

The logo for CEA (Commissariat à l'énergie atomique) is displayed in white text on a red square background.The logo for IRFU (Institut de Recherche Fondamentale sur les Uclides) is displayed in red text.

AAIMME: Matching Learning in ClearMind

Apprentissage Automatique pour l'Imagerie Moléculaire et la MÉdecine du futur

ANR project 2025-2029

V. Sharyy for the AAIMME collaboration

CSTD October 2026

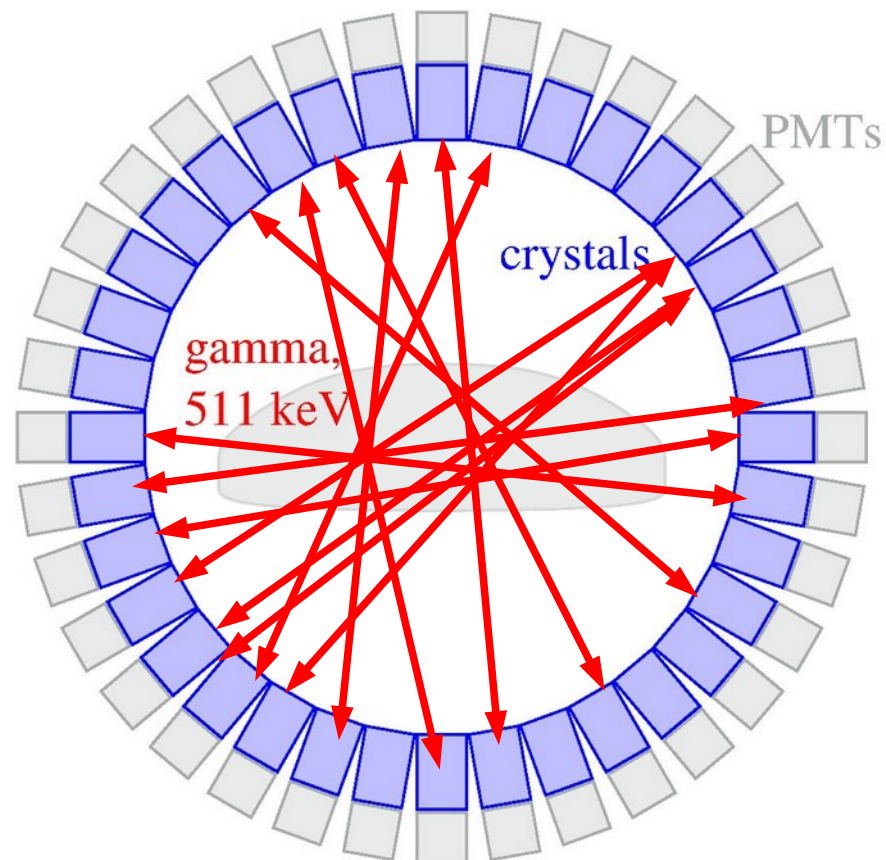
TEP in Nutshell

- **What is PET?**

- Nuclear imaging technique that maps metabolic/biochemical activity inside the body, unlike CT/MRI, which show anatomy.

- **How it works?**

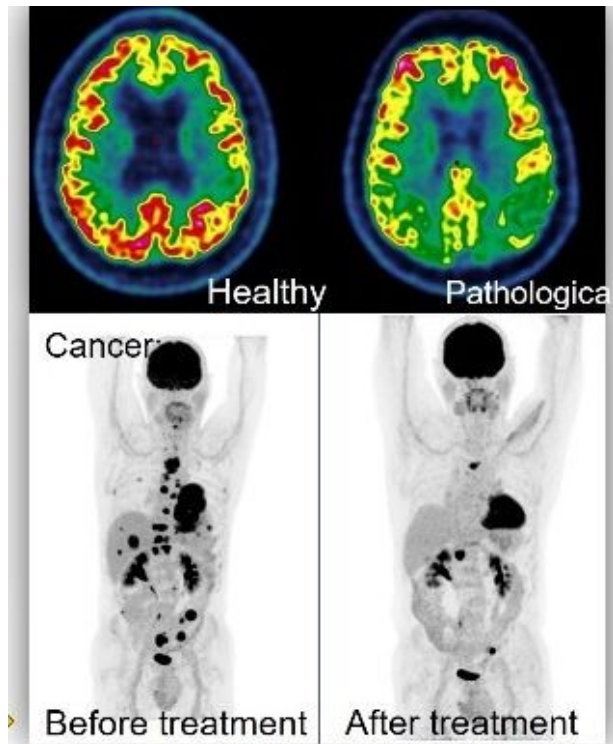
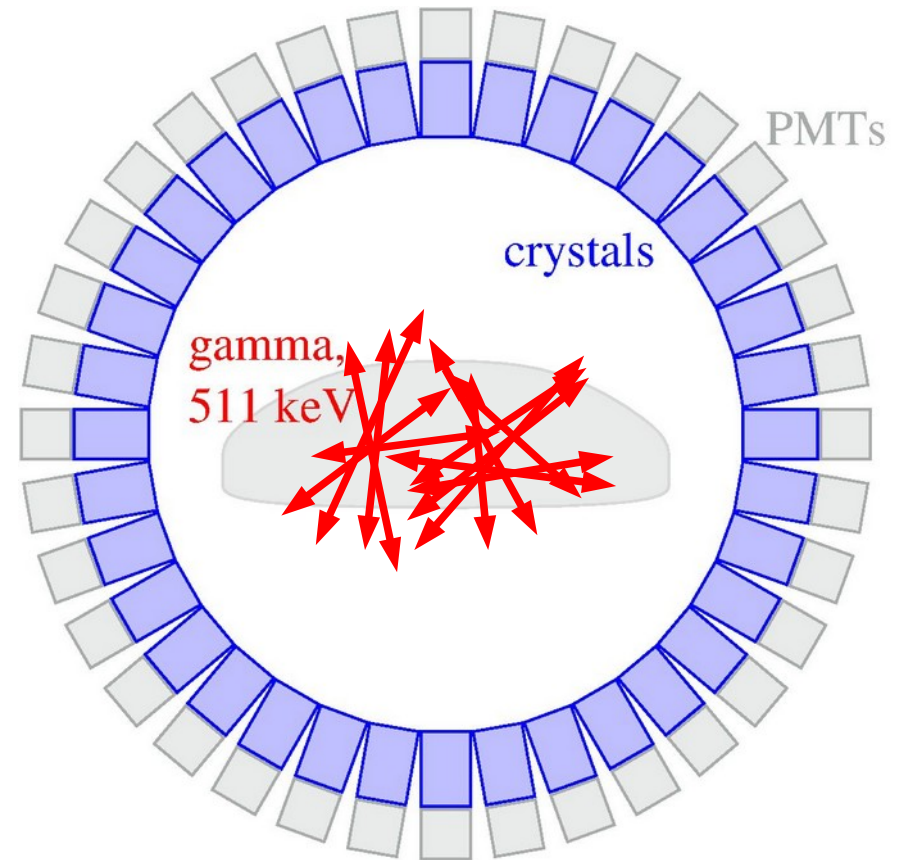
- Inject a radiotracer (e.g. ^{18}F -FDG), a molecule tagged with a positron-emitting isotope
- Tracer concentrates in metabolically active tissues (e.g. tumours, brain, heart)
- Positron annihilates with an electron $\rightarrow$ two 511 keV gamma photons emitted back-to-back
- Ring of crystal detectors + PMTs registers photon pairs in coincidence
- Each coincident pair defines a Line of Response (LOR) $\rightarrow$ intersection of many LORs reconstructs the emission map



TEP in Nutshell

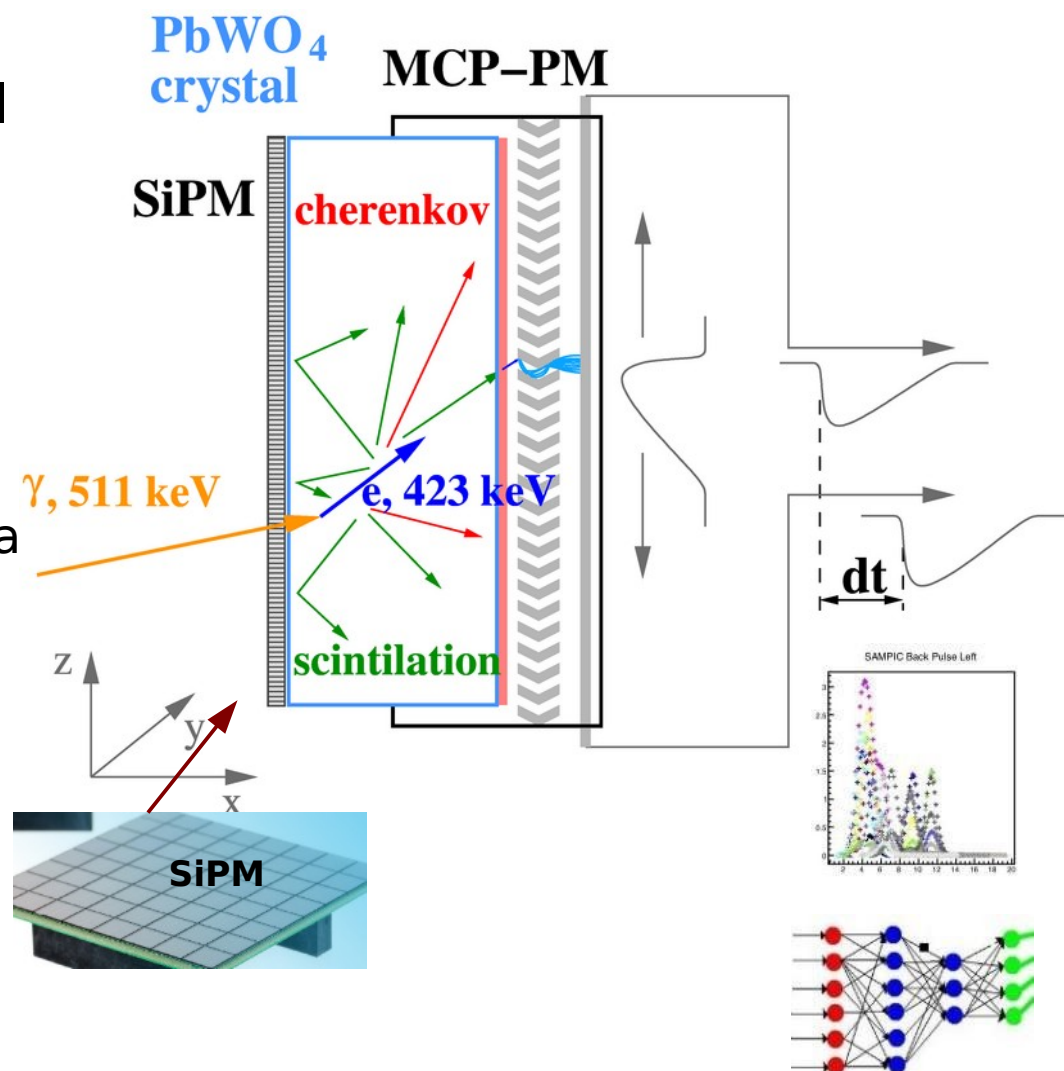
- **Time-of-Flight**

- Measuring the arrival-time difference
- Each LOR contributes only to a short segment → better SNR, especially in large patients
- Best current scanners: 200 ps, corresponds to ~ 3 cm
- “Ideal” TOF: ~ 10 ps → 1.5 mm, direct imaging



ClearMind Project

- Direct photocathode deposition on PWO crystal → “**scintronic**” crystal
 - boost Cherenkov photons detection
 - additional fast scintillation photons
- Use of monolithic crystal
 - 3D interaction position reconstruction
 - Corrects Depth-of-Interaction (DOI) bias
- Performance targets:
 - Time resolution: < 100 ps
 - Spatial resolution: 1-2 mm
- Use MCP for electron multiplication
- Use transmission line approach to reduce number of channels and improve PMT calibration
- Instrument 2^d face with SiPMs



Patent CEA, FR1759065, 2017

D. Yvon et al, 2020, JINST 15 P07029

AI Reconstruction

G. Daniel et al. Engineering Applications of Artificial Intelligence, 131, 2024, 107876

- Modified loss function

- Event-by-event uncertainty reconstruction

- Account for the detector boundaries

- Spatial resolution (one side)

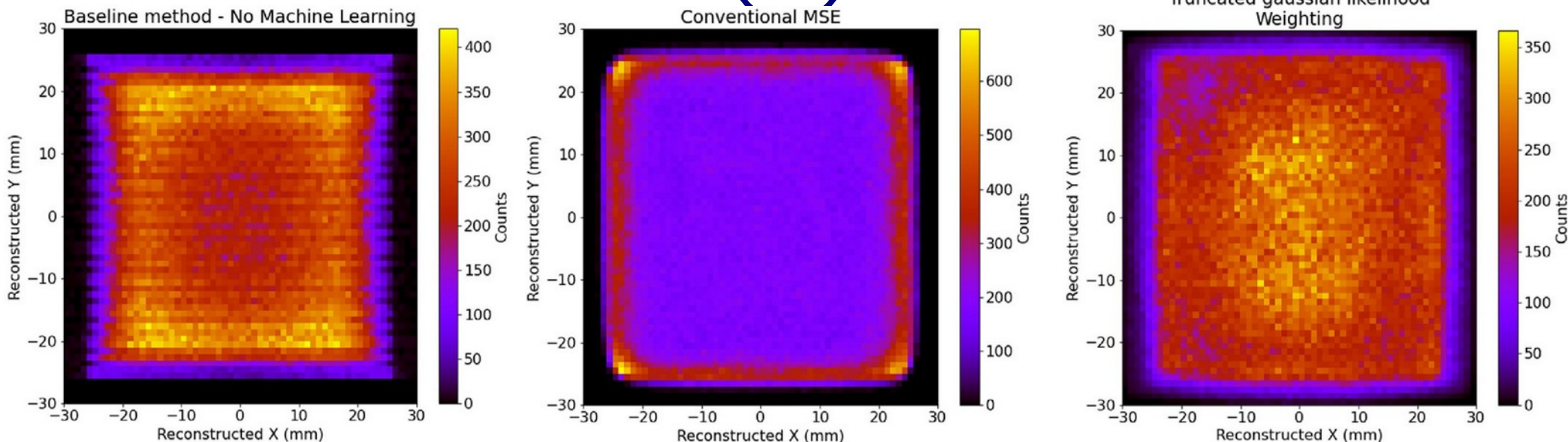
- Along lines ~2.6 mm

- Across lines ~1.9 mm

$$l(\theta) = -\log(L(\theta))$$

$$= \sum_i \sum_{z \in \{x, y\}} \log \left(\Phi \left(\frac{b - \mu_{\theta, z}(\mathbf{s}_i)}{\sigma_{\theta, z}(\mathbf{s}_i)} \right) - \Phi \left(\frac{a - \mu_{\theta, z}(\mathbf{s}_i)}{\sigma_{\theta, z}(\mathbf{s}_i)} \right) \right)$$

$$+ \frac{1}{2} \log(2\pi\sigma_{\theta}^2(\mathbf{s}_i)) + \frac{(z_i - \mu_{\theta, z}(\mathbf{s}_i))^2}{\sigma_{\theta, z}^2(\mathbf{s}_i)}$$



Consortium

1 CEA-DM2S

- Responsable : Geoffrey DANIEL, coordinateur du projet
- *Machine Learning, quantification d'incertitudes*



2 CEA-IRFU

- Responsable : Viatcheslav SHARYY
- *Instrumentation, simulation détecteurs, bancs expérimentaux*



3 UMR BioMaps

- Responsable : Florent SUREAU
- *Imagerie Biomédicale, simulation Monte-Carlo, méthodes IA pour la TEP*



4 INRIA Saclay – IdF/OPIS

- Responsable : Émilie CHOUZENOUX
- *Analyse et traitement de données volumineuses et complexes, méthodes de reconstructions robustes et explicables*



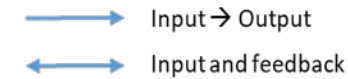
5 CNRS-CPPM imXgam

- Responsable : Christian MOREL
- *Techniques d'imagerie X et gamma, banc mécanique d'expérimentation tomographique tomXgam*

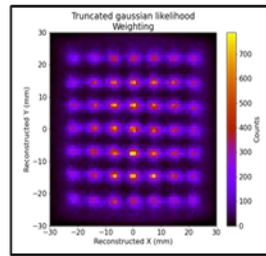
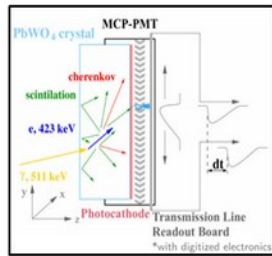
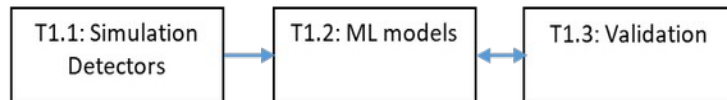


Project

WP0: Coordination and dissemination



WP1: Detector's signal processing



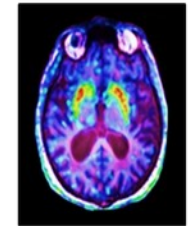
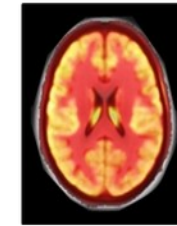
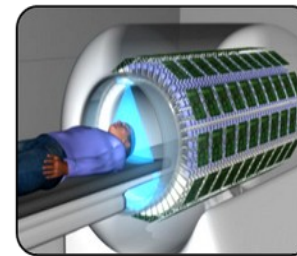
Inputs:

- Detector's specifications
- Simulation model

Outputs:

- ML model for interaction reconstruction

WP2: Image reconstruction



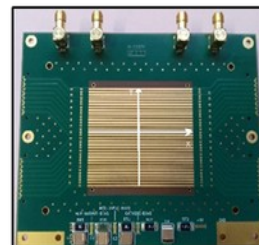
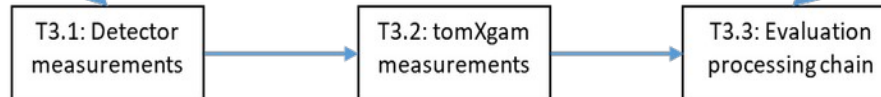
Inputs:

- Simulation PET
- ML model's from WP1

Outputs:

- Image reconstruction algorithms

WP3: Experimental demonstrator



Inputs:

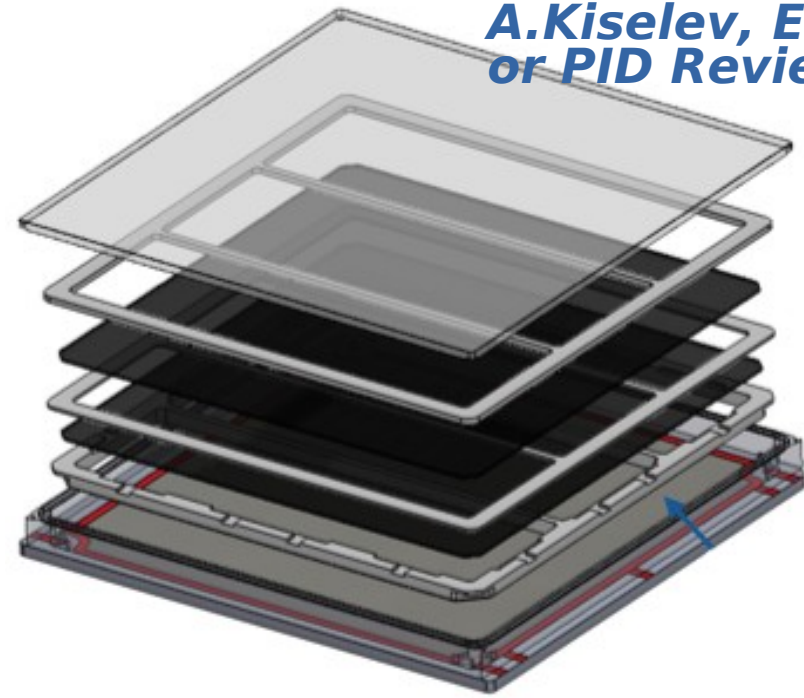
- Experimental bench
- Processing models from WP1 and WP2

Outputs:

- Performance evaluation on real data

HRPPD: High Rate Picosecond PhotoDetector

*A.Kiselev, EIC Project Detect
or PID Review, 5-6 July 2023*



MCP's Pore Diameter: $10\ \mu\text{m}$

Fused silica glass, 5.0 mm thickness

Bi-Alkali Photocathode

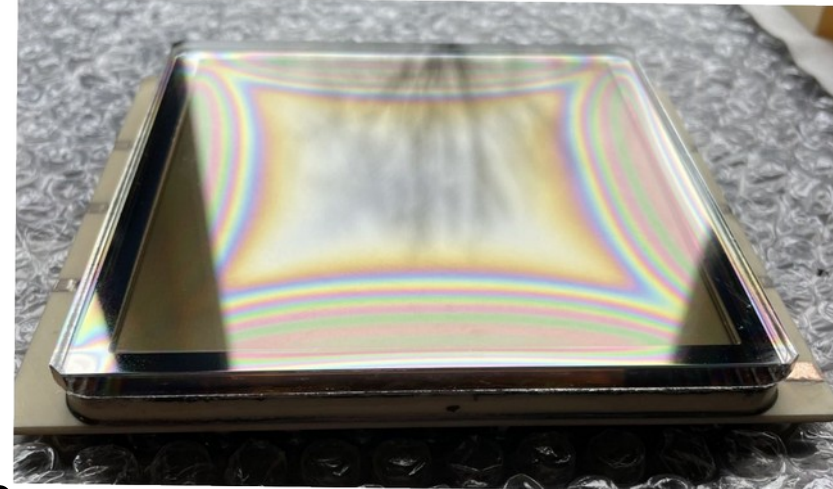
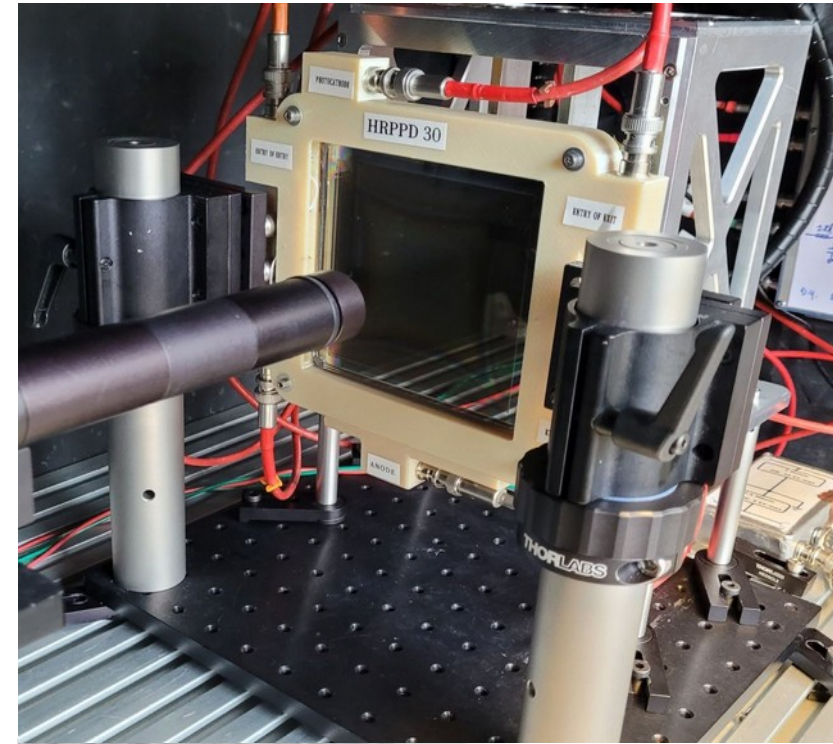
Photodetector Active Area: 95 mm x 95 mm

Resistive anode ($50\ \text{k}\Omega/\square$)

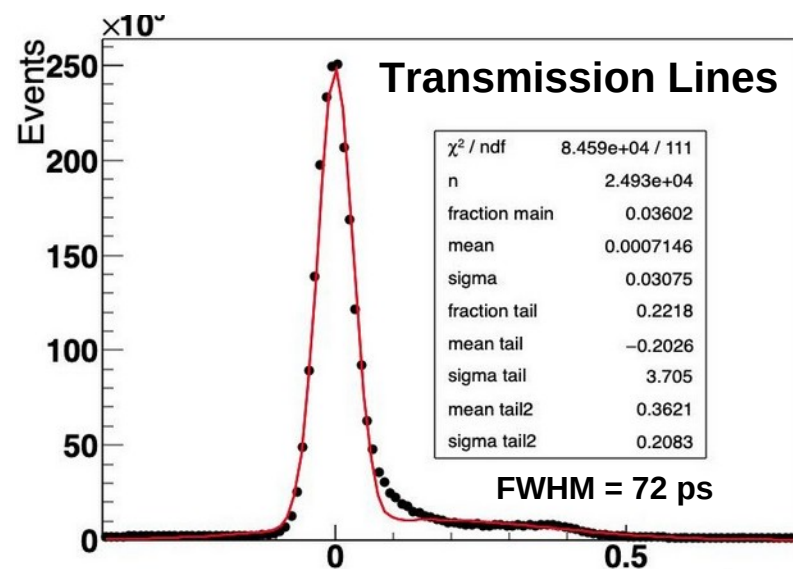
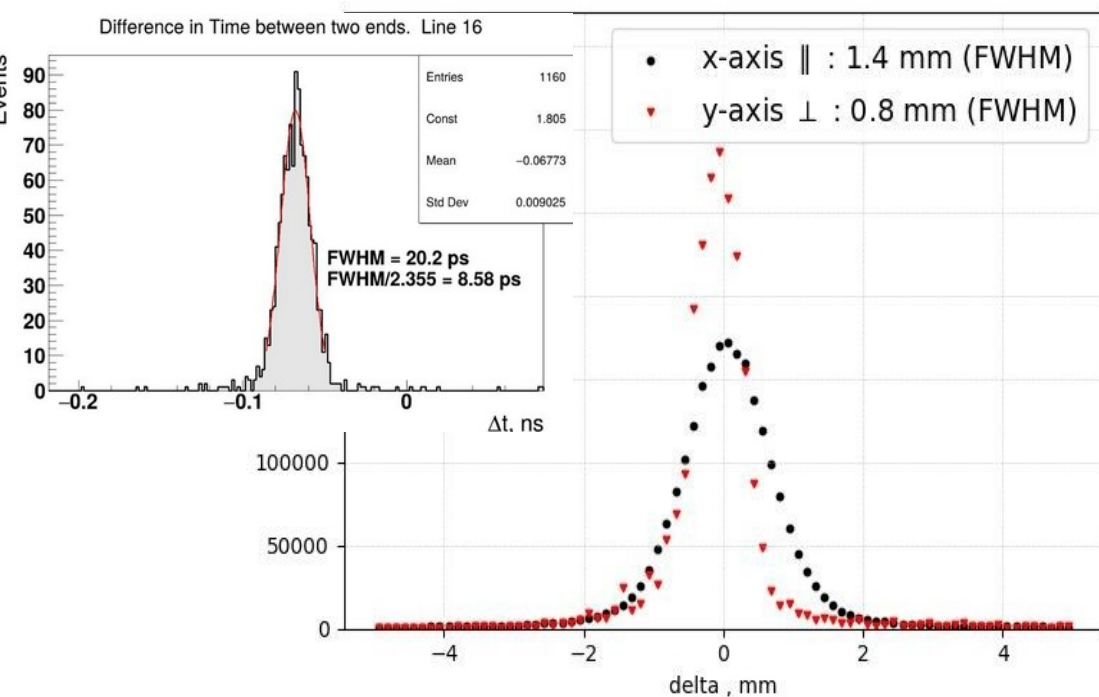
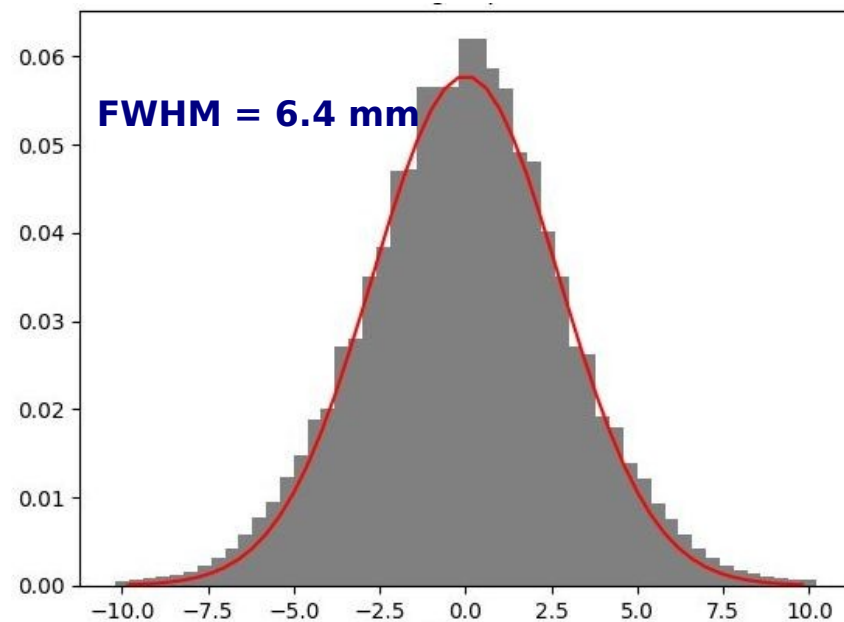
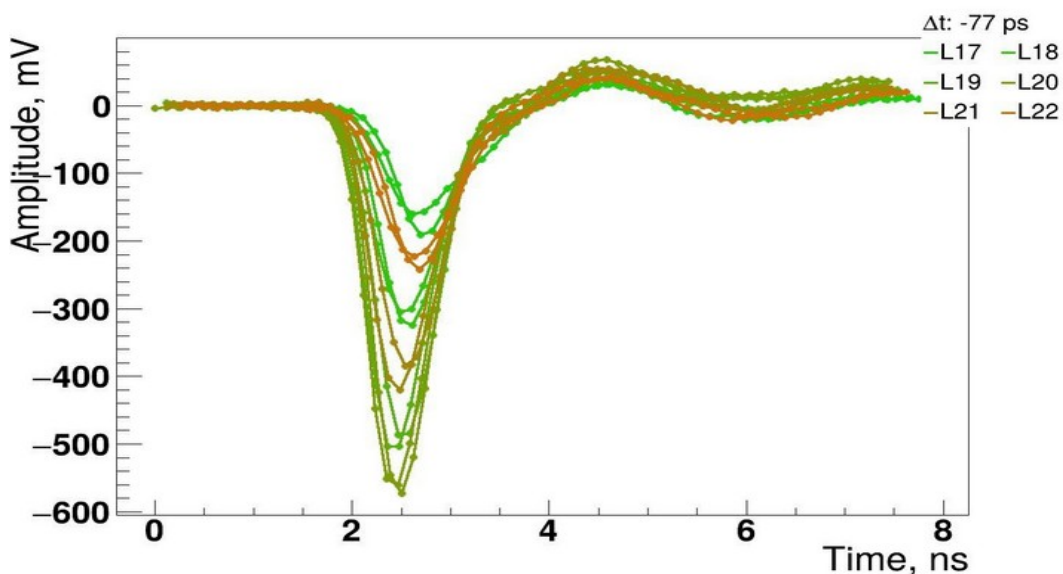
Capacitively Coupled ReadOut:

→ Mode: charge relaxation time $\gg$ signal time

→ Flexible use of the readout PCB

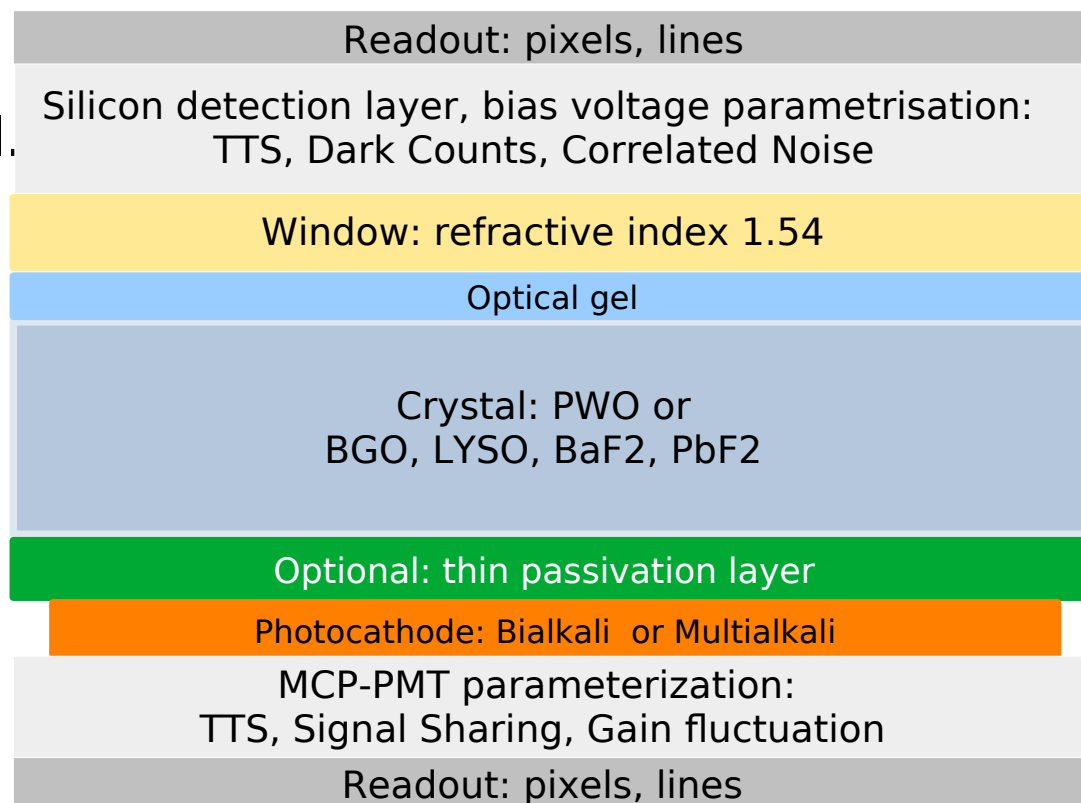


HRPPD Tests: Simulation inputs



ClearMind Simulation

- Geant4:
 - Gamma interaction in the crystal.
 - Photon emission: Cherenkov radiation (~ 20 photons) and scintillation (~ 165 photons).
 - Optical photon propagation
- Realistic photocathode simulation: Fresnel reflection and photon absorption by Geant 4, photoelectron extraction as a function of wavelength.
- Parameterized MCP-PMT response: gain fluctuation, time resolution and signal sharing between anodes
- Signal readout simulation: photoelectron overlay, propagation by the transmission lines, realistic signal shapes, electronics noise, and digitization sampling.



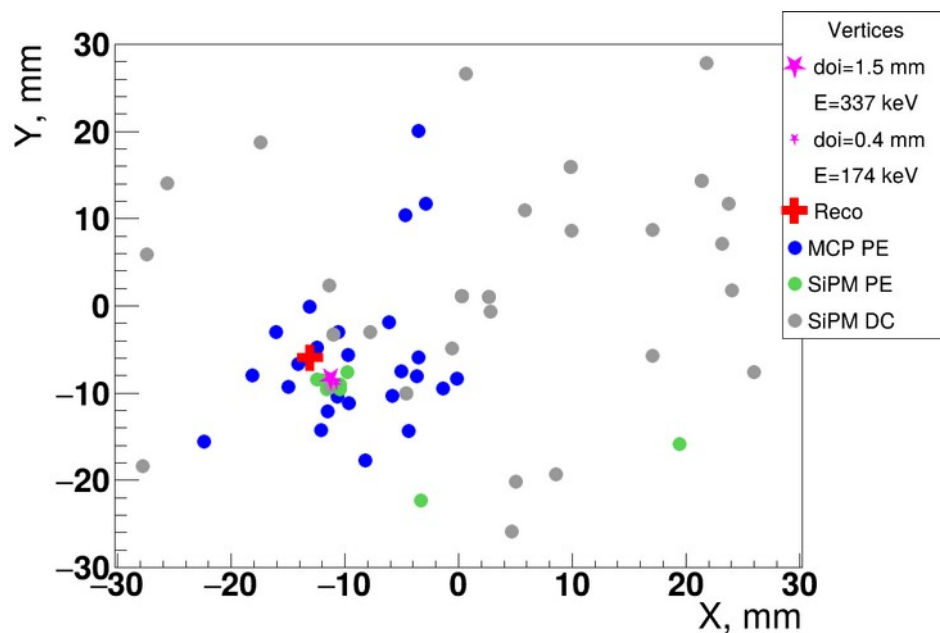
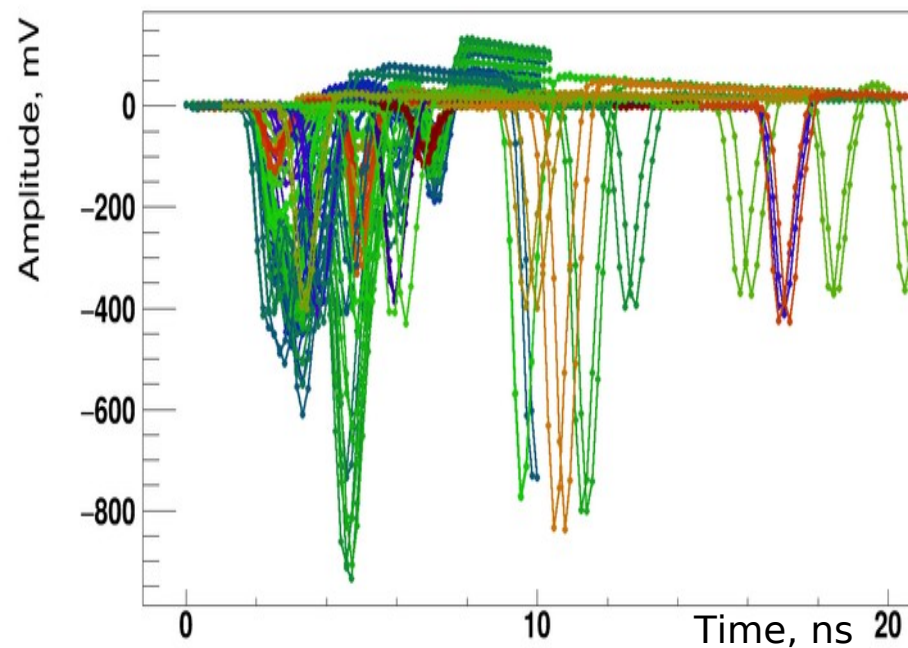
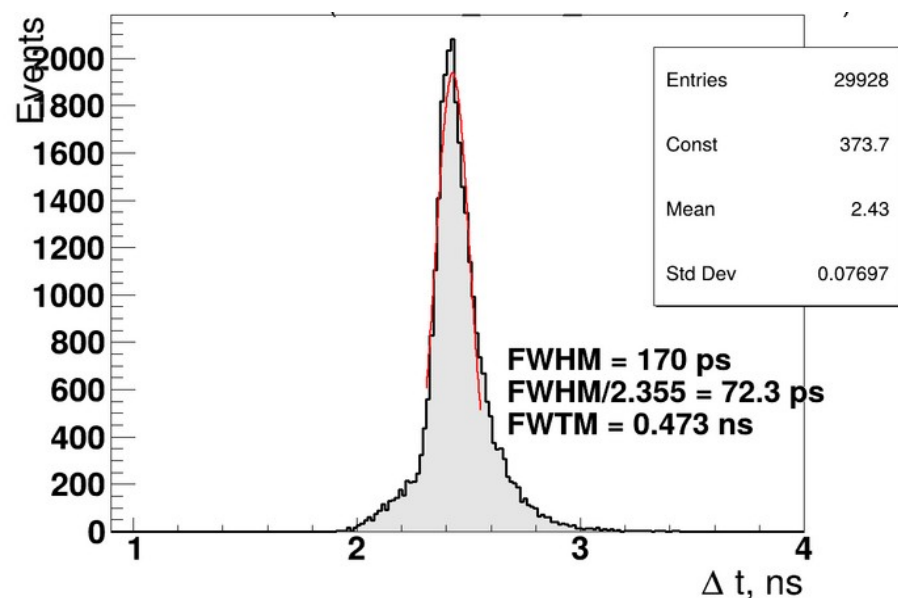
Zoé Zobundzija: NDIP poster P3-16

[L. Cappellugola et al., in IEEE NSS/MIC Conference, 2021, pp 1-5](#)

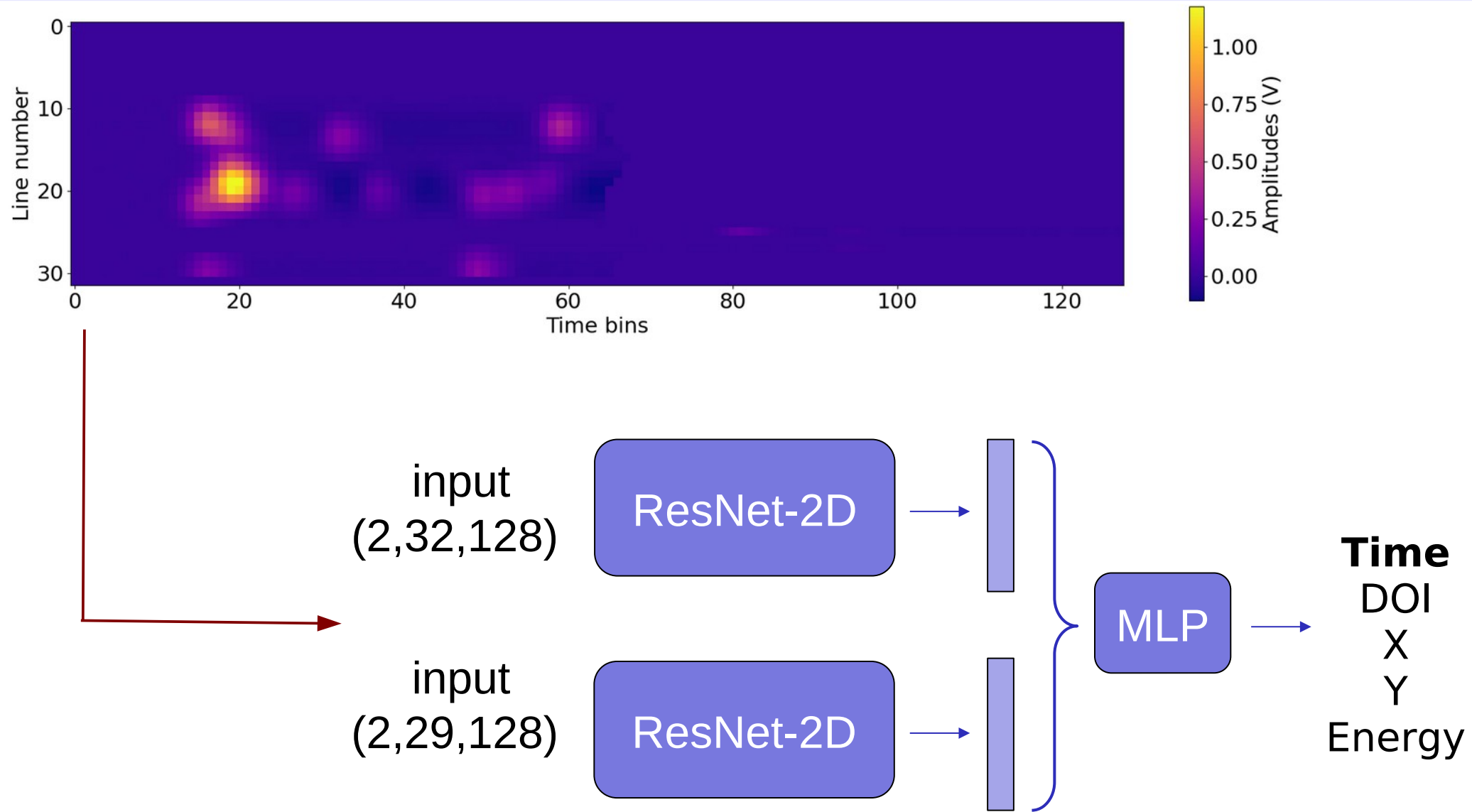
[C.-H. Sung, et al., NIM A Volume 1053, 2023, 168357](#)

Simulated Signals

- Transmission line read-out limits the number of channels, but produce complicated signals due-to the overlap
 - Machine learning reconstruction

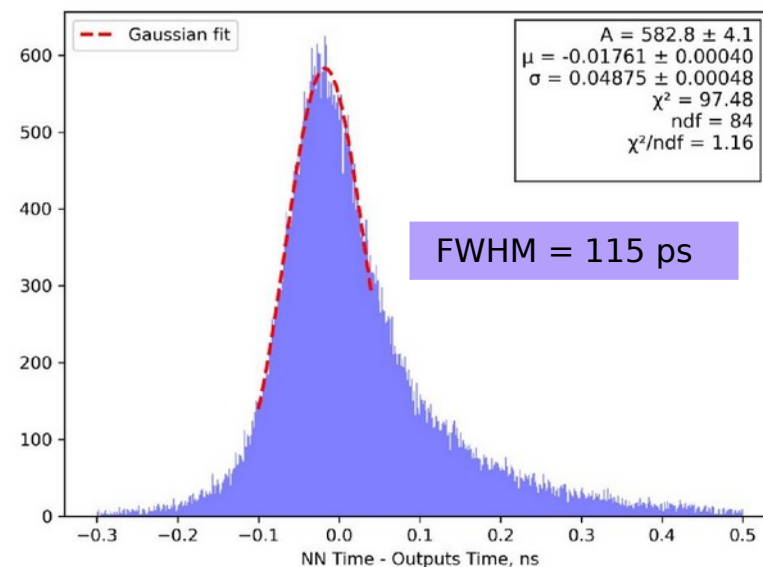
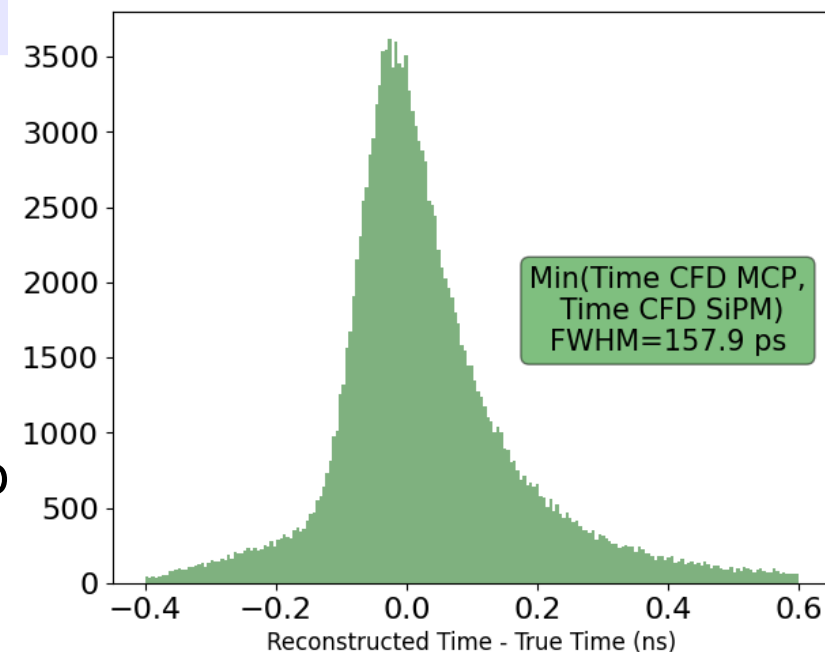


Reconstruction: NN architecture

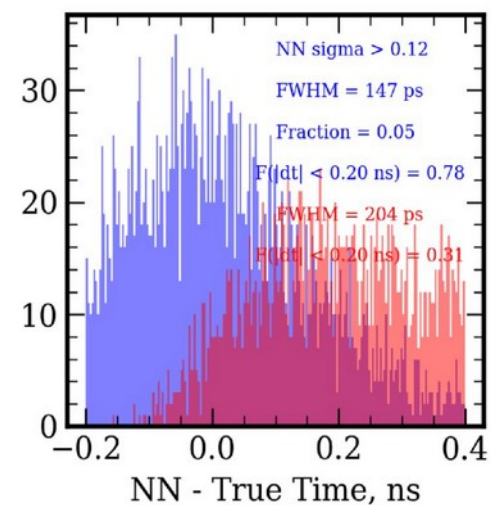
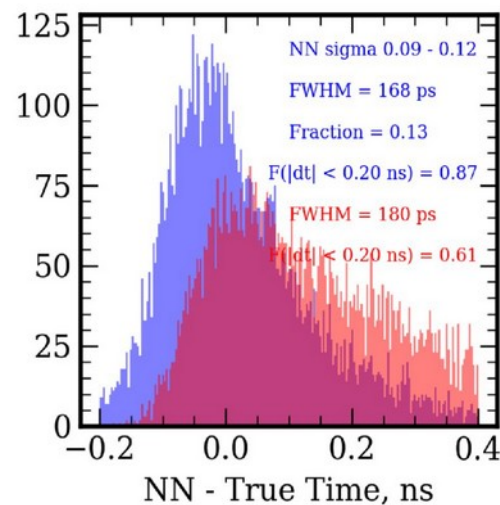
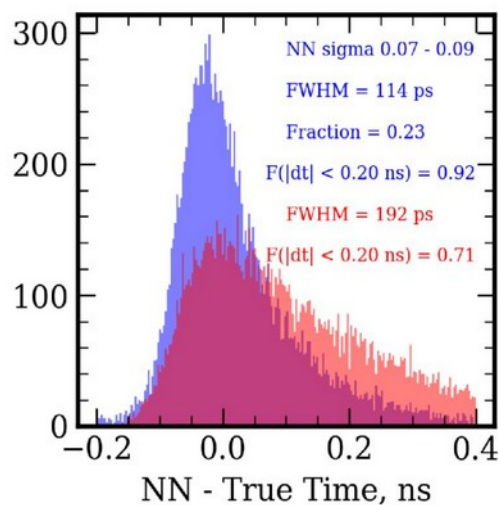
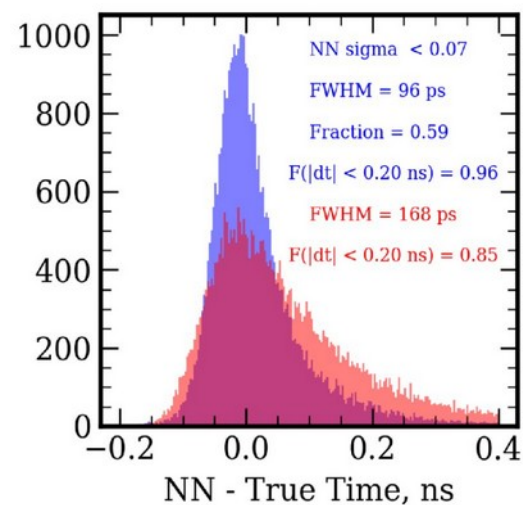
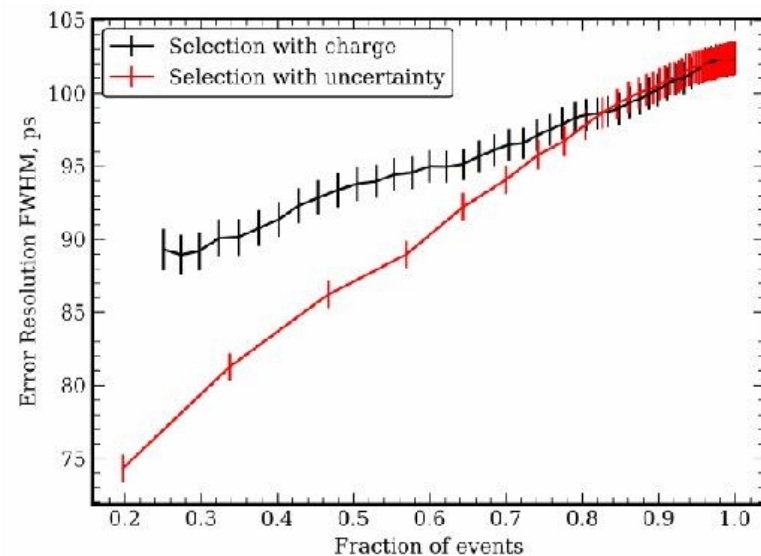
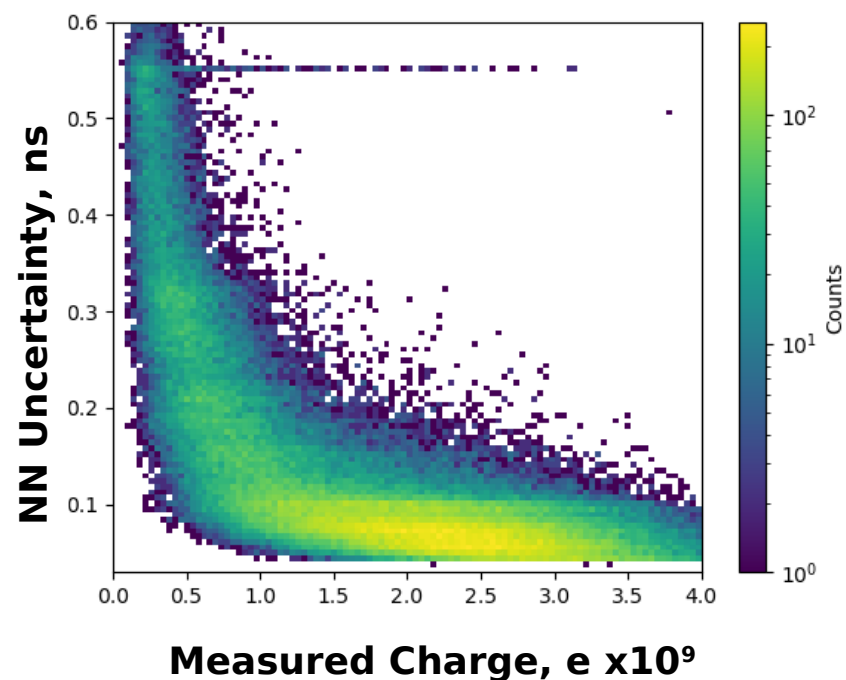


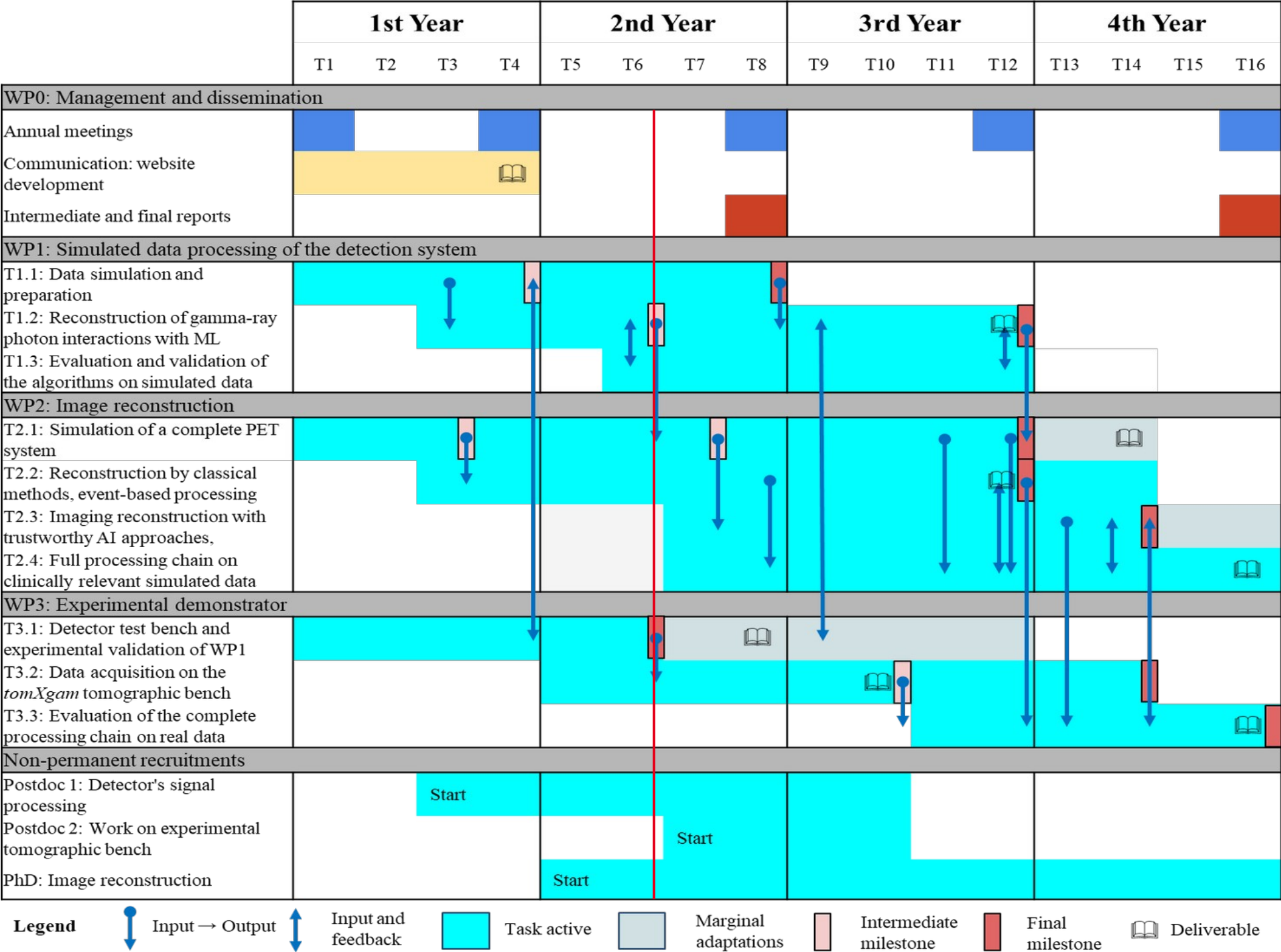
Time Reconstruction

- Similar approaches for the time and DOI reconstruction
- Use digitized signal shapes
- Compute resolution ~ 120 ps (FWHM)
- Event-by-event uncertainty will be used to enhance the image reconstruction of the PET-scanner (selection or weighting)



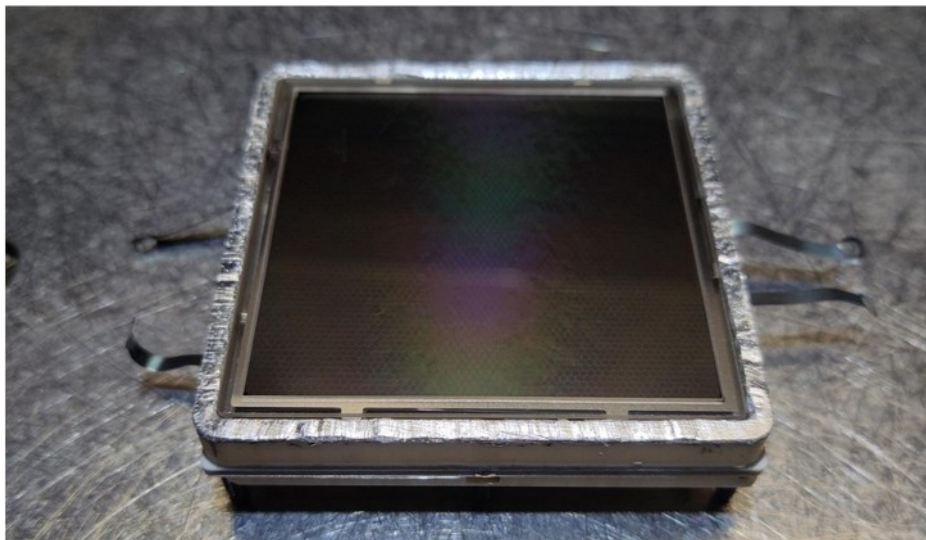
Time Uncertainty



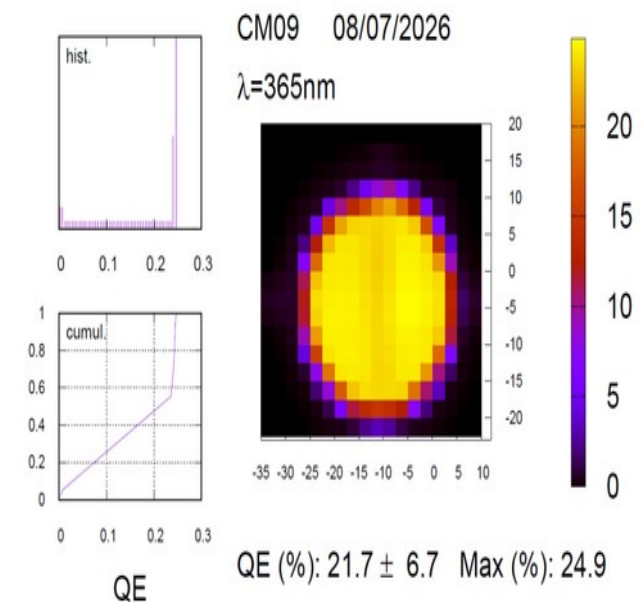
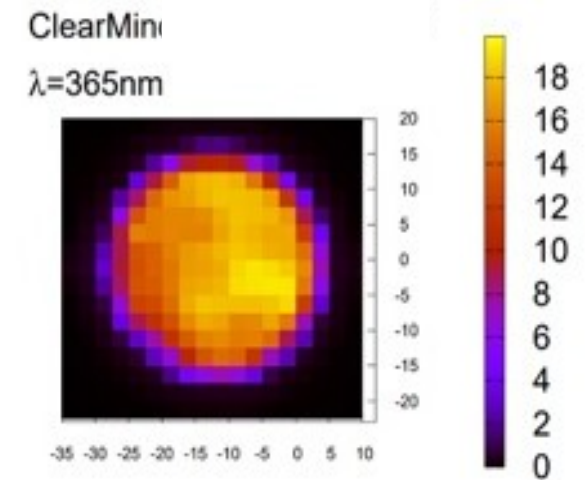


Photocathode Test at Incom

- Successful deposition of Bialkali photocathode:
 - Uniform coating
 - Stable over time
 - Efficiency: still non-optimal
- On-going work: Improve deposition process to enhance efficiency
- Wait for the prototype to test reconstruction procedure on real events



56 mm prototype assembling



AAIMME Related Scientific Production

- Conference Presentations
 - Z. Zobundzija, “Pixel and Transmission Line Readouts in Capacitive-Coupled HRPPD MCP-PMTs for High-Precision Timing”, presentation at IEEE NSS MIC RSTD, Novembre 2025, Japan
 - M. Granado González "Evaluation performance of ClearMind: A Large-Axial-FOV Monolithic-Crystal PET System with GATE", poster at IEEE NSS MIC RSTD, Novembre 2025, Japan
 - T. Kareljan, Reconstruction of Gamma-ray photon interaction in the ClearMind detector using neural network with uncertainty quantification”, poster at NDIP 2026, Troyes
 - Z. Zobundzija, “Photodetector model in ClearMind project : Toward ultra-high time resolution”, poster at NDIP 2026, Troyes
 - V. Sharyy, “ClearMind: fast photo-detection for TOF-PET” presentation at NDIP 2026, Troyes
 - D. Yvon, “Toward SiPN matrix multiplexing ...”, presentation at NDIP 2026, Troyes
 - 2 posters + one presentation on IEEE 2026 conference in November
- Papers
 - M. Granado González et al. “Simulation study for performance of a ClearMind PET with Large Axial Field of View based on PbWO 4 monolithic crystals”, submitted to ...
 - Z. Zobundzija et al. “Pixel and Transmission Line Readouts in Capacitive-Coupled HRPPD MCP-PMTs for High-Precision Timing” under preparation

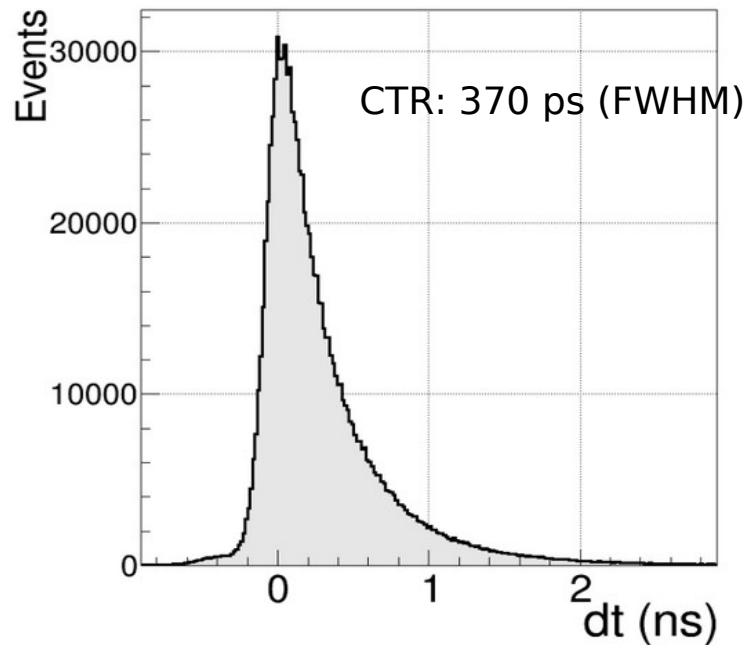
Conclusion

- AAIMME project is at 6/16 of its duration
 - WP1 “Signal Processing” is the most advanced stage: simulation → OK , encouraging results on reconstruction, working on the detector optimization, and model preparation for the full-size scanner simulation
 - WP2 “Image reconstruction”: preliminary results on the full scanner simulation. Start the preliminary work on the image reconstruction algorithms
 - WP3 “Experimental demonstrator”: waiting for the INCOM’s prototypes.

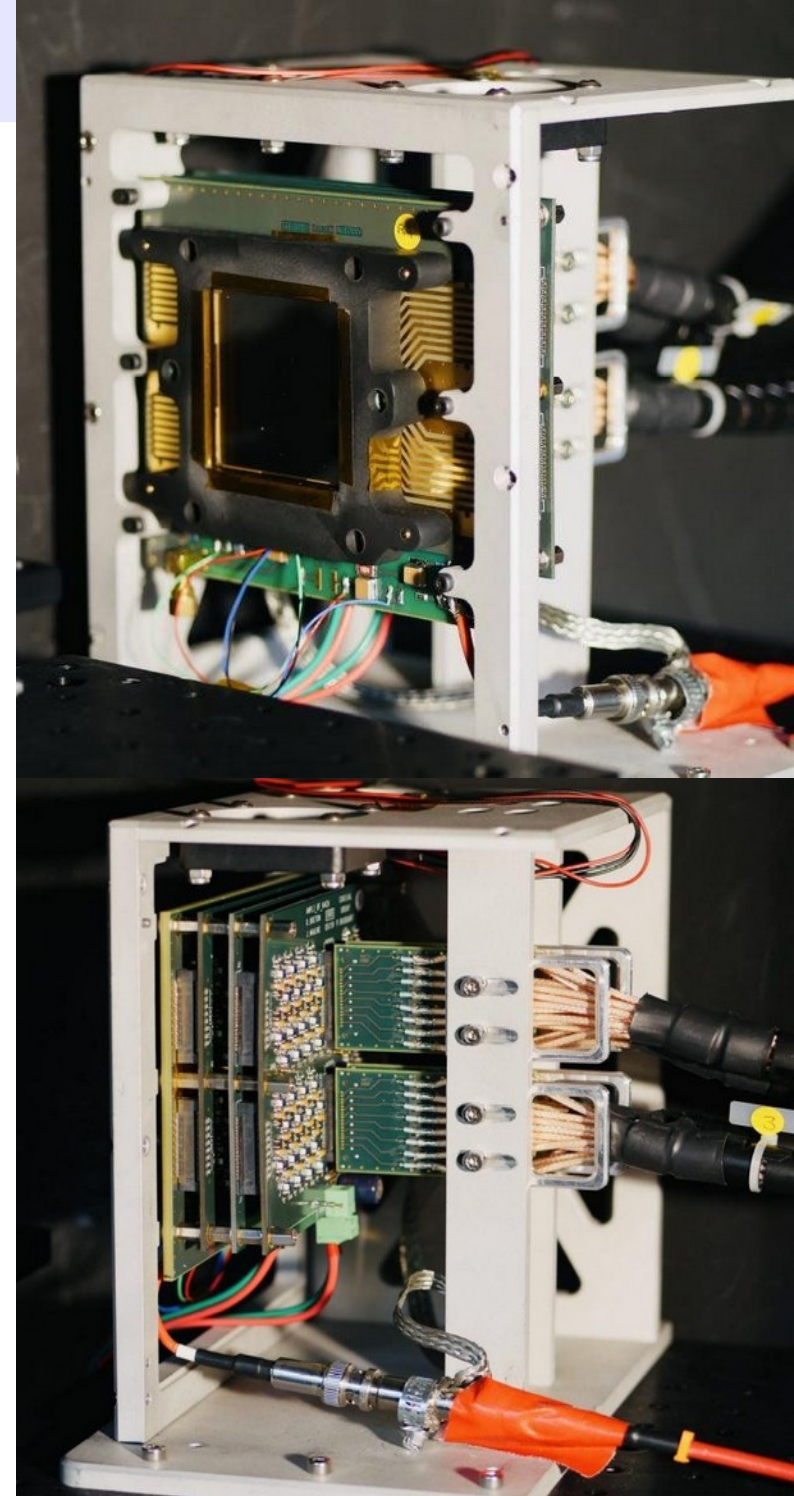
Back-up

First Prototype

- Proof of Concept
 - Photo-cathode deposition on the PWO crystal
 - Constructed by Photek (UK)
- Resolution is limited by the non optimal quantum efficiency $\sim 16\%$
- Start a collaboration with Incom (USA) to optimize photocathode efficiency

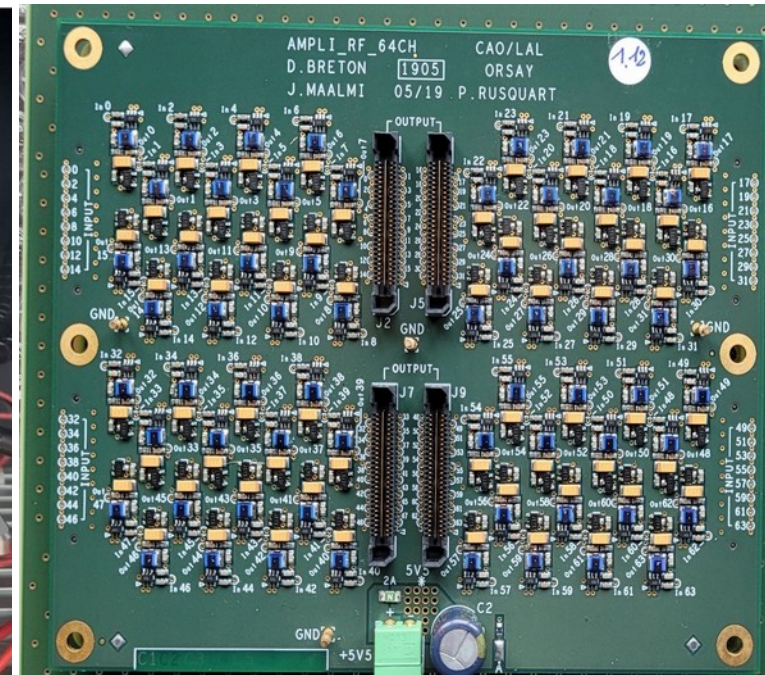
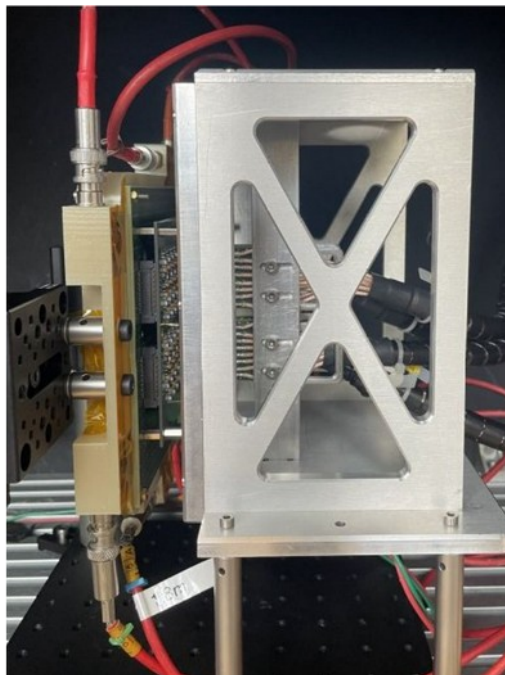


A. Galindo-Tellez, et al., 2024, 19 P07037



Test with pulsed laser

- Pulsed laser Pilas by A.L.S.
 - Single photon regime
 - pulse duration 20 ps (FWHM)
 - Spot size 200 μm (FWHM)
- Home made (IJCLab) Amplifiers: 64 channels
 - Gain 2x20 dB
 - Band-width 1 GHz
- Digitizations: SAMPIC crate
 - 6.4 GSamples/s (available 8.5 GS/s)
 - Accuracy up to 5 ps (SD)
 - Need to have signals 100 mV – 1V
 - Noise 1-2 mV



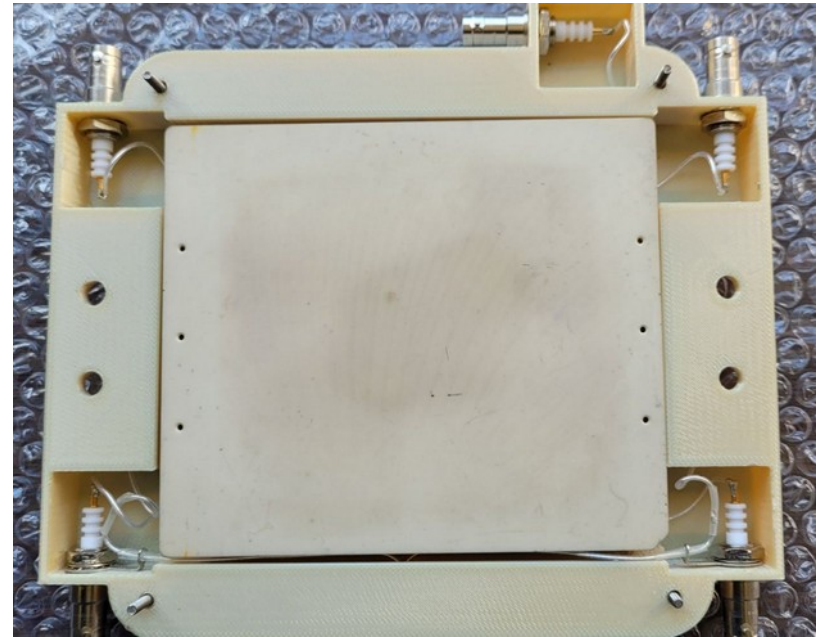
D. Breton et al., Nucl. Instrum. Meth. A 835 (2016), 51-60

Read-out PCB

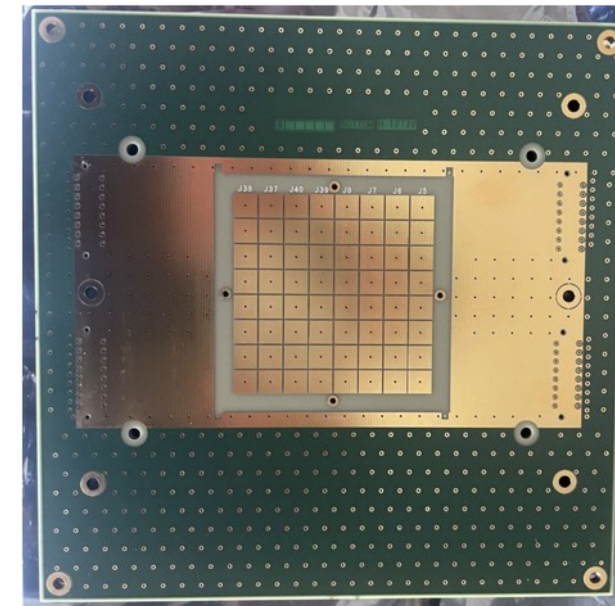
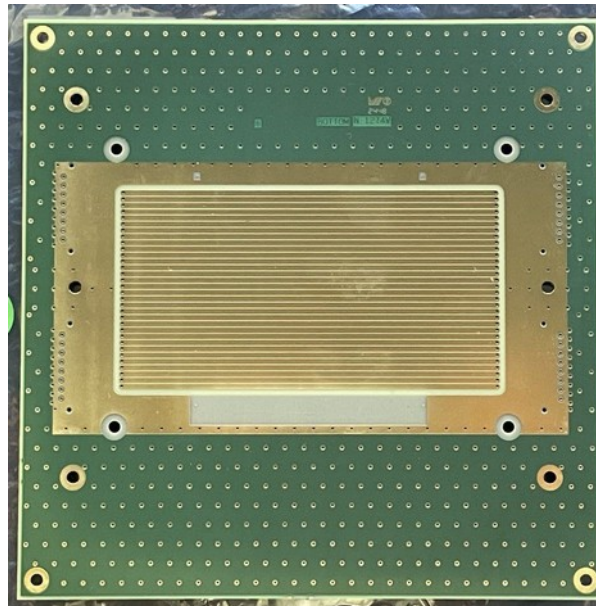
Resistive Anode $50\text{k}\Omega/\square$

Ceramics 2 mm

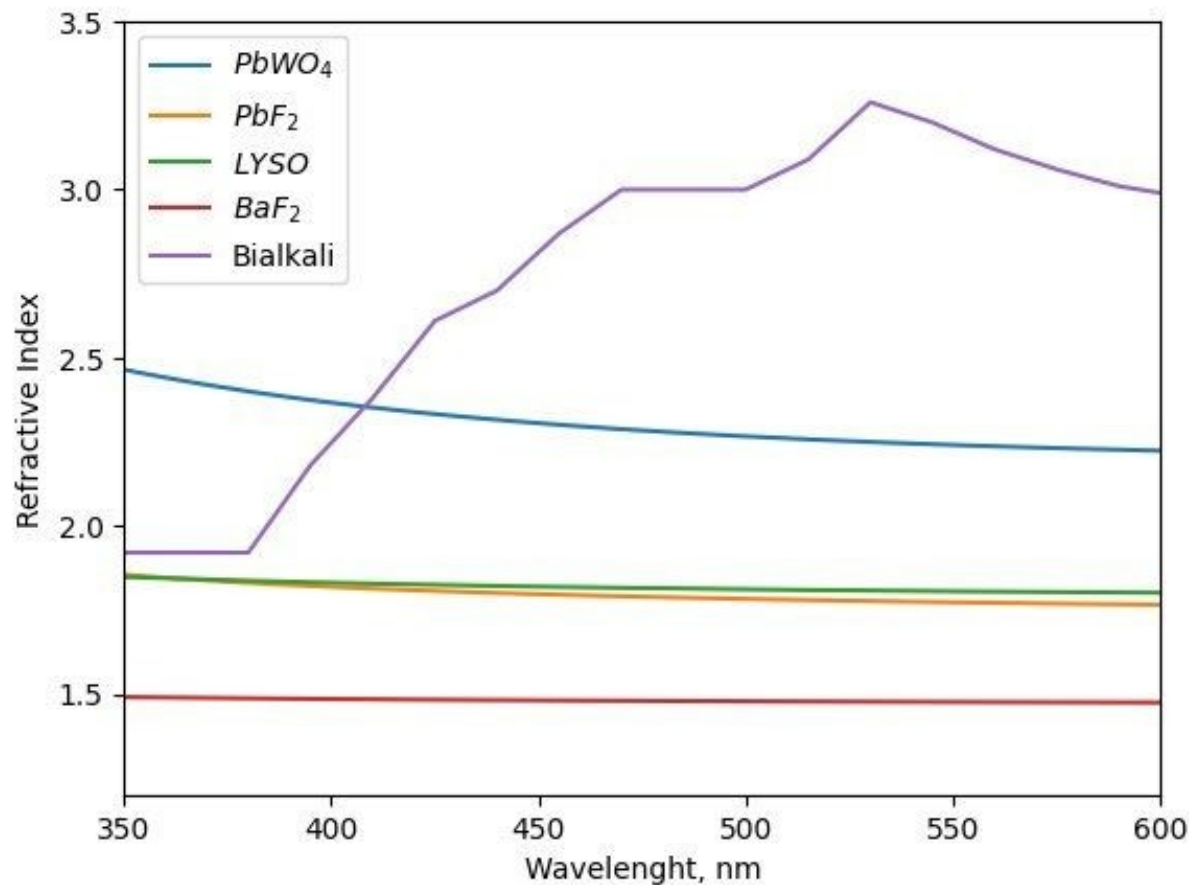
PCB



- Previous ClearMind Prototype (Photek): Direct Read-Out
- HRPPD: Capacitive Read-Out
- Test PCBs
 - Transmission Lines: 100 mm x 1.5 mm
 - Pixels: 6 mm x 6 mm
- 64 channels:
 - 32 lines left & right
 - 64 pixels
 - Central part covered



Refractive Index



PbF₂ & BaF₂ <https://refractiveindex.info>

Bialkali : Ch.-H. Sung et al., Nuclear Instruments and Methods in Physics Research A, Volume 1053 (2023), 168357

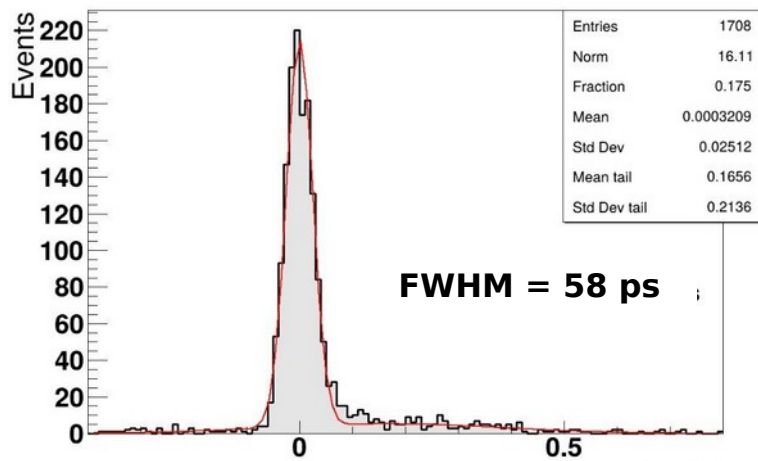
D. Motta & al, Optical properties of bialkali photocathodes, Nucl. Instruments Methods Phys. Res, 539 (2005) 217–235

LYSO : G. Ender et al., Optical Materials, Vol. 32, Issues 6 (2012), pp. 781–785

PbWO₄ : S. Baccaro et al., NIMA, Vol. 385 (1997), pp. 209–214

Measured Time Resolution

Fixed Laser position

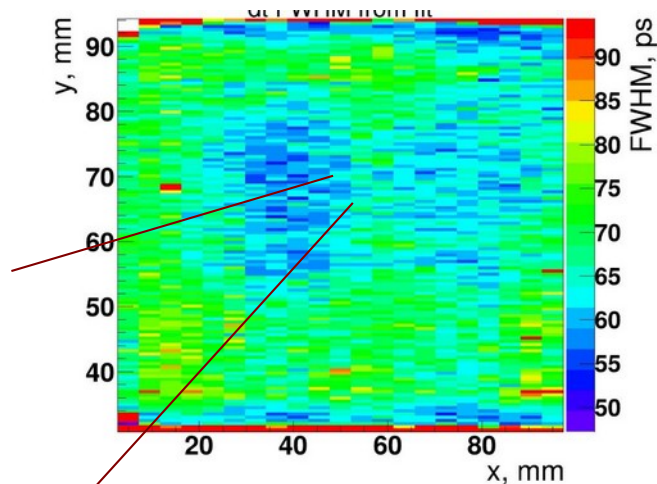


dT: laser - PMT, ns

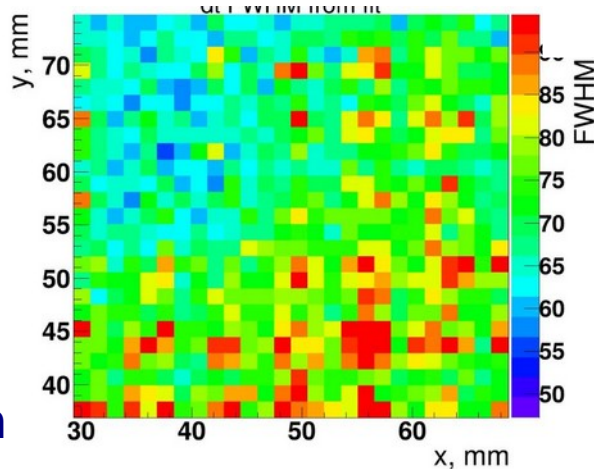
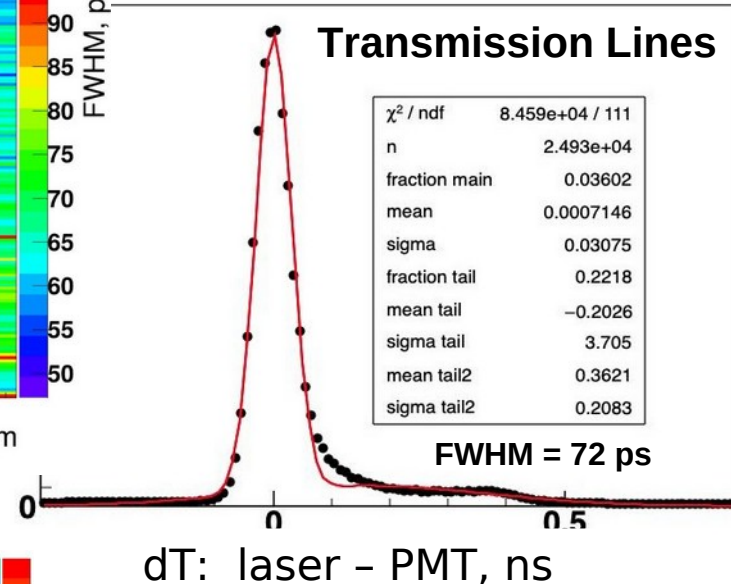
Tail: backscattered electrons
Time resolution with lines and pixels are similar

Depends on: amplitude cut, gain fluctuation, saturation

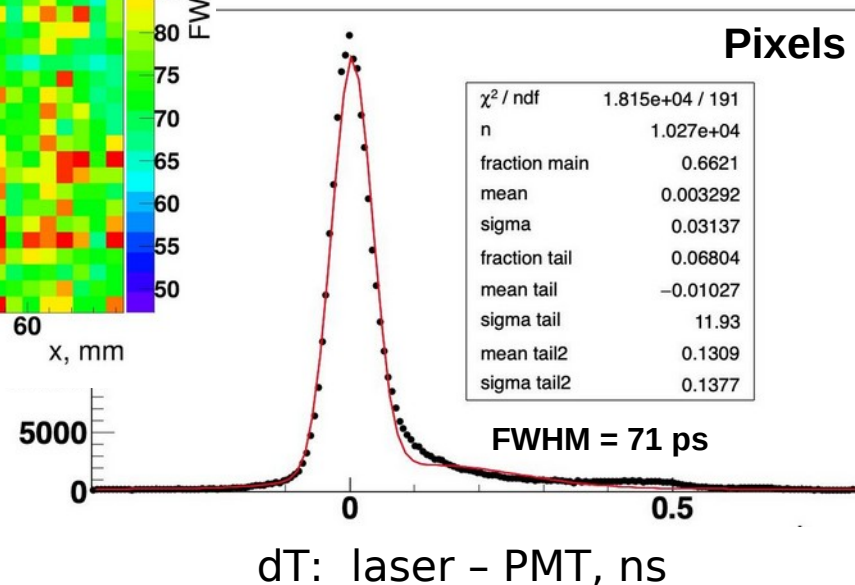
Non homogeneous time resolution → gain fluctuation



Transmission Lines

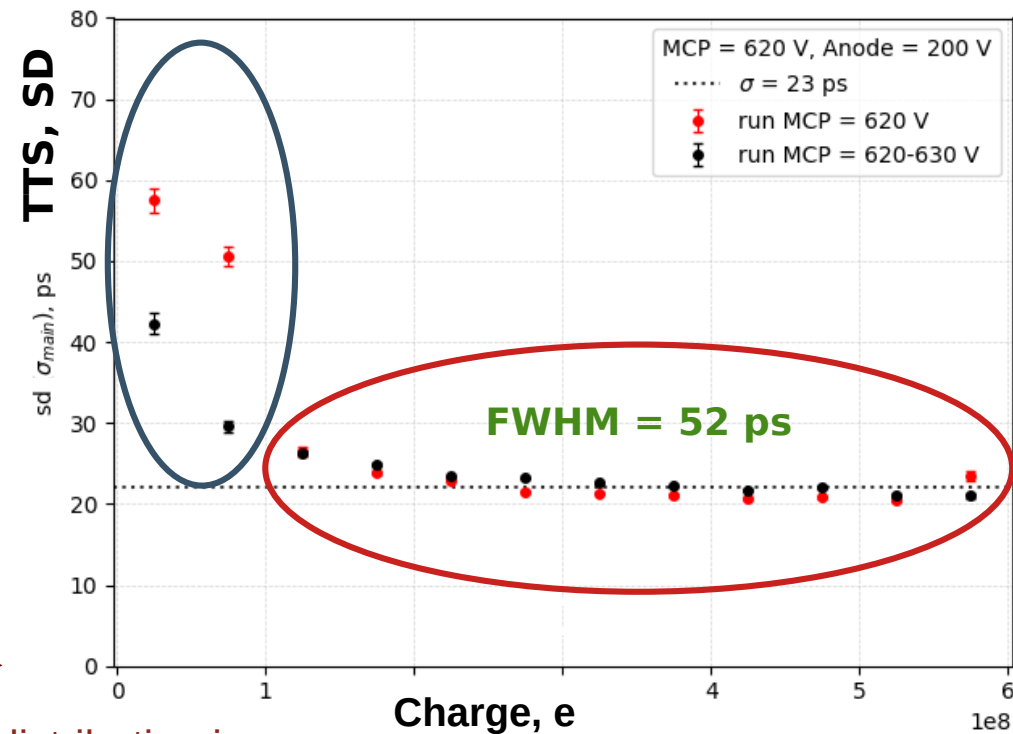
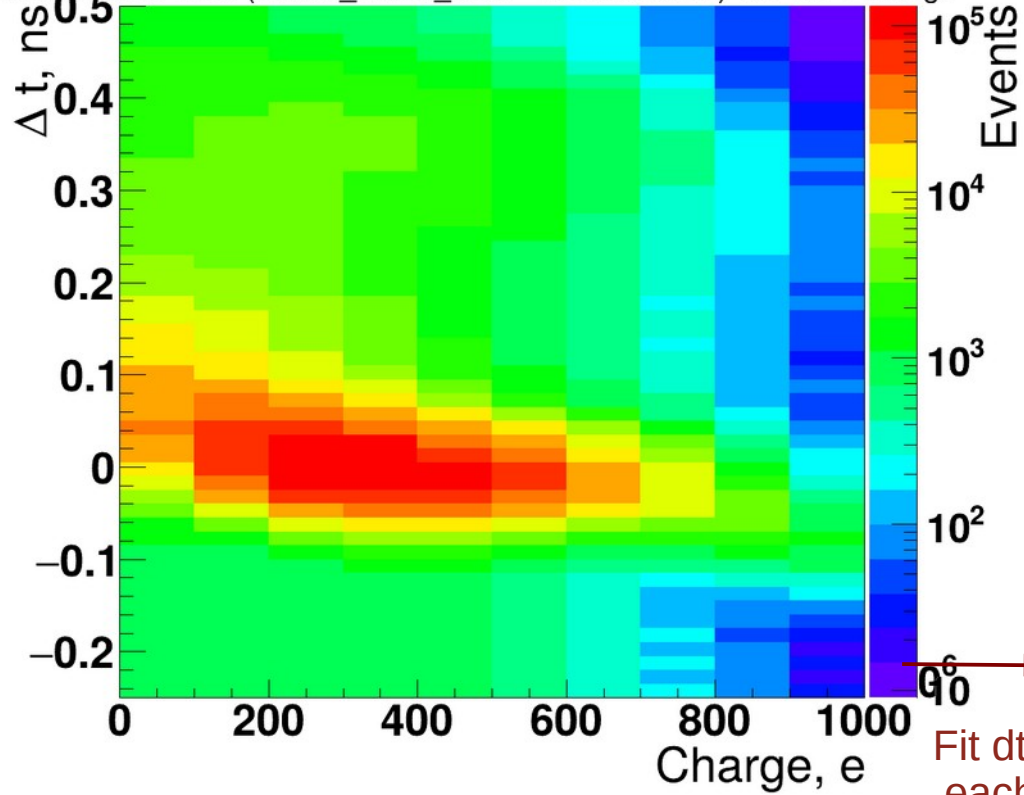


Pixels



Time Resolution vs Signal Amplitude

Difference in Time (FIRST_PEAK_CFD - THRESHOLD) vs PMT1 Charge



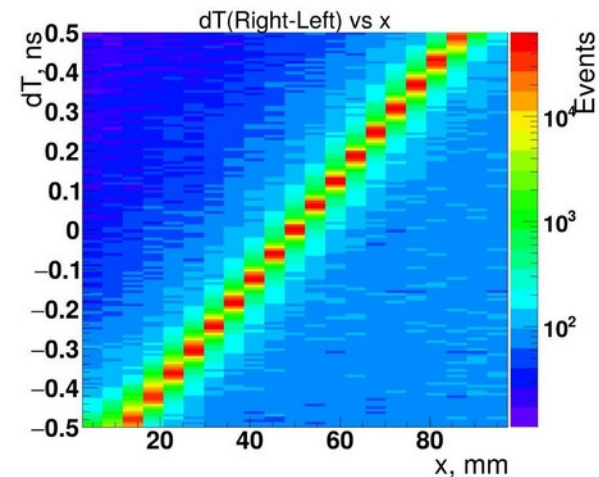
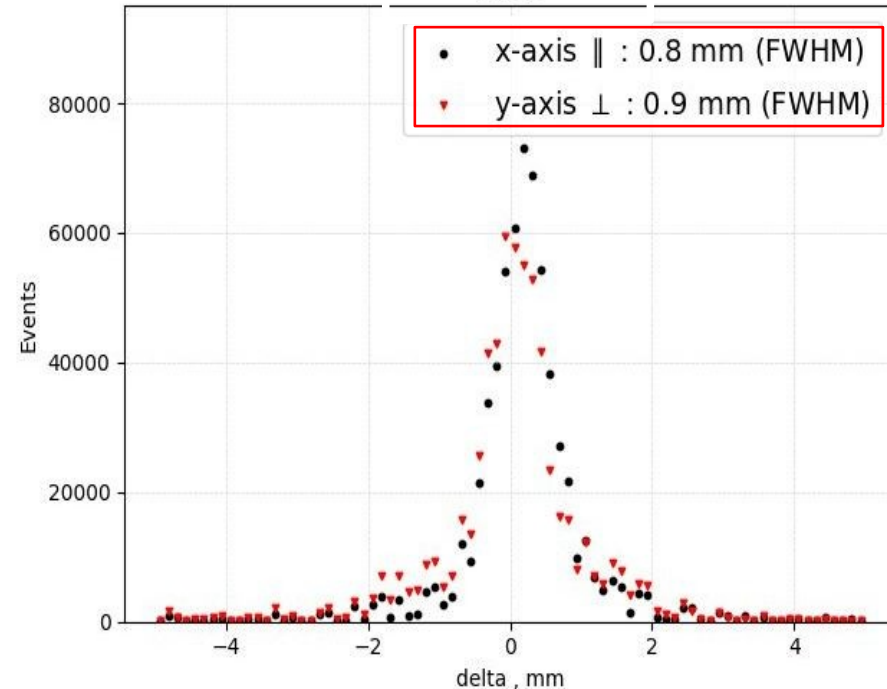
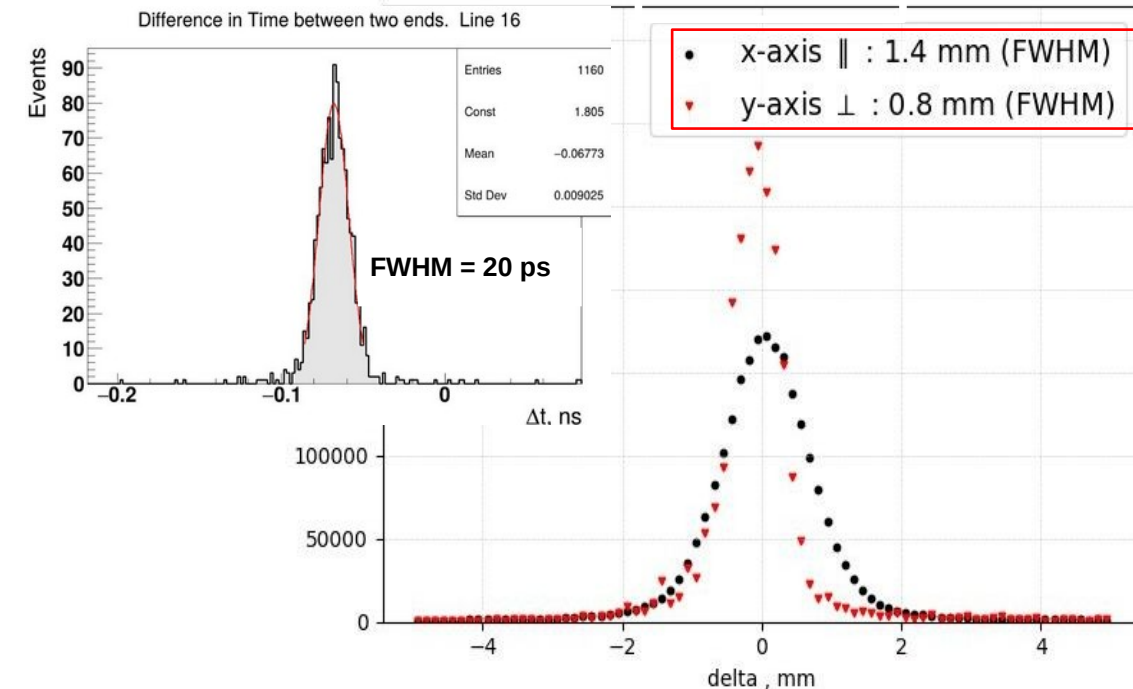
- Difference in temporal resolution observed with different voltages on MCPs related to low-amplitude signals
- Observation of a plateau beginning at a certain amplitude: weak dependency of the MCPs voltage

⇒ Time resolution depend on pulse amplitude selection

Measured Spatial Resolution

Transmission Lines
100 mm x 1.5 mm

Pixels
6 mm x 6 mm



$$X_R = \frac{(t_R - t_L)s}{2}$$

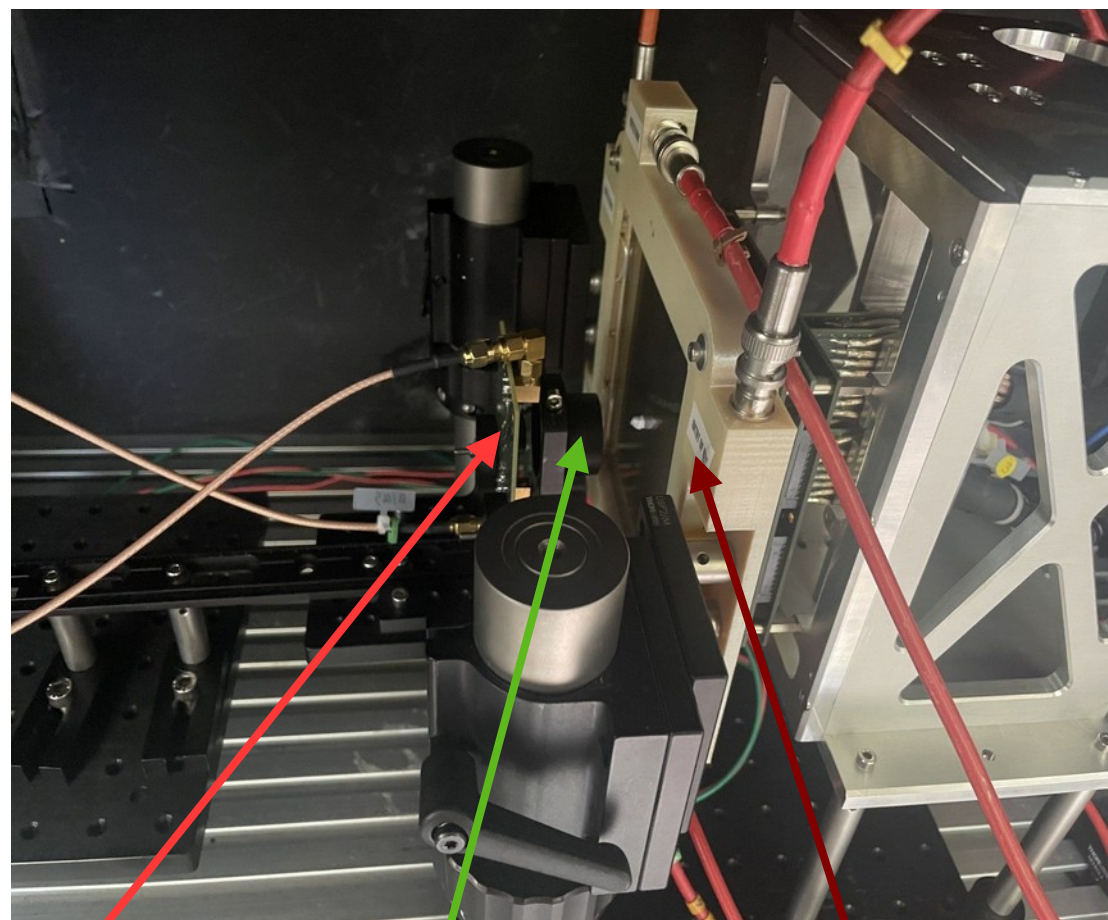
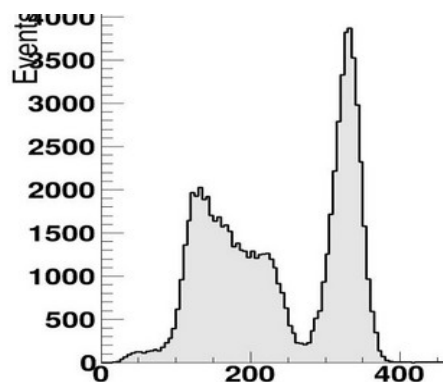
Signal speed (s) $\sim 0.4 c$

$$Y_R = \frac{\sum_{k=1}^N y_k C_k}{\sum_{k=1}^N C_k}$$

Good spatial resolution due to charge sharing
Better resolution with pixels (multiple pixel activation)

Test with Different Crystals

- Crystals, disc $\varnothing 16\text{mm} \times 2\text{mm}$:
 - BaF₂** (EPIC)
 - PbWO₄** (CRYTUR),
 - PbF₂** (EPIC)
 - LYSO** (LUXIUM France):
 $3 \times 3 \times 3 \text{ mm}^3$
- optical coupling (oil)
- Reference detector : LYSO + SiPM (Broadcom), time resolution $\sim 100 \text{ ps}$ (FWHM)
- Radioactive source: ^{22}Na
- Photoelectric peak selection



LYSO +
SiPM

3 cm

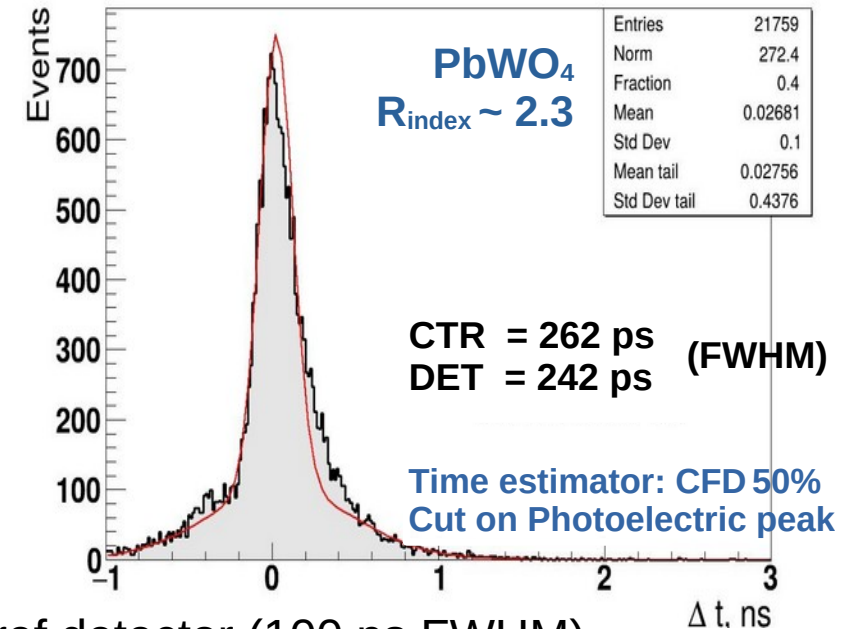
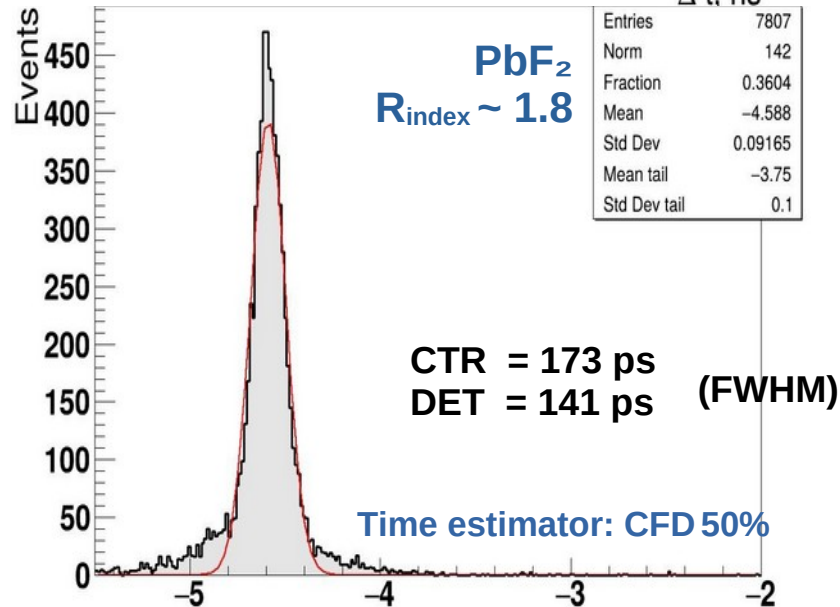
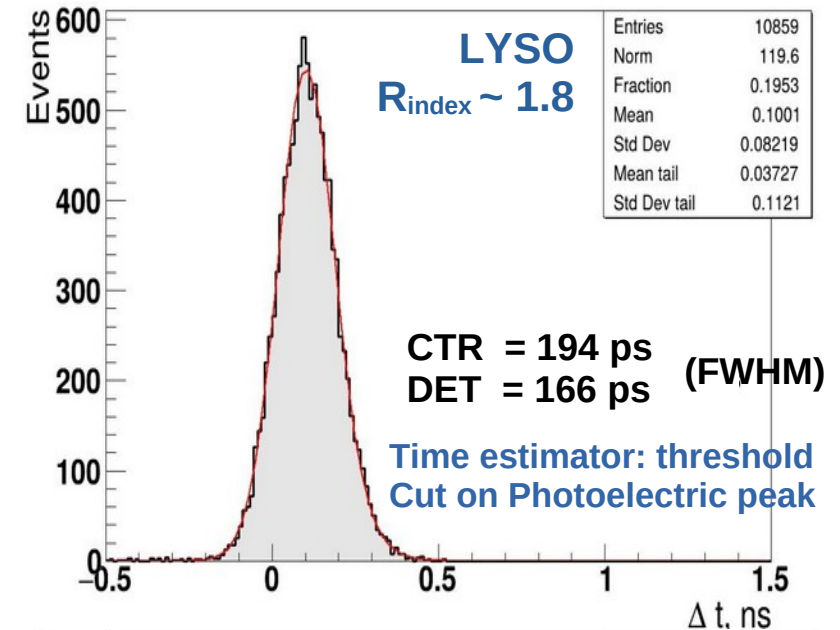
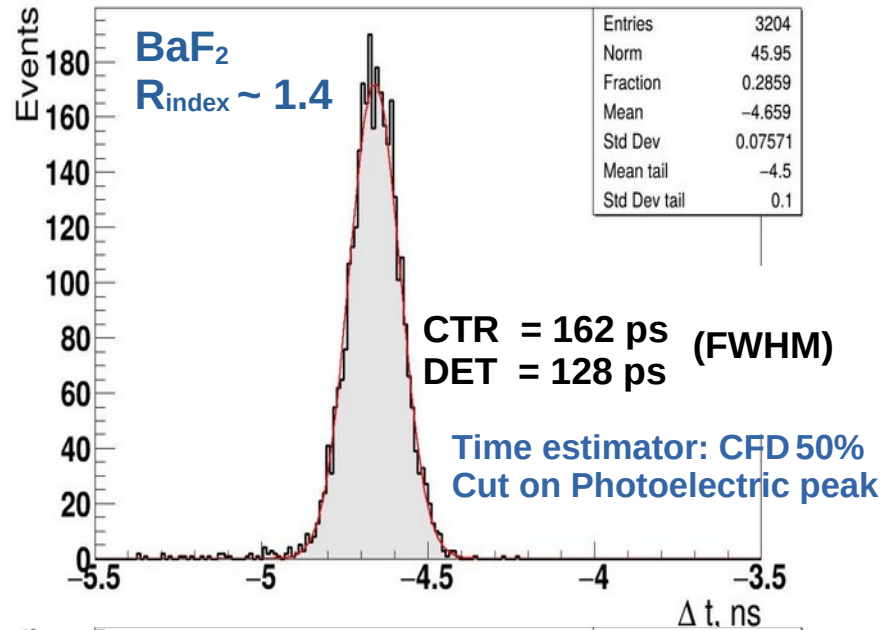
Source

3 - 4 cm

Crystal + optical
coupling + HRPPD

ATTENTION: not yet ClearMind prototype, window of Fused Silica → optical coupling not optimal

Measured Resolution With Crystals



CTR : coincidence time resolution relative to ref detector (100 ps FWHM)

DET: detector resolution = $\sqrt{CTR^2 - (100 \text{ ps})^2}$