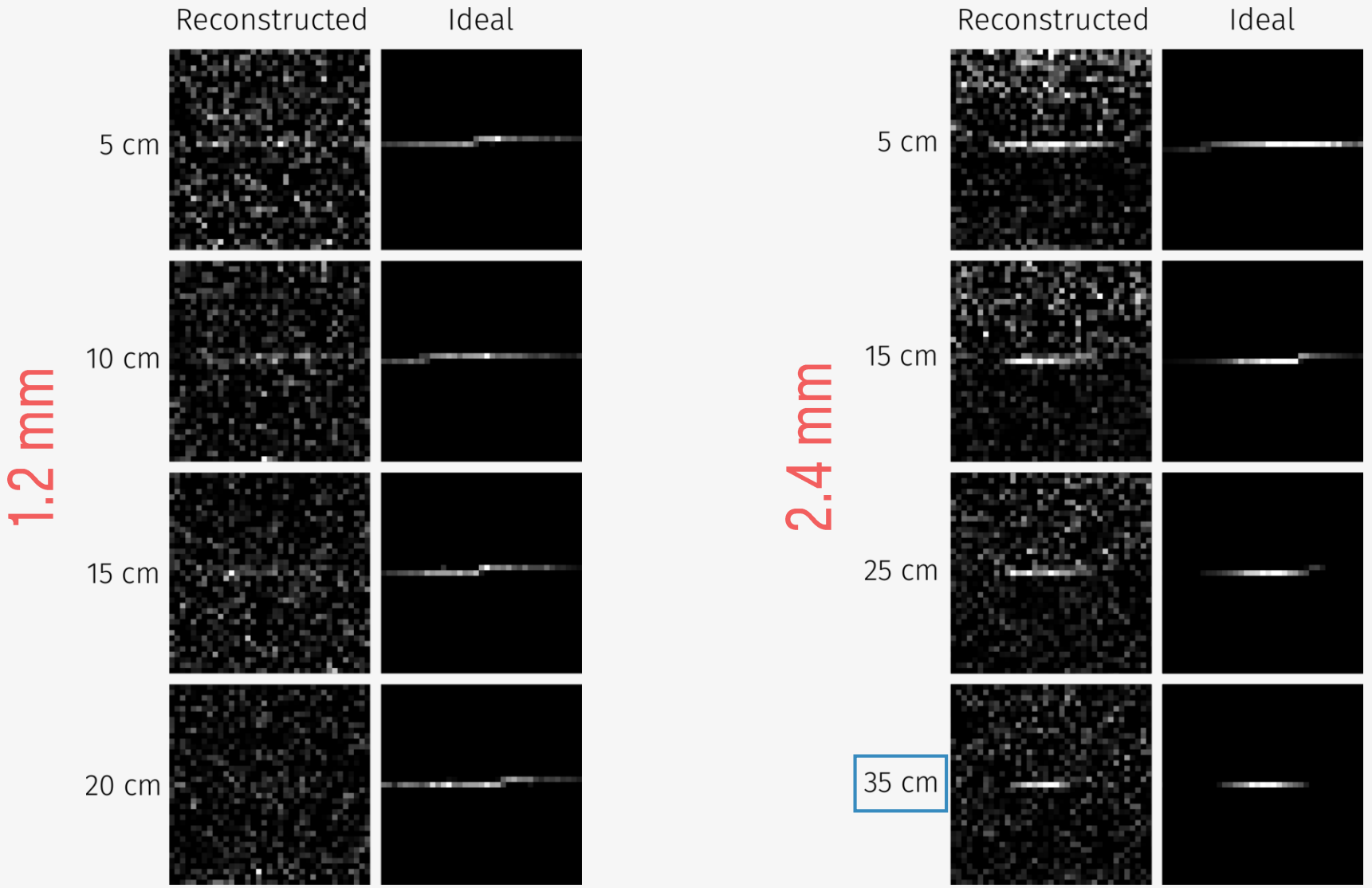
SAMPLING ARTIFACTS

$$\alpha = \frac{\left(1 + \frac{b}{a}\right) p_m}{p_d}$$



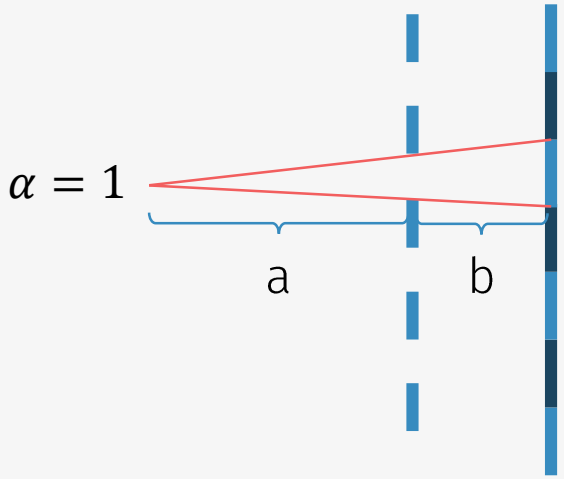


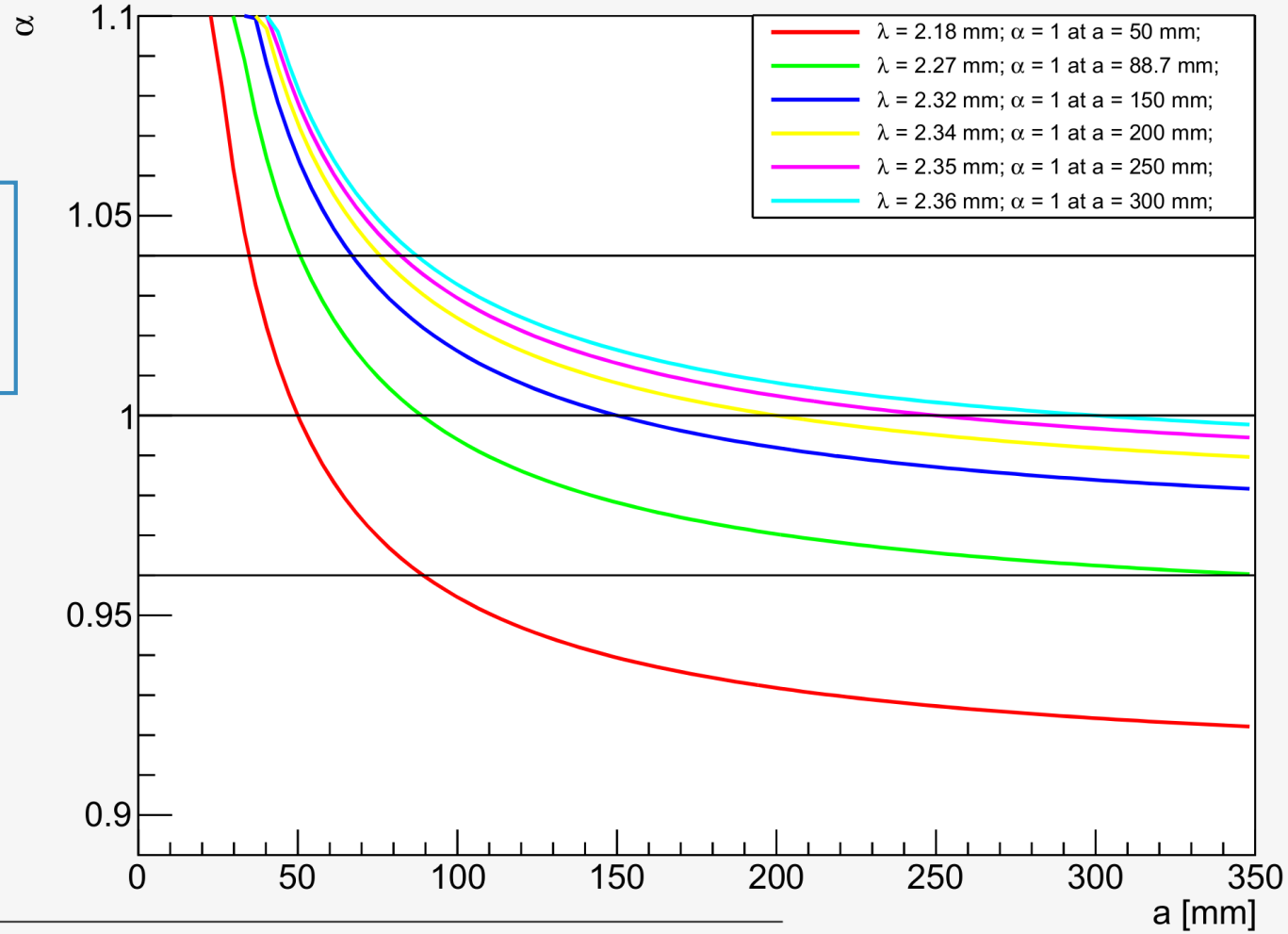
OPTIMIZATION – PIXEL SIZE



OPTIMIZATION – ALPHA

$$\alpha = \frac{\left(1 + \frac{b}{a}\right)\lambda}{p_d} \rightarrow \boxed{\frac{d\alpha}{da} = -\frac{\lambda b}{p_d a^2}}$$



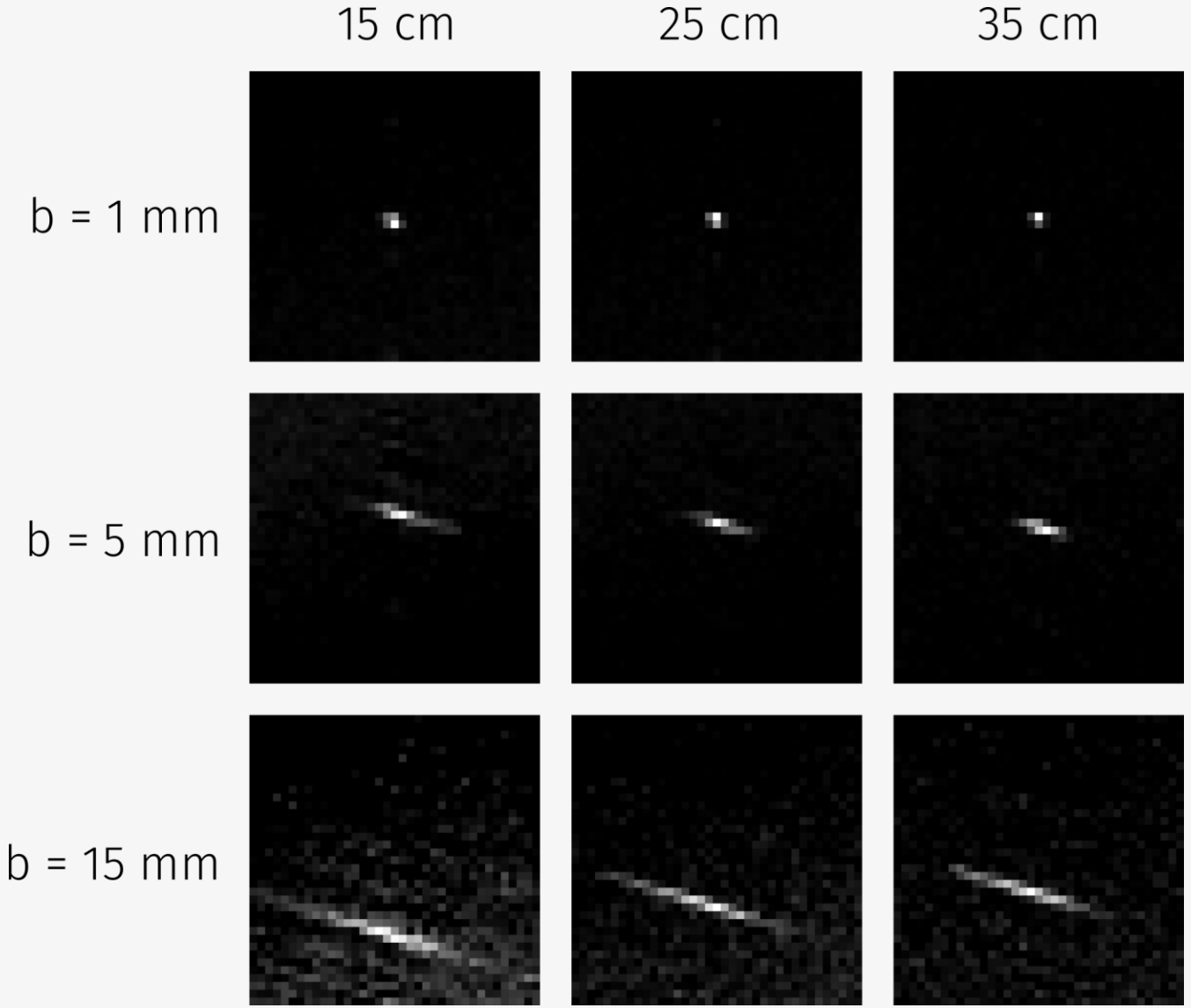


	$a(\alpha = 1)$	$a(\alpha = 0.96)$	$a(\alpha = 1.04)$	Covered distance
$\lambda = 2.27$	87.31	50.22	333.82	283.6
$\lambda = 2.272$	88.75	50.71	350	299.29
$\lambda = 2.28$	95	52.78	350	297.

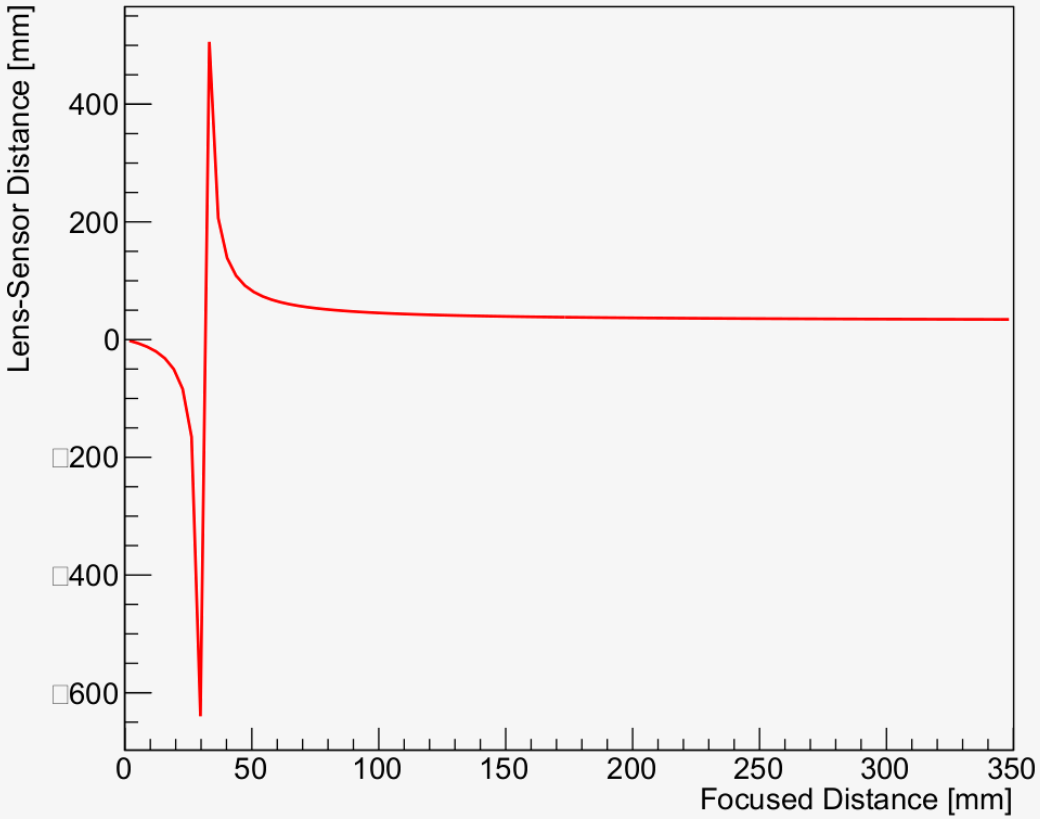
OPTIMIZATION – b

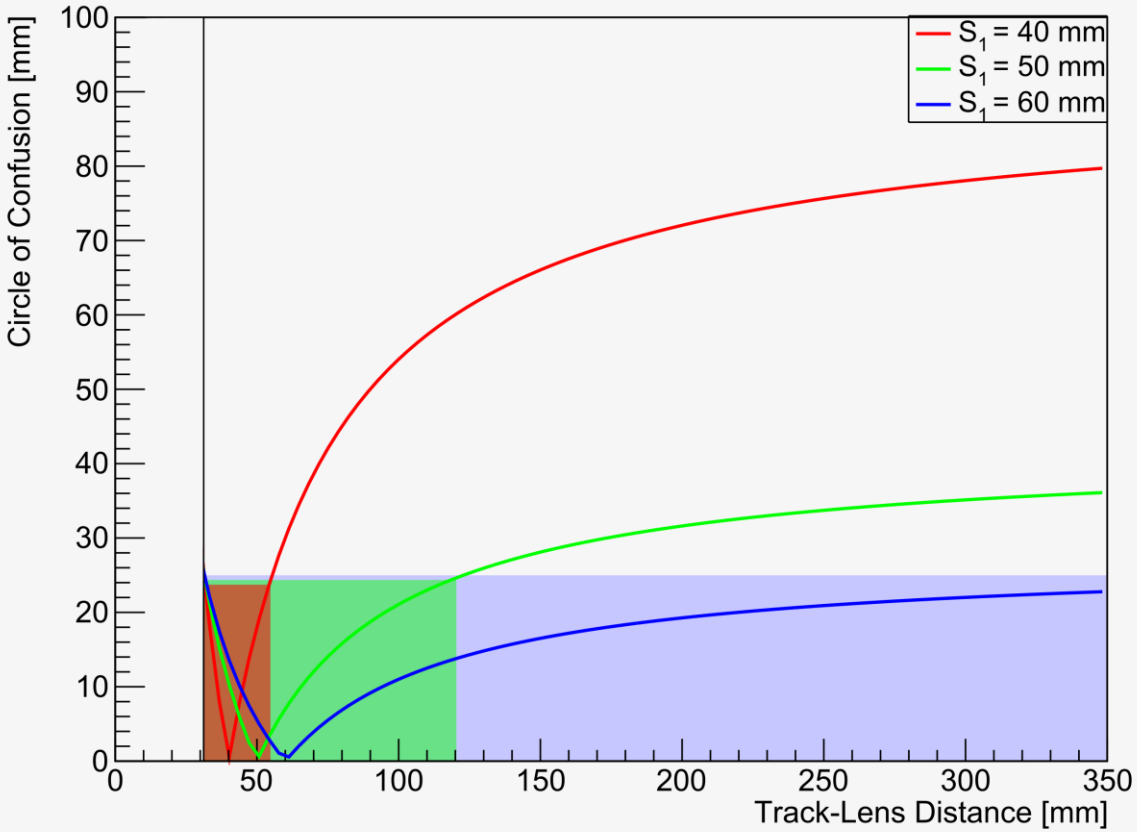
$$\alpha = \frac{\left(1 + \frac{b}{a}\right)\lambda}{p_d}$$

$$\frac{d\alpha}{da} = -\frac{\lambda b}{p_d a^2}$$

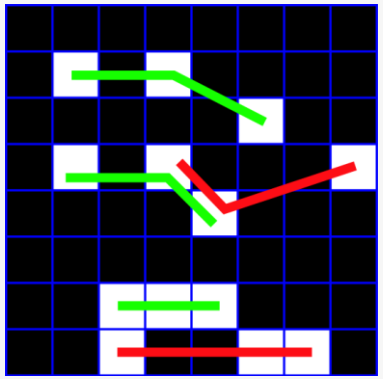


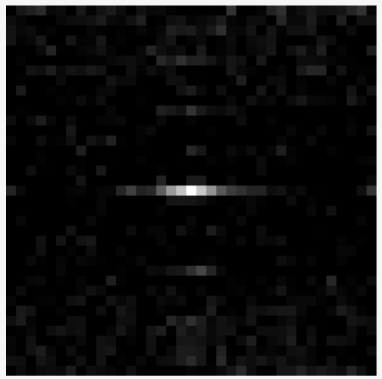
OPTIMIZATION – LENS

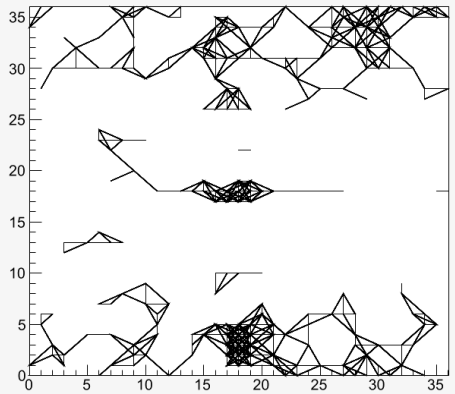


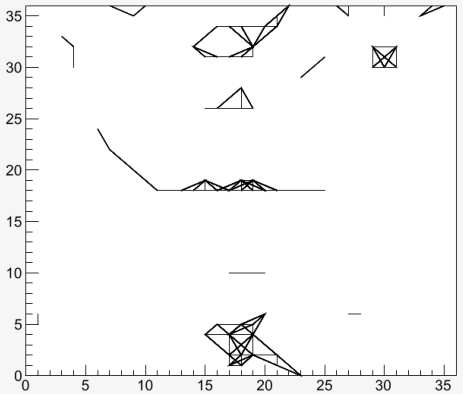


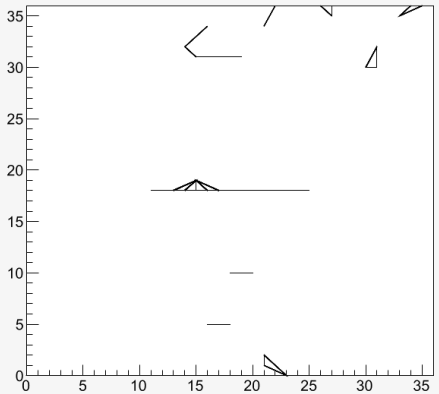
TRACK FINDING ALGORITHM

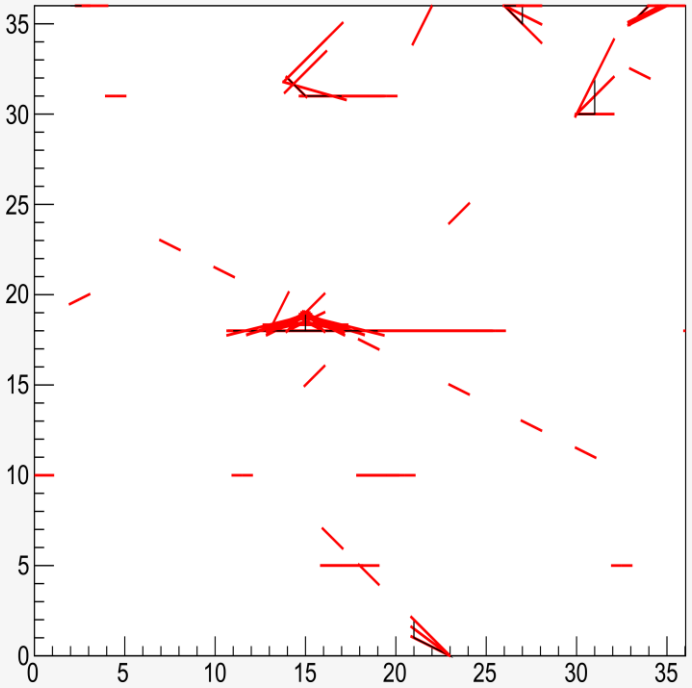


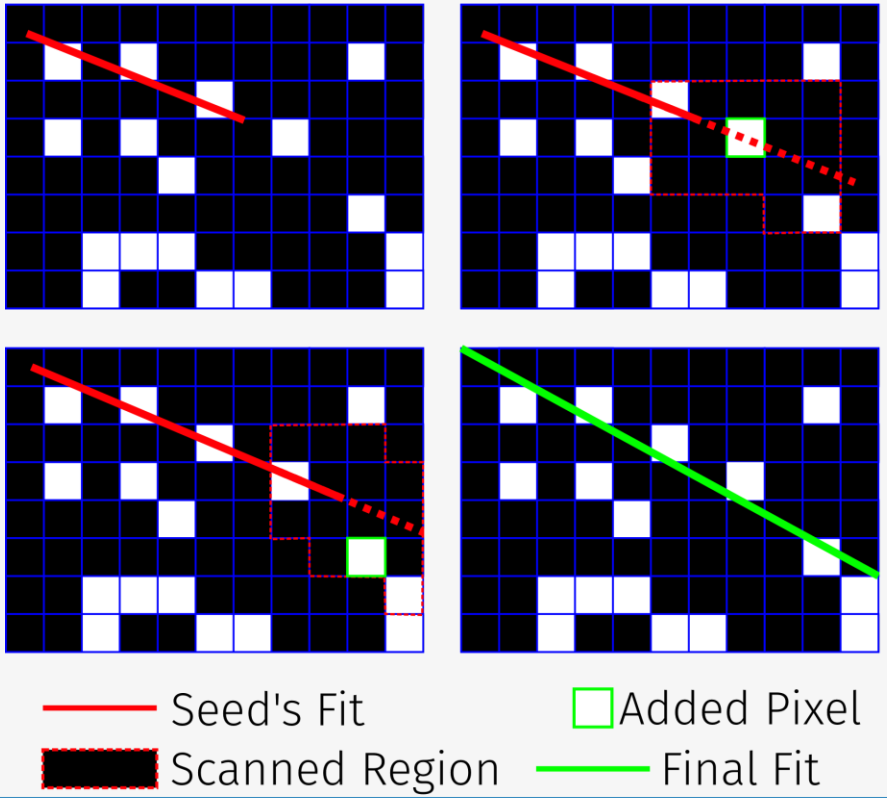












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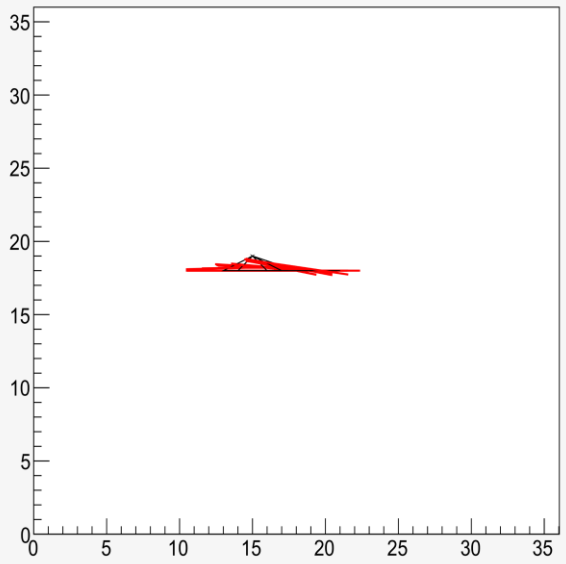
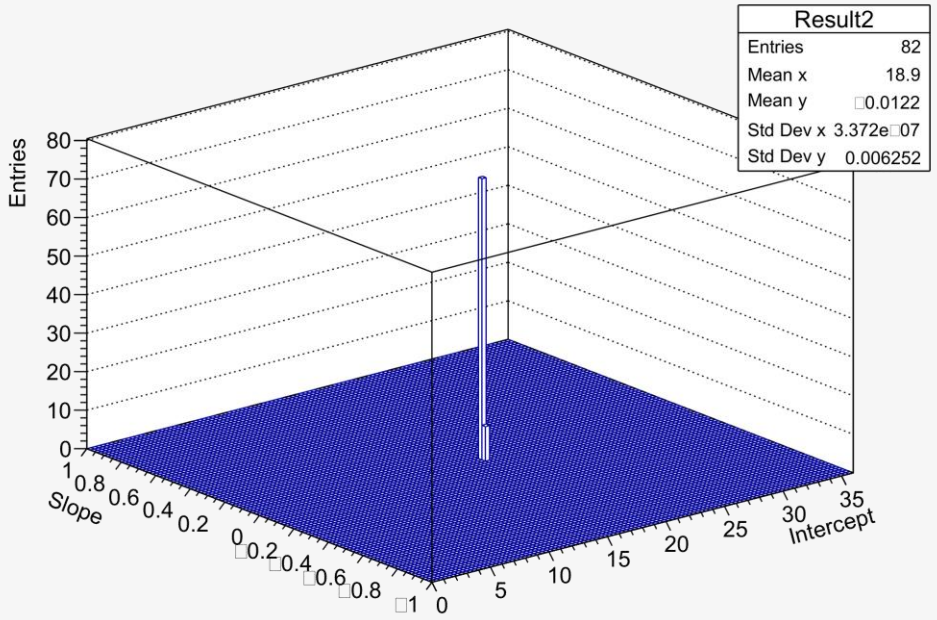
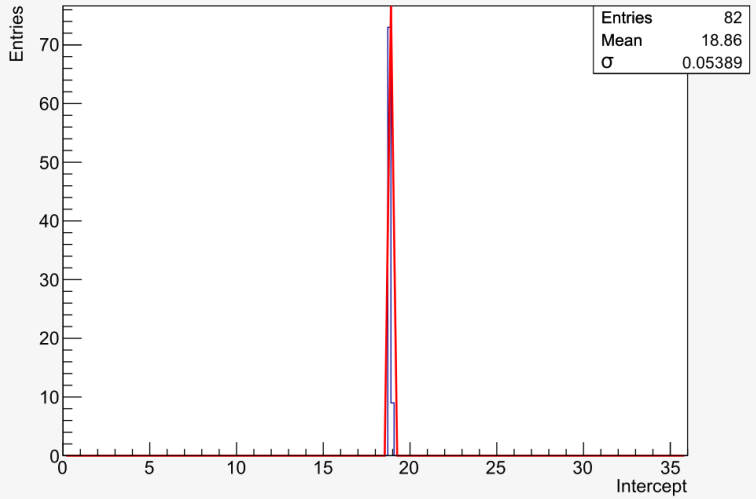
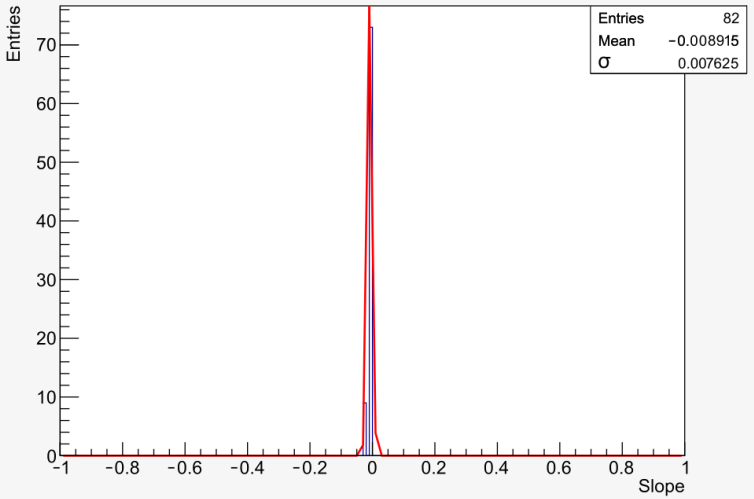
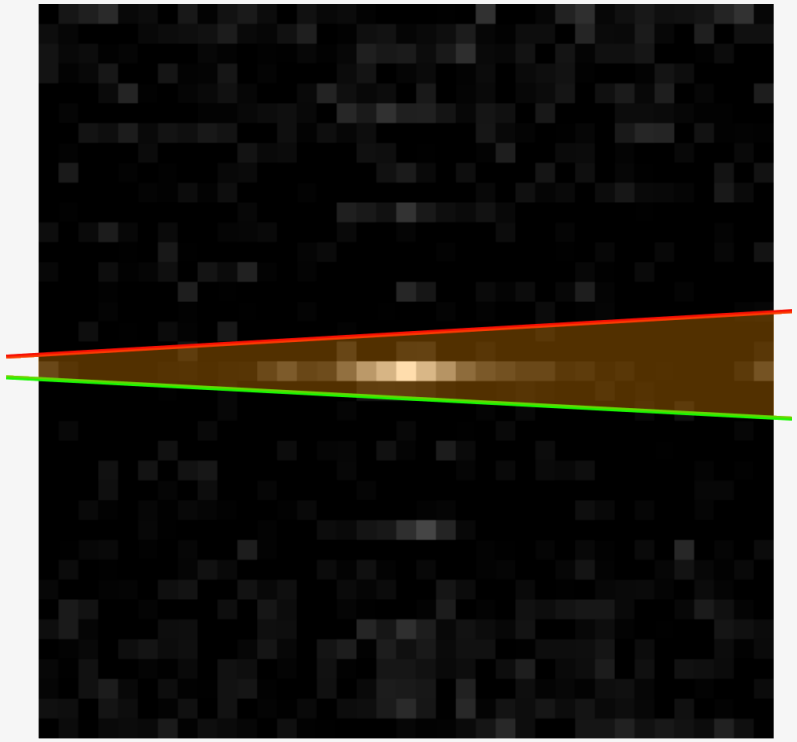


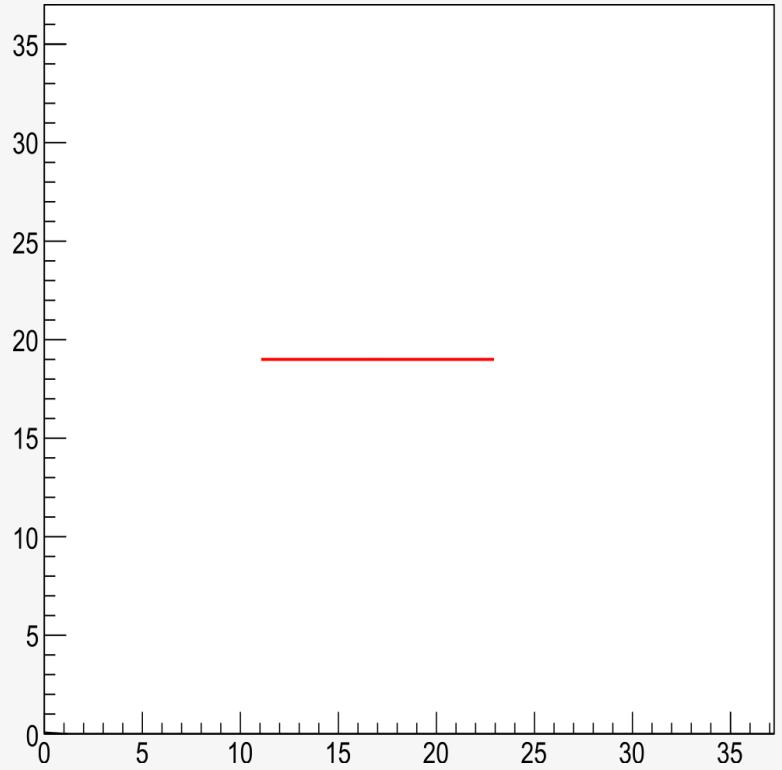






TRACK FINDING ALGORITHM





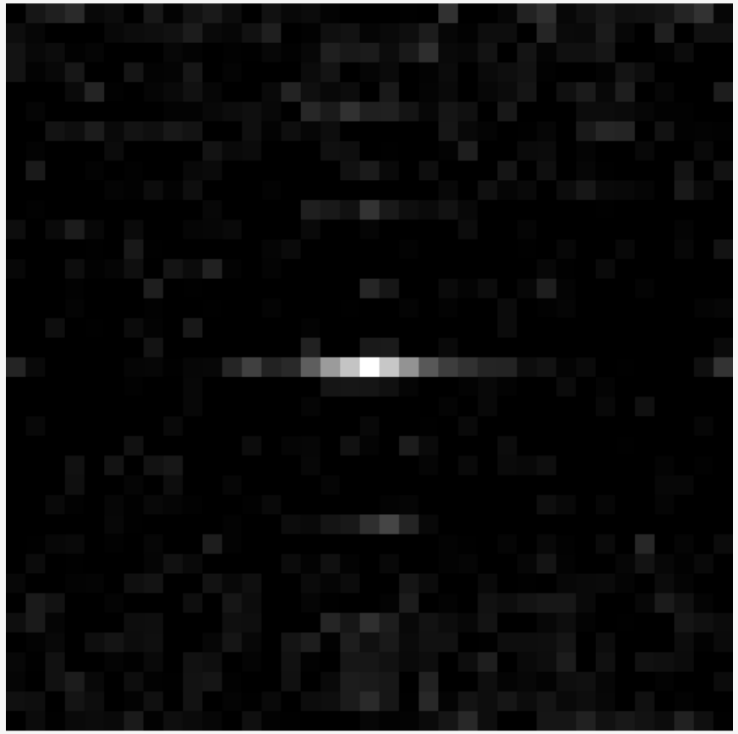
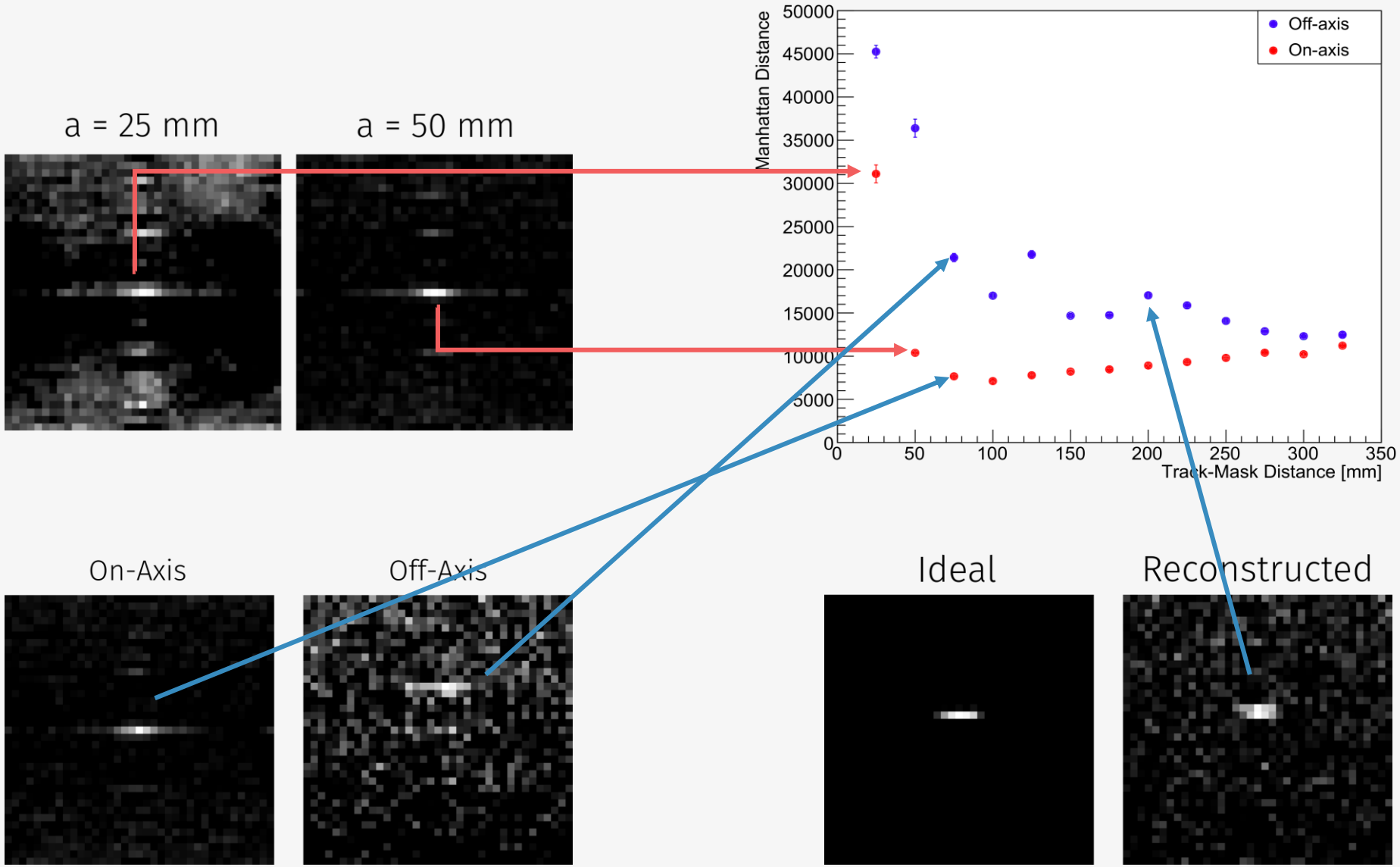
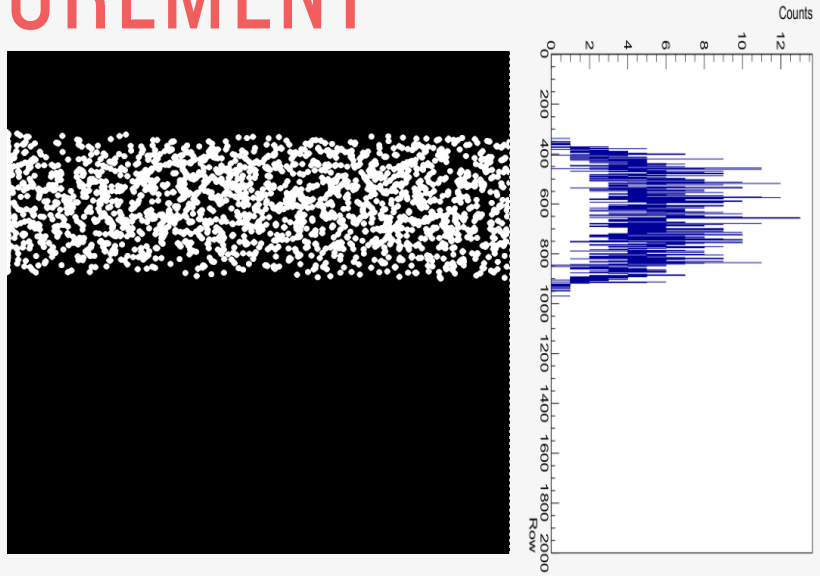
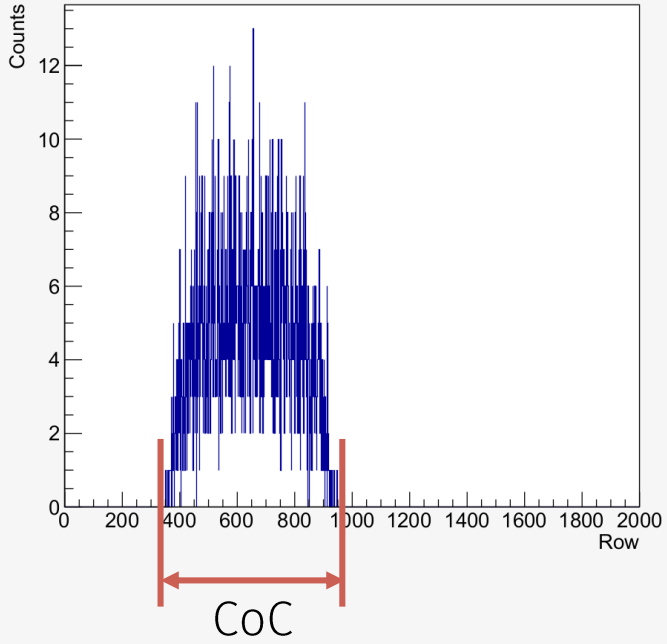


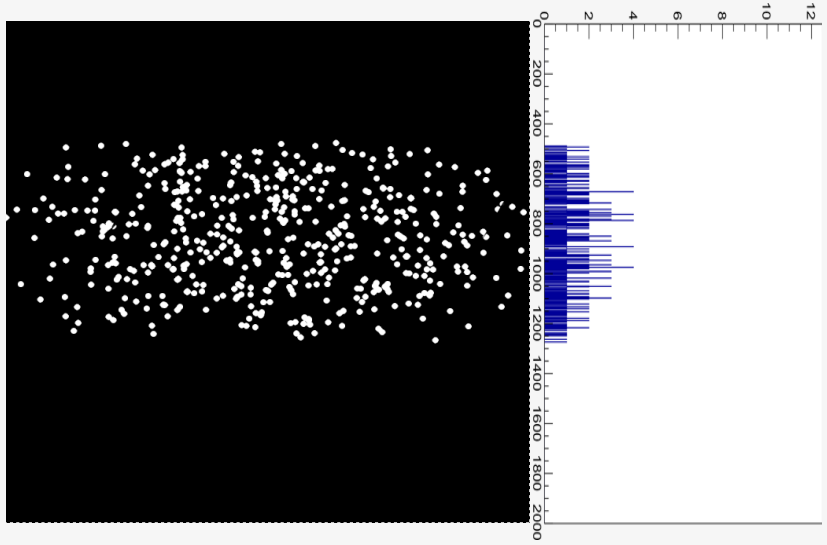
IMAGE QUALITY RESULT

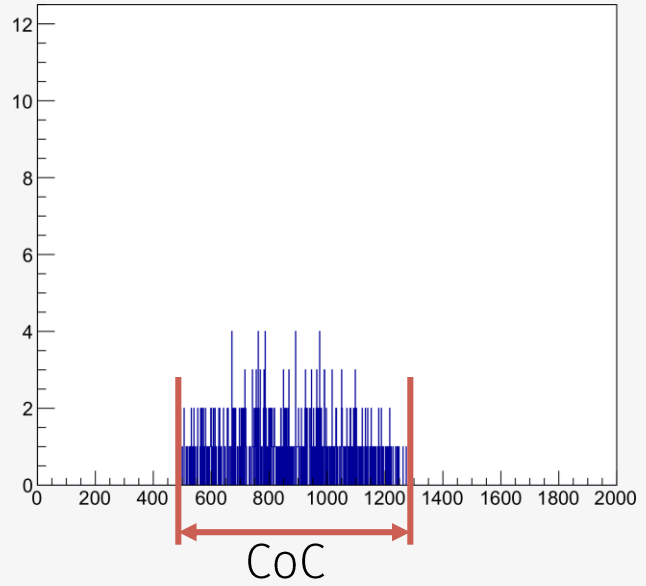


CoC MEASUREMENT

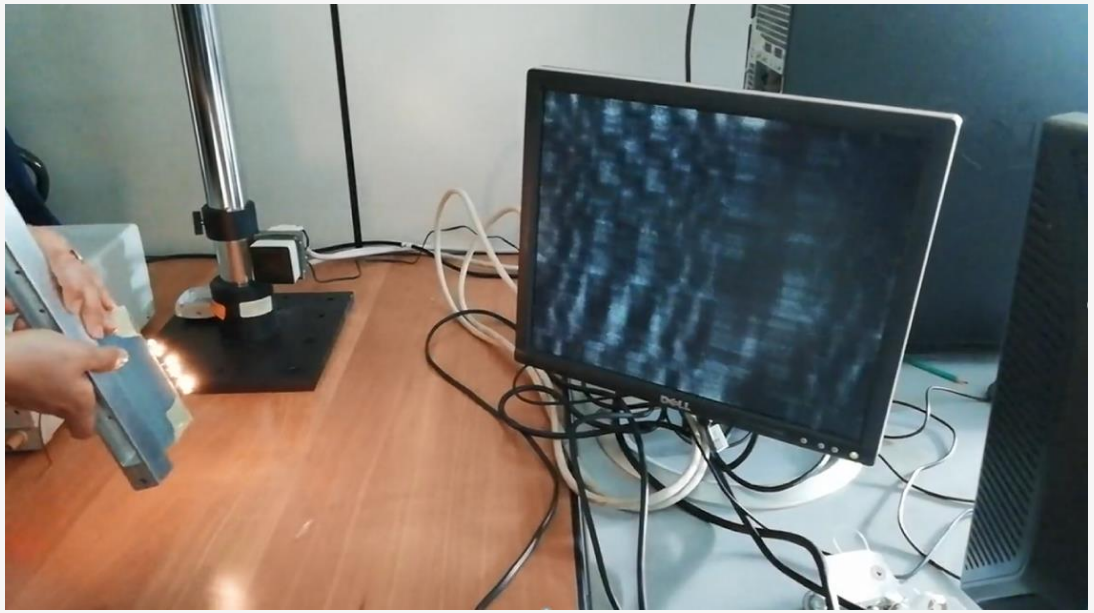


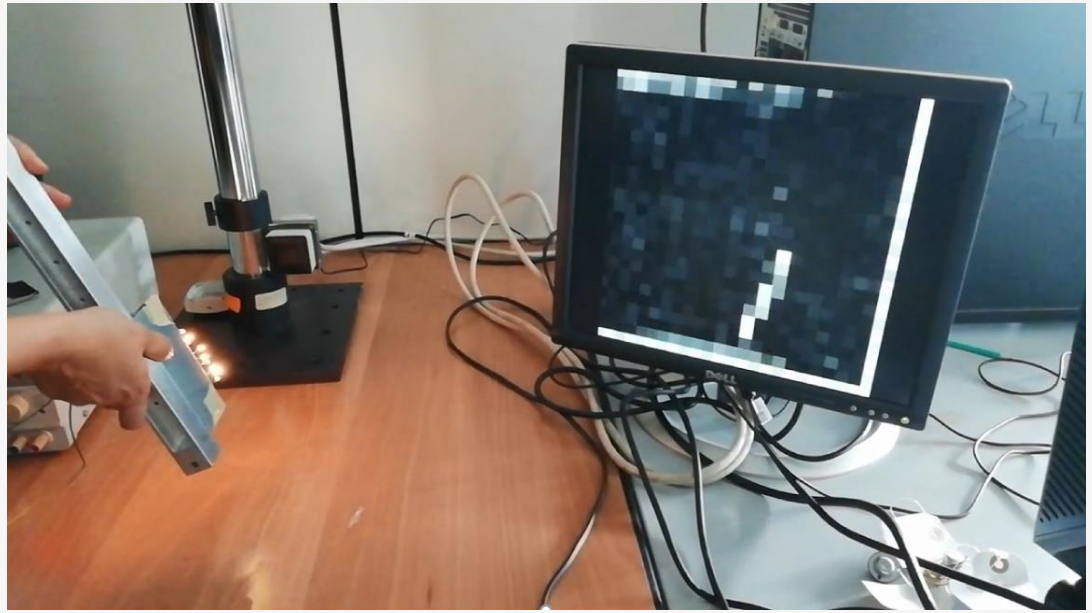




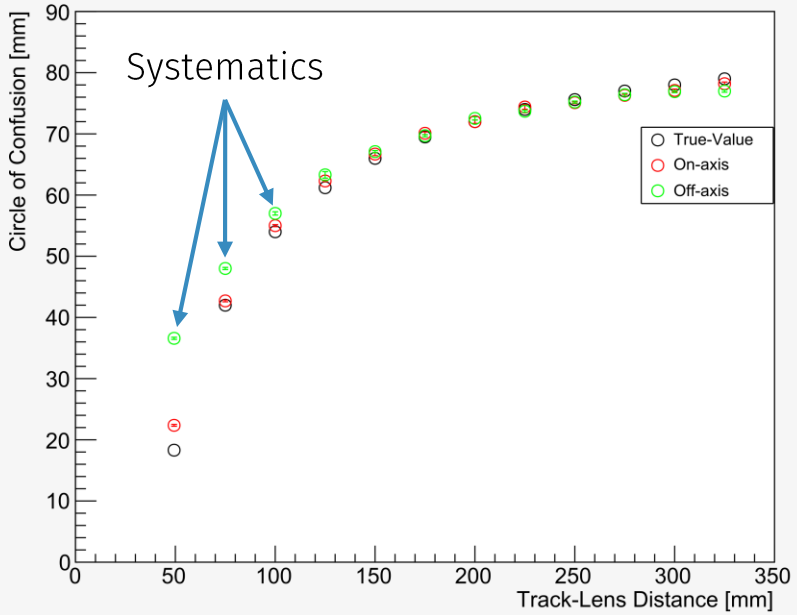


REAL TIME



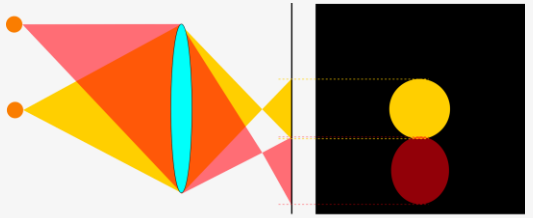


CIRCLE OF CONFUSION



The Circle of Confusion plot represents the mean value of the 20 events for each configuration.

Systematics are due the different size of the CoC for the off-axis tracks.

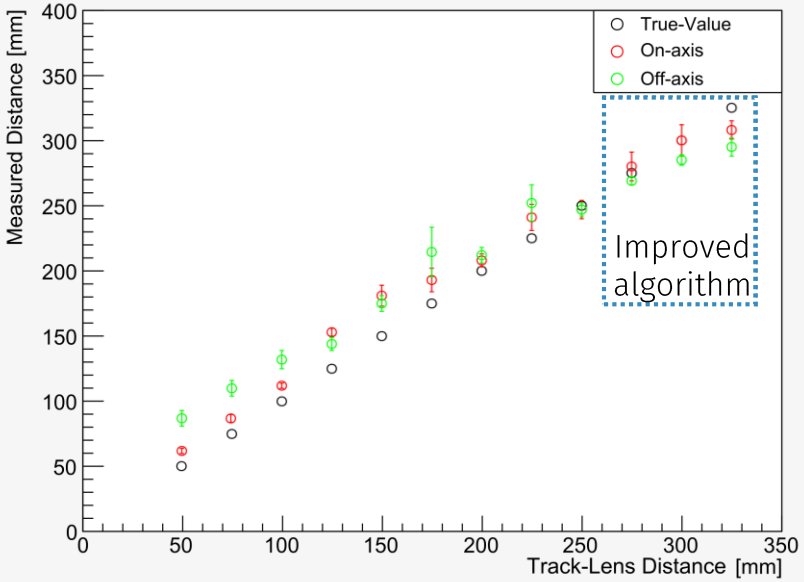


The algorithm can be modified to improve the result for the farther configurations.

The measured distances are used to estimate the detector resolution.

$$\sigma = \frac{\Sigma}{\sqrt{12}} \qquad \Sigma = width\ of\ the\ differences\ distribution$$

TRACK DISTANCE



RESOLUTION