Positron emission tomography imaging with measurements of the polarization-correlated Compton events with single-layer gamma-ray polarimeters

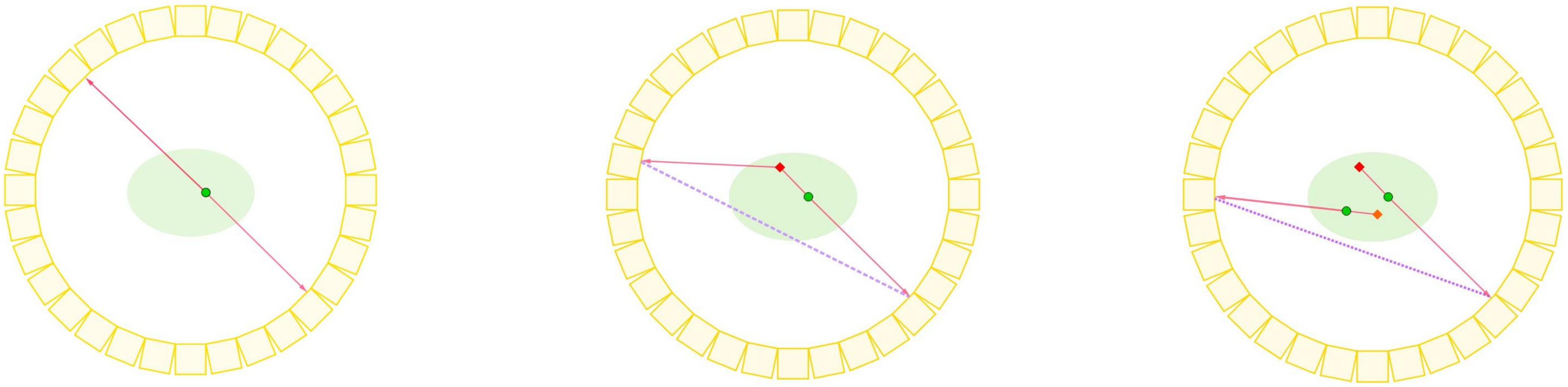
Ana Marija Kožuljević[1], Tomislav Bokulić[1], Darko Grošev[2], Zdenka Kuncic[3], Siddharth Parashari[1], Luka Pavelić[4], Marijan Žuvić[2] and Mihael Makek[1]

16th Pisa Meeting on Advanced Detectors
May 26th, 2024 – June 1st, 2024

[1] Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia
[2] Department of Nuclear Medicine and Radiation Protection, University Hospital Centre Zagreb, Zagreb, Croatia
[3] School of Physics, The University of Sydney, Sydney, NSW, Australia
[4] Institute for Medical Research and Occupational Health, Zagreb, Croatia

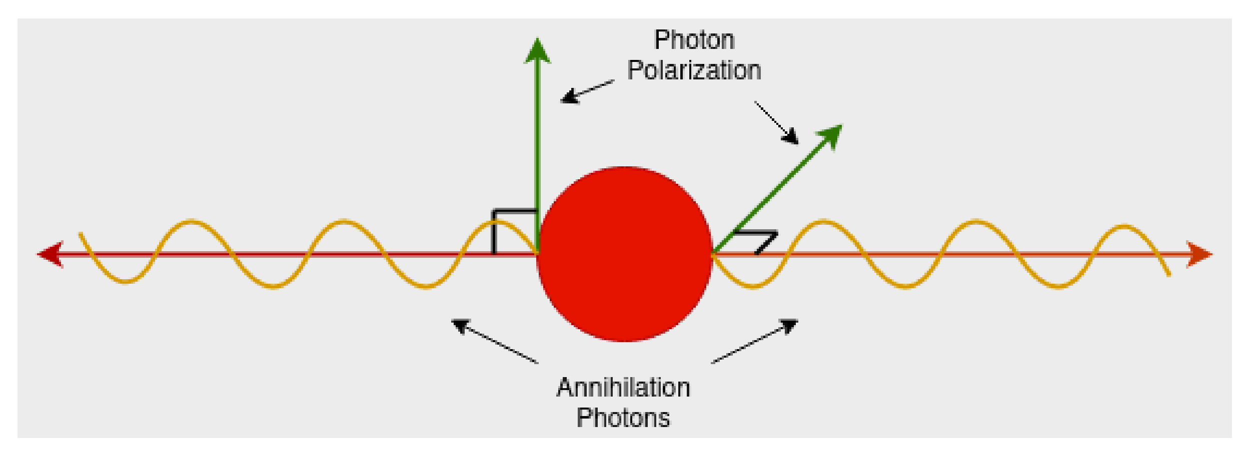
Positron emission tomography

- Diagnostic tool in medical imaging
- Based on coincidence detection of the two gammas from positron annihilation



True coincidences Scatter coincidences Random coincidences

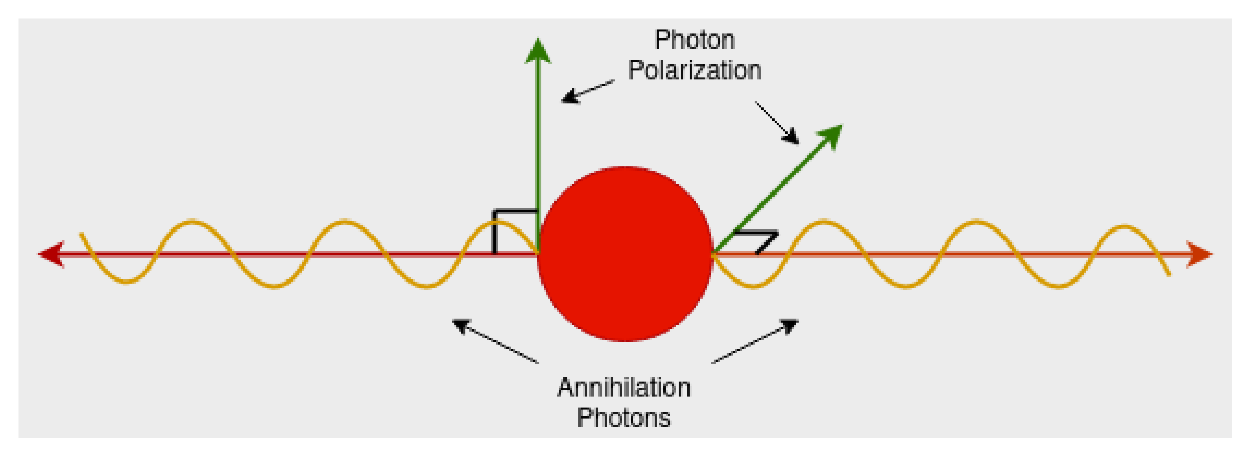
Motivation



Two gammas from positronium annihilation have:

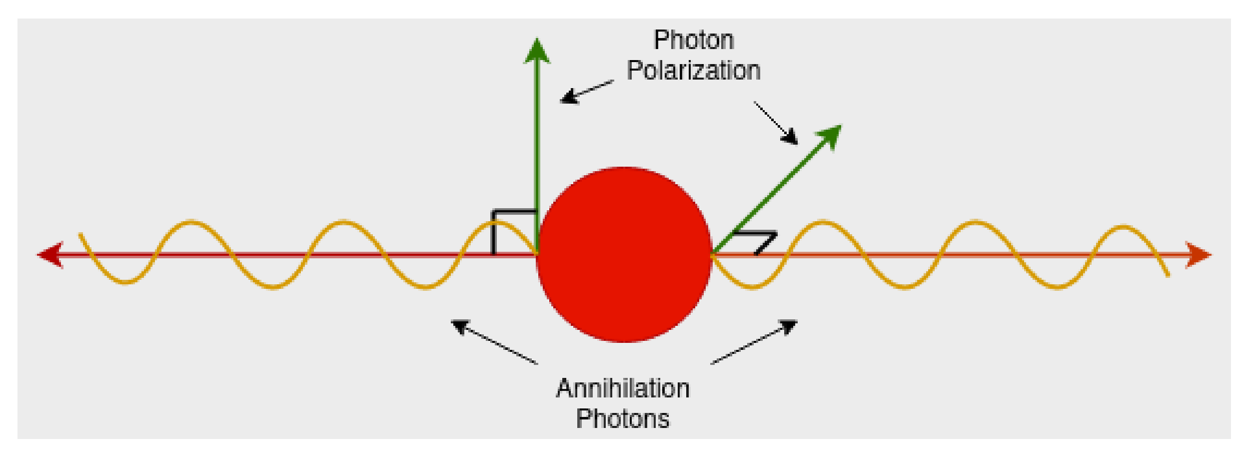
- 511 keV energy
- opposite momenta
- orthogonal polarizations

Motivation



Two gammas from positronium annihilation have:	Implemented in PET
• 511 keV energy	**YES**
• opposite momenta	**YES**
• orthogonal polarizations	**NO**

Motivation



Two gammas from positronium annihilation have:

	Implemented in PET
• 511 keV energy	YES
• opposite momenta	YES
• orthogonal polarizations	NO

Polarization correlations could be used as an additional handle to reduce background in PET → Improved image quality

*McNamara A et al. (2014) Phys. Med. Biol., 59: 7587; Toghyani M et al. (2016) Phys. Med. Biol., 61: 5803; Watts DP et al. (2021) Nat. Commun., 12: 2646; Kim D et al. (2023) JINST, 18(07):P07007

Azimuthal correlations of annihilation quanta

Double Klein-Nishina differential cross section:

$$\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = \frac{r_0^4}{16} F(\theta_1)F(\theta_2)\left\{1 - \frac{G(\theta_1)G(\theta_2)}{F(\theta_1)F(\theta_2)}\cos[2(\phi_1 - \phi_2)]\right\}$$

$$F(\theta_i) = \frac{[2 + (1 - \cos\theta_i)^3]}{(2 - \cos\theta_i)^3}, \quad G(\theta_i) = \frac{\sin^2\theta_i}{(2 - \cos\theta_i)^2}$$

Azimuthal correlations of annihilation quanta

Double Klein-Nishina differential cross section:

$$\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = \frac{r_0^4}{16} F(\theta_1)F(\theta_2)\left\{1 - \frac{G(\theta_1)G(\theta_2)}{F(\theta_1)F(\theta_2)}\cos[2(\phi_1 - \phi_2)]\right\}$$

$$F(\theta_i) = \frac{[2 + (1 - \cos\theta_i)^3]}{(2 - \cos\theta_i)^3}, \quad G(\theta_i) = \frac{\sin^2\theta_i}{(2 - \cos\theta_i)^2}$$

Maximum at $|\varphi_1 - \varphi_2| = 90°$

Azimuthal correlations of annihilation quanta

Double Klein-Nishina differential cross section:

$$\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = \frac{r_0^4}{16} F(\theta_1)F(\theta_2)\left\{1 - \frac{G(\theta_1)G(\theta_2)}{F(\theta_1)F(\theta_2)}\cos[2(\phi_1 - \phi_2)]\right\}$$

$$F(\theta_i) = \frac{[2 + (1 - \cos\theta_i)^3]}{(2 - \cos\theta_i)^3}, \quad G(\theta_i) = \frac{\sin^2\theta_i}{(2 - \cos\theta_i)^2}$$

Maximum at $|\varphi_1 - \varphi_2| = 90°$

Polarimetric modulation factor:

$$\mu \equiv \frac{P(\phi_1 - \phi_2 = 90°) - P(\phi_1 - \phi_2 = 0°)}{P(\phi_1 - \phi_2 = 90°) + P(\phi_1 - \phi_2 = 0°)}$$

Azimuthal correlations of annihilation quanta

Double Klein-Nishina differential cross section:

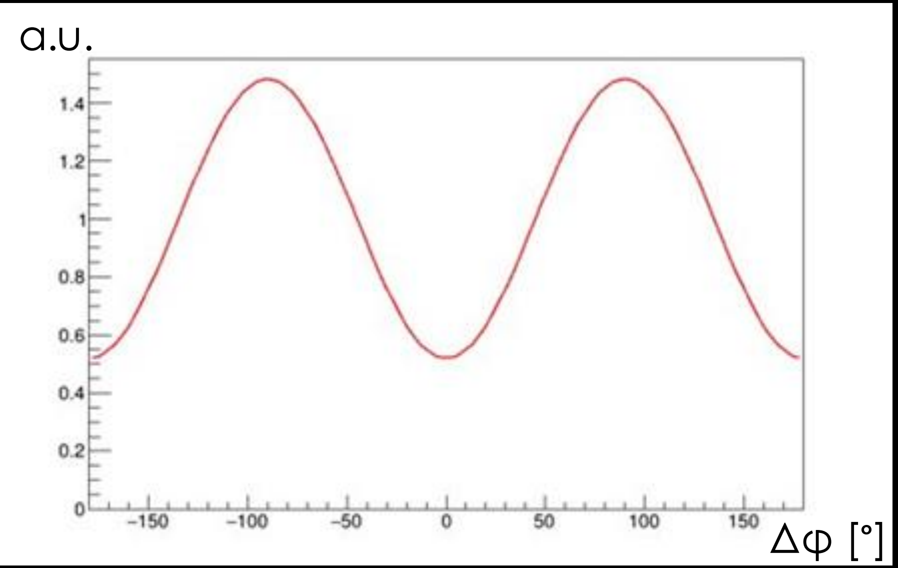
$$\frac{d^2\sigma}{d\Omega_1 d\Omega_2} = \frac{r_0^4}{16} F(\theta_1)F(\theta_2)\left\{1 - \frac{G(\theta_1)G(\theta_2)}{F(\theta_1)F(\theta_2)}\cos[2(\phi_1 - \phi_2)]\right\}$$

$$F(\theta_i) = \frac{[2 + (1 - \cos\theta_i)^3]}{(2 - \cos\theta_i)^3}, \quad G(\theta_i) = \frac{\sin^2\theta_i}{(2 - \cos\theta_i)^2}$$

Maximum at $|\varphi_1 - \varphi_2| = 90°$

Polarimetric modulation factor:

$$\mu \equiv \frac{P(\phi_1 - \phi_2 = 90°) - P(\phi_1 - \phi_2 = 0°)}{P(\phi_1 - \phi_2 = 90°) + P(\phi_1 - \phi_2 = 0°)}$$

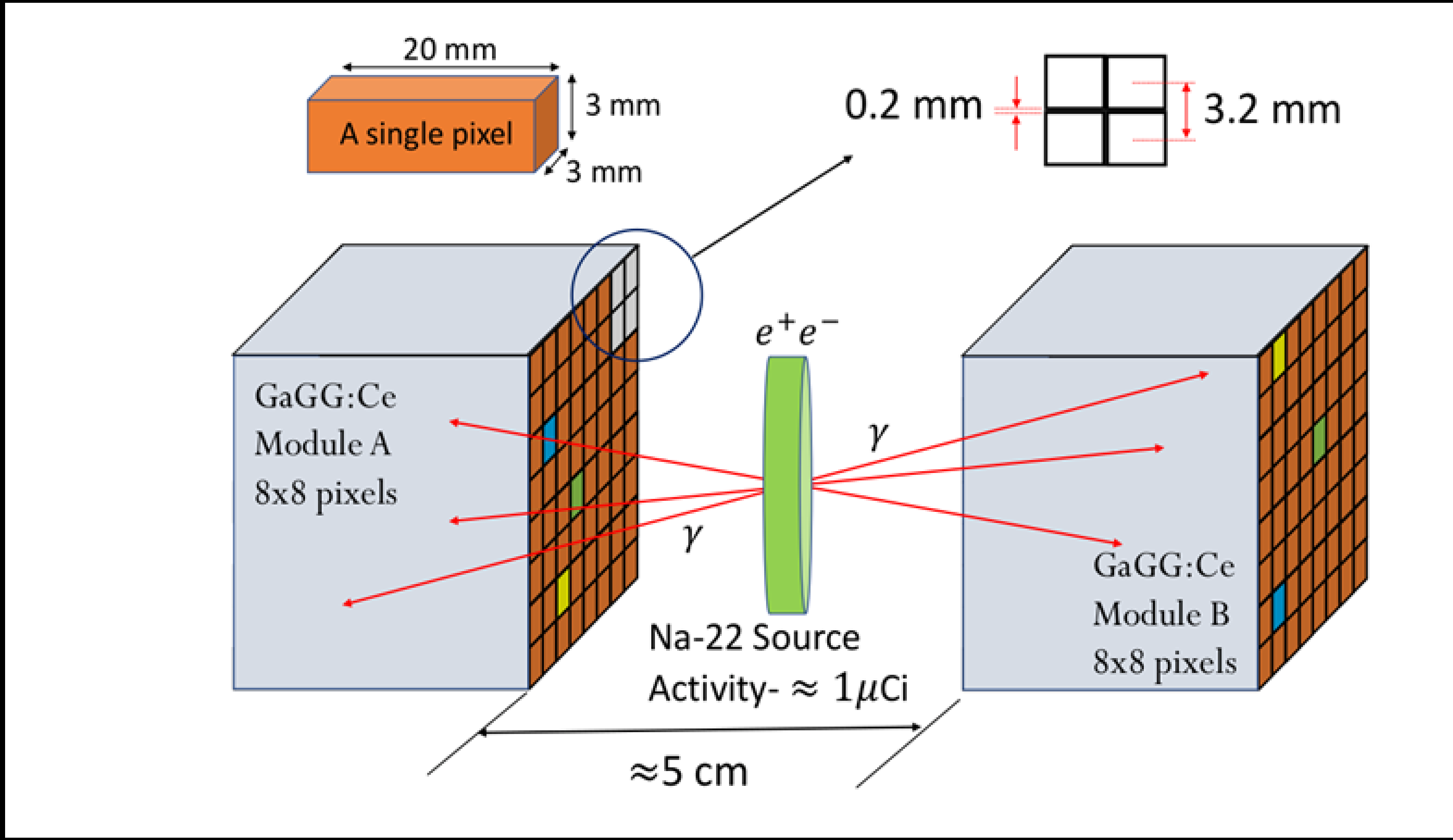


Double K-N function with polarimetric modulation factor 0.48

- Max for $\Theta_1 = \Theta_2 = 82°$:
  $\mu = 0.48$

Background events will lack such correlation!

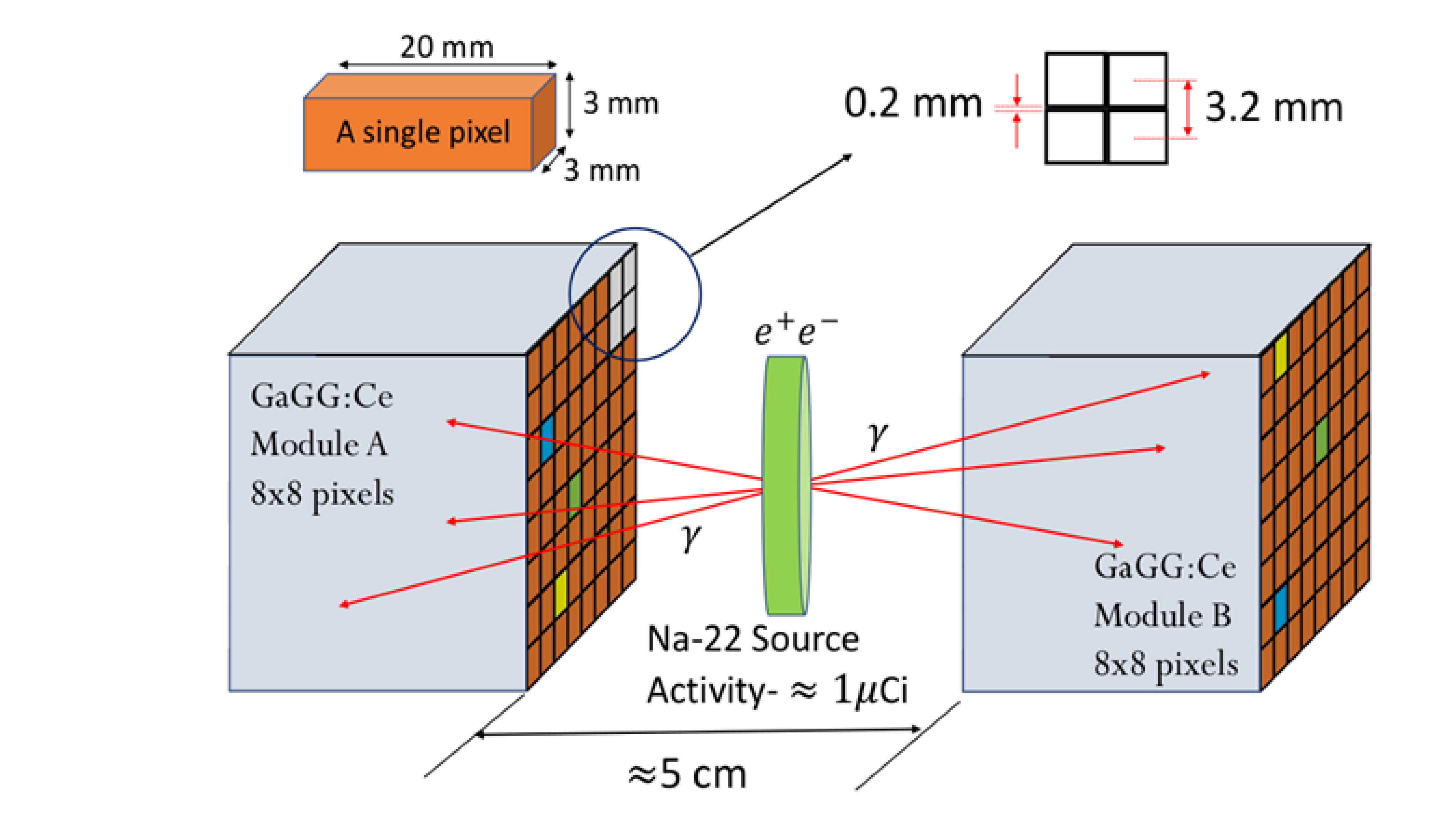
Laboratory setup



Parashari *et al.*, Nucl. Instrum. Methods Phys. Res. A (2022) 167186

Pixelated Compton polarimeters in one layer

Laboratory setup



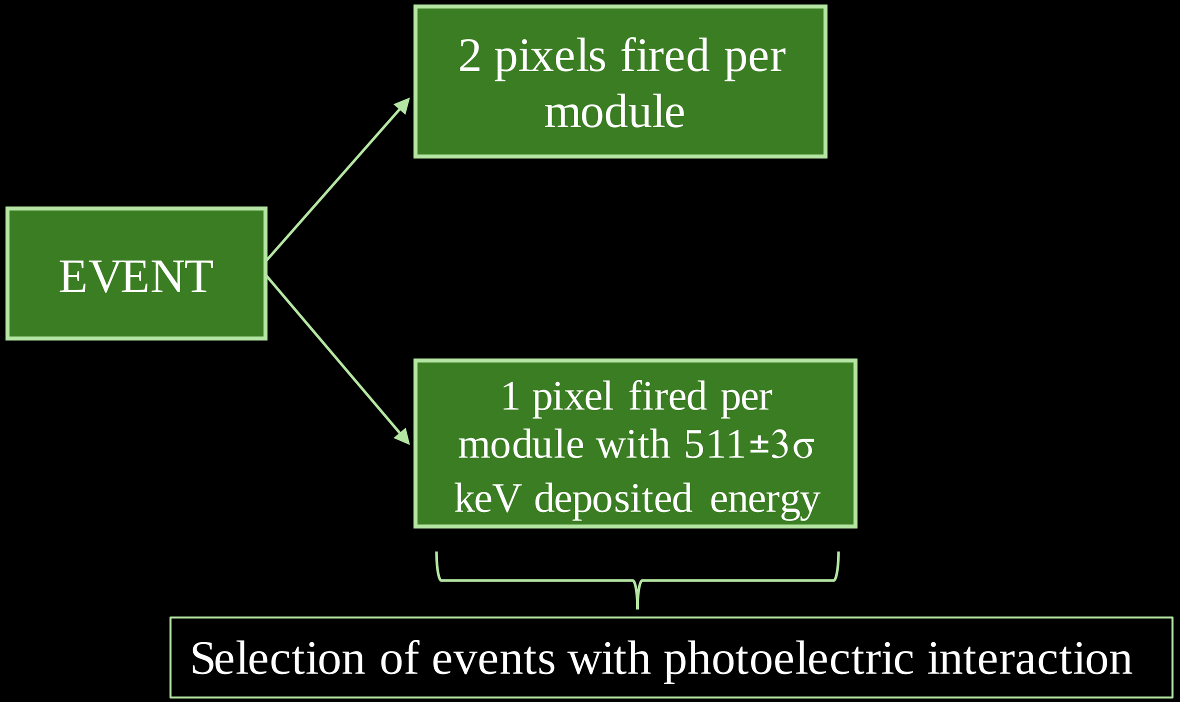
Parashari *et al.*, Nucl. Instrum. Methods Phys. Res. A (2022) 167186

Pixelated Compton polarimeters in one layer

- Scintillating crystals
  - GaGG:Ce
    - 8.1% ± 0.5% at 511 keV
  - LYSO:Ce
    - 13.7% ± 0.9% at 511 keV

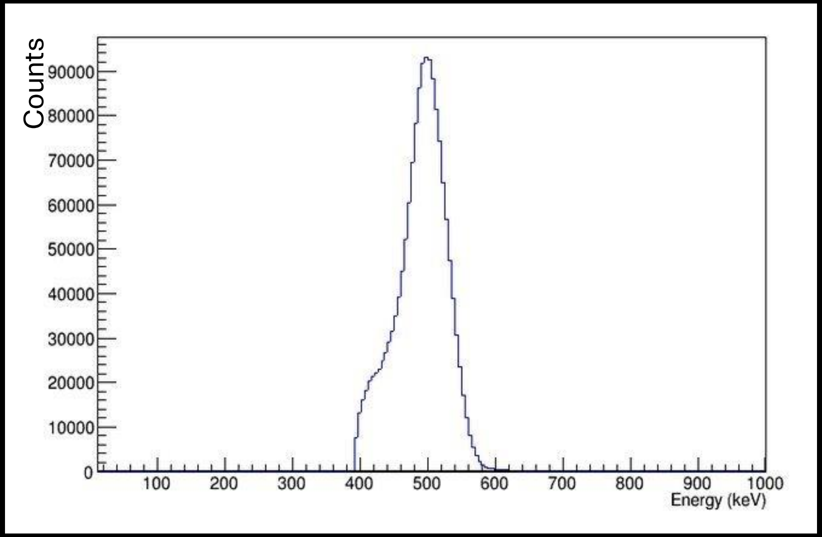
- Silicon Photomultiplier (SiPM)
- (Hamamatsu Photonics, Japan, model S13361-0808AE), 1:1 coupling
- ToFPET2 ASIC read-out system

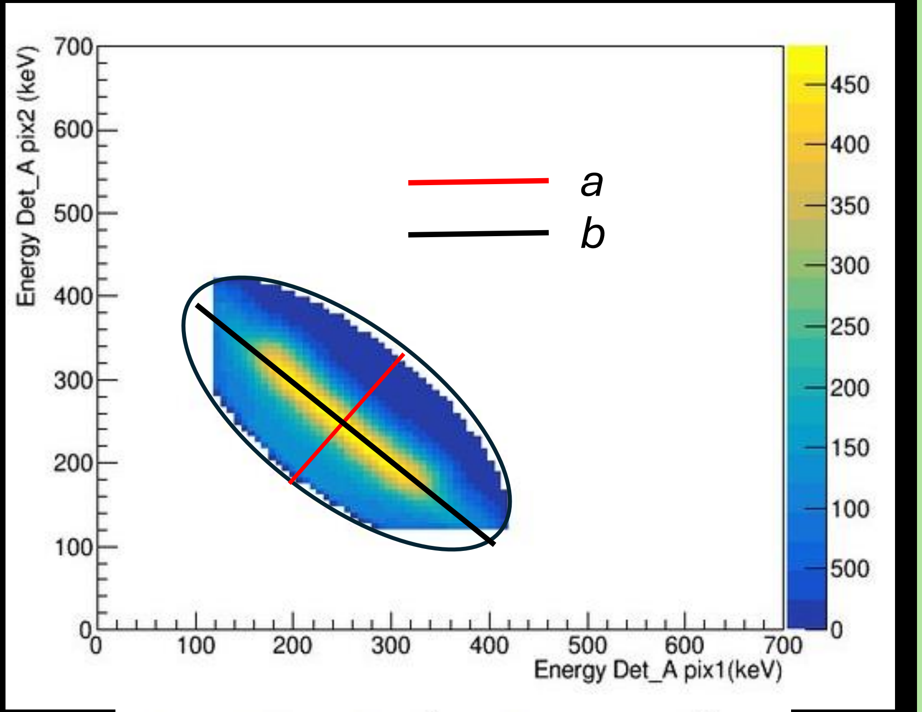
Data selection



Data selection

Selection of events with two pixels fired with sum of deposited energies 511±3σ keV





$$\left(\frac{E_{px_1}+E_{px_2}-E_{\gamma}}{a}\right)^2+\left(\frac{E_{px_1}-E_{px_2}}{b}\right)^2<1$$

Selection of Compton events with two pixels fired with sum of deposited energies 511±3σ keV

EVENT

2 pixels fired per module → elliptical cut with sum of deposited energies 511±3σ keV

Compton scattering events

1 pixel fired per module with 511±3σ keV deposited energy

Selection of events with photoelectric interaction

First pixel - lower energy deposition!

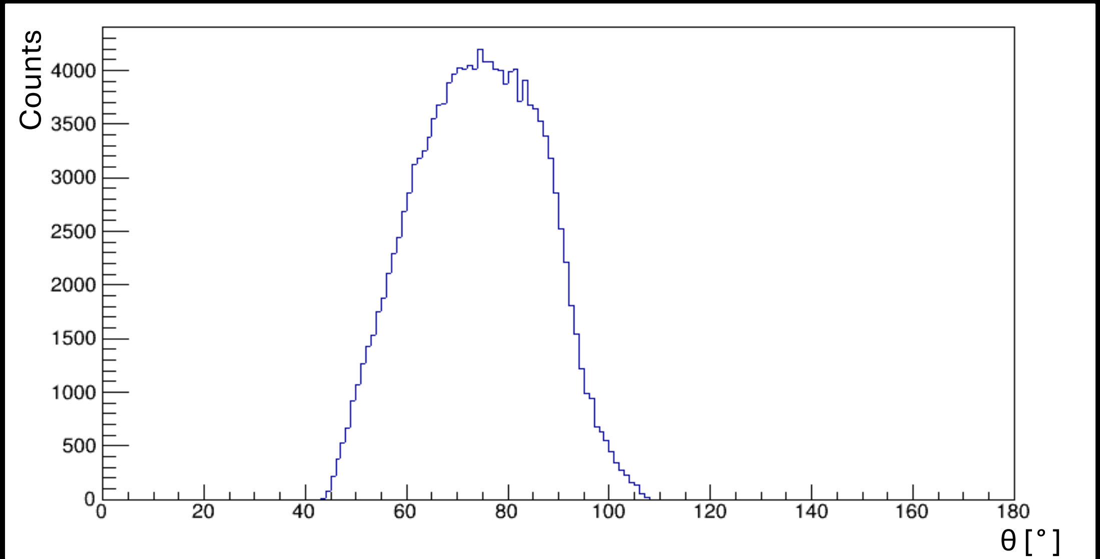
True for ~55% of the events

(A. M. Kožuljević *et al.*, Condensed Matter (2021), 6, 43)

Data selection

$$\theta = \mathrm{acos}\left(\frac{m_e c^2}{E_{px_1}+E_{px_2}} - \frac{m_e c^2}{E_{px_2}} - 1\right)$$

Distribution of the selected events' Compton scattering angles Θ



EVENT

2 pixels fired per module → elliptical cut with sum of deposited energies 511±3σ keV → Θ angle reconstruction

Compton scattering events

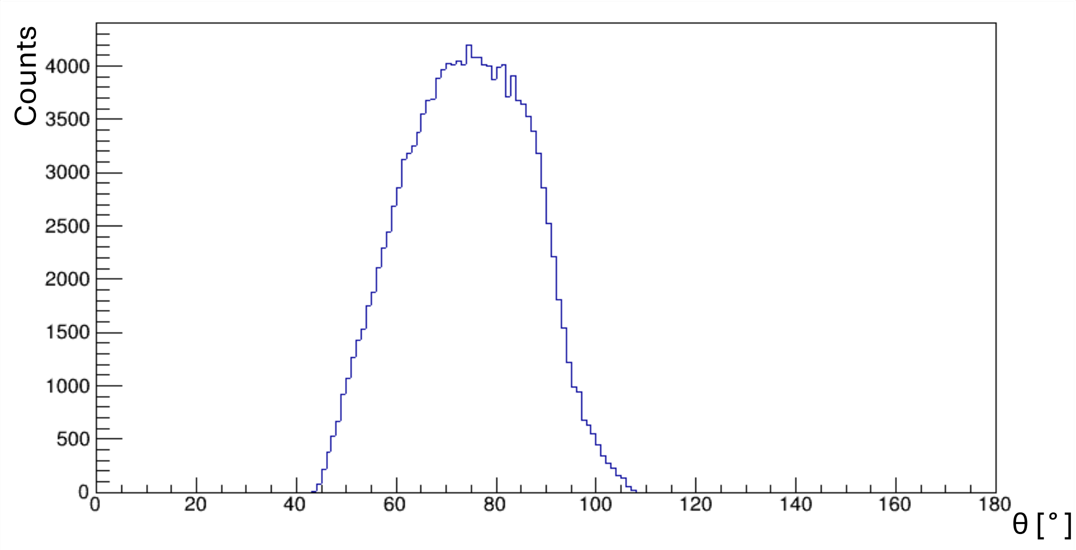
1 pixel fired per module with 511±3σ keV deposited energy

Selection of events with photoelectric interaction

Data selection

$$\theta = \mathrm{acos}\left(\frac{\mathrm{m_e c^2}}{\mathrm{E_{px_1}+E_{px_2}}} - \frac{\mathrm{m_e c^2}}{\mathrm{E_{px_2}}} - 1\right)$$

Distribution of the selected events' Compton scattering angles Θ



EVENT

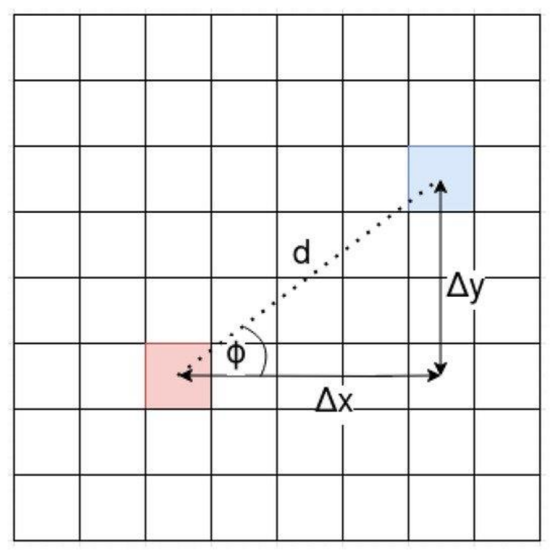
2 pixels fired per module → elliptical cut with sum of deposited energies 511±3σ keV → Θ angle reconstruction → ϕ angle reconstruction

Compton scattering events

1 pixel fired per module with 511±3σ keV deposited energy

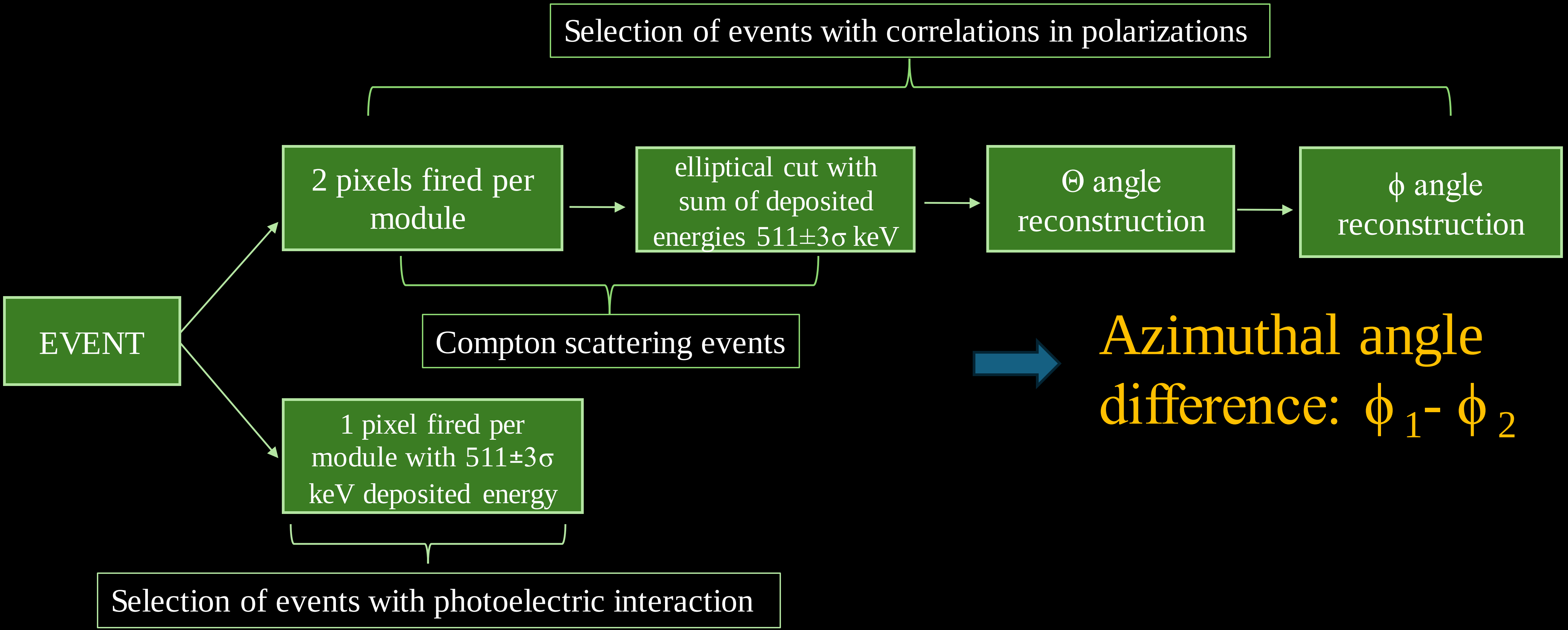
Selection of events with photoelectric interaction

$$\phi = \mathrm{atan}\left(\frac{\Delta y}{\Delta x}\right)$$



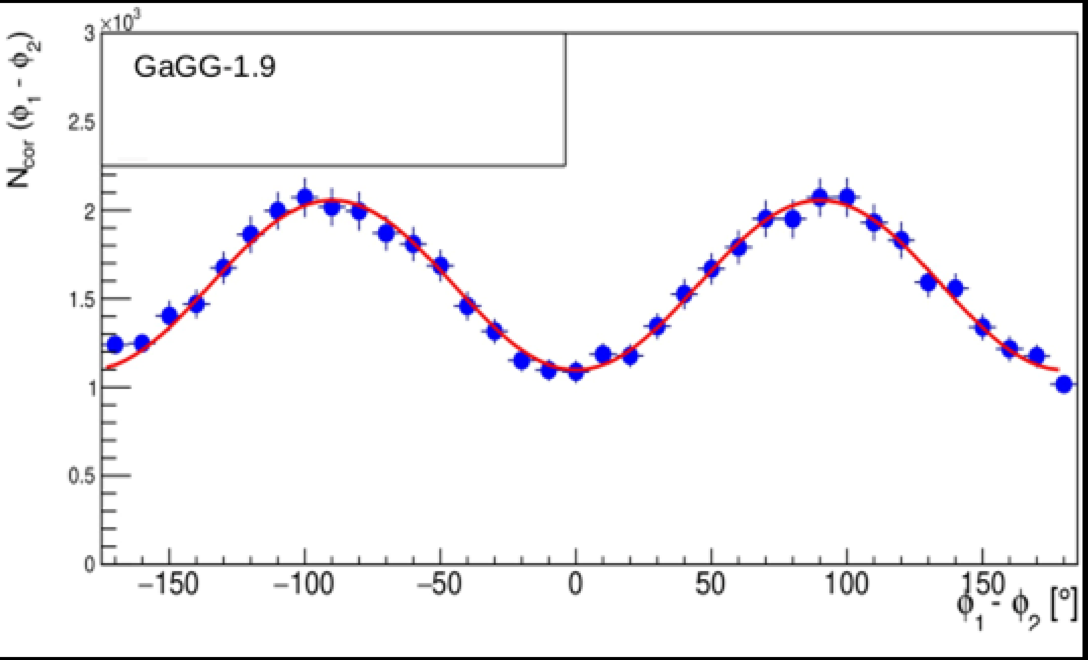
A. M. Kožuljević *et al.*, Condensed Matter (2021), 6, 43

Data selection



Polarization correlations - reconstruction

After the acceptance correction $N_{\text{corr}}(\phi_1 - \phi_2) = \frac{N(\phi_1 - \phi_2)}{A_n(\phi_1 - \phi_2)}$

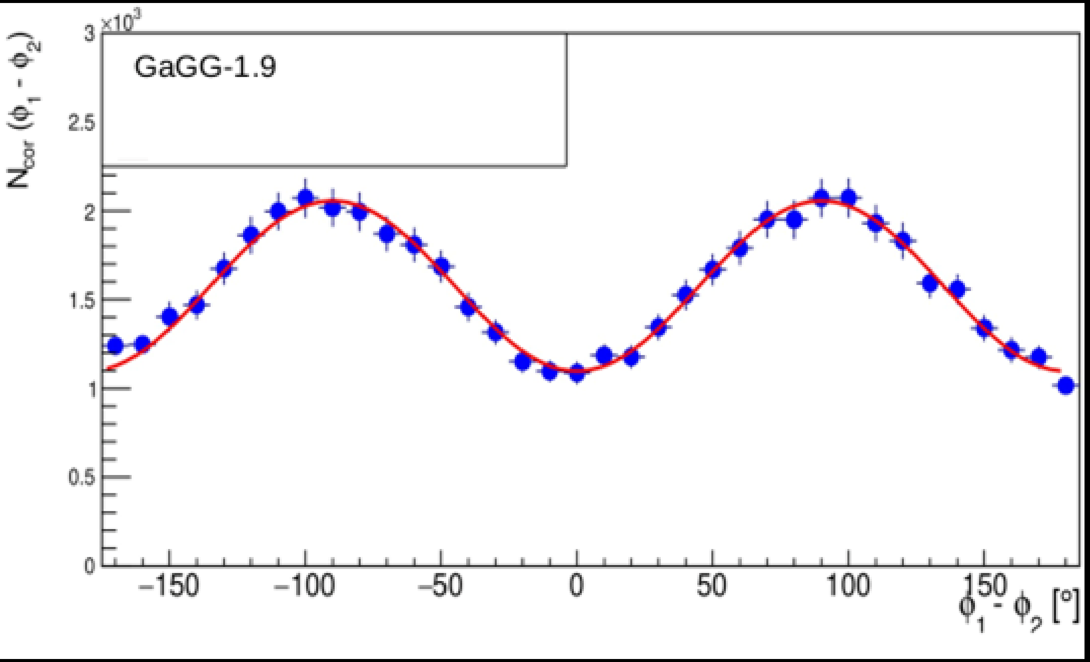


Distribution of the azimuthal angle differences after both gammas undergo Compton scattering

Blue – measured data
Red – Klein-Nishina fit function $\text{N}_{\text{cor}}(\phi_1 - \phi_2) = \text{M}[1 - \mu\cos(2(\phi_1 - \phi_2)]$

Polarization correlations - reconstruction

After the acceptance correction $$N_{\mathrm{corr}}\left(\phi_1-\phi_2\right)=\frac{N\left(\phi_1-\phi_2\right)}{A_n\left(\phi_1-\phi_2\right)}$$



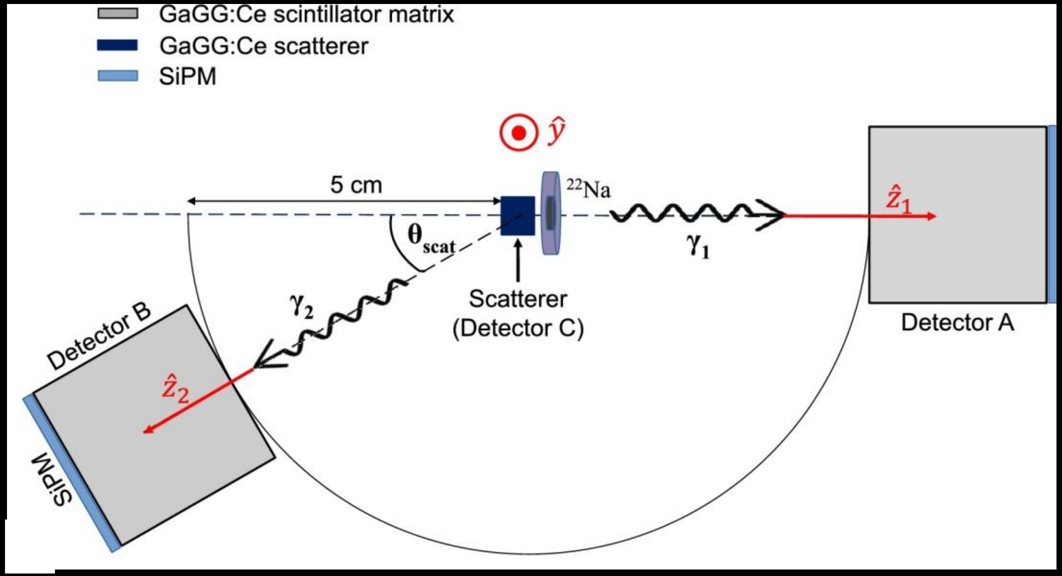
Distribution of the azimuthal angle differences after both gammas undergo Compton scattering

- More precise energy and angular selection criteria lead to higher modulation factors
- Finely segmented scintillators are the best choice to distinguish between the true and false coincidences

Blue – measured data
Red – Klein-Nishina fit function $$\mathrm{N}_{\mathrm{cor}}(\phi_1-\phi_2)=\mathrm{M}[1-\mu\cos(2(\phi_1-\phi_2)]$$

Polarization correlations - addendum

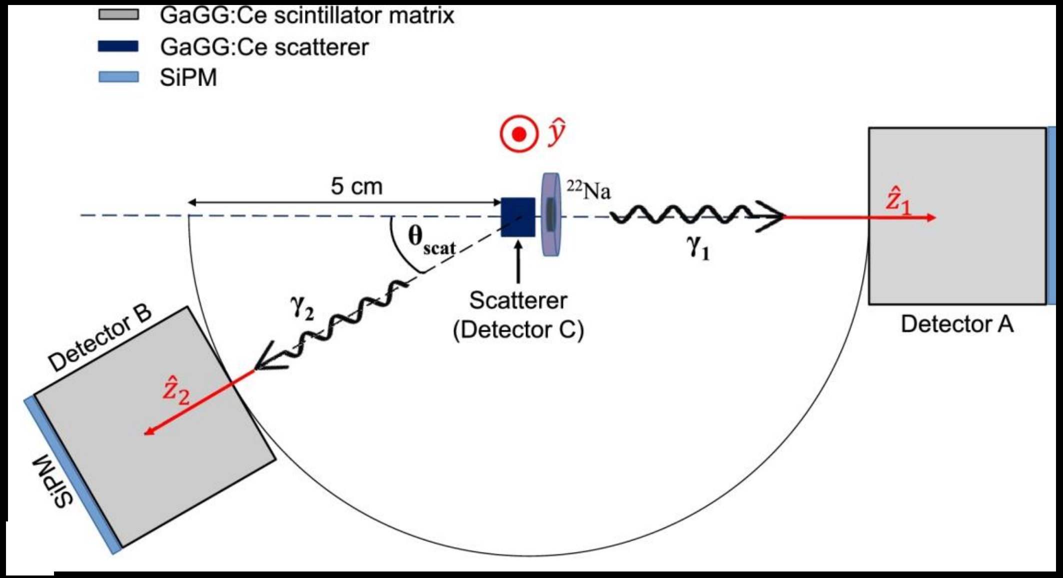
Parashari et al. (2024) Physics Letters B, 852:138628



Experimental setup for measuring polarization correlations after one of the annihilation photons undergoes previous scatter

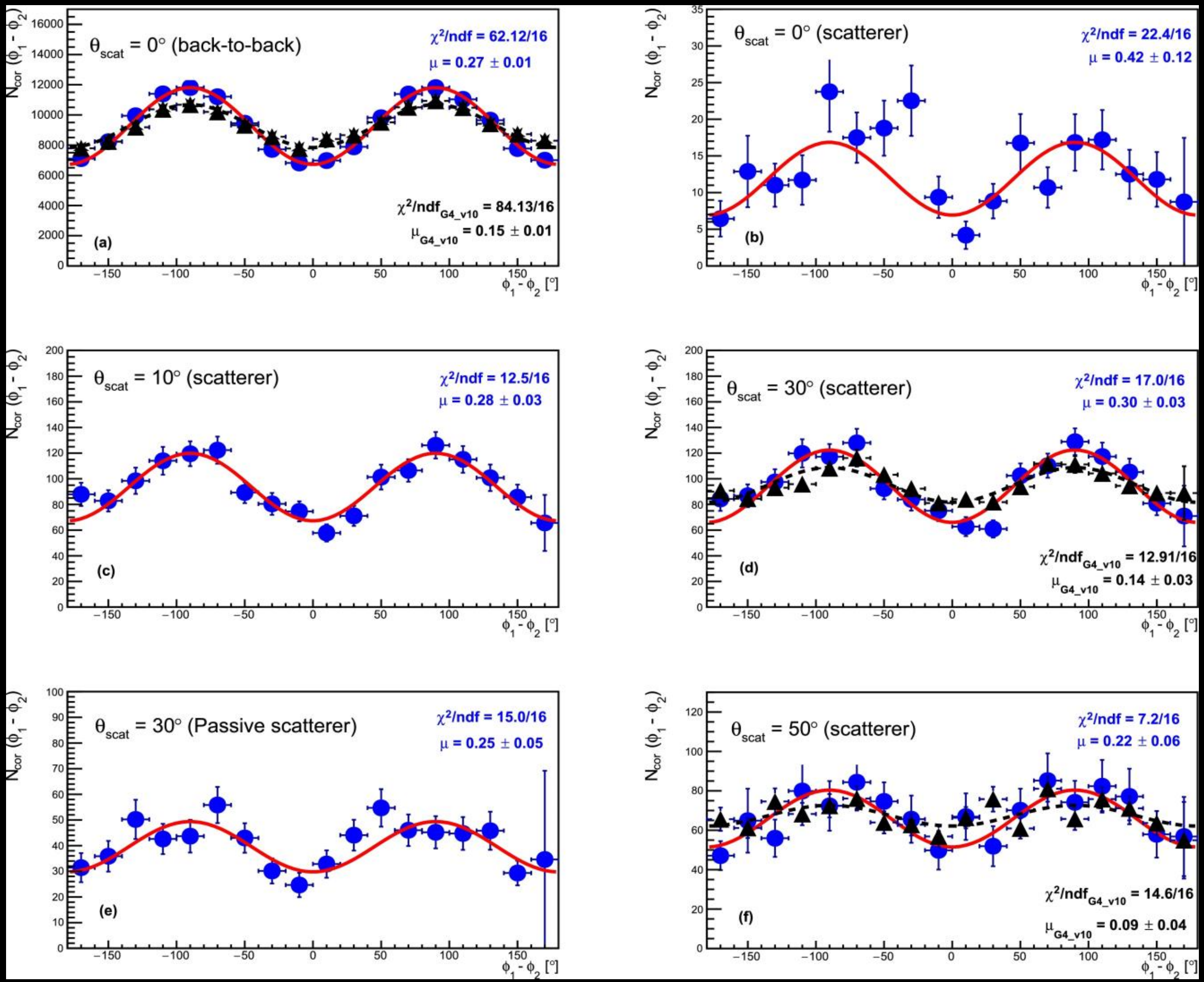
Polarization correlations - addendum

Parashari et al. (2024) Physics Letters B, 852:138628



Experimental setup for measuring polarization correlations after one of the annihilation photons undergoes previous scatter

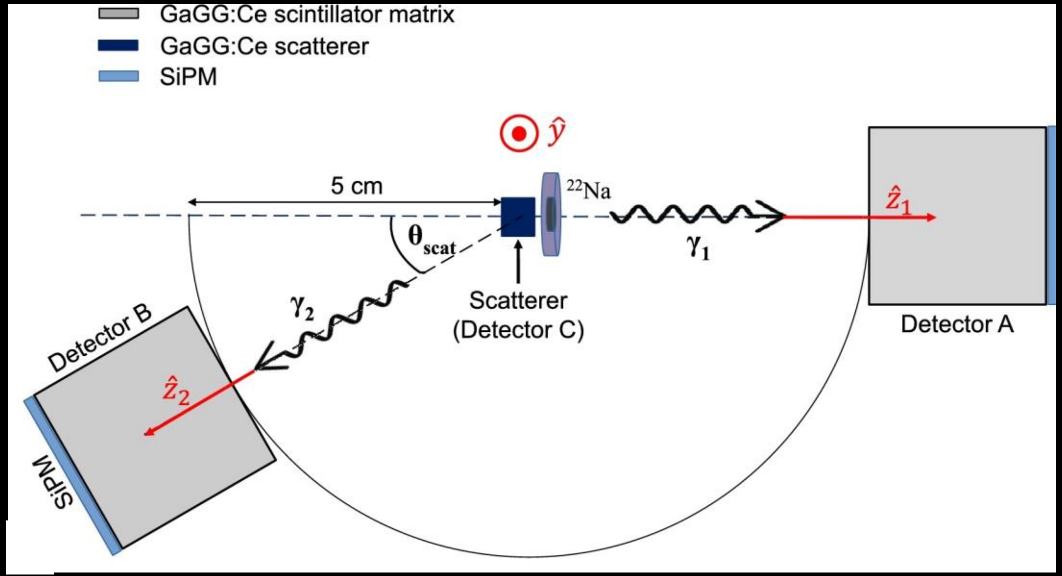
Polarization correlations observed even after the scatter of one of the annihilation gammas



Azimuthal angle difference distributions observed for different Compton scattering angles of the scattered annihilation photons

Polarization correlations - addendum

Parashari et al. (2024) Physics Letters B, 852:138628

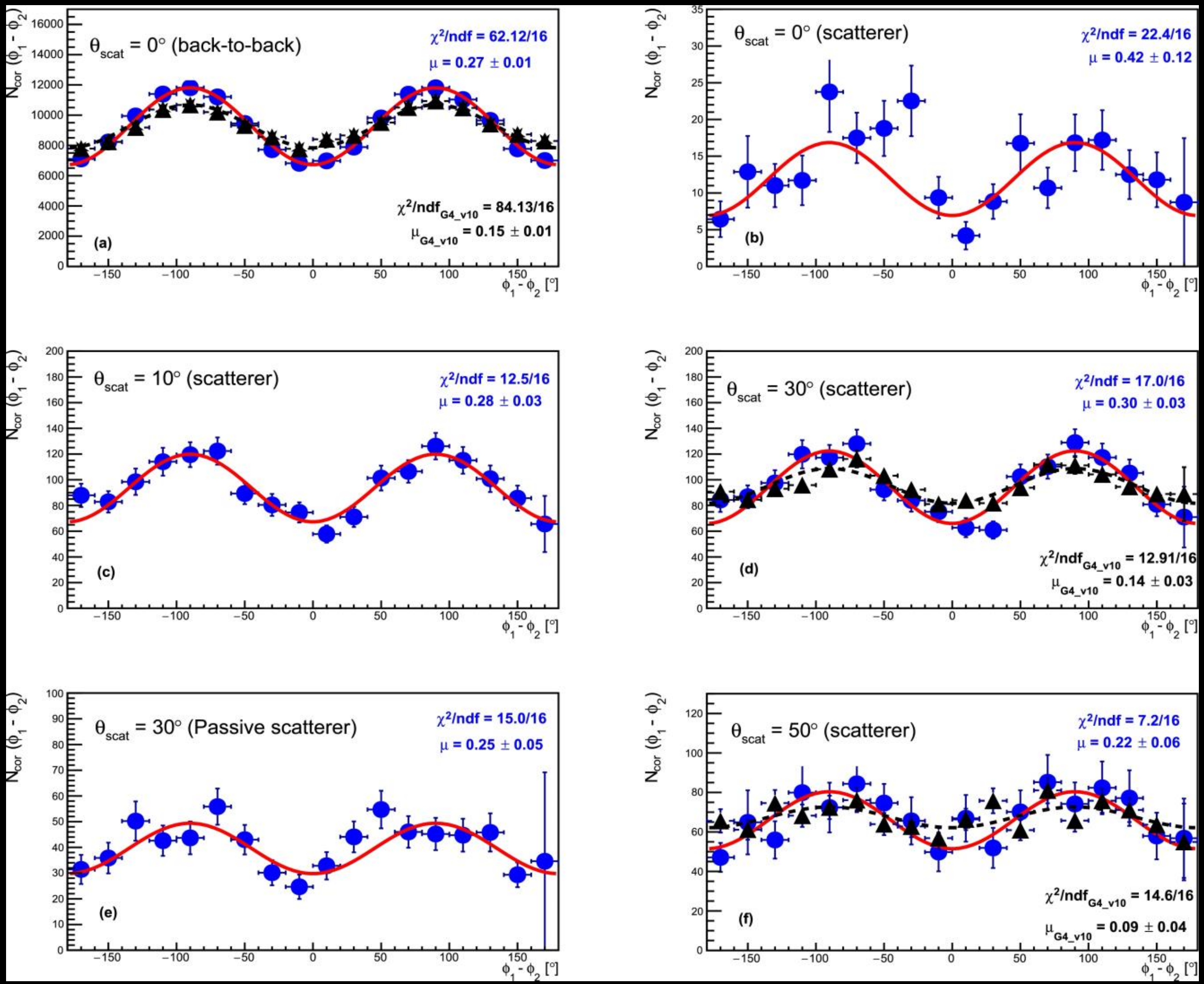


Experimental setup for measuring polarization correlations after one of the annihilation photons undergoes previous scatter

Polarization correlations observed even after the scatter of one of the annihilation gammas

Limits the ability of the method to reduce background by eliminating scatter coincidences

The method is still applicable for random and multiple coincidences

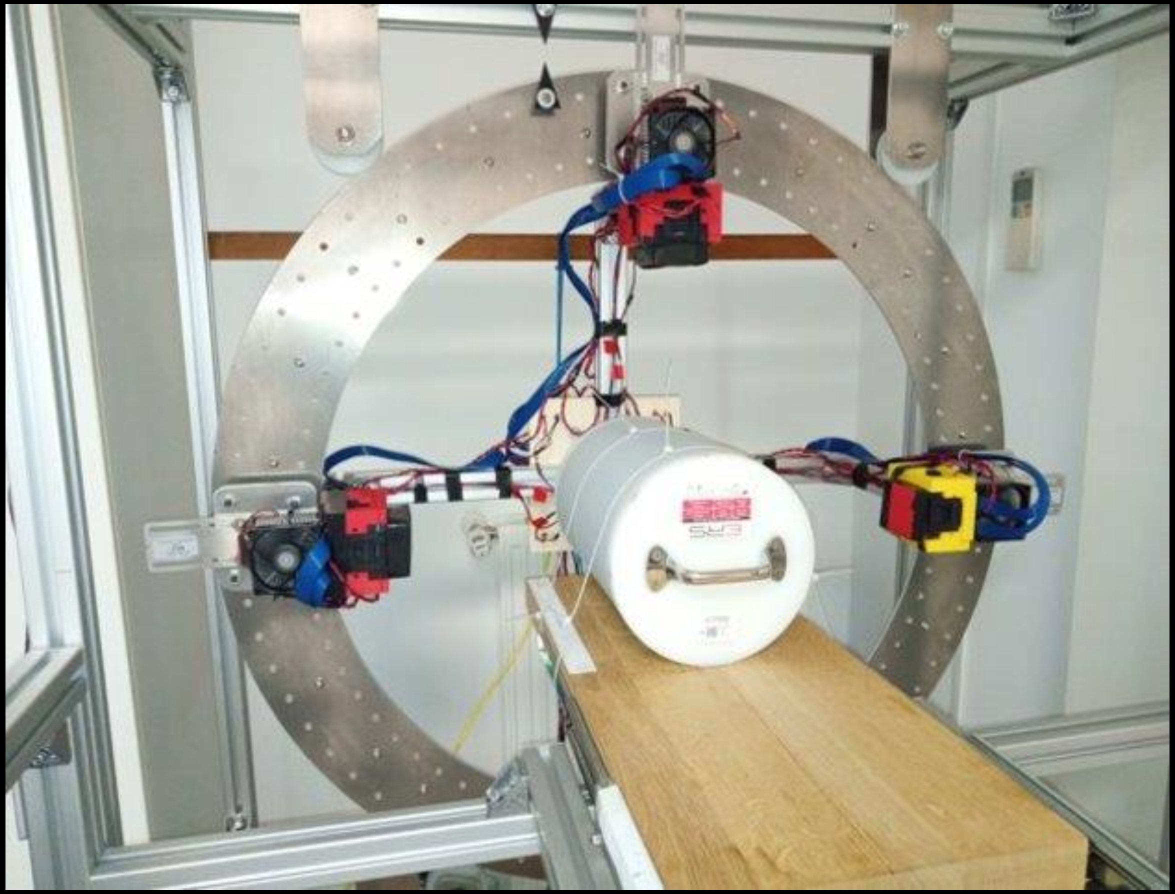


Azimuthal angle difference distributions observed for different Compton scattering angles of the scattered annihilation photons

The PET Demonstrator

- Four super-modules of segmented scintillators
  - 16 x 16 pixels in each module

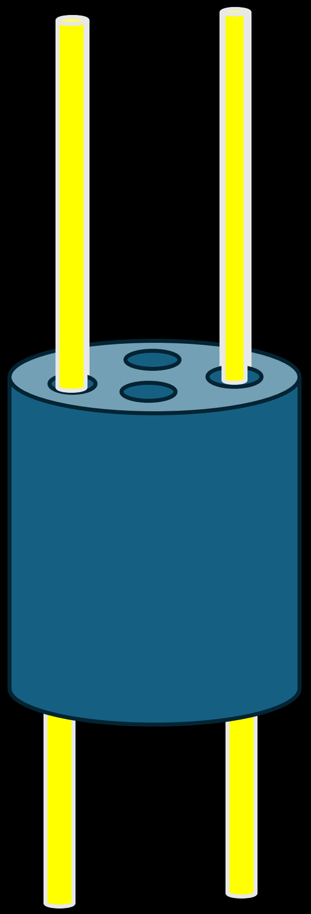
- Diameter range: 420 – 700 mm
- Precise rotation around the scanner axis



Preliminary results

- Two Ge-68 extended sources in aluminum encapsulation
- Epoxy phantom, 3 cm in diameter
- Data acquired with 3.2 mm matrix pitch GaGG:Ce modules

Activity (each source):	45.5 MBq
Distance between the sources:	~ 2 cm
Number of positions (angle):	12 (15 deg)
Time of acquisition (per position):	~ 2.3 h
Diameter of the PET ring:	430 mm



Extended sources (2 Ge-68 sources in stainless steel, 45.5 MBq each)

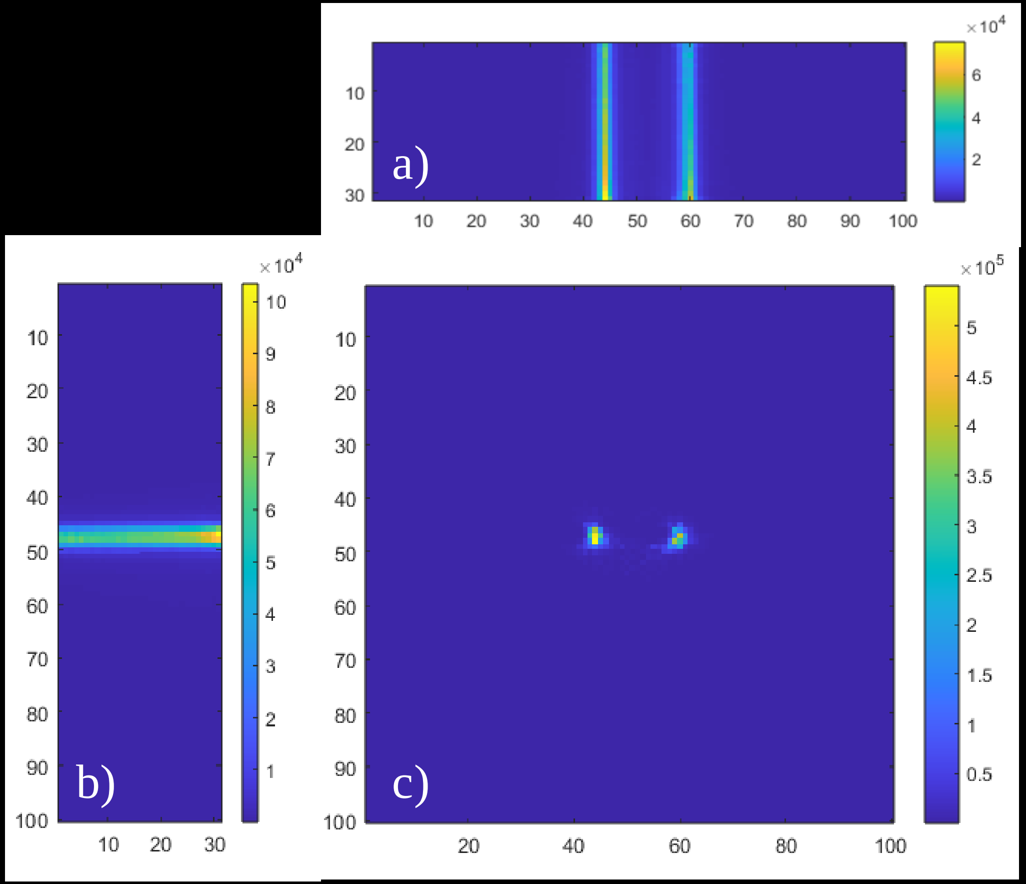
RAW IMAGES!

Preliminary results

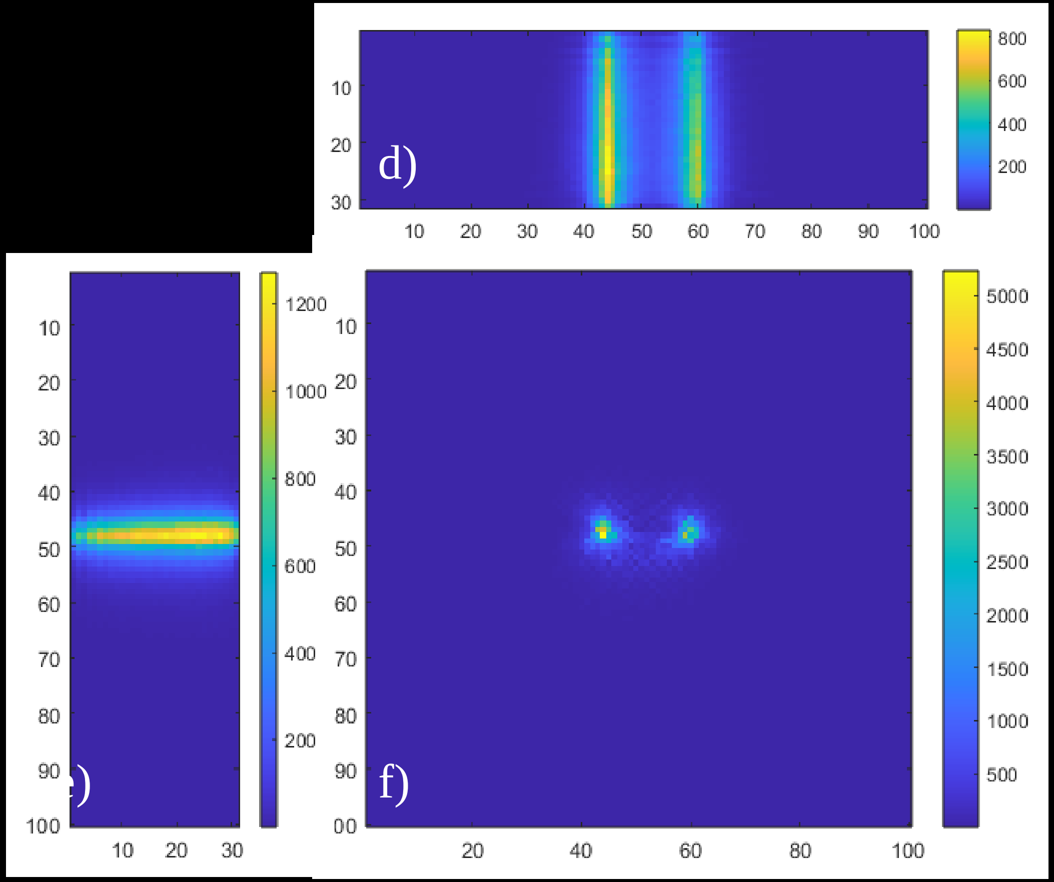
OMEGA software (MATLAB), OSEM reconstruction algorithm

Grid: 100x100 pixels; FOV: 100, 31 slices; OSEM: 10 iterations, 6 subsets

Images reconstructed from events which are selected as the ones with photoelectric interactions



Images reconstructed from events which are selected as the ones with polarization correlations where $\Theta \in [72,90]$, $|\Delta\phi| \in [70, 110]$



a & d - coronal view

b & e – sagittal view

c & f - axial view

Spatial resolution of the novel PET device

Preliminary results

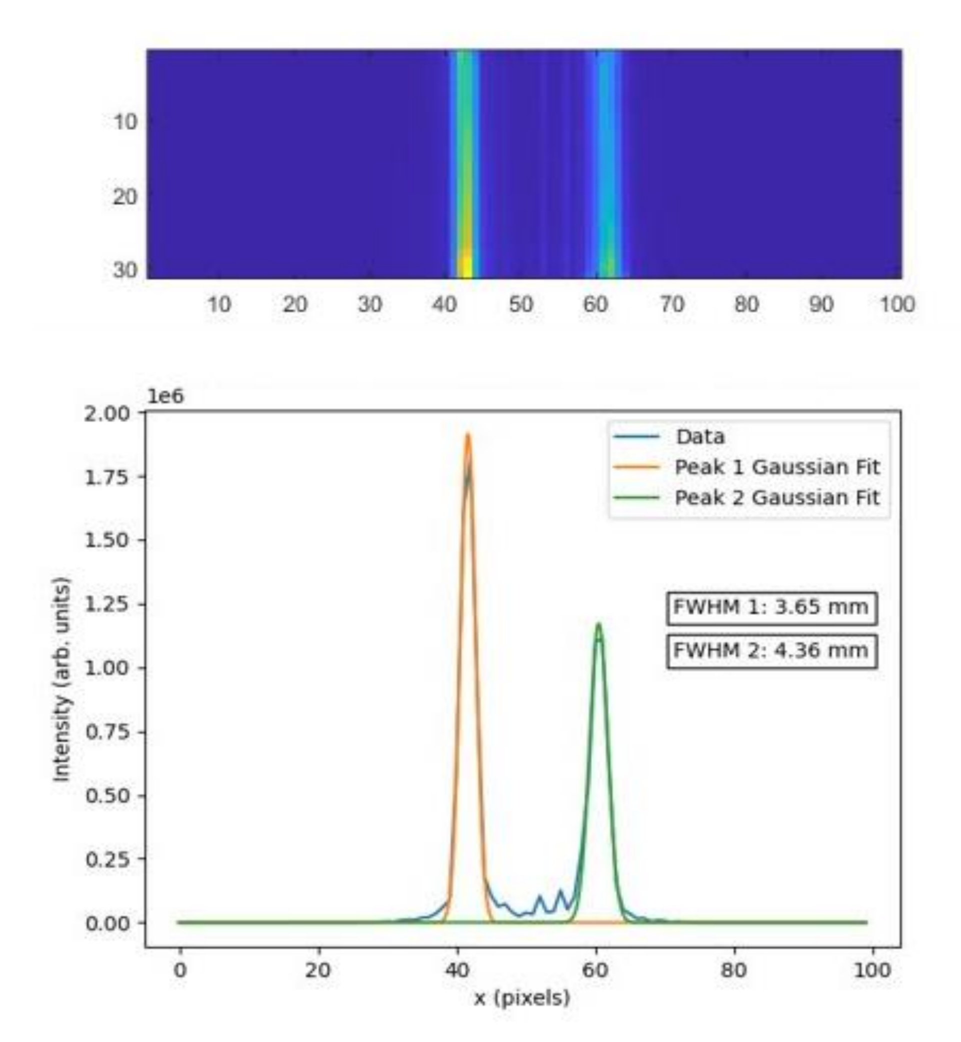


Image profile from PE events

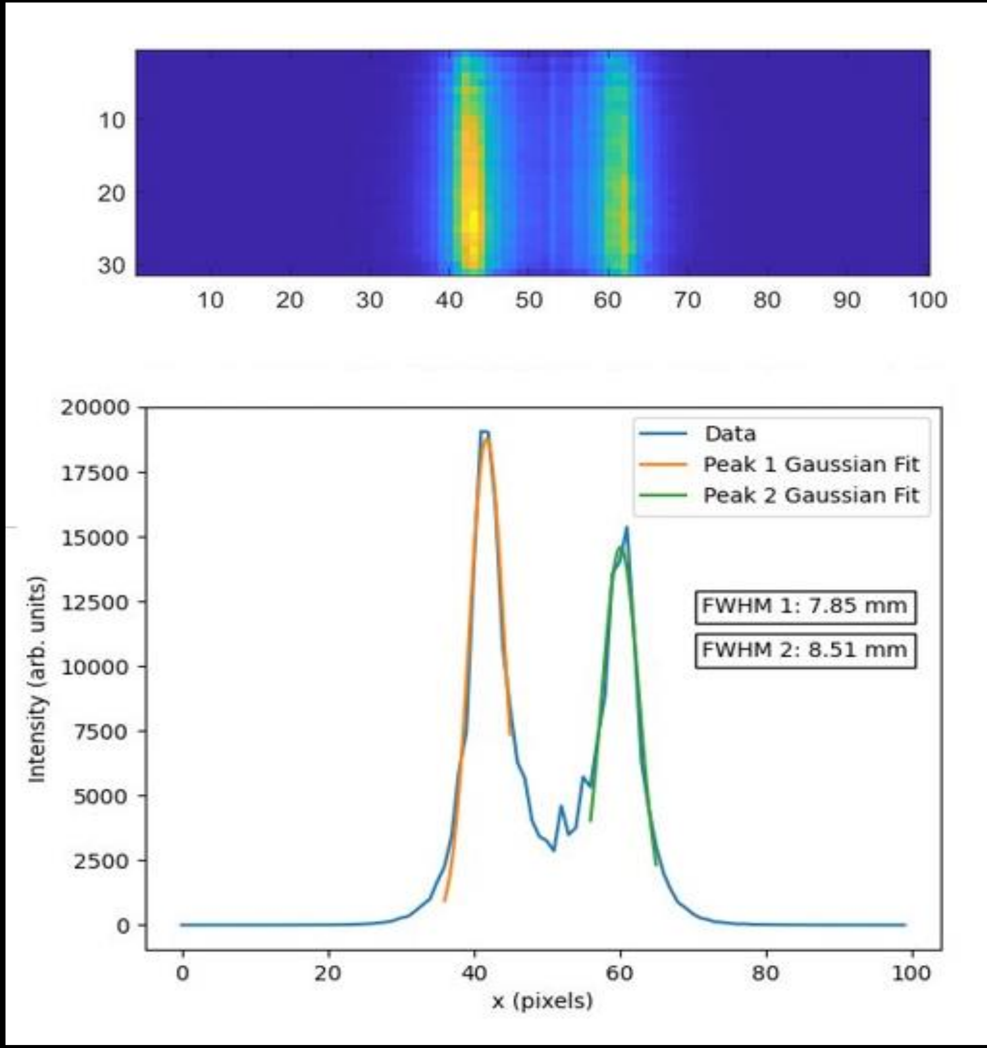


Image profile from events with polarization correlations where $\Theta \in [72,90]$, $|\Delta\phi| \in [70, 110]$

Spatial resolution of the novel PET device

Preliminary results

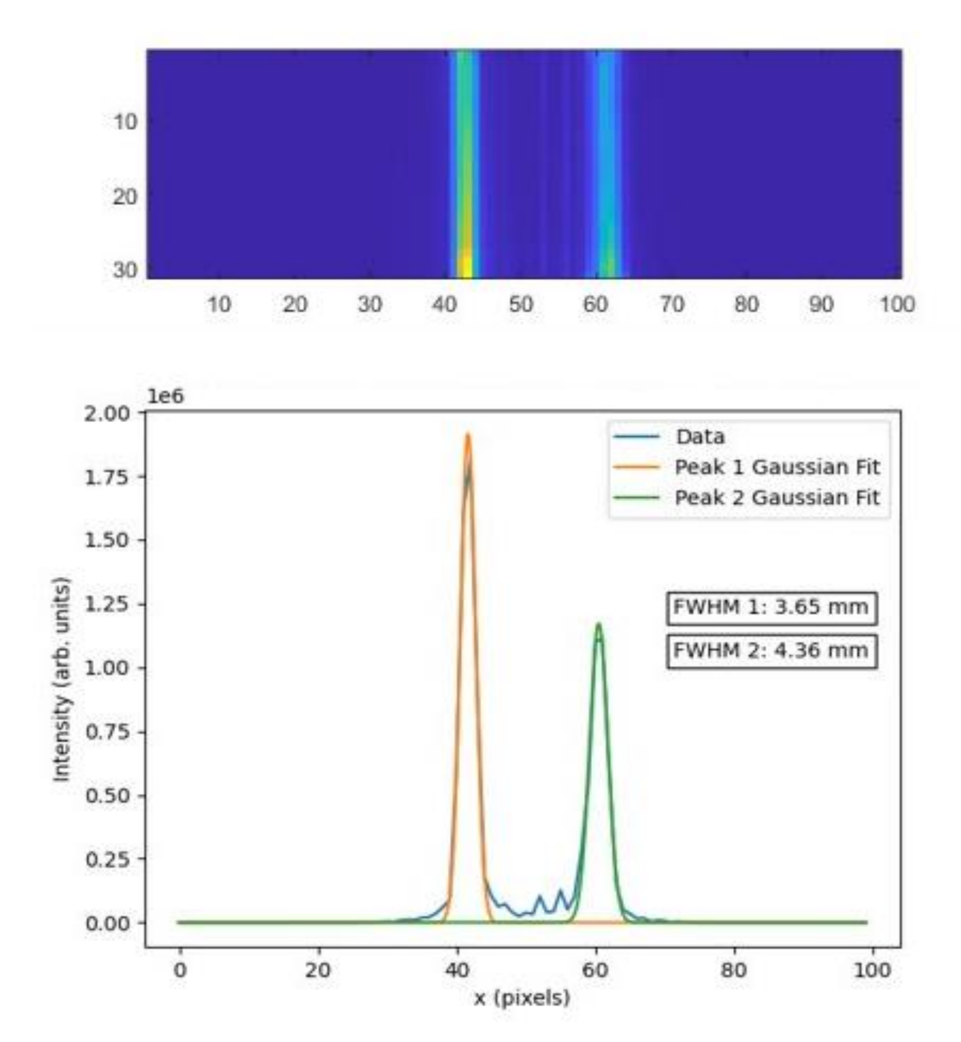


Image profile from PE events

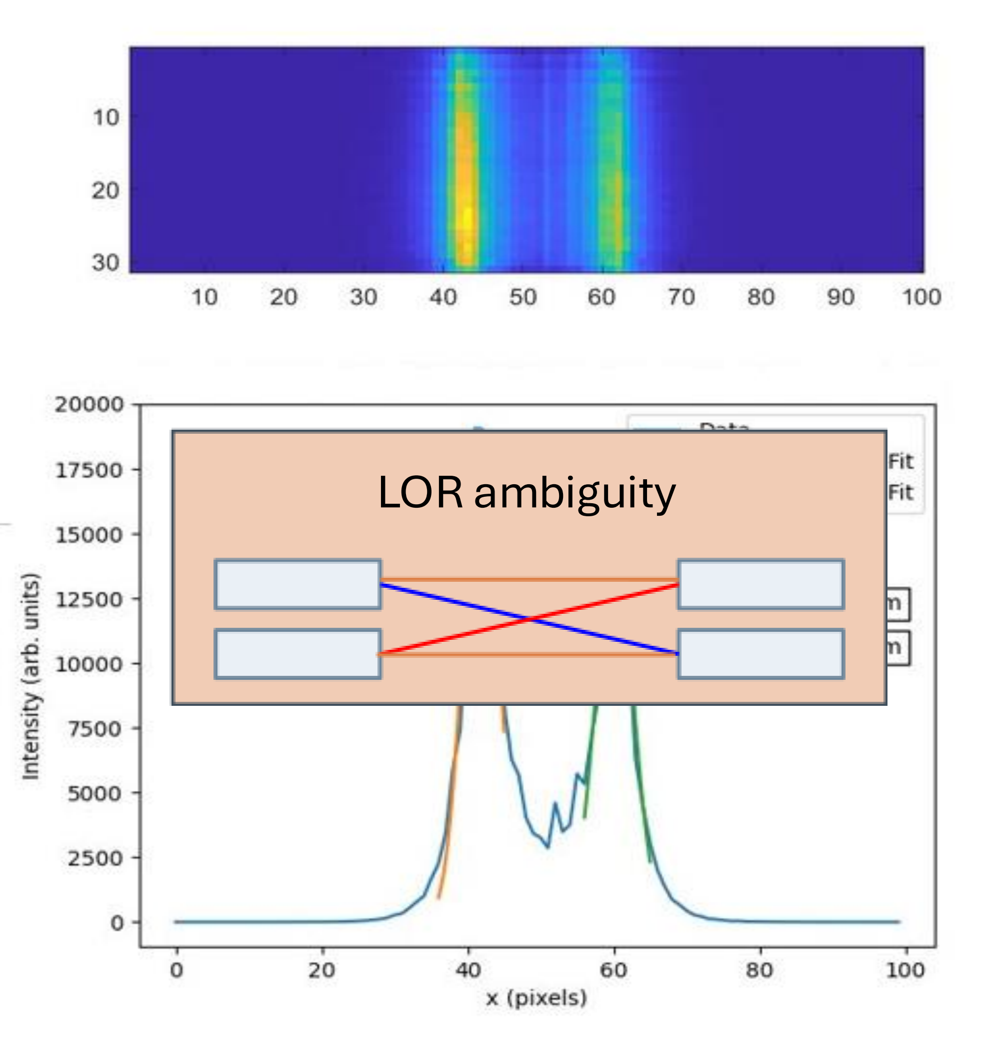
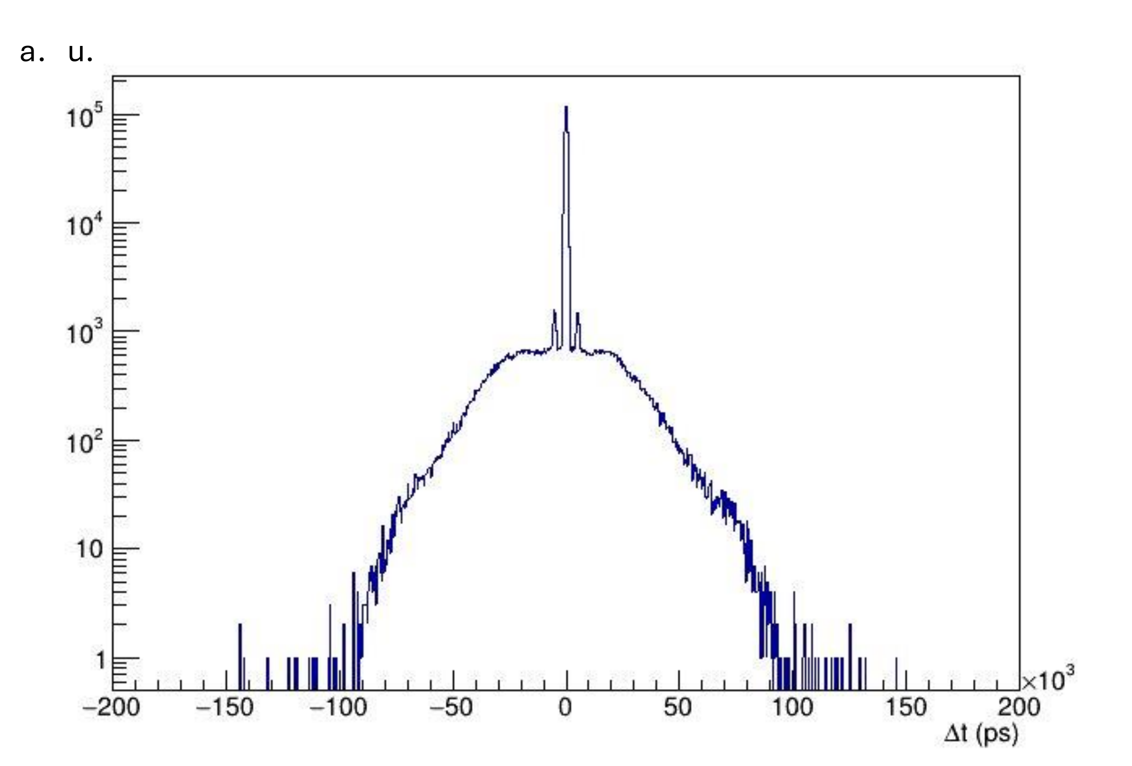
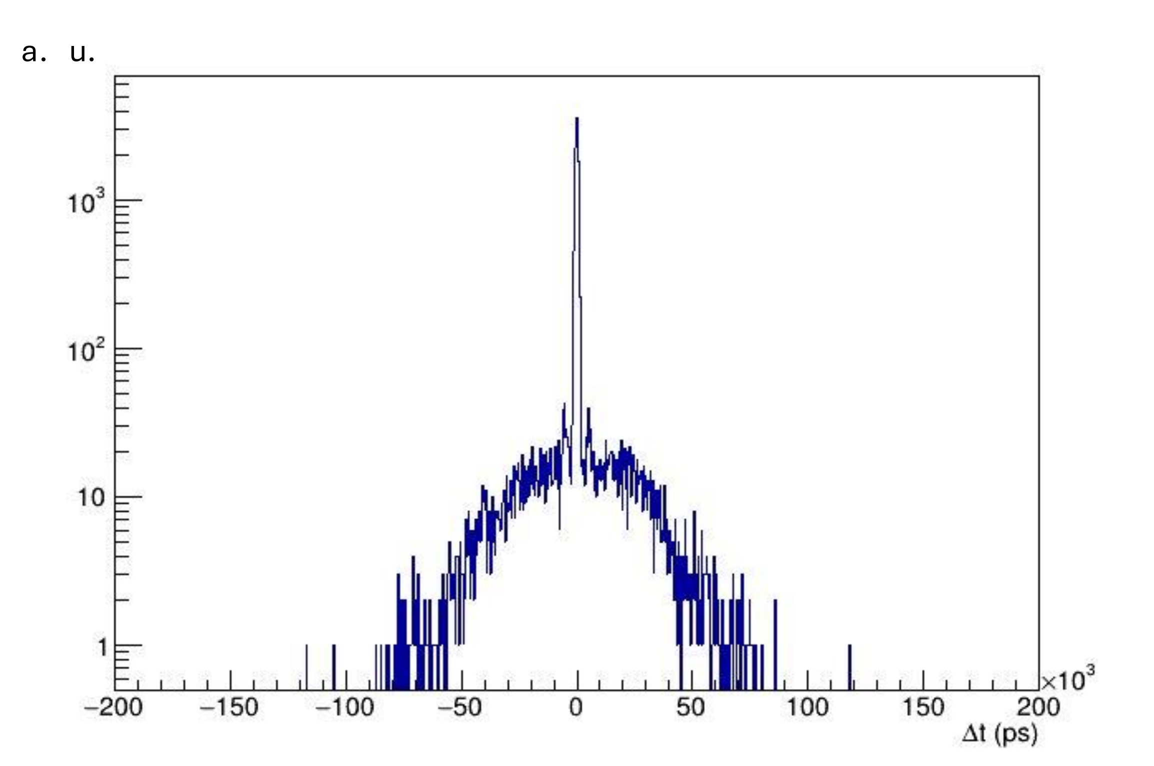


Image profile from events with polarization correlations where $\Theta \in [72,90]$, $|\Delta\phi| \in [70, 110]$

Signal to random background ratio (from coincidence time spectra)

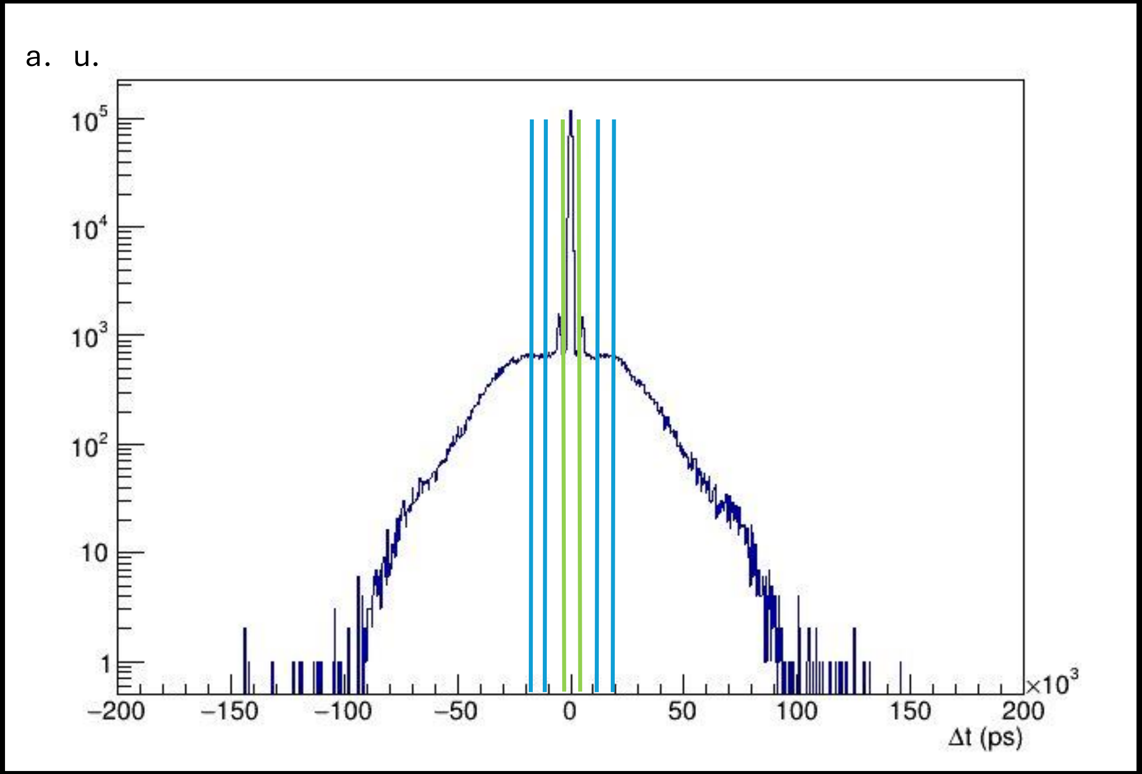


Coincidence time spectrum from PE events

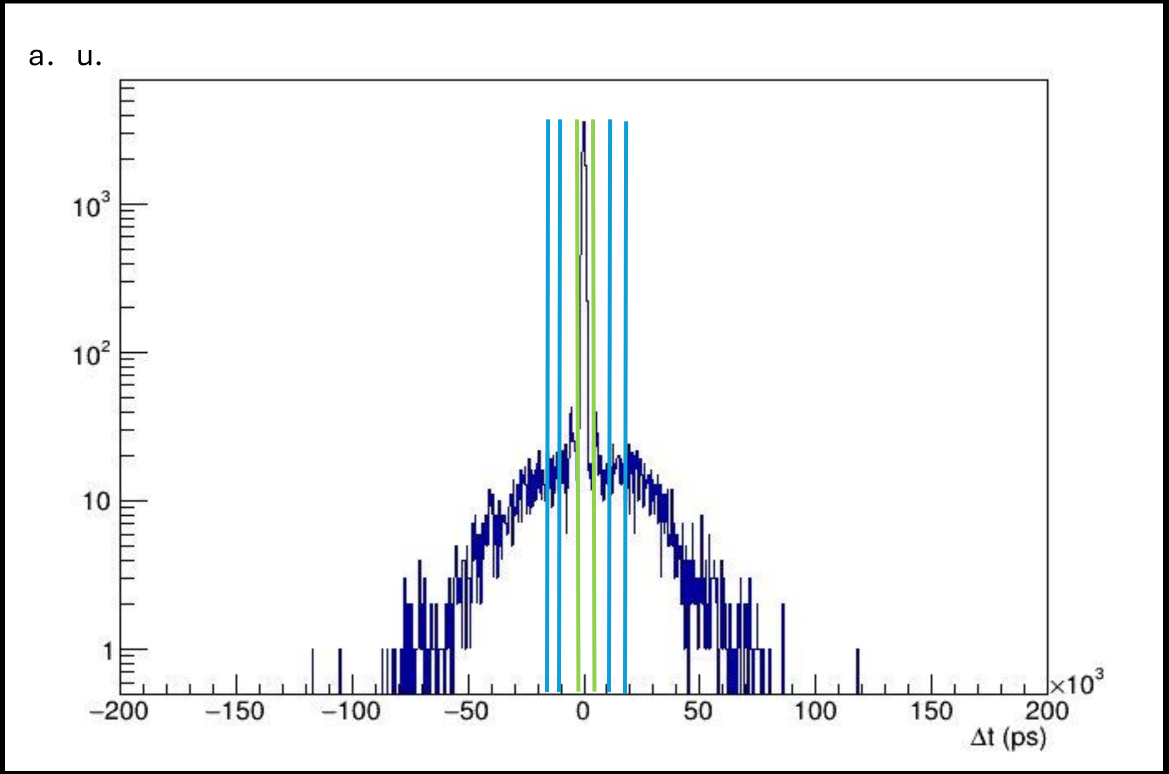


Coincidence time spectrum from events with polarization correlations where $\Theta \in [72,90]$, $|\Delta\phi| \in [70, 110]$

Signal to random background ratio (from coincidence time spectra)



Coincidence time spectrum from PE events



Coincidence time spectrum from events with polarization correlations where $\Theta \in [72,90]$, $|\Delta\phi| \in [70, 110]$

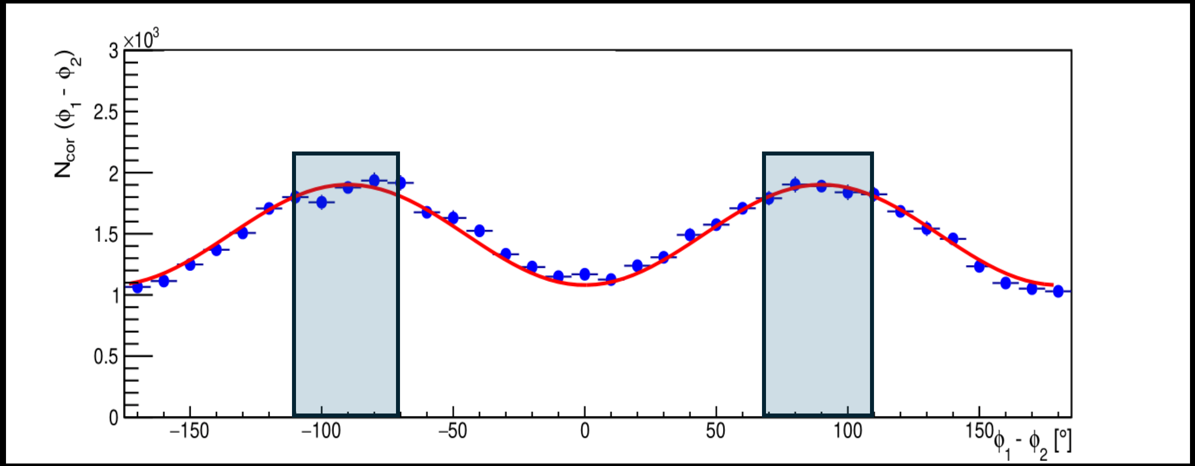
Total signal (**|Δt| < 2500 ps**)

Background signal
(|Δt| >10 000 ps & |Δt| <15 000 ps)

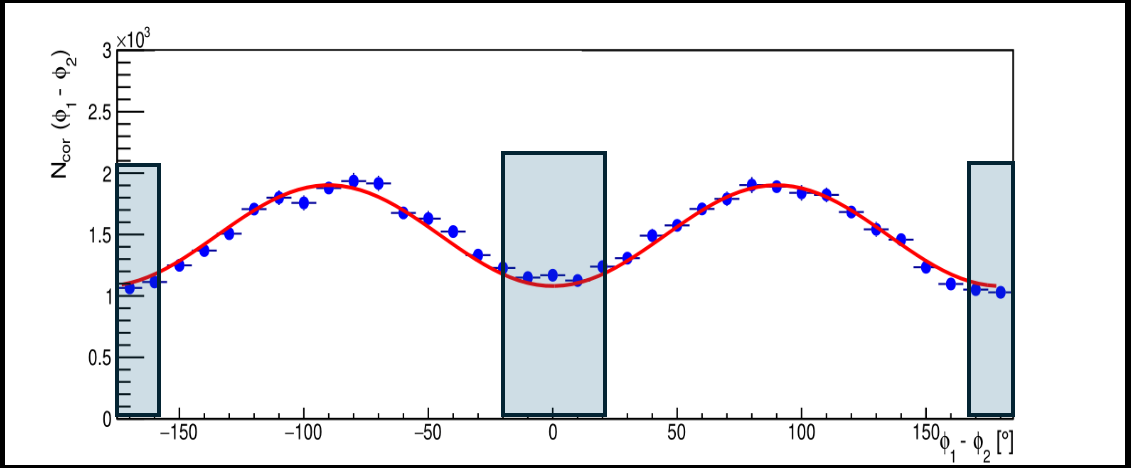
$$SBR = (A_{tot} - A_{BG})/A_{BG}$$

Signal to random background ratio (from coincidence time spectra)

Preliminary results



Selection of events with polarization correlations where $\Theta \in [72,90]$, $|\Delta\phi| \in [70, 110]$

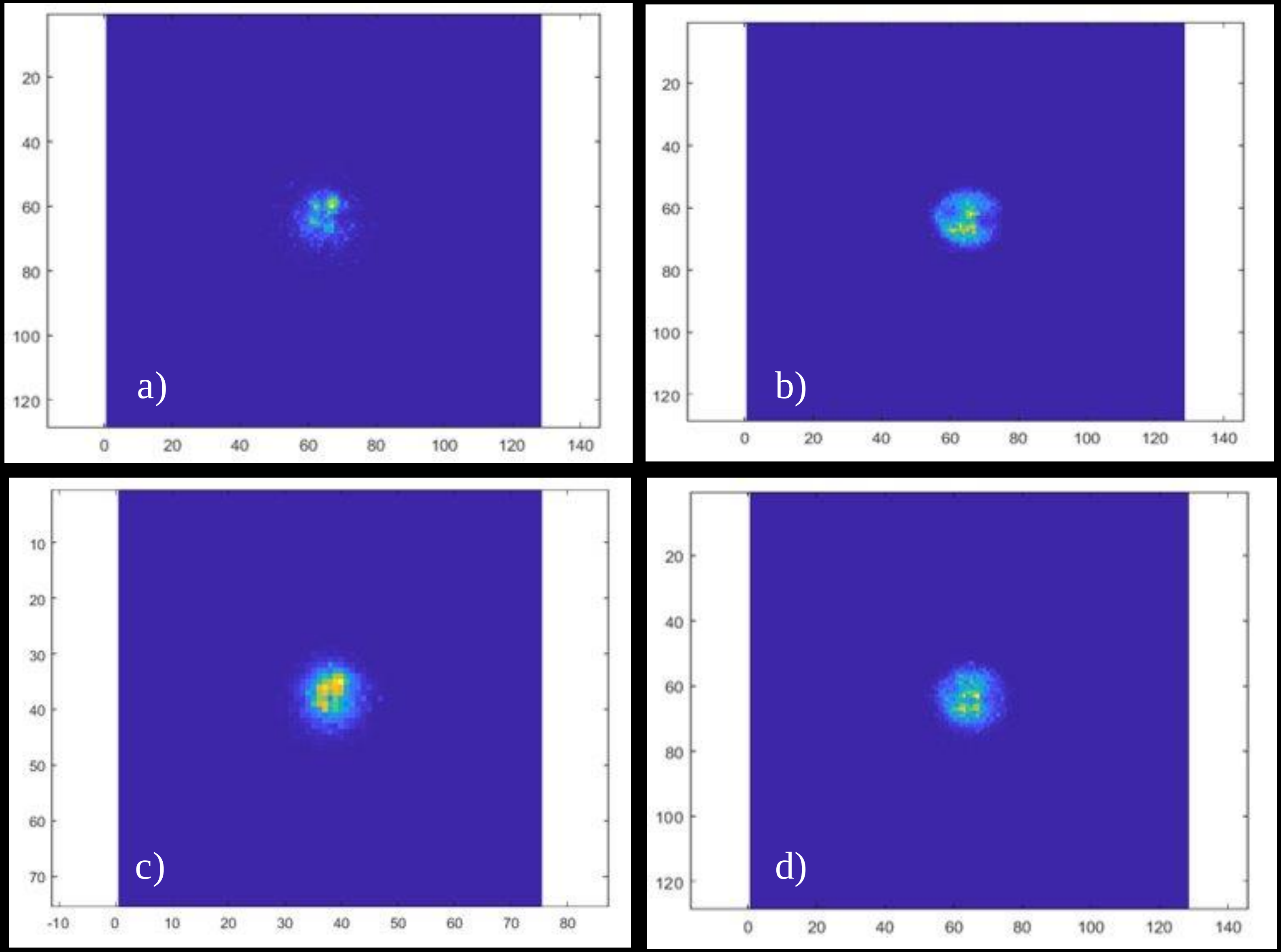


Selection of events with polarization correlations where $\Theta \in [72,90]$, $|\Delta\phi| \in [-20, 20]$

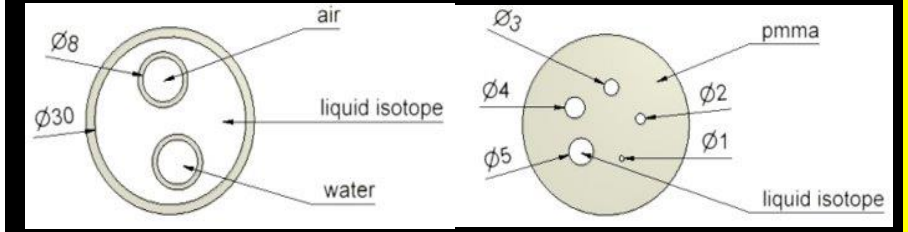
		Polarization correlations	
Type of interaction	**Photoelectric effect**	$\Theta \in [72,90]$, $\|\Delta\phi\| \in [70, 110]$	$\Theta \in [72,90]$, $\|\Delta\phi\| \in [-20, 20]$
SBR	46.84	58.86	39.42
Difference	-	**~ +25%**	**~ -15%**

NEMA NU-4 Small Animal Phantom

Preliminary results



b) and d) a) and c)



a) and b): Photoelectric events

- 128x128 pixels
- FOV: 200

c) and d): Polarization correlated events

- 75x75 pixels
- FOV: 195
- Initial activity: ~ 400 MBq Ga-68
- Number of positions: 12 (15 deg)
- Total acquisition length: ~ 1h
- 3.2 mm detector matrix pitch

Limitations of the current setup

- Small field of view
- Limited opportunities for testing with strong sources
- Ambiguity in the first hit selection resulting in reduced spatial resolution

Conclusions

- It is possible to measure polarization correlations of the annihilation quanta using single-layer Compton polarimeters.

- We have demonstrated that image reconstruction solely from polarization correlated annihilation quanta is possible.

- SBR from coincidence time spectra of correlated events exhibits background reduction when compared to events with PE.

Thank you!

This work was supported by the "Research Cooperability" Program of the Croatian Science Foundation funded by the European Union from the European Social Fund under the Operational Program Efficient Human Resources 2014–2020, Grant number PZS-2019-02-5829.

HRZZ
Croatian Science Foundation

European Union
Together towards the EU funds
EUROPSKI STRUKTURNI I INVESTICIJSKI FONDOVI
ESF UČINKOVITI LJUDSKI POTENCIJALI

The project is funded by the European Union under the European Social Fund