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Towards High-Performance TOF-PET: Development of Innovative Detector Concepts at IRFU

V. Sharyy for the ClearMind and AAIMME collaborations

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French-Ukrainian W O R K S H O P

**Instrumentation developments
for high energy physics**



October 12-14, 2026

IJCLab, Orsay - France

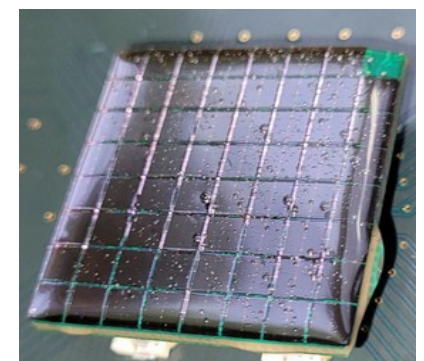
PET in Nutshell

- **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 → 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) → intersection of many (~10M) LORs reconstructs the emission map



PET Physics

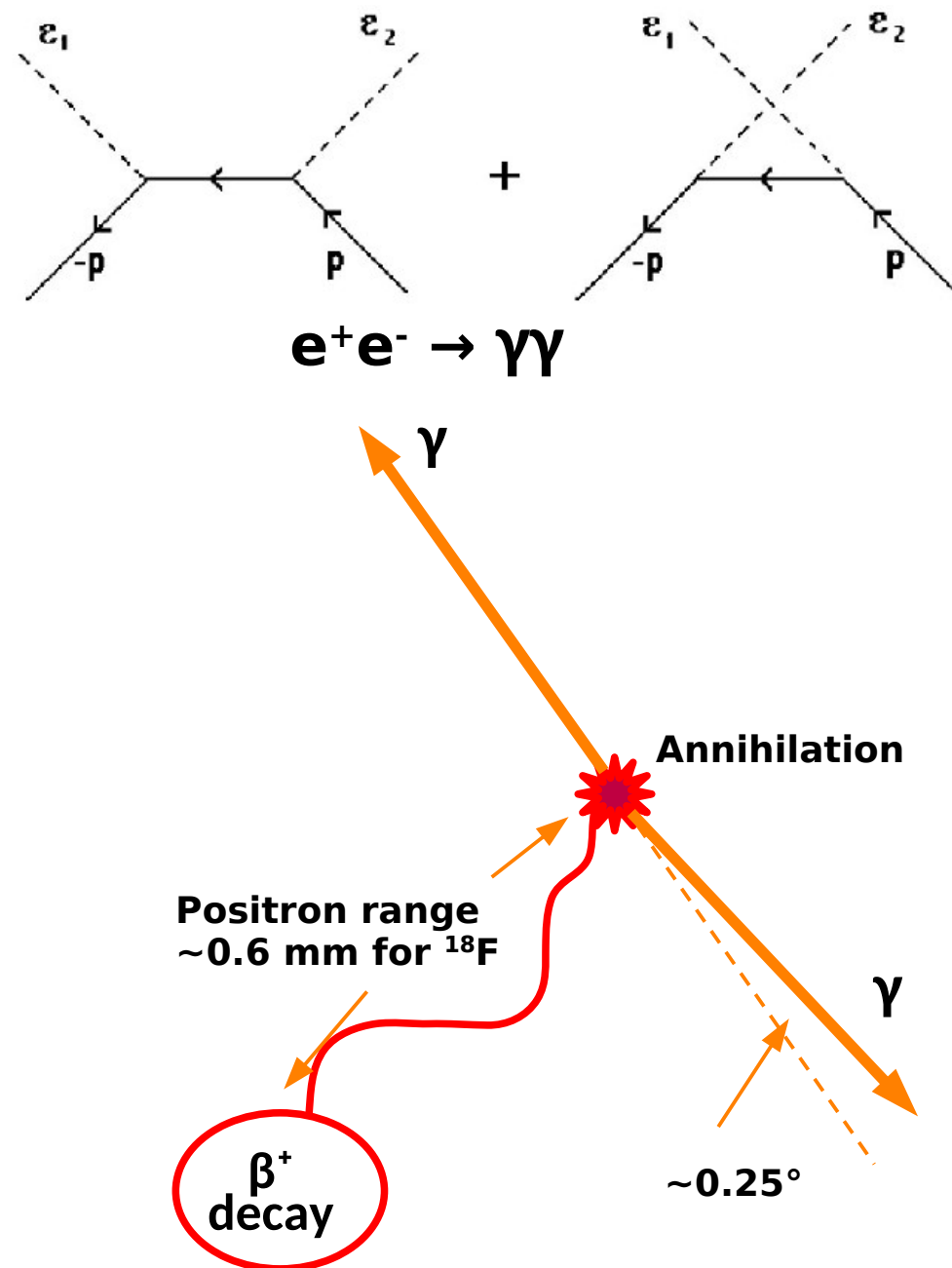
- **Production**

- β^+ decays: $p \rightarrow n + e^+ + \nu$
- Kinetic Energy, e.g. $^{18}\text{F} \sim 250 \text{ keV}$

- **Thermalisation** $\rightarrow$ Positron range: $\sim 0.6 \text{ mm}$ (^{18}F)

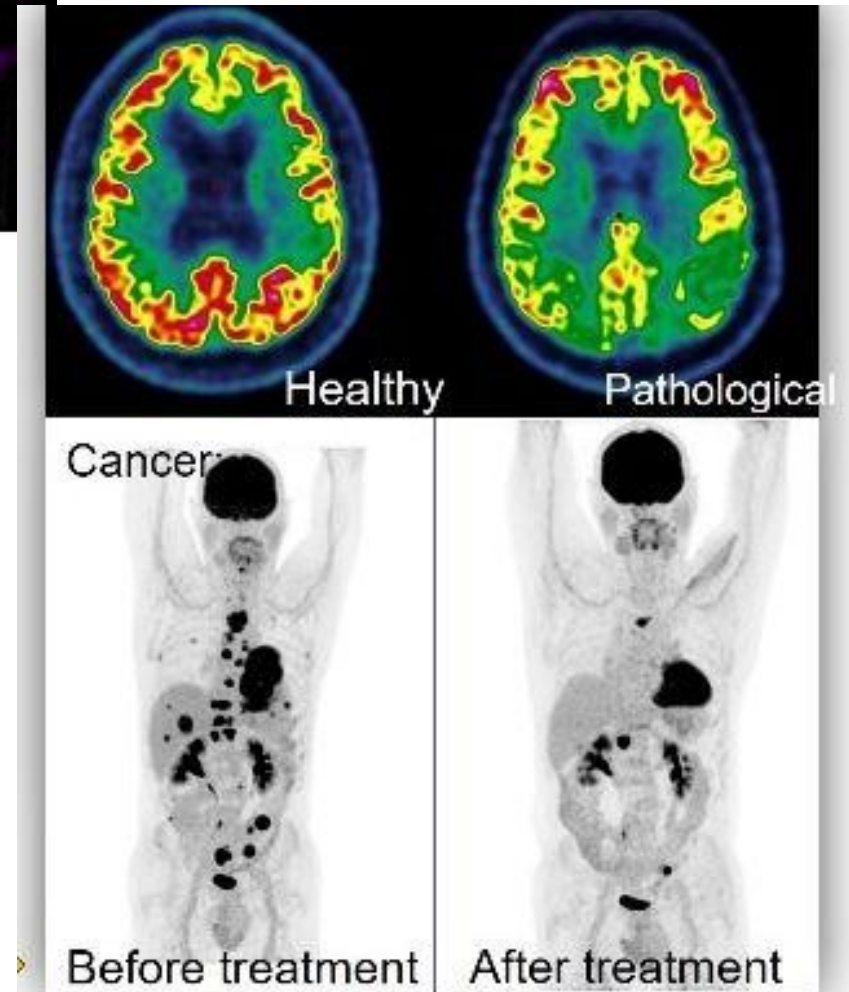
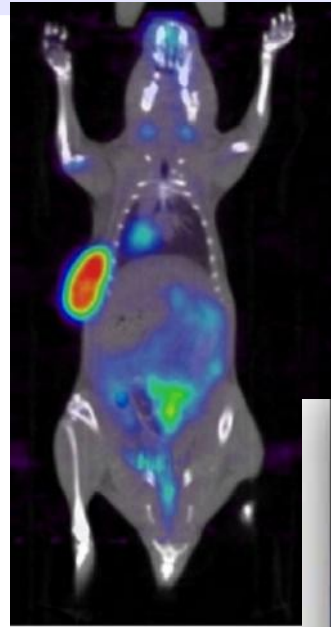
- **Annihilation:**

- On-flight $\rightarrow$ low ($\sim 2\%$)
- After thermalisation direct annihilation $\rightarrow 2\gamma$
- Positronium formation $\cong 40\%$
- $\frac{1}{4}$ para-positronium ($\uparrow \downarrow$), $t \sim 125 \text{ ps}$, 2γ decay
- $\frac{3}{4}$ orto-positronium ($\uparrow \downarrow$), $t \sim 142 \text{ ns}$, 3γ decay $\rightarrow$ spin flip due to the interaction with tissue $\rightarrow 2\gamma$ decay, $t \sim 1\text{-}2 \text{ ns}$



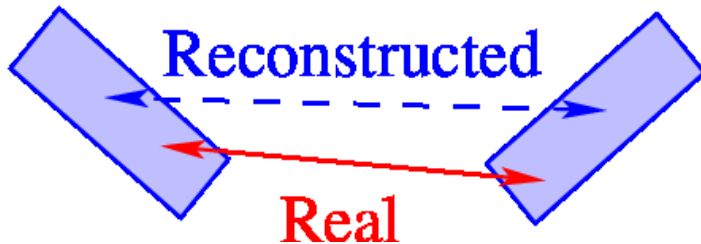
Scanner Types

- Preclinical (small animals)
 - Small aperture
 - High spatial resolution
 - Small sensitivity
- Brain scanner
 - Limited aperture
 - High sensitivity
 - Good spatial resolution
- Whole-body
 - Large aperture
 - High sensitivity
 - Low spatial resolution
 - Full body dose ~ **5 - 15 mSv**
(natural radioactivity per year France : 2 mSv)

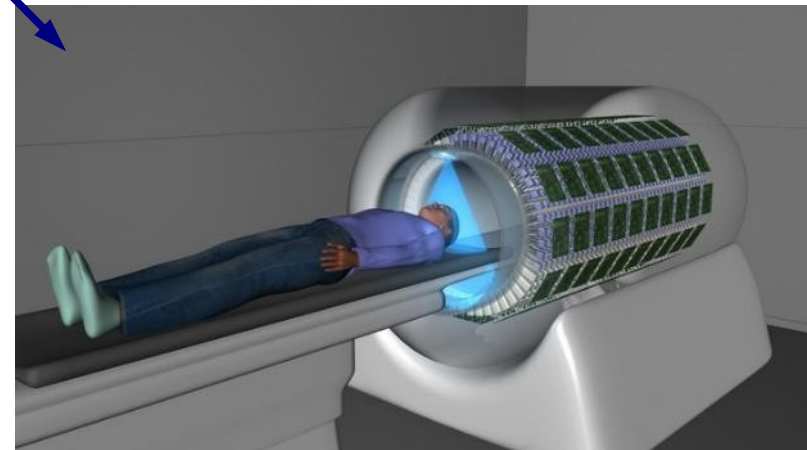
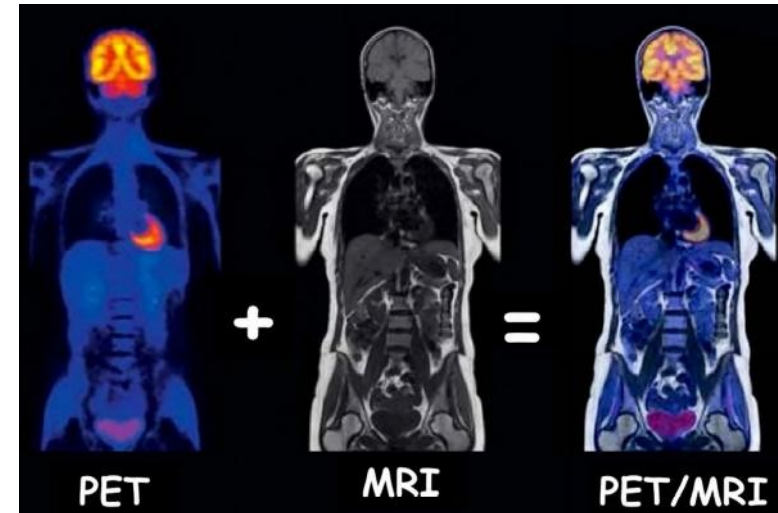


PET Evolution

- Combined modalities: CT/PET, MRI/PET
- Improvement sensitivity: total-body PET → 40 fold improvement in sensitivity
- *Reduce bias: depth-of-interaction reconstruction*

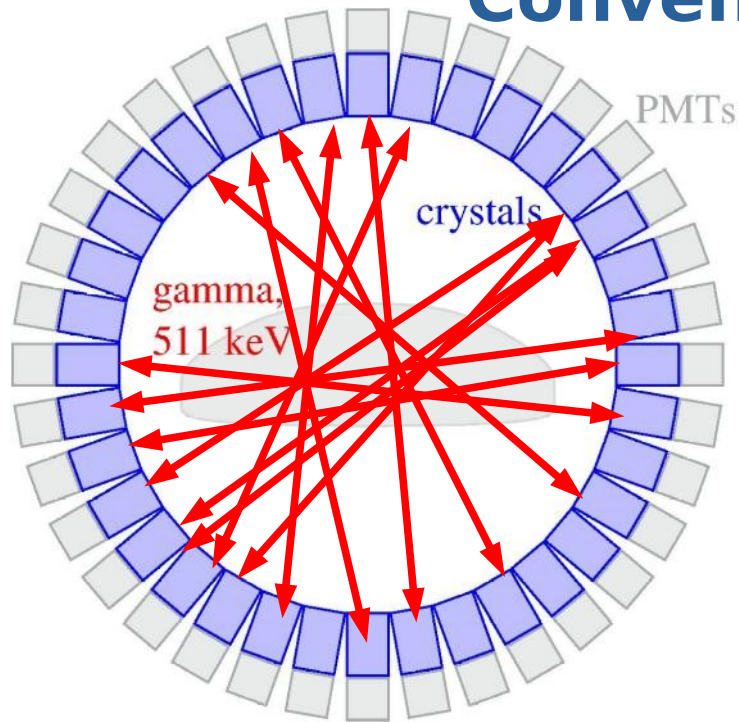


- *New developments in electronics, and gamma-detection*
- *Time-of-flight technique (TOF) ⇒ see next slides*

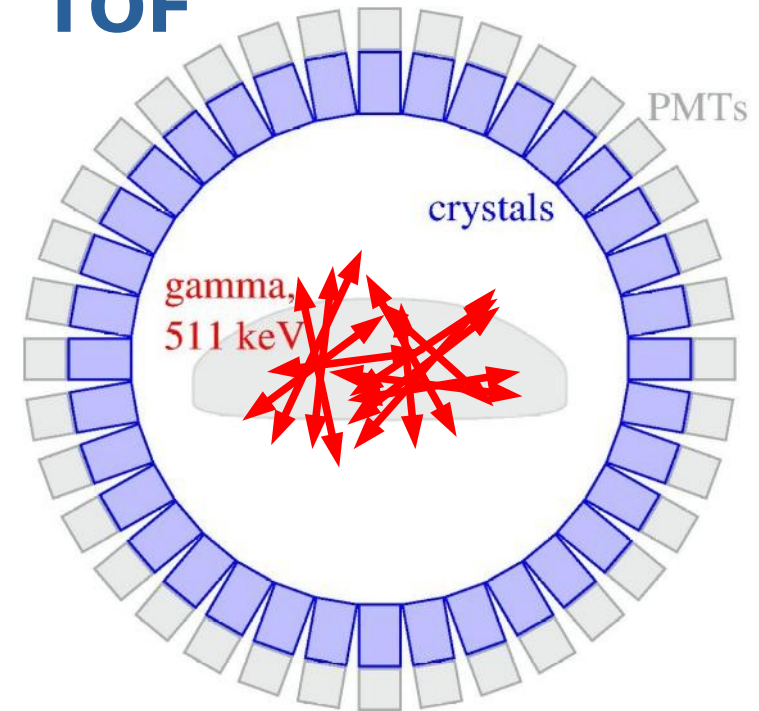


TOF Technique

Conventional



TOF



- TOF techniques: measure the difference in time $\Rightarrow$ improve S/B

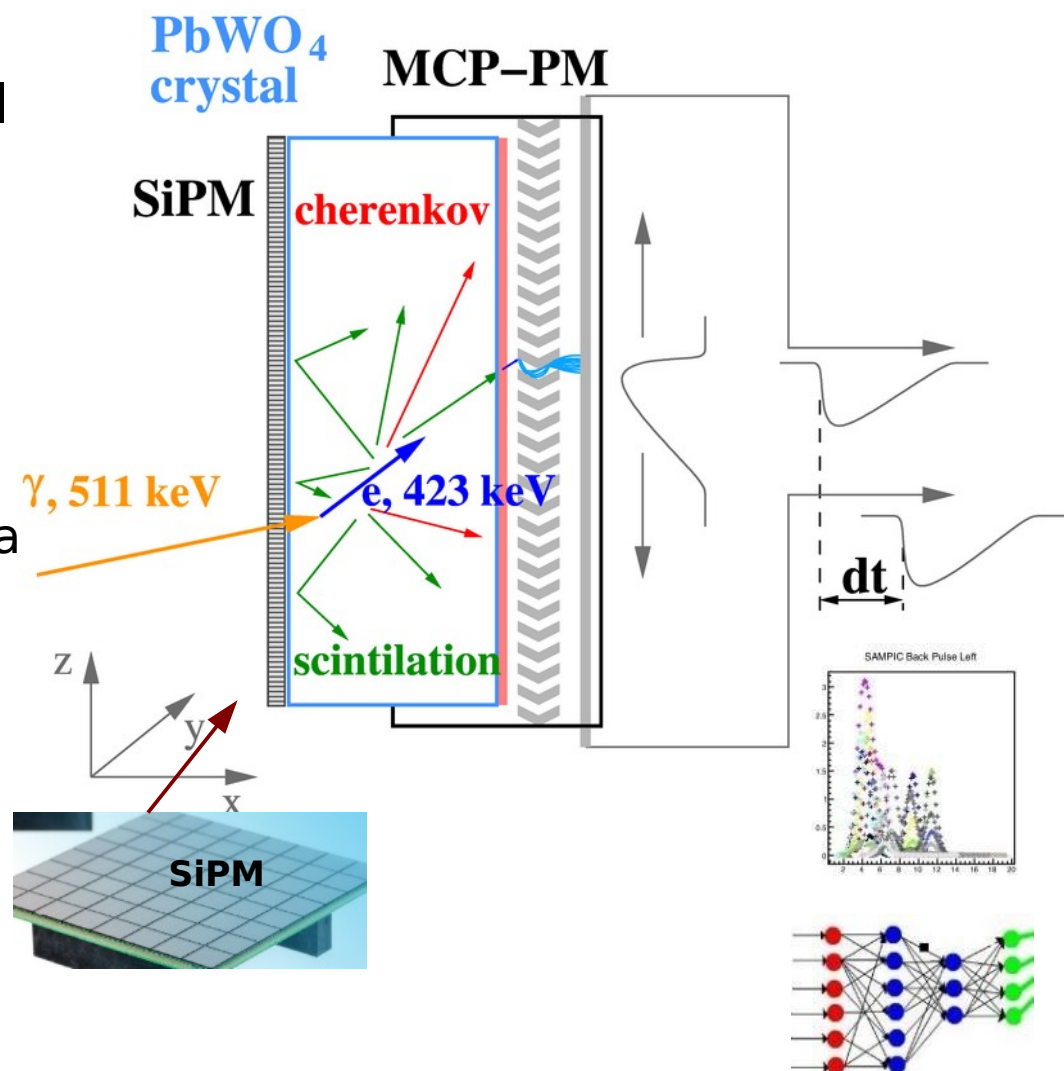
- TOF gain estimation:
$$G = \frac{S/N_{TOF}}{S/N_{noTOF}} \sim \sqrt{\frac{D}{\delta x}} \sim \sqrt{\frac{D}{c/2 \delta t}}$$

$D=20 \text{ cm} \Rightarrow \text{CTR}=\mathbf{150 \text{ ps}}$ (FWHM) $\Rightarrow G\sim 2.9 \Rightarrow \mathbf{8x \text{ lower dose}}$

- Best commercial detectors: $\sim 200 \text{ ps}$ (FWHM, coincidence time resolution)
- In the Lab: below 100 ps , but on small crystals $\rightarrow$ low efficiency

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 (see **Dominique Yvon S14**)

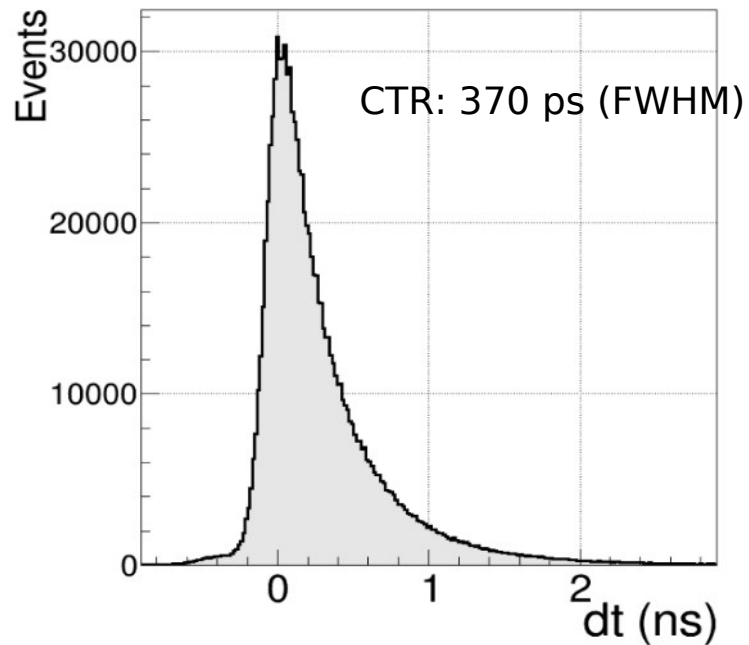


Patent CEA, FR1759065, 2017

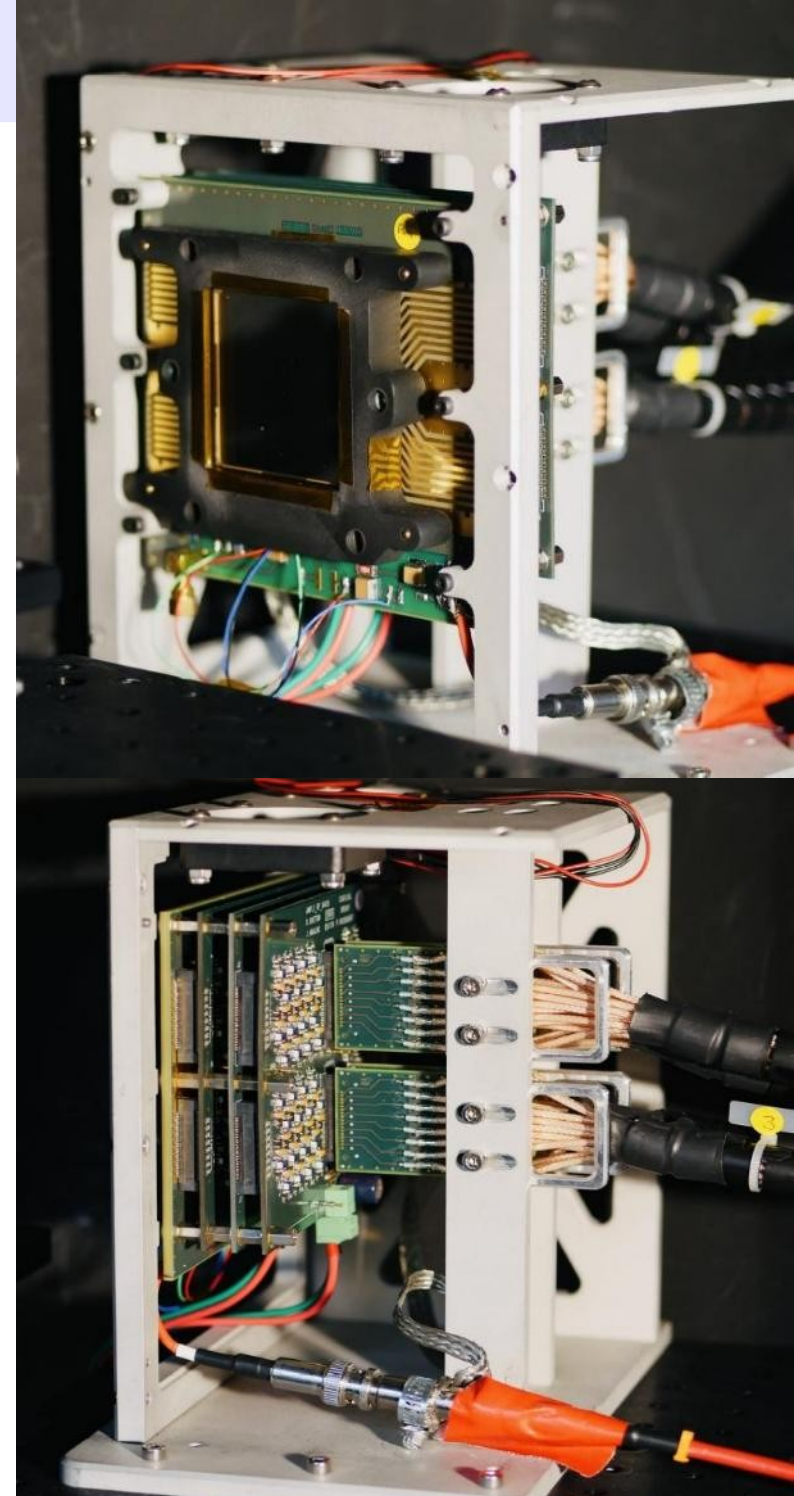
D. Yvon et al, 2020, JINST 15 P07029

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

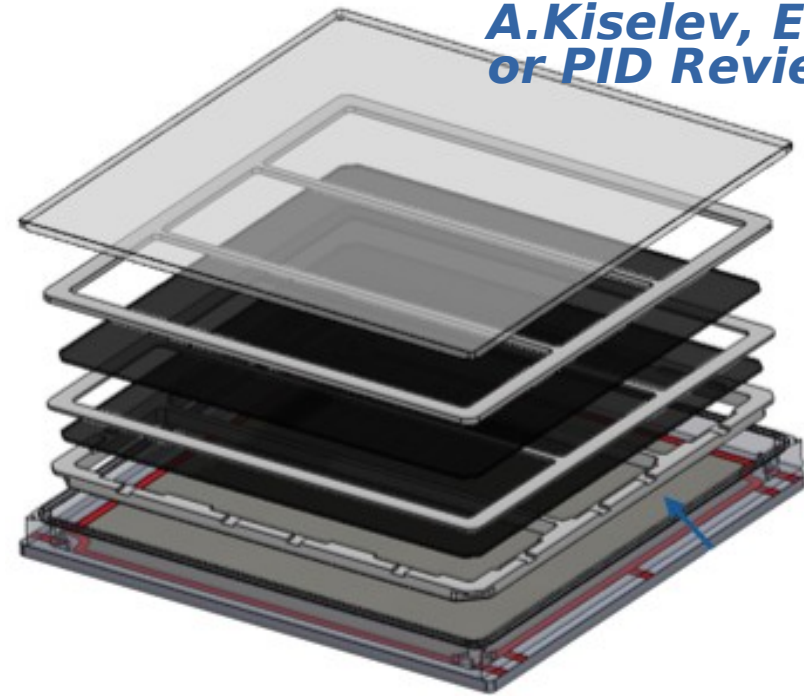


A. Galindo-Tellez, et al., 2024, 19 P07037



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

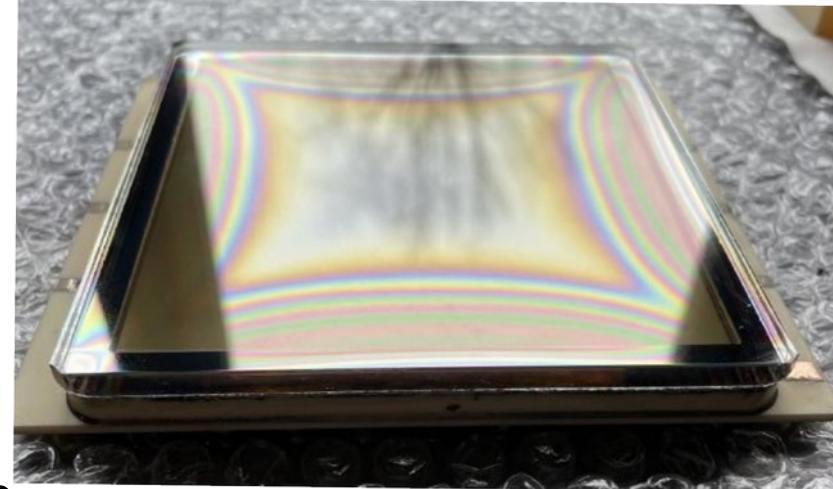
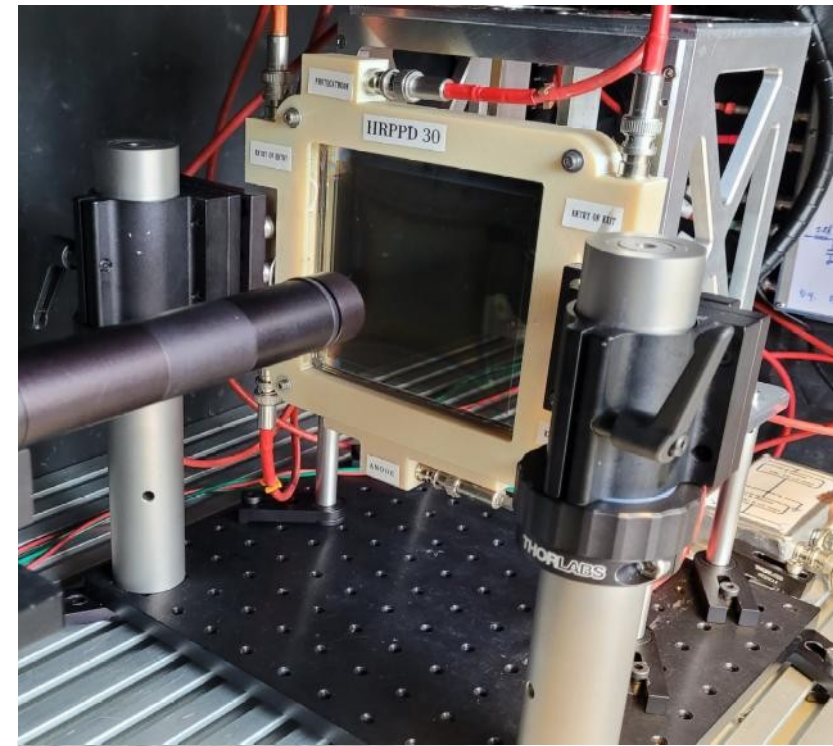
Photodetector Active Area: 95 mm x 95 mm

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

Capacitively Coupled ReadOut:

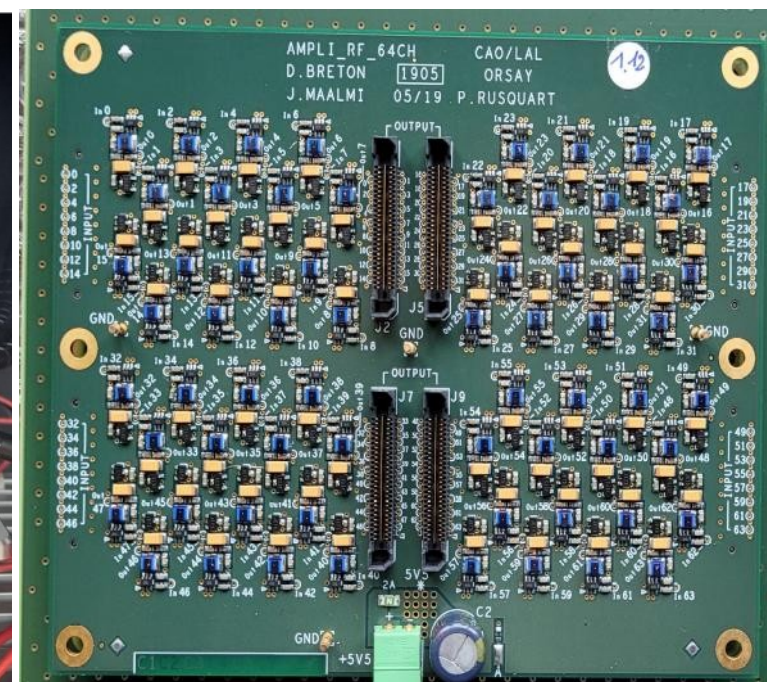
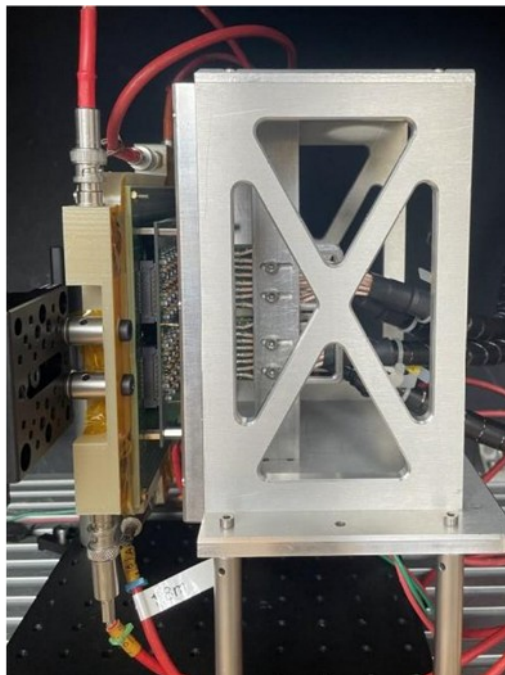
→ Mode: charge relaxation time $\gg$ signal time

→ Flexible use of the readout PCB



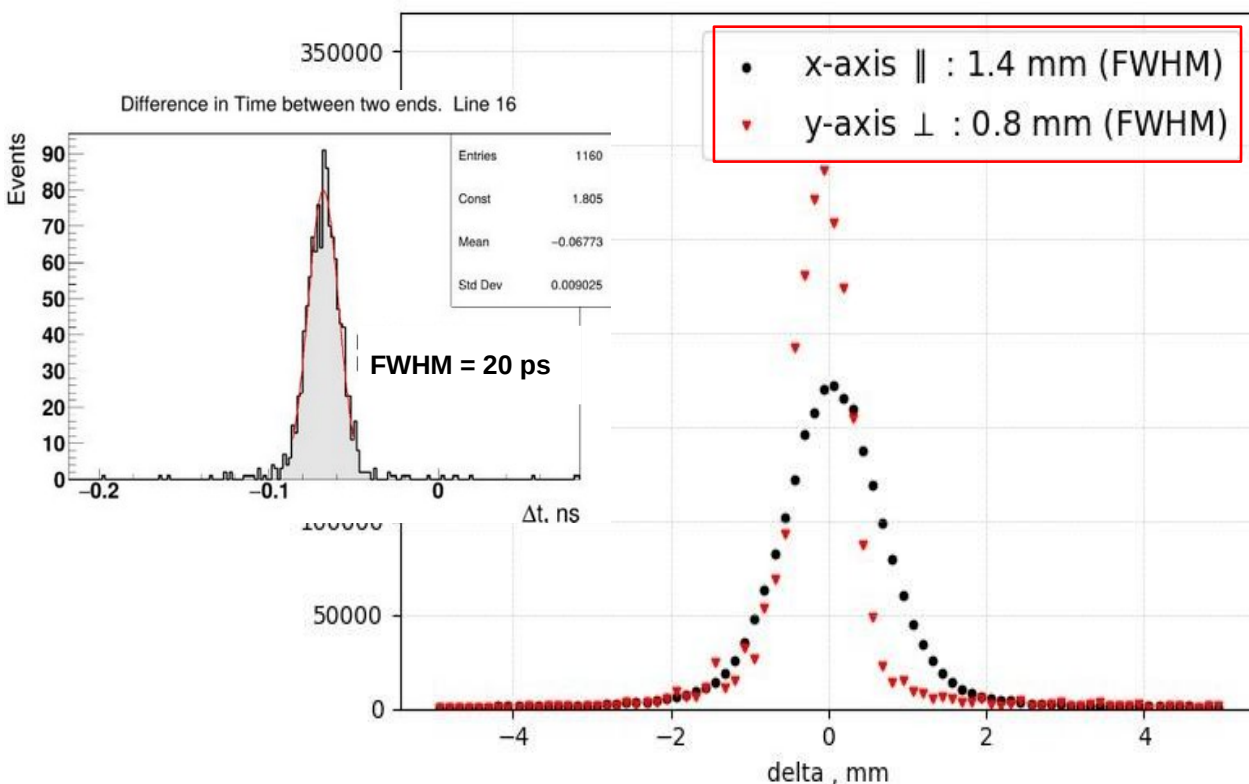
Test with pulsed laser

- 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

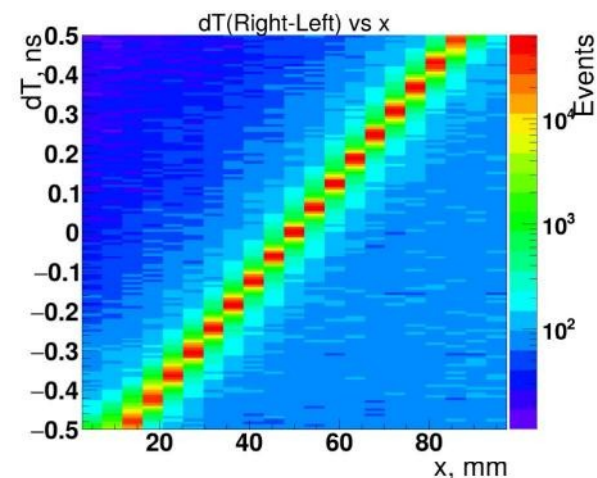
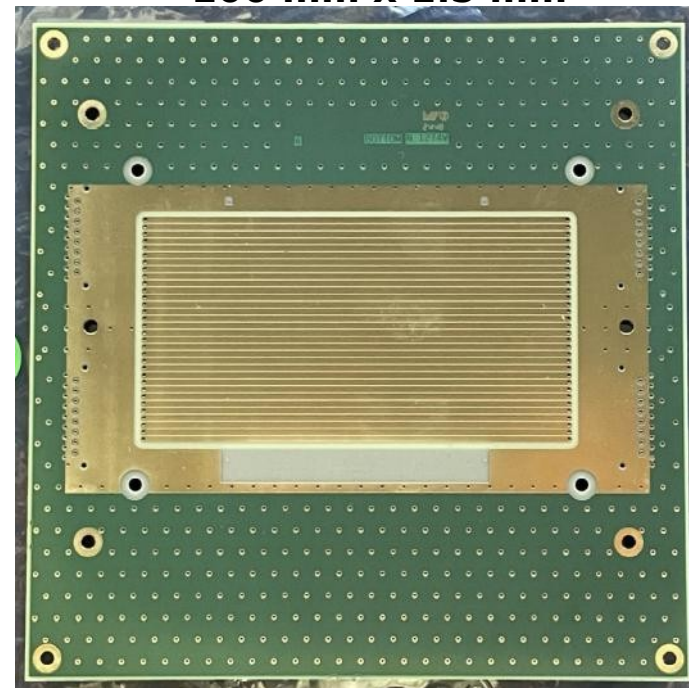


D. Breton et al., Nucl. Instrum. Meth. A 835 (2016), 51-60

Measured Spatial Resolution



Transmission Lines
100 mm x 1.5 mm



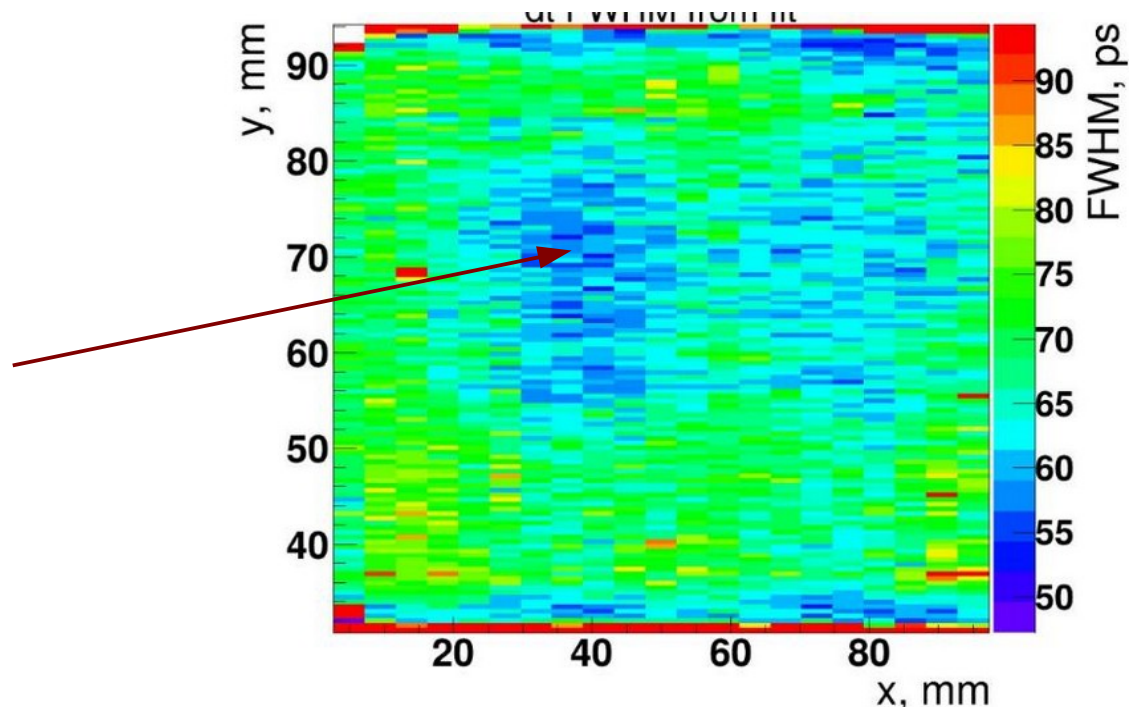
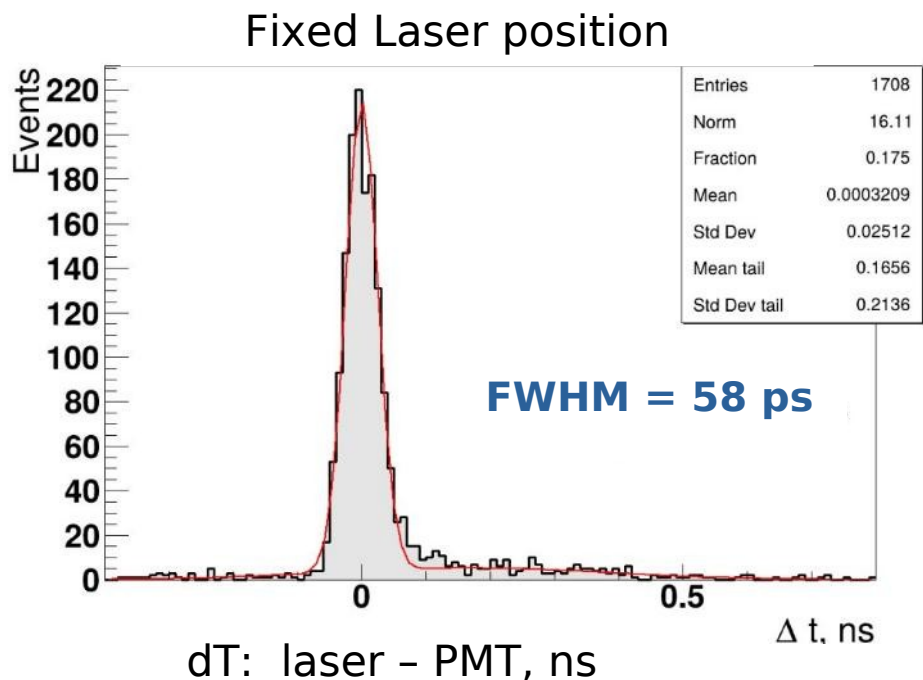
$$X_R = \frac{(t_R - t_L)s}{2}$$

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)

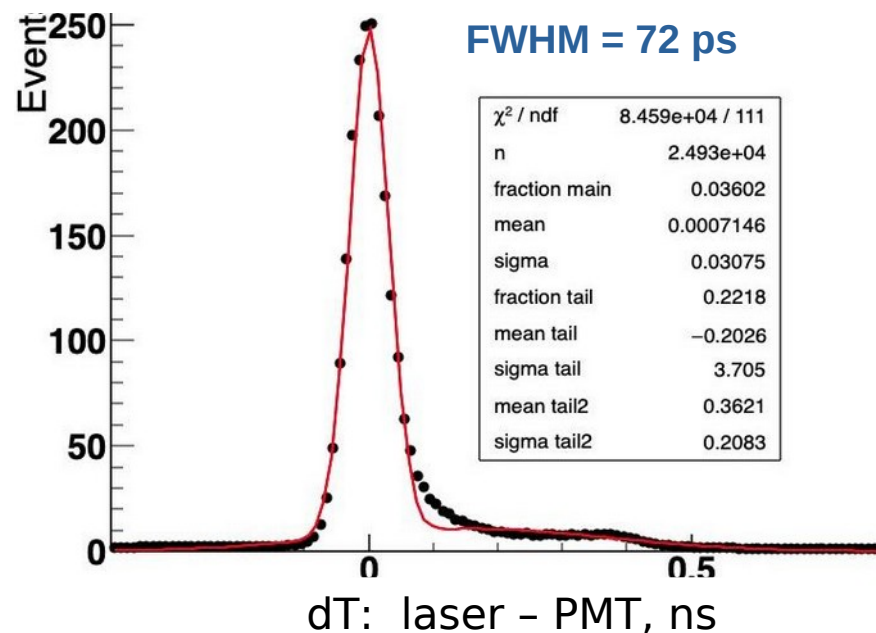
Measured Time Resolution



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

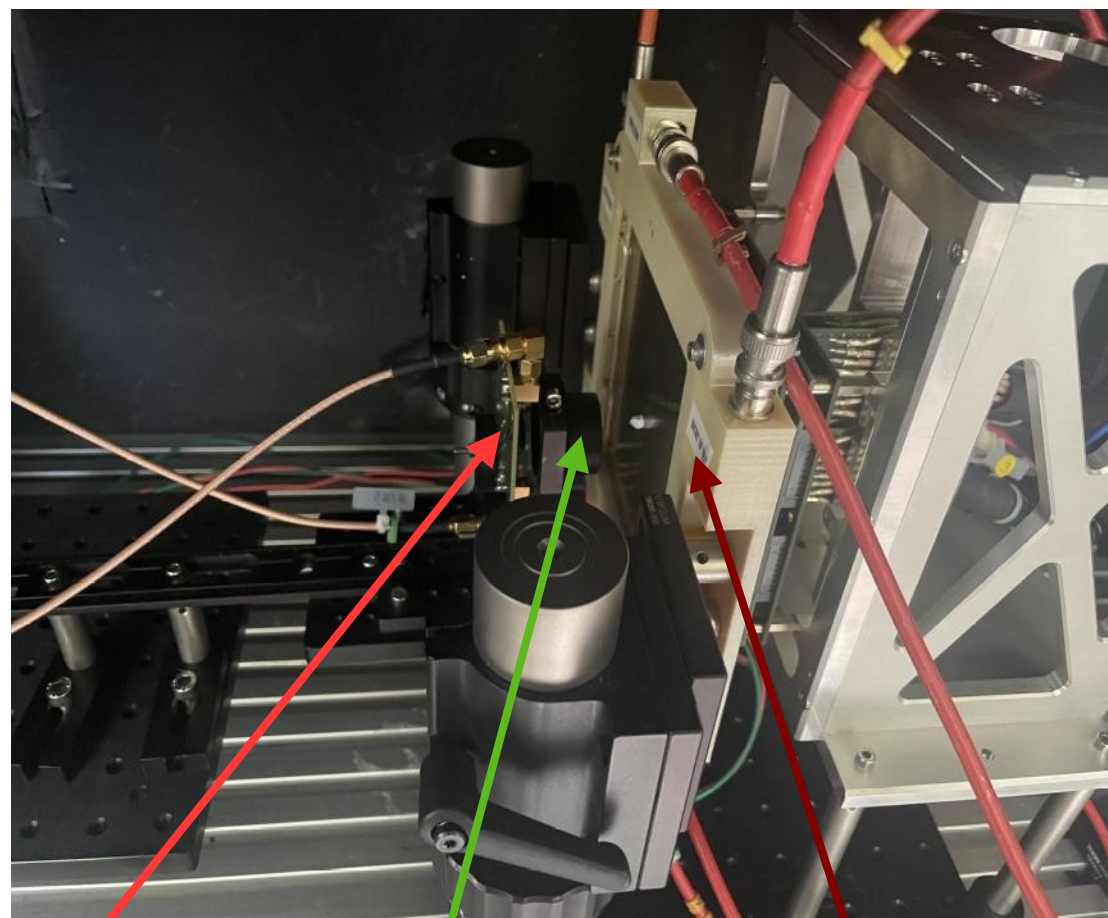
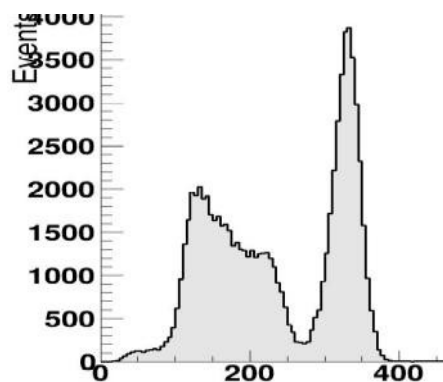
Depends on: amplitude cut, gain fluctuation, saturation

Non homogeneous time resolution → gain fluctuation



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

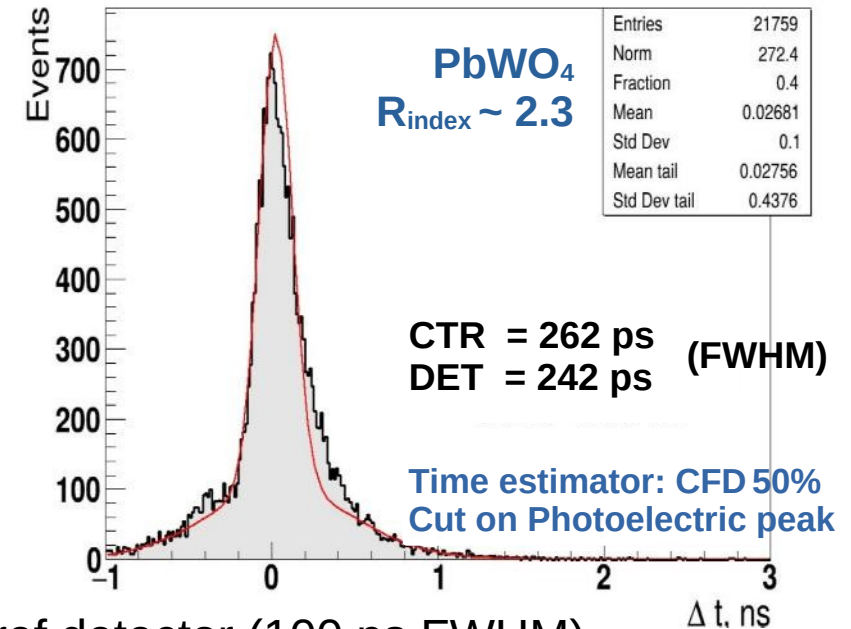
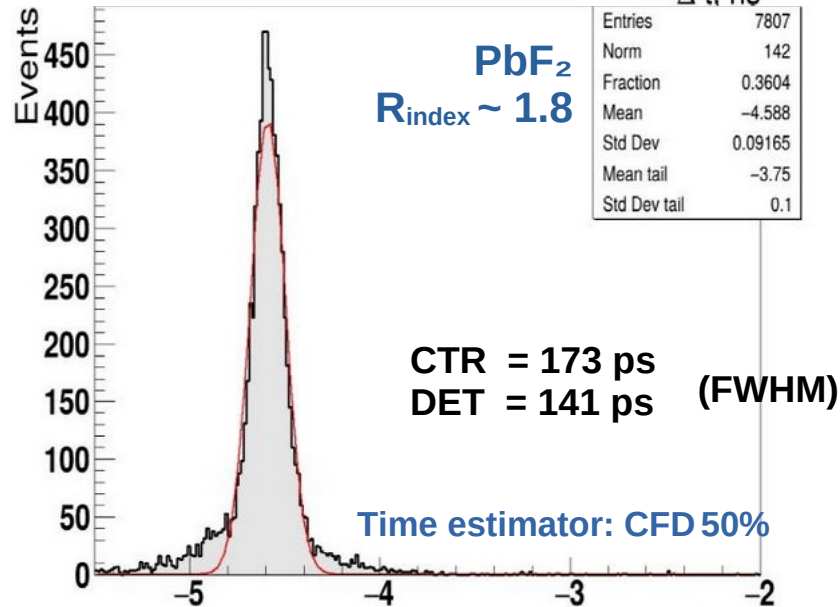
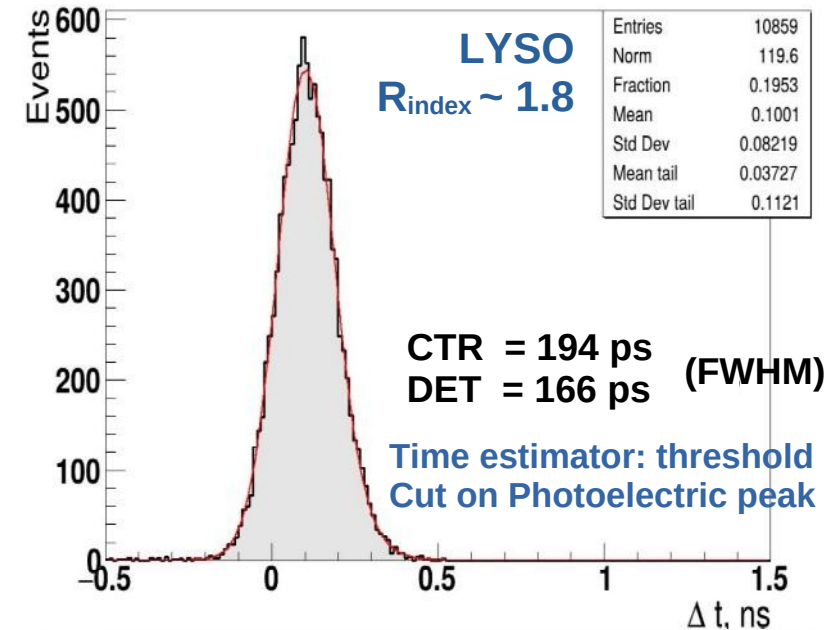
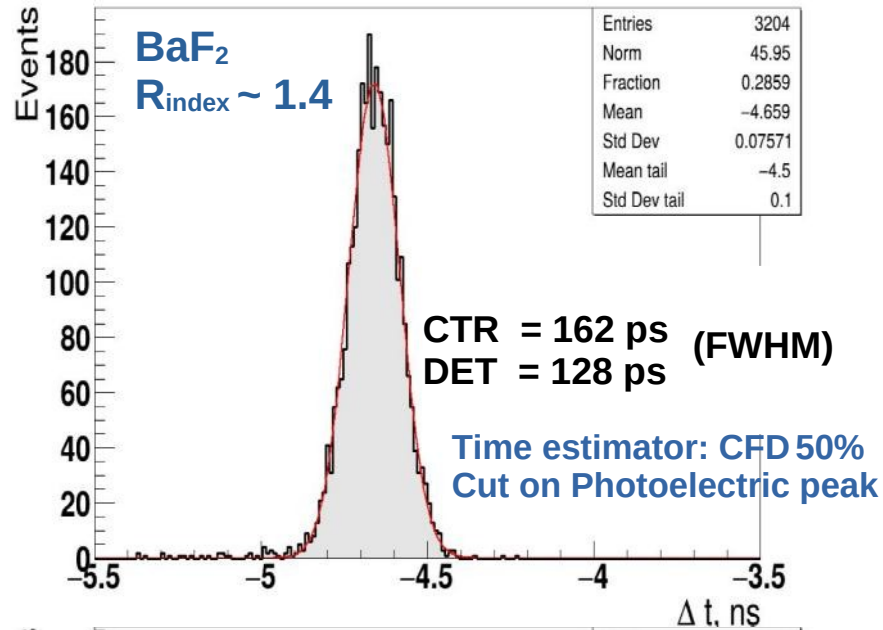
Source

3 - 4 cm

Crystal + optical
coupling + HRPPD

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

Measured Resolution With Crystals

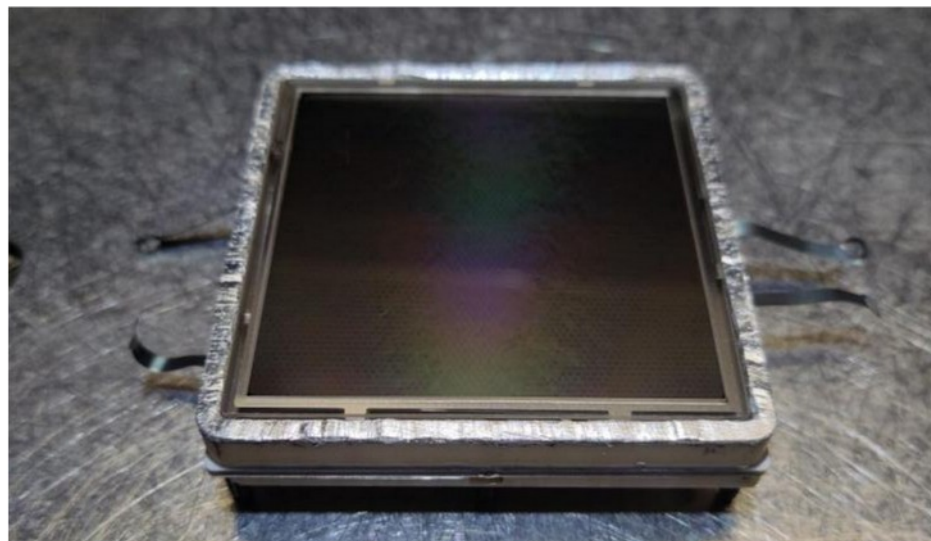


CTR : coincidence time resolution relative to ref detector (100 ps FWHM)

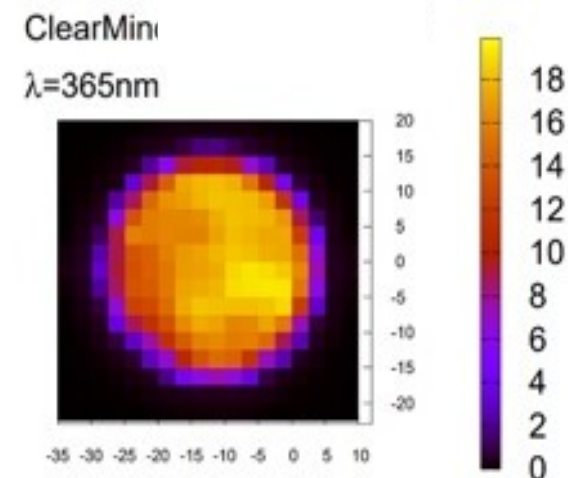
DET: detector resolution = $\sqrt{CTR^2 - (100 \text{ ps})^2}$

Photocathode Test at Incom

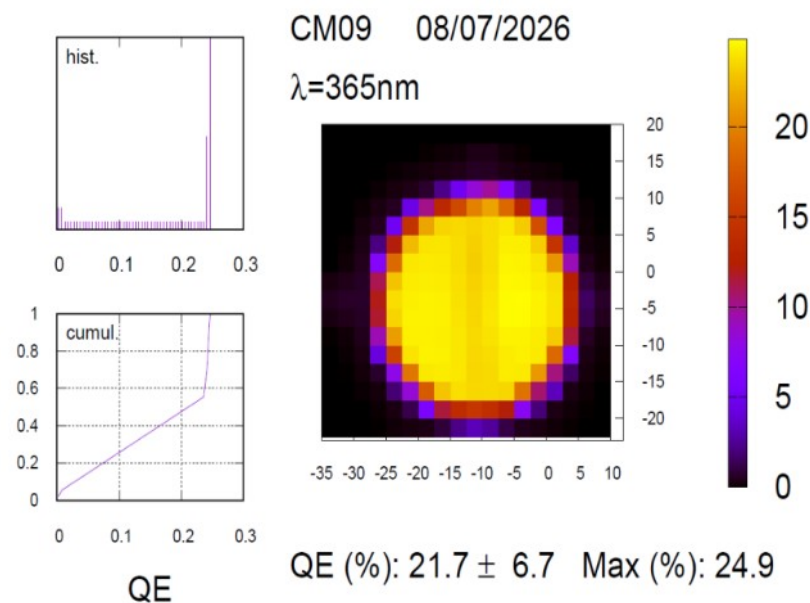
- Successful deposition of Bi-alkali photocathode:
 - Uniform coating
 - Stable over time
 - Efficiency: still non-optimal
- On-going work: Improve deposition process to enhance efficiency
- Wait for the prototype to test reconstruction procedure on real events



56 mm prototype assembling



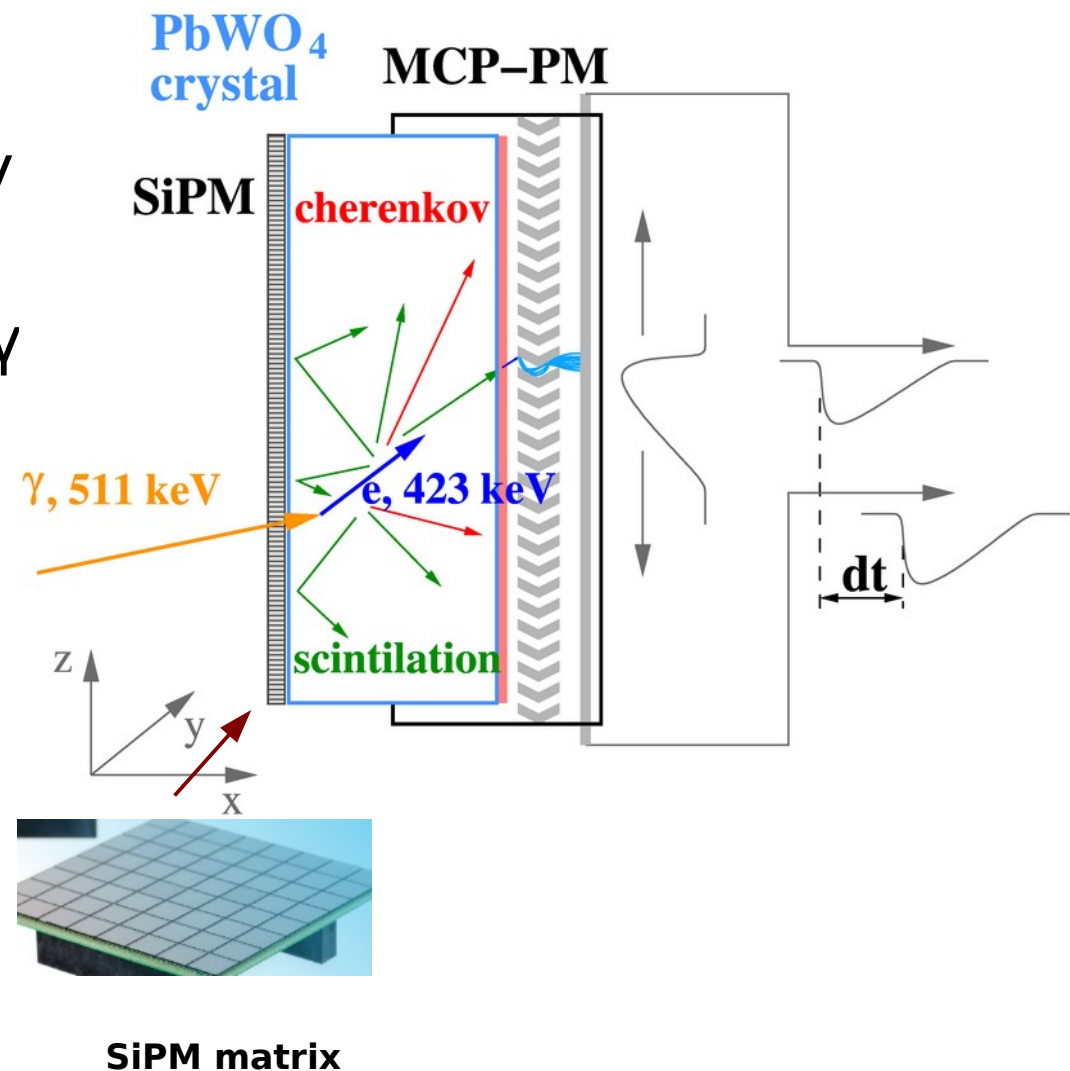
QE (%): 16.8 ± 1.9 Max (%): 19.9



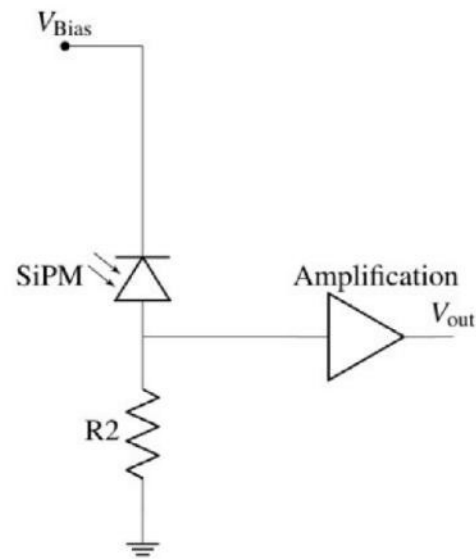
QE (%): 21.7 ± 6.7 Max (%): 24.9

Front Crystal Face: SiPM detection

- Goals:
 - Improve DOI and timing on γ interaction reconstruction
 - Minimize matter density on γ path
- Use thin SiPM matrix with
 - $\sim$ single photon detection
 - Large DCR, use in coincidence with MCP-PMT



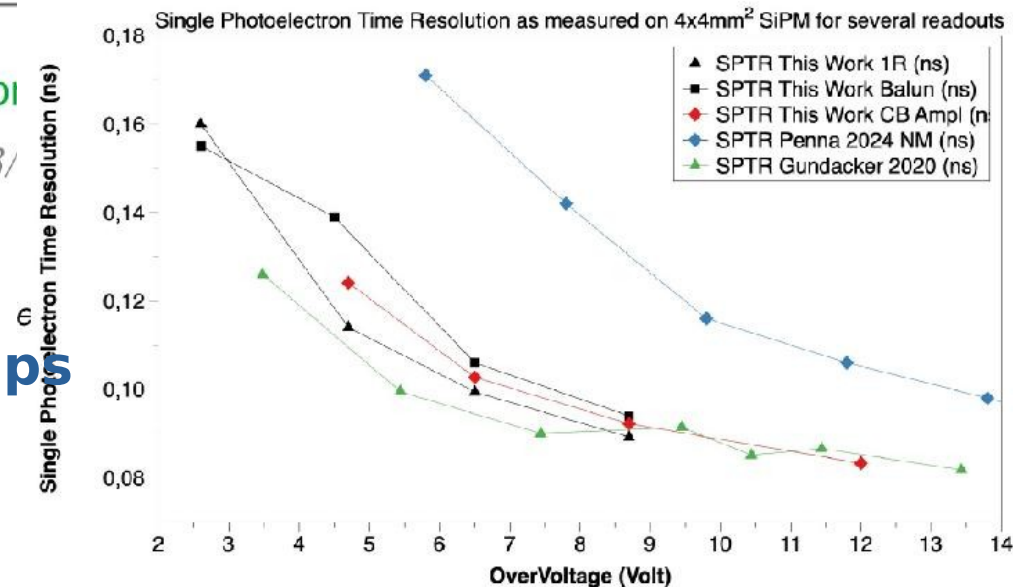
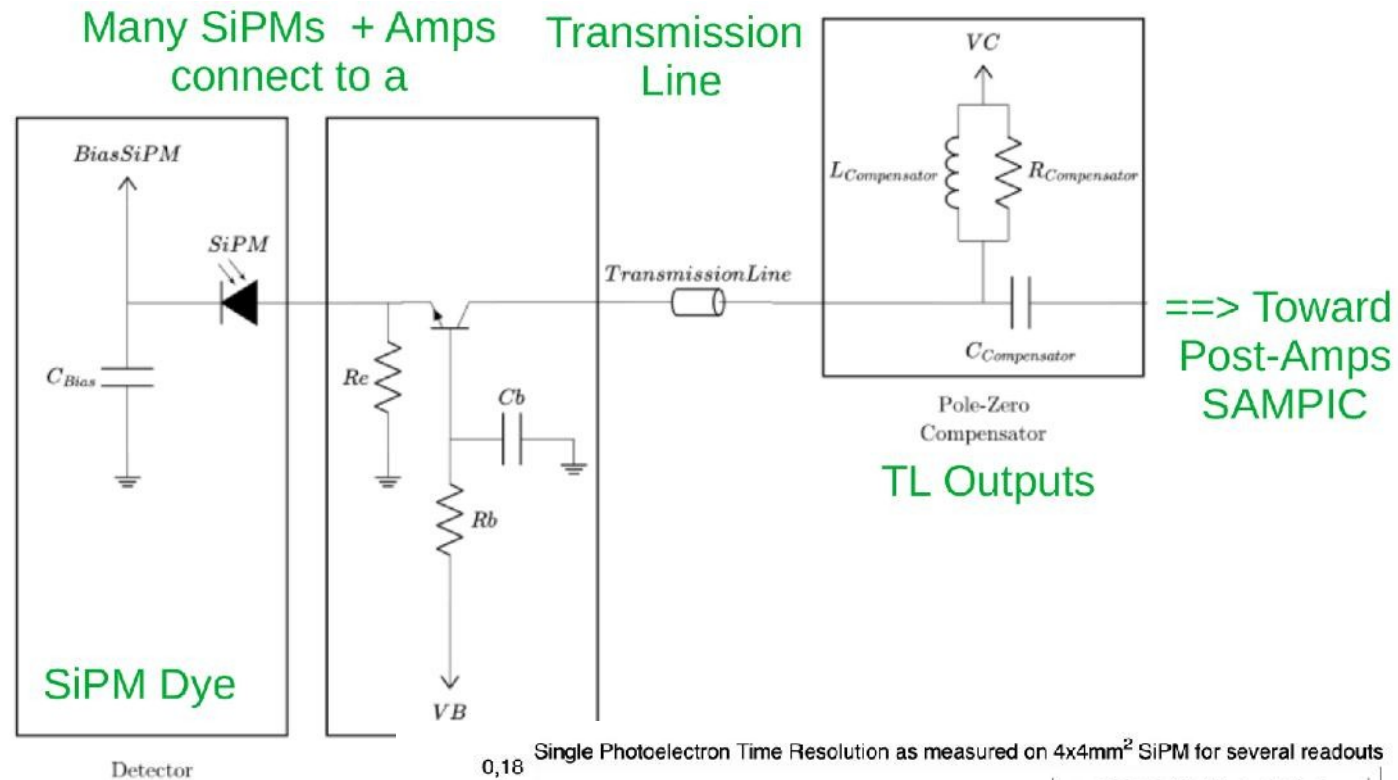
Single PE SiPM Matrix Read Out



Simplest “1R readout”
As a reference

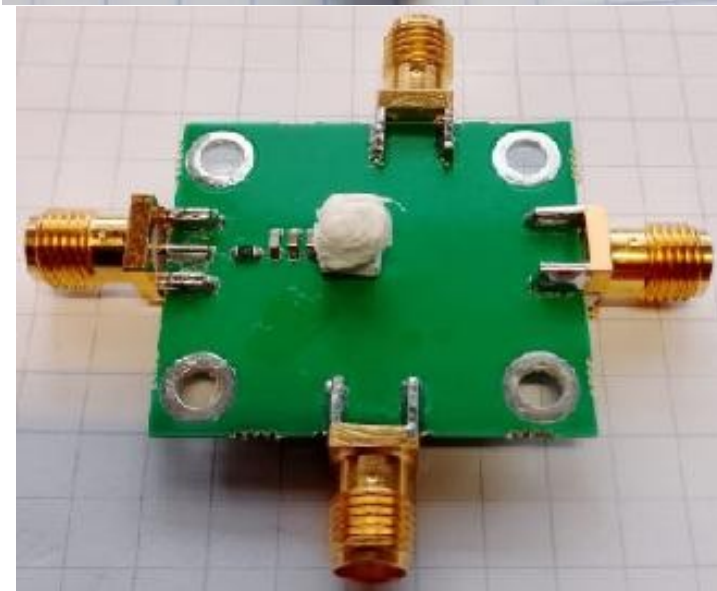
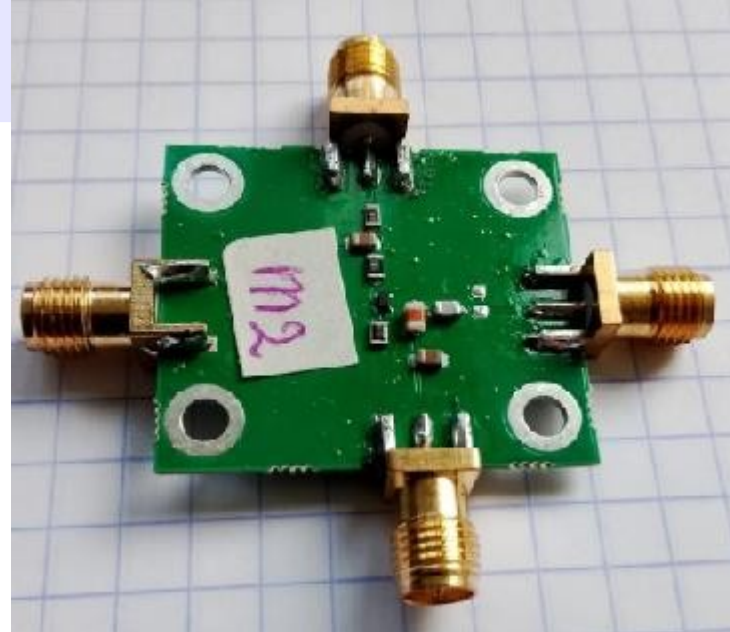
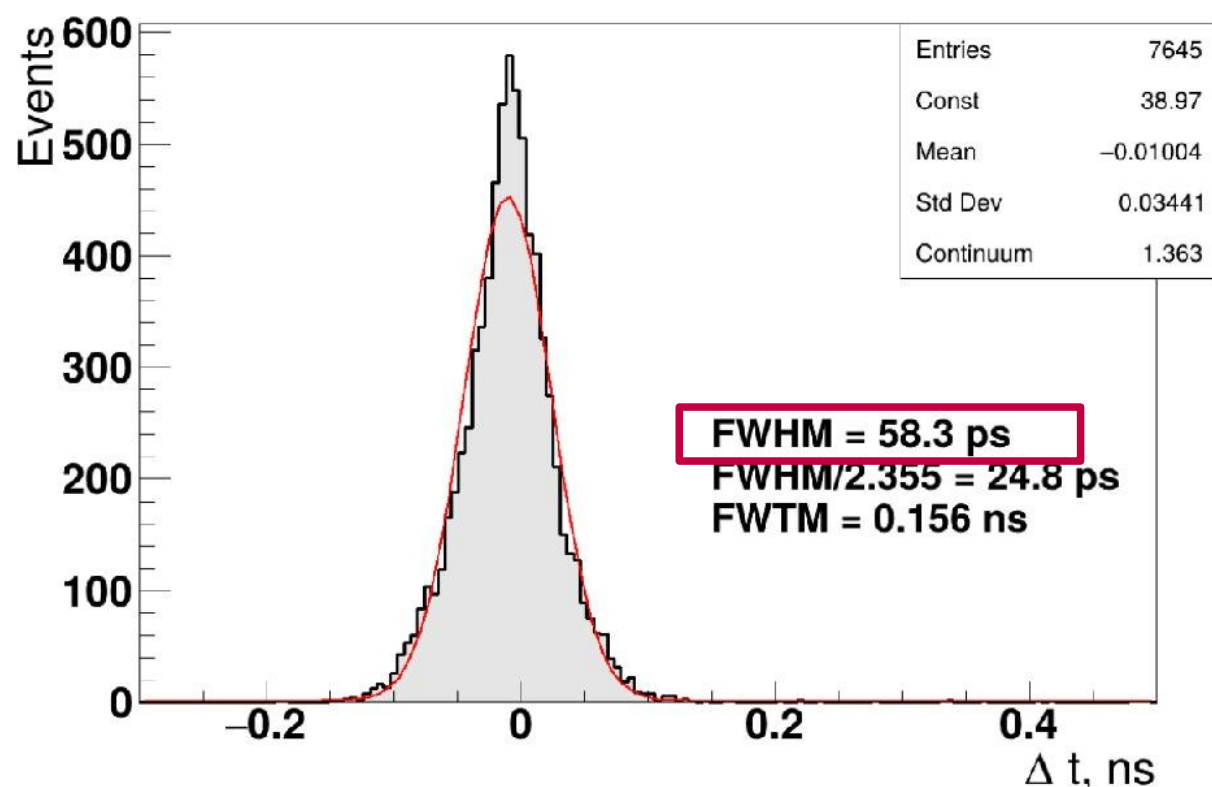
R. Belkacem et al., CEA Saclay, Patent Filed, FR2516403, 23/

Best achieved SPTR : 85 ps (FWHM)



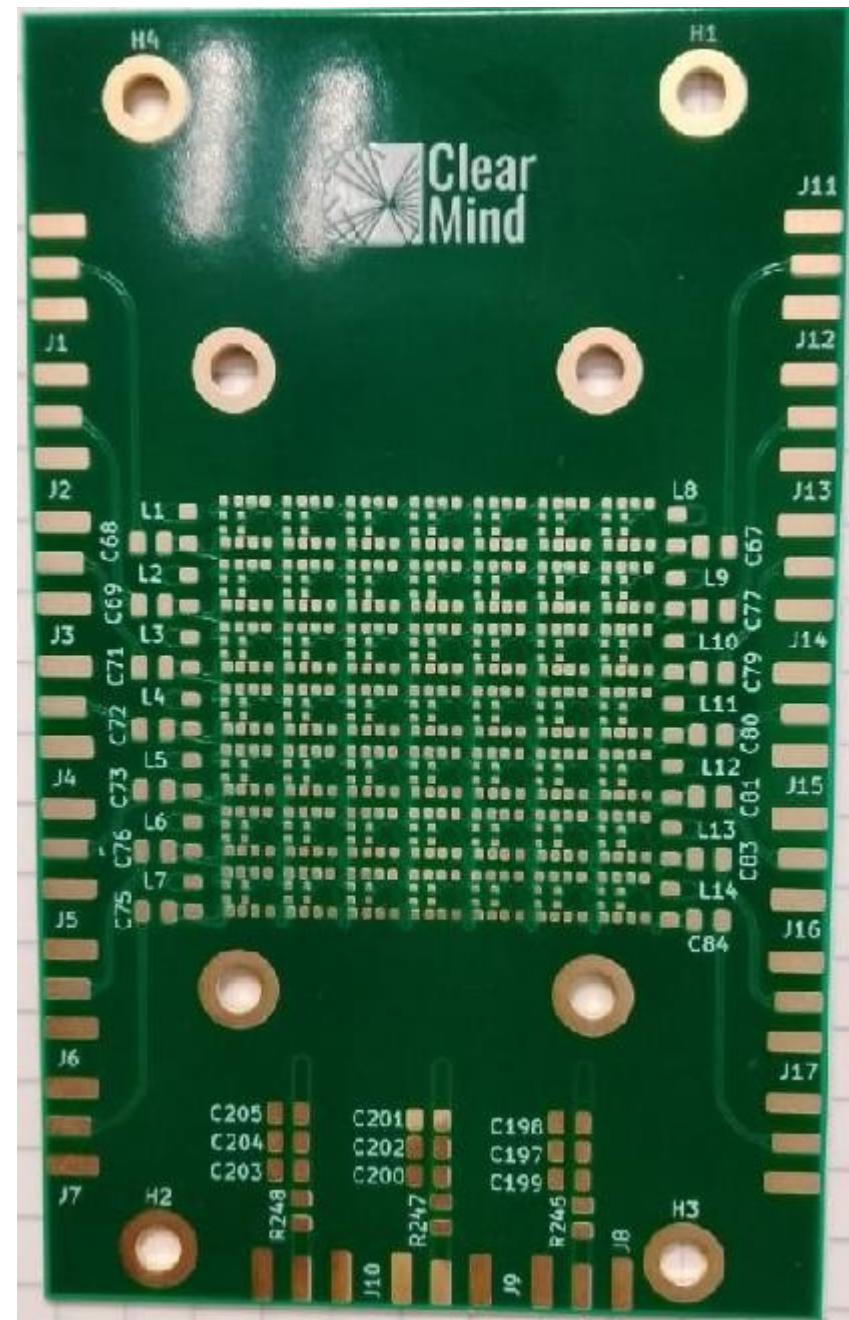
Gamma Spectrometer

- 3x3x3 mm³ LYSO:Ca:Ce (Luxium France)
- White Teflon Coating
- Broadcom SiPM-NUV-MT, 4x4 mm², 40 μ m
- Common Base preamplifier (this work).
- SAMPIC WaveShape Recorder



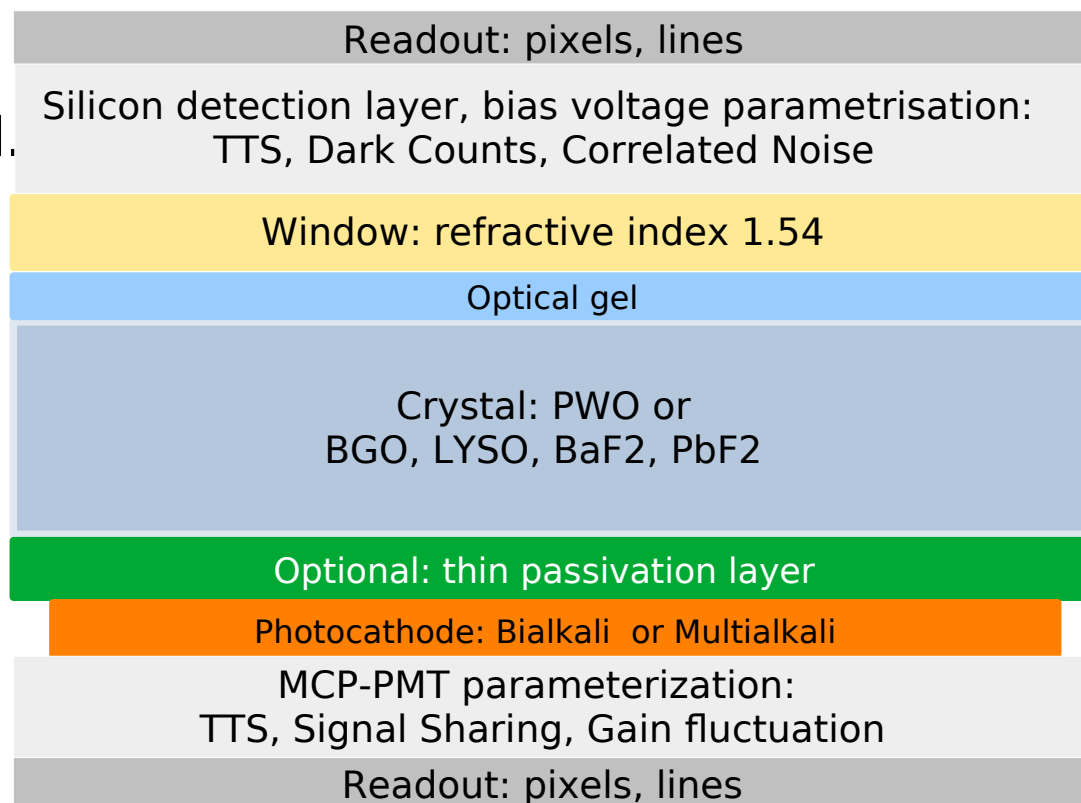
Toward SiPM matrix readout

- RF Readout for large SiPM dyes
 - Low power dissipation (10 mW/dye)
 - Small footprint (10 mm²)
 - High Output impedance → Transmission lines
- Best SPE timing
 - 85 ps (FWHM) on 16 mm² SiPM dyes.
- Best single pixel LYSO g Spec. Timing
 - 58 ps (FWHM) @ 511 keV (Preliminary)
- Designed for SiPM RF Matrix multiplexing
- Now proceed to 7 x 7 SiPMs RF matrix readout



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.



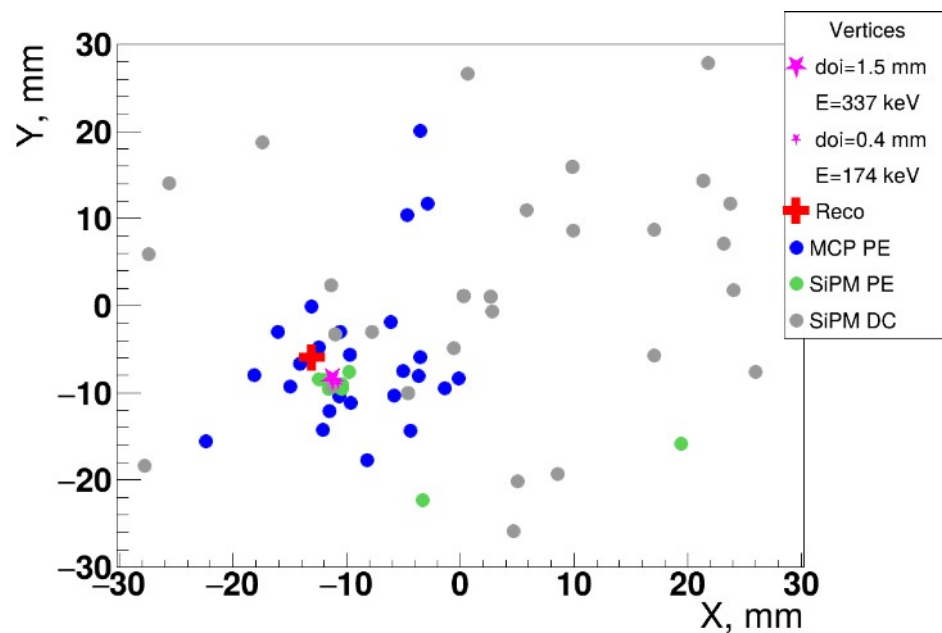
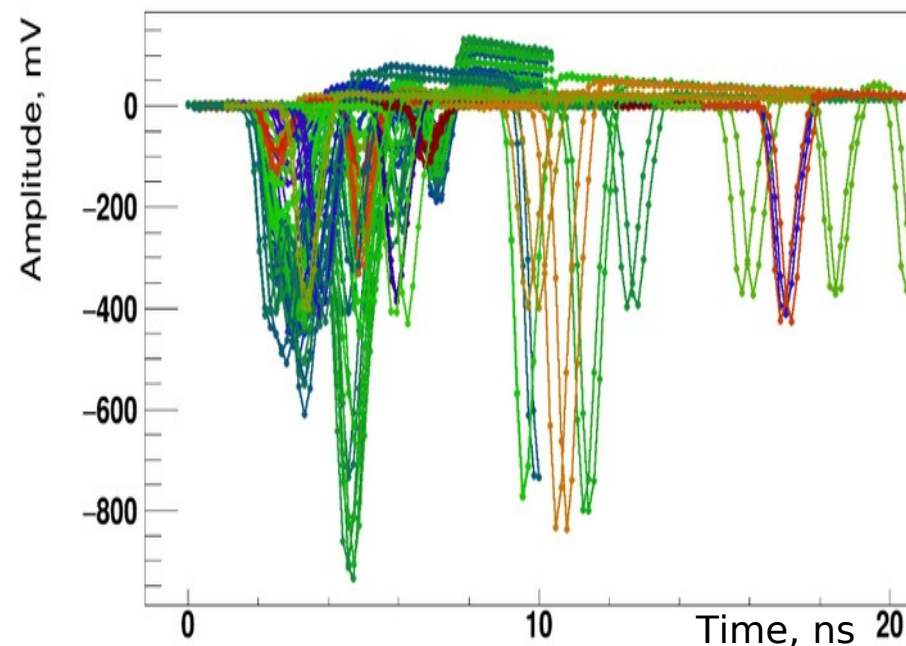
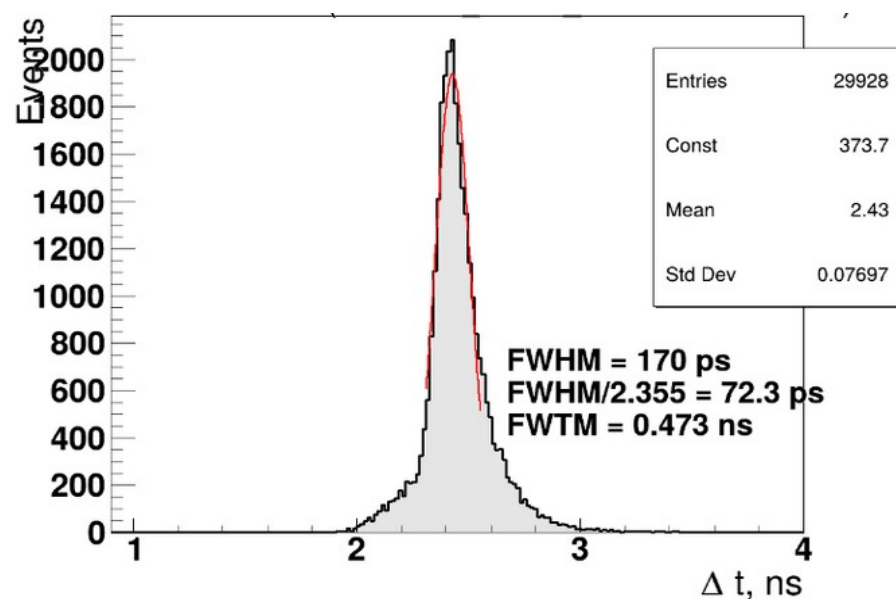
Zoé Zobundzija: NDIP poster P3-16

[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



AI Reconstruction: AAIMME Project

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)

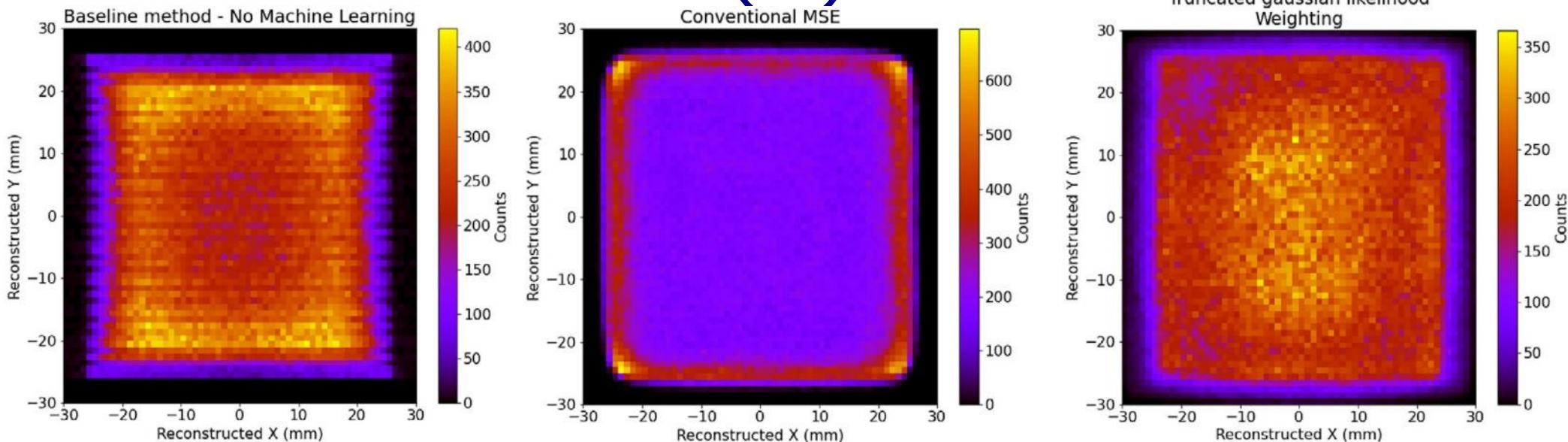
- Along lines ~2.6 mm

- Across lines ~1.9 mm

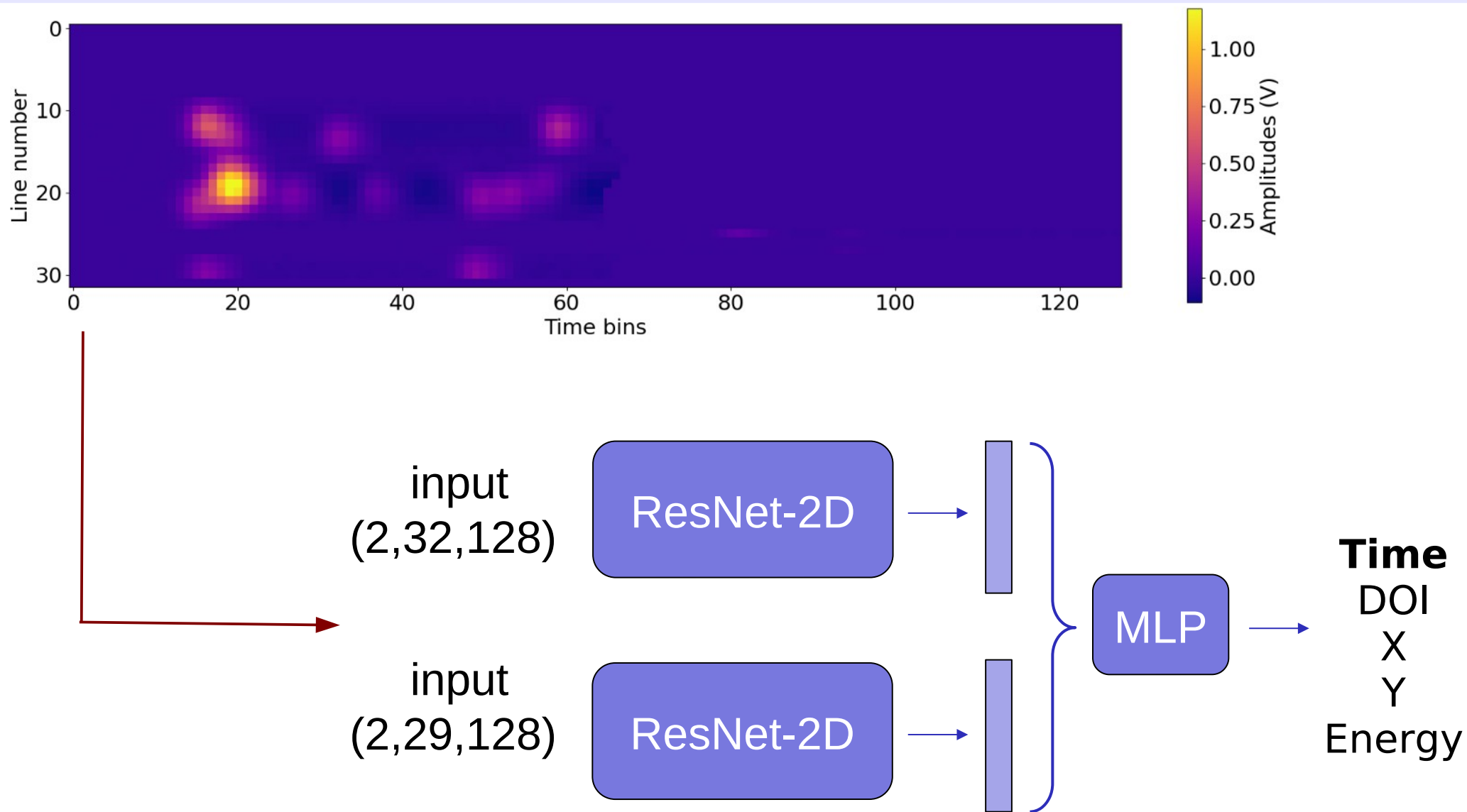
$$l(\theta) = -\log(L(\theta))$$

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

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

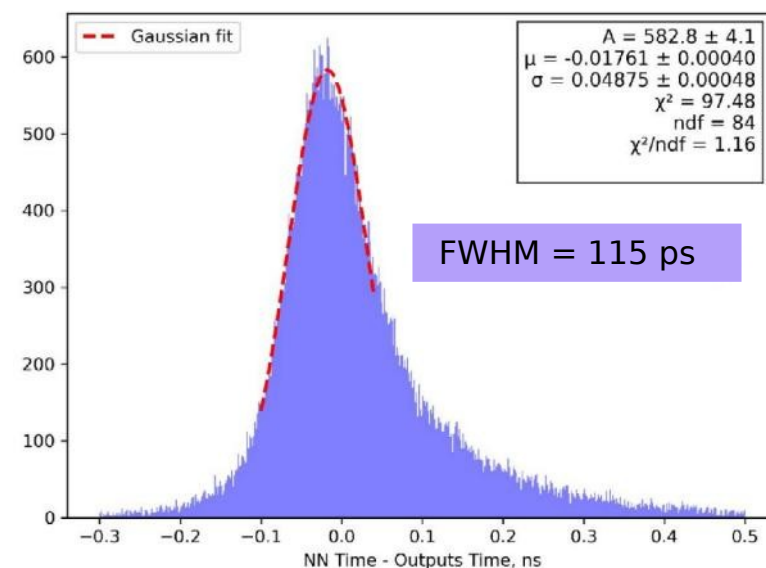
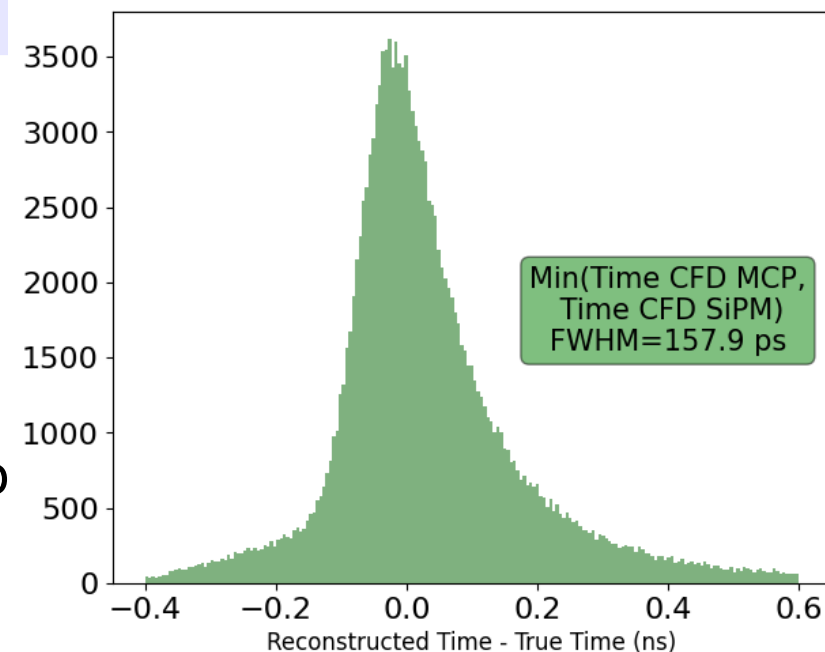


Time Reconstruction: NN architecture

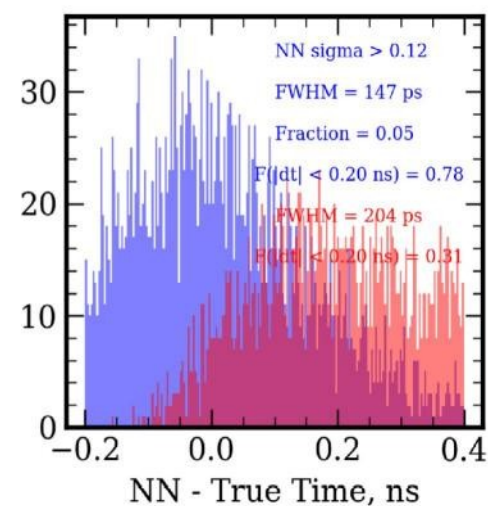
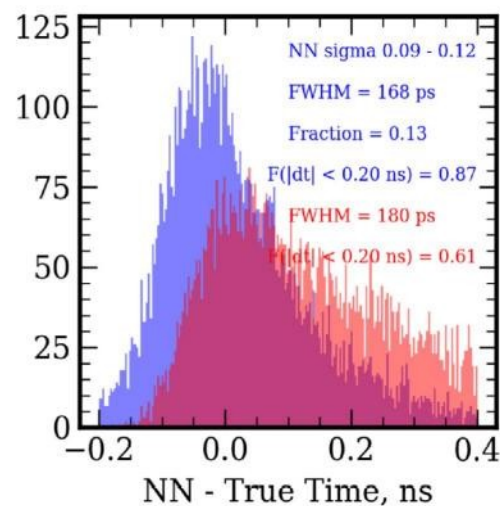
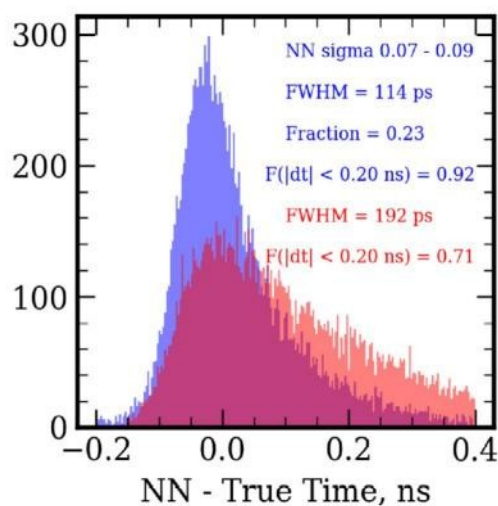
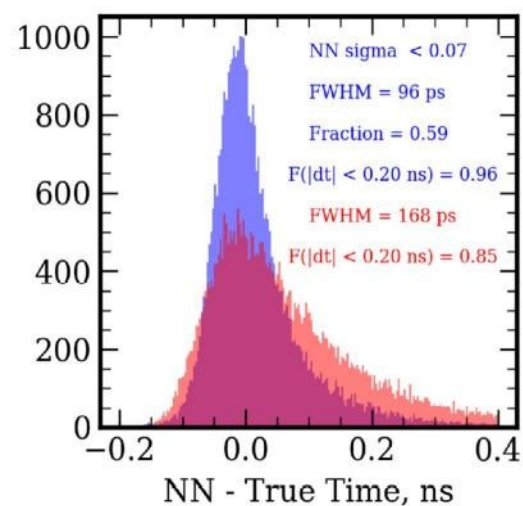
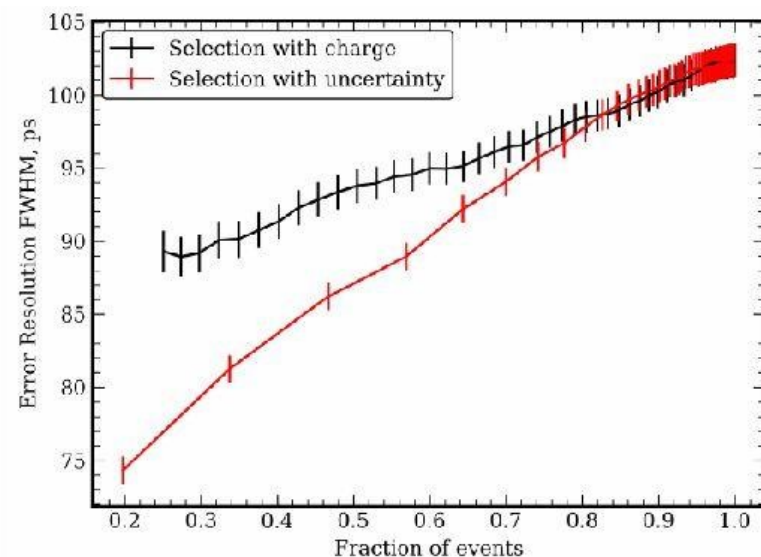
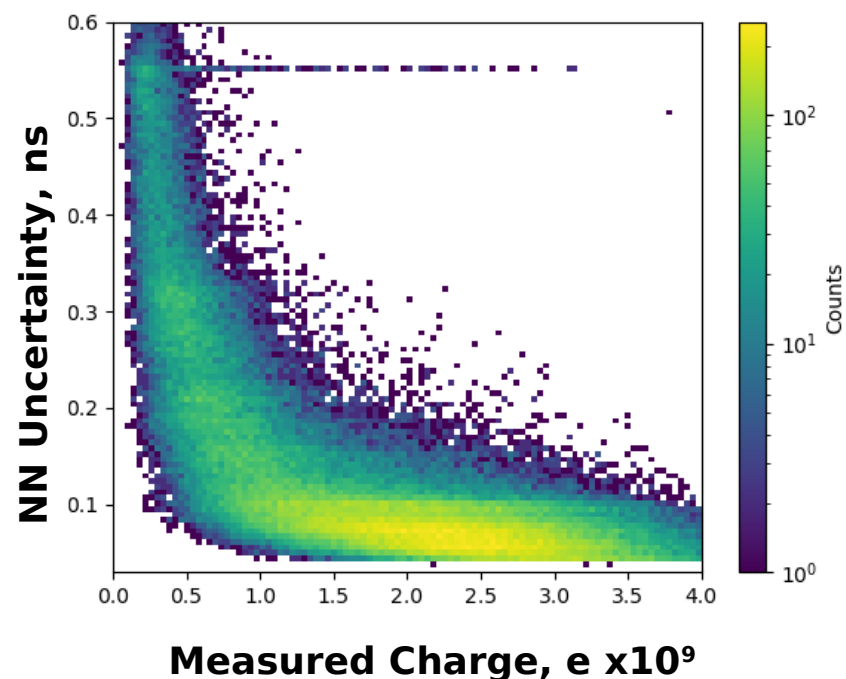


Time Reconstruction

- 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



Conclusion

- Working on the optimizing Cherenkov detection in the crystal: experimental development of the **photocathode deposition** directly on crystal, MCP multiplication, transition line readout
- **SiPM** matrix detection of the **single-photon** signals with an excellent time resolution and transition line readout
- Development of the **AI** vertex reconstruction in crystal with **uncertainty estimation**
 - Develop new methodology to account for this uncertainty in the tomographic reconstruction
- Working also on the development of the new crystal to enhance TOF performance on TEP

Collaborators

1 CEA-IRFU

- Experimental development, detector simulation, test bench measurements.

2 UMR BioMaps

- *Biomadical Imaging, scanner-level simulation, IA methods for TEP reconstruction*

3 CEA-DM2S

- *Machine Learning, uncertainty reconstruction*

4 CNRS-IJCLab

- *Fast analogical and digital electronics*

5 CNRS-CPPM imXgam

- *Gamma imaging technique, tomographic test bench tomXgam, MC simulation*

6 INRIA Saclay – IdF/OPIS

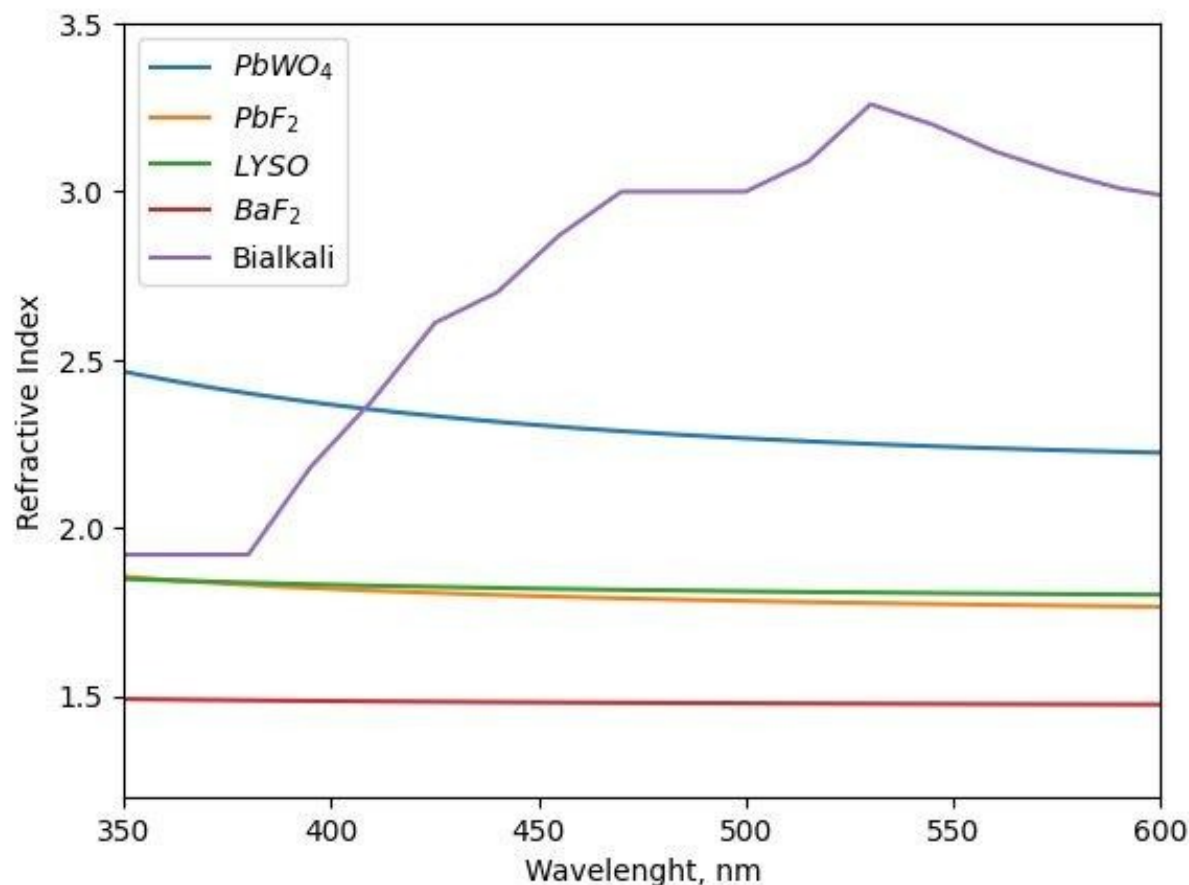
- *Stable and explicable reconstruction methods*

7 Estonian, Czech, German laboratories

- *Crystal growth*

Back-up

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

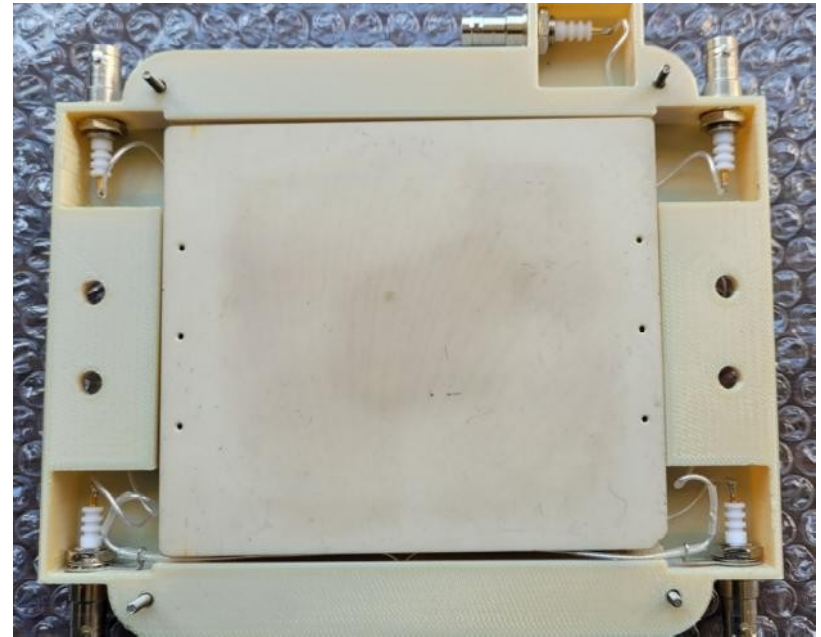
PbWO₄ : S. Baccaro et al., NIMA, Vol. 385 (1997), pp. 209–214

Read-out PCB

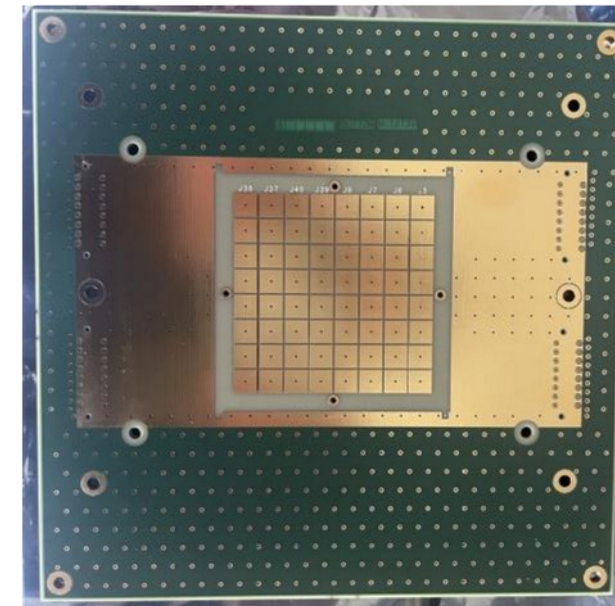
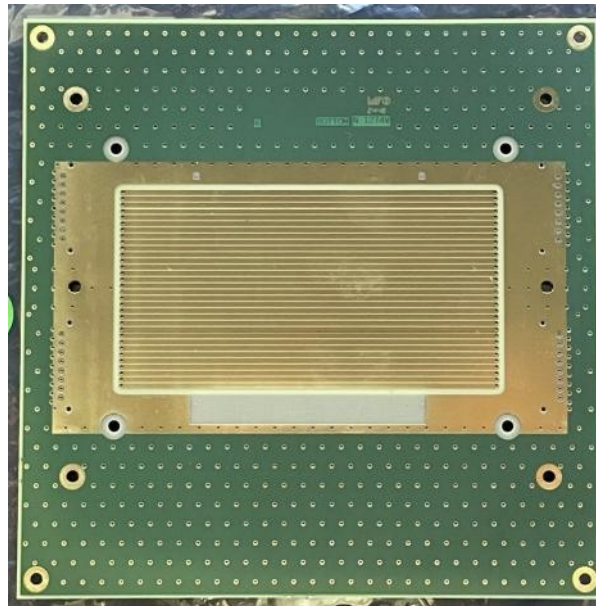
Resistive Anode $50\text{k}\Omega/\square$

Ceramics 2 mm

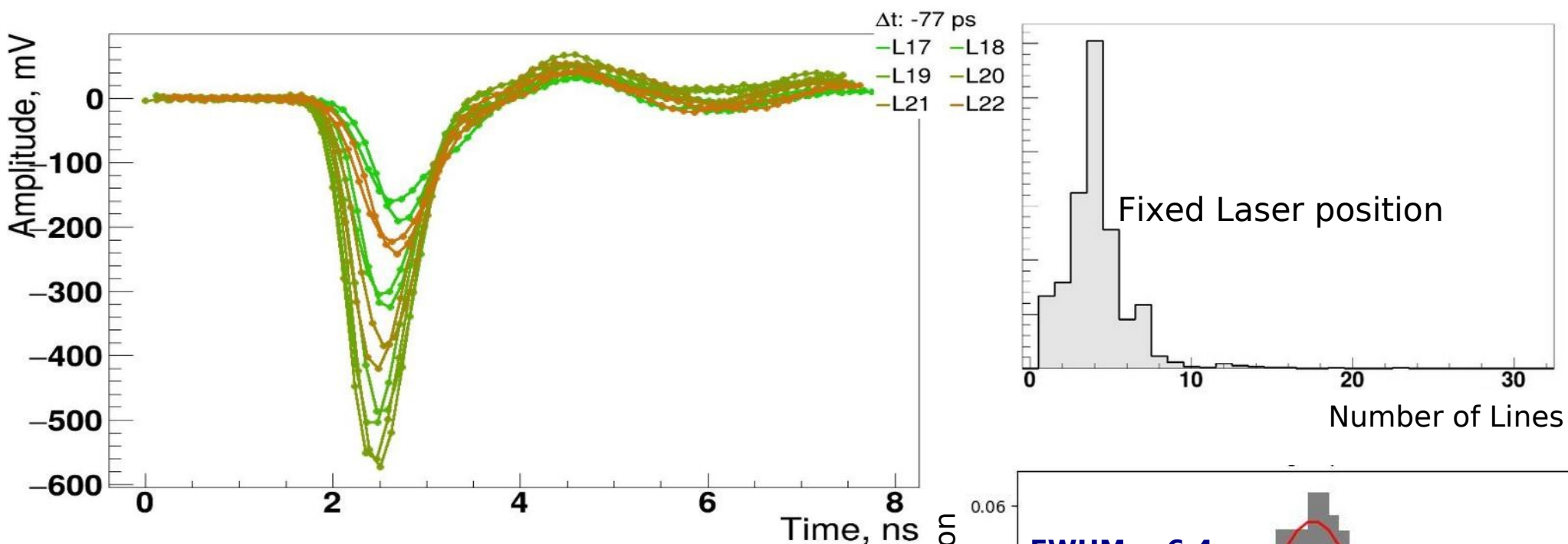
PCB



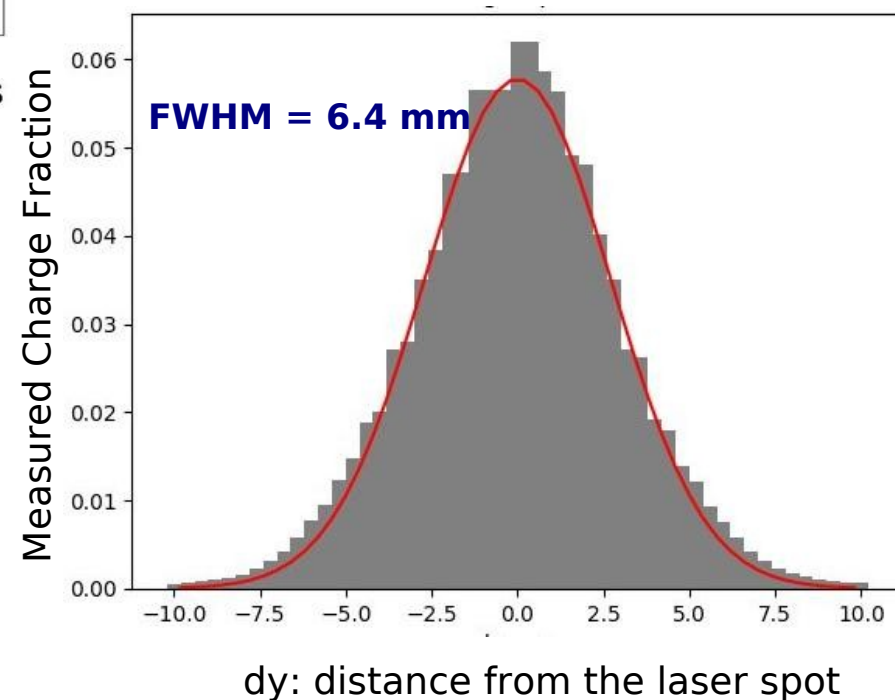
- Previous ClearMind Prototype (Photek): Direct Read-Out
- HRPPD: Capacitive Read-Out
- Test PCBs
 - Transmission Lines: 100 mm x 1.5 mm
 - Pixels: 6 mm x 6 mm
- 64 channels:
 - 32 lines left & right
 - 64 pixels
 - Central part covered



Single Photoelectron Detection

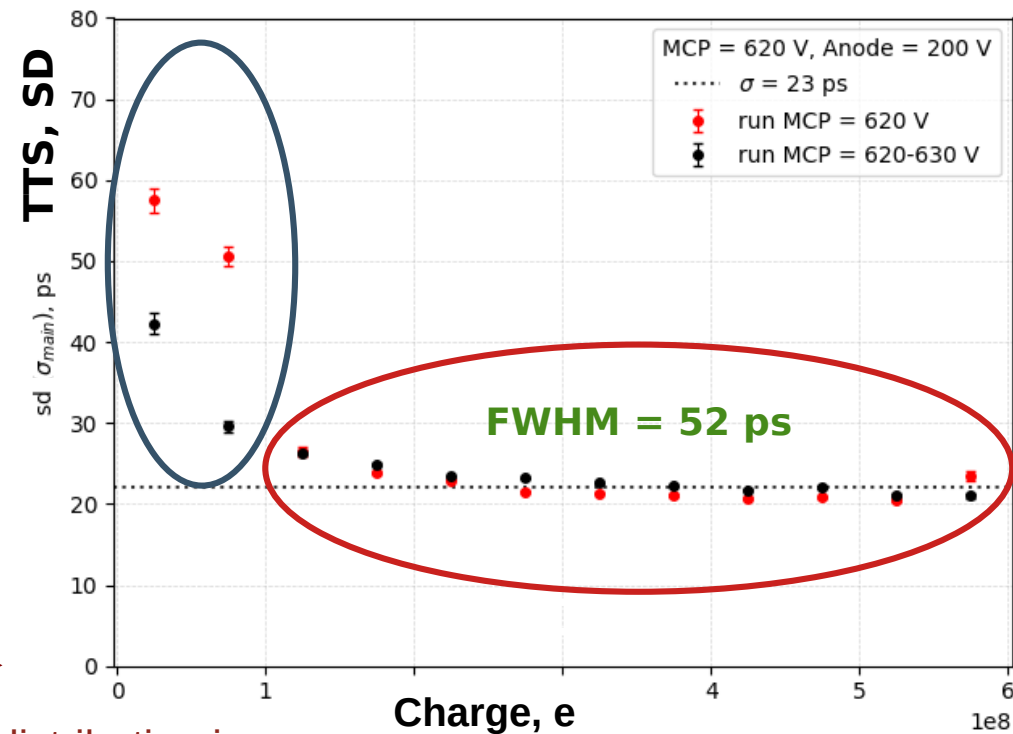
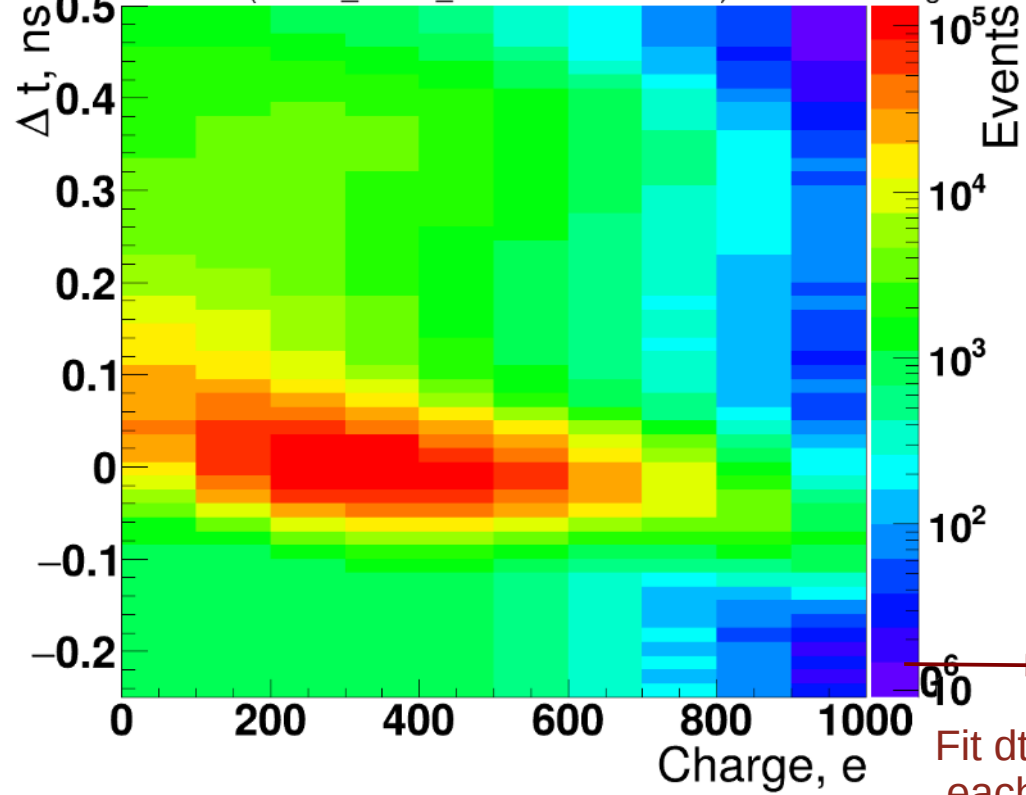


- Mean numbers of activated lines per events: 5 (direct read-out: 3)
- Charge spread: signal induction + capacitive coupling



Time Resolution vs Signal Amplitude

Difference in Time (FIRST_PEAK_CFD - THRESHOLD) vs PMT1 Charge

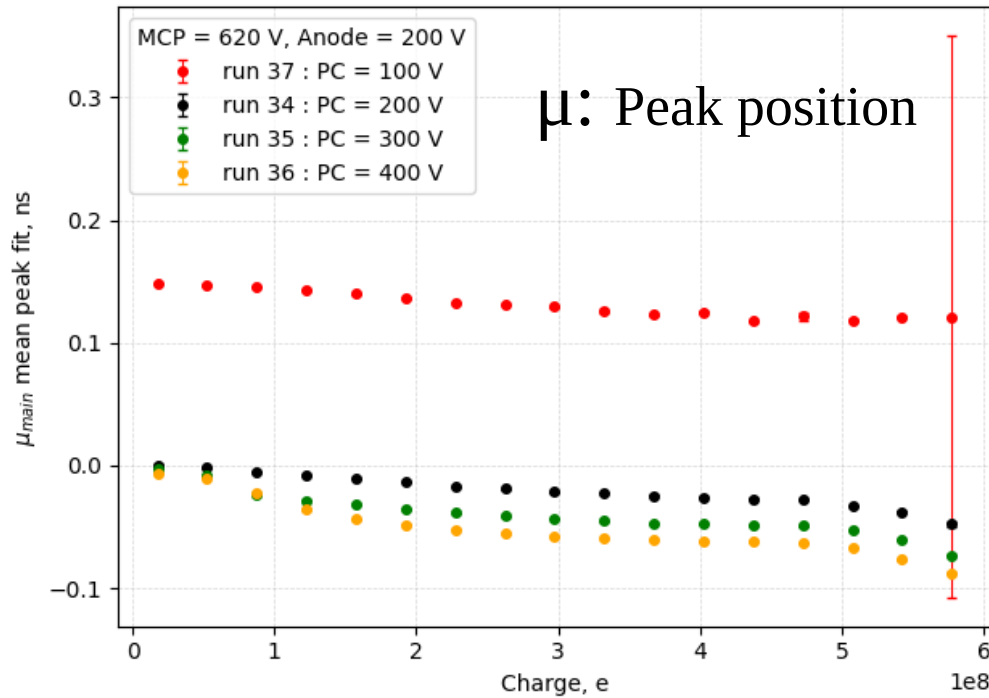


- Difference in temporal resolution observed with different voltages on MCPs related to low-amplitude signals
- Observation of a plateau beginning at a certain amplitude: weak dependency of the MCPs voltage

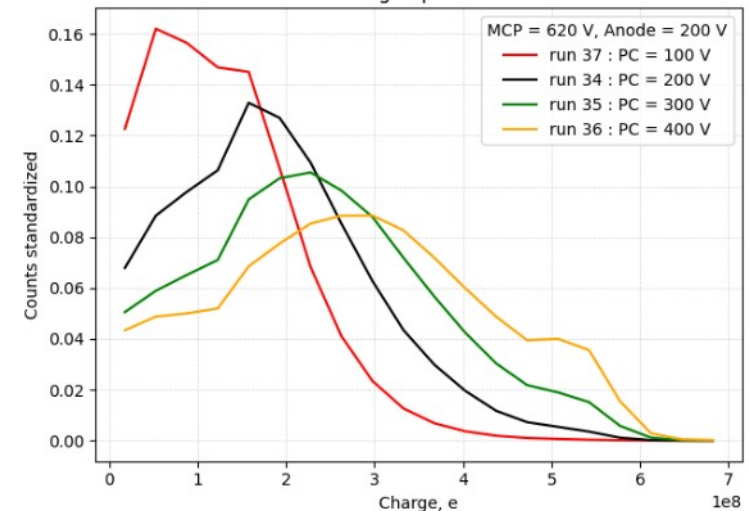
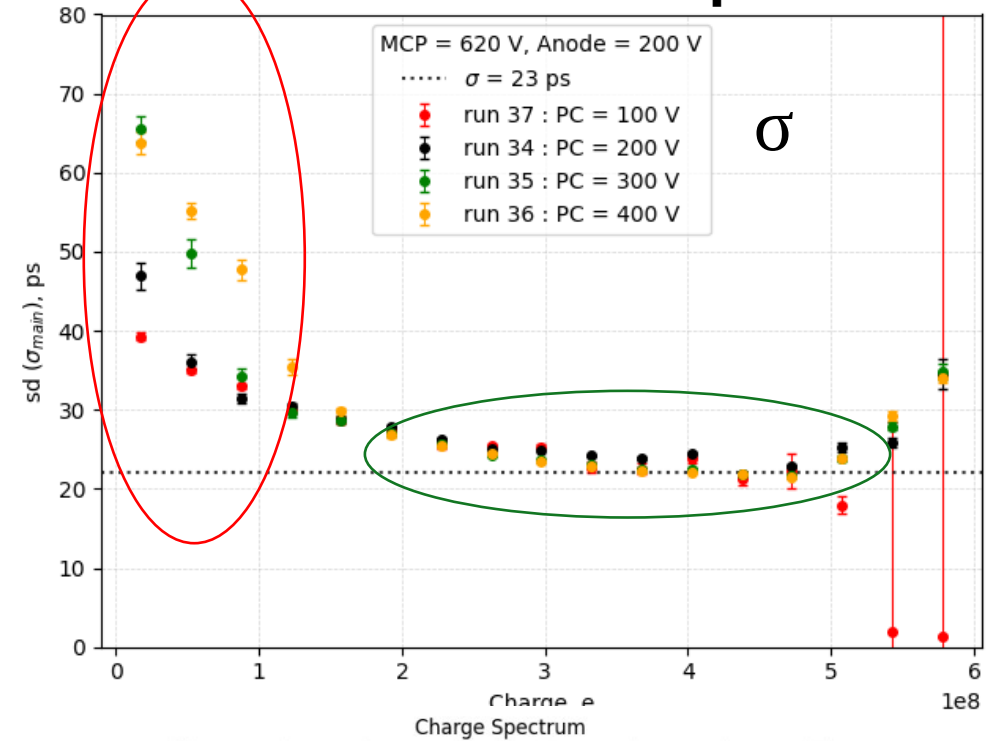
⇒ Time resolution depend on pulse amplitude selection

Time resolution vs Charge vs Photocathode Voltage

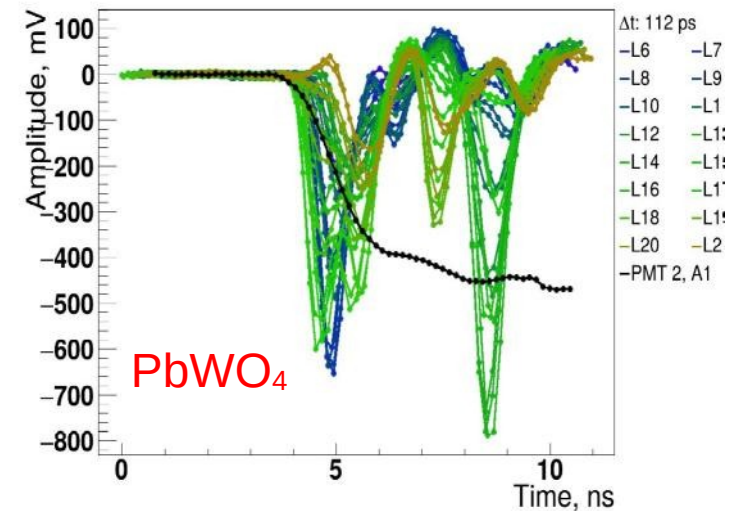
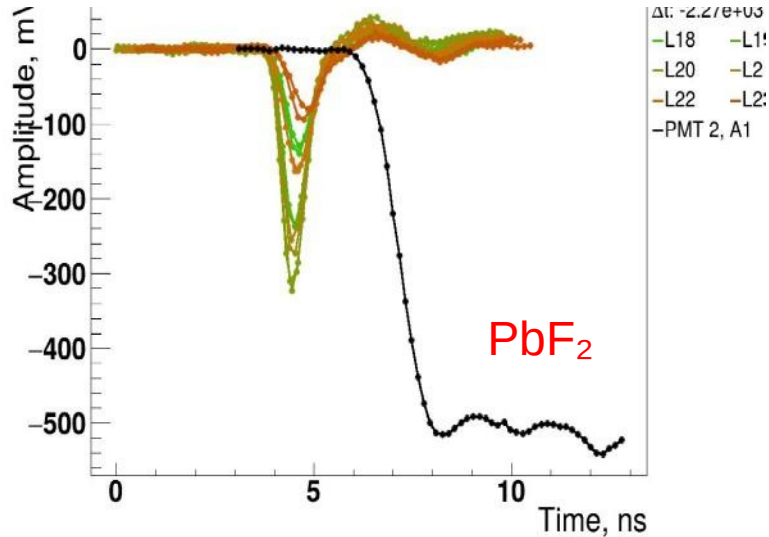
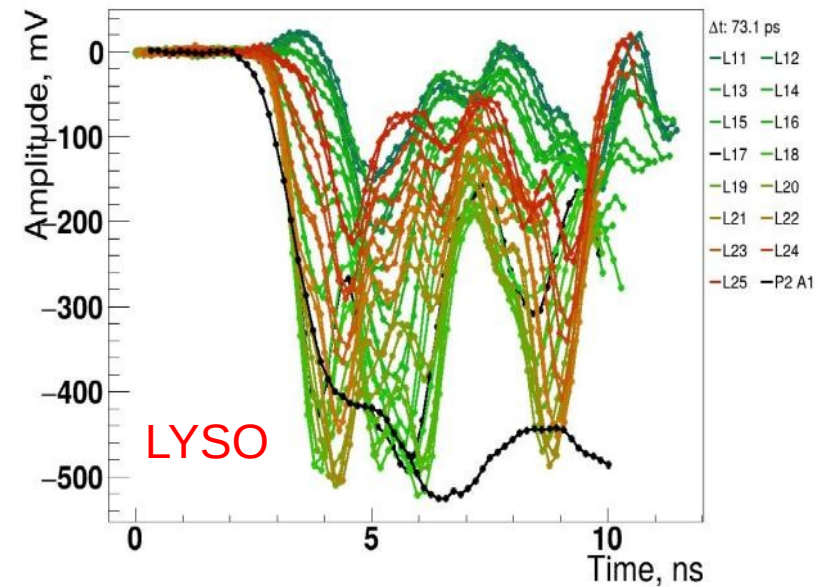
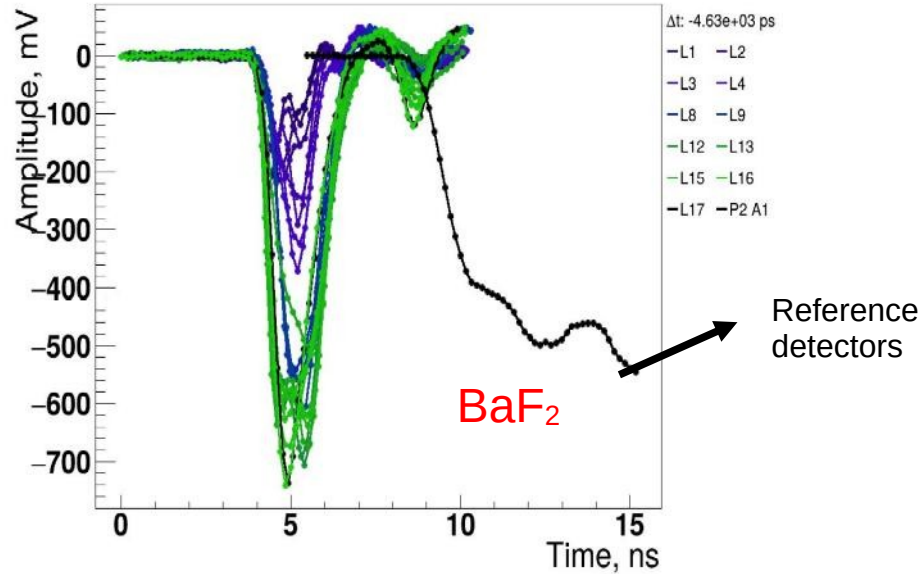
Transit-Time



Transit-Time Spread



Signals with crystals with Transmission Lines



Gain estimation :

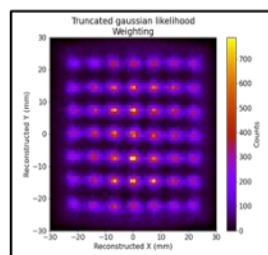
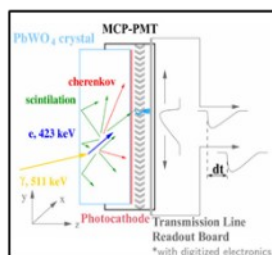
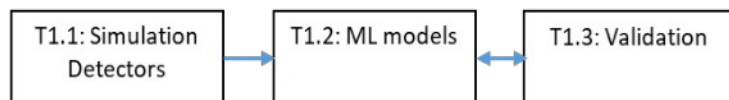
$$1 \times 10^5 (\text{LYSO}) < 3 \times 10^5 (\text{BaF}_2) < 6 \times 10^5 (\text{PbWO}_4) < 10^6 (\text{PbF}_2)$$

AIMME Project

WP0: Coordination and dissemination

→ Input → Output
 ↔ Input and feedback

WP1: Detector's signal processing



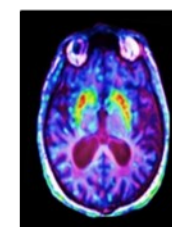
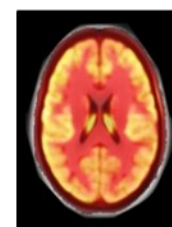
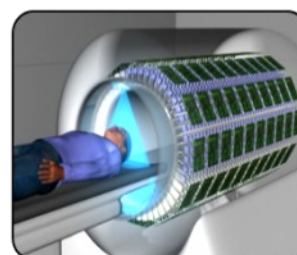
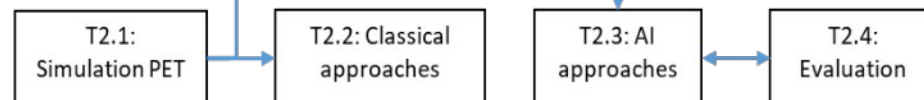
Inputs:

- Detector's specifications
- Simulation model

Outputs:

- ML model for interaction reconstruction

WP2: Image reconstruction



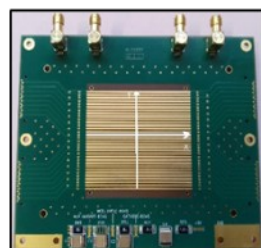
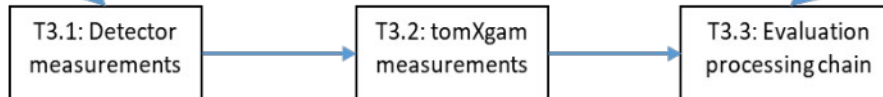
Inputs:

- 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

AAIMME 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*

