LDRD @ Jefferson Lab

PICOSEC Micromegas

CPAD 2024

µRWELL-PICOSEC: Fast timing detector with µRWELL gaseous amplification technology

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on behalf PICOSEC collaboration

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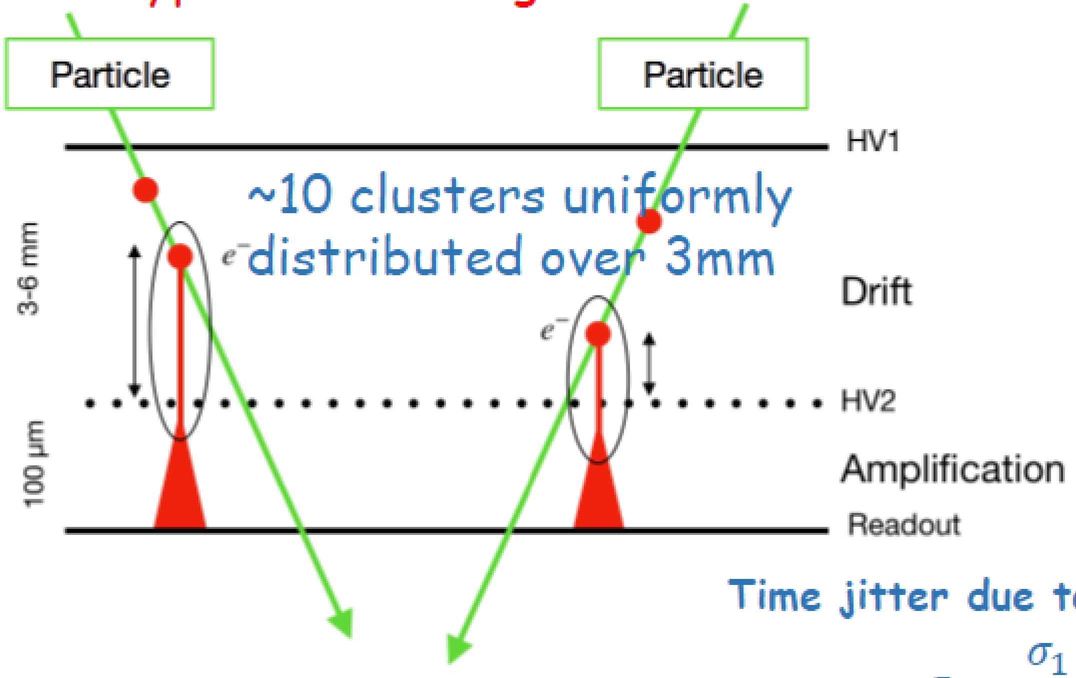
Coordinating Panel for Advanced Detector Workshop (CPAD2024) – Nov. 18 - 22, 2024 University of Tennessee, Knoxville

Outline

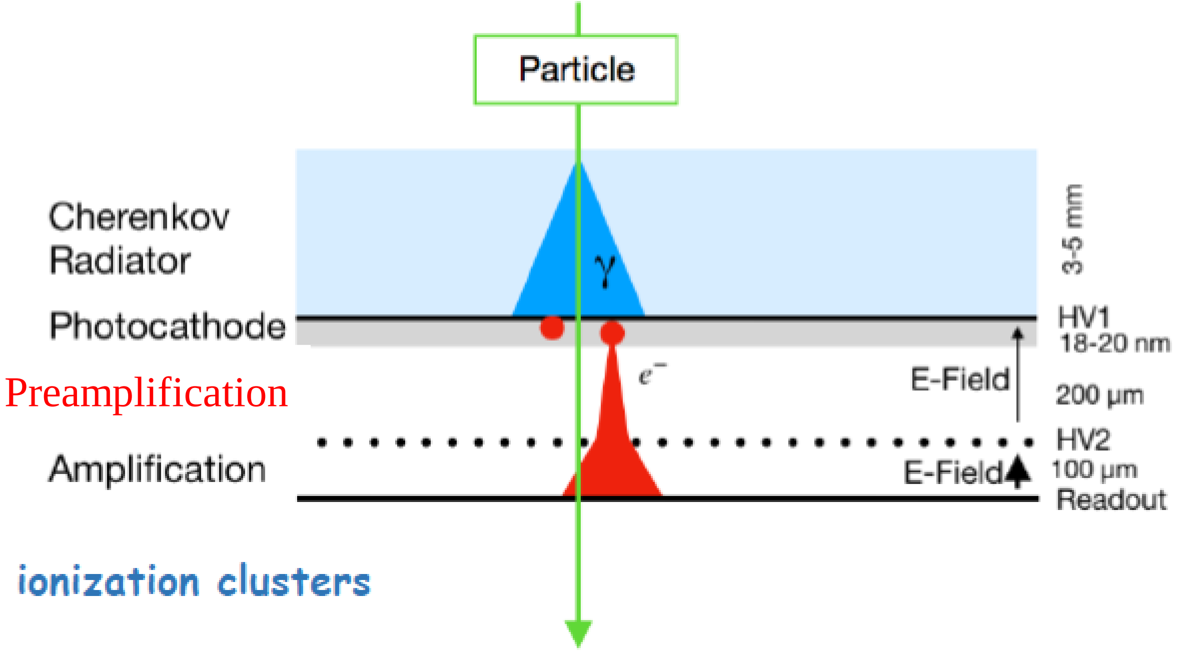
- Concept of MPGD-based picosecond timing & the PICOSEC collaboration.
- The µRWELL-PICOSEC Detector.
- Preliminary results from beam tests
- Summary & Plans for future R&D

Concept of MPGD-based picosecond Detector: MM-PICOSEC

Typical MicroMegas detector



Picosec-Micromegas (ps-MM) detector



Time jitter due to multiple ionization clusters

$$\sigma_t = \frac{\sigma_1}{v_e} \sim \frac{300\mu m}{50\frac{mm}{\mu s}} = 6ns$$

The time resolution is mainly limited to the direct initial ionization in the drifting zone:

- Uncertain of the collision position
- Small velocity of electrons
- Spread of electrons during the drifting progress

Novel fast time Micromegas detectors:

- Reducing the directly initial ionization by reducing the length of drifting zone
- Increasing the electric field
- Cerenkov Radiator and Photocathode produce photoelectrons, small longitudinal diffusion

Courtesy Xu Wang, MPGD-China 2017

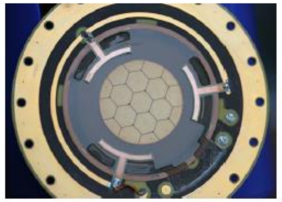
PICOSEC Collaboration at CERN

PICOSEC Coll.: Development of fast timing (picosecond resolution) MPGD based on Micromegas technology (MM-PICOSEC)

- ❖ Large collaboration based at CERN with several major institutions from Europe, Asia and US (JLab, SBU …)
- ❖ Proof of principle of picosecond timing with MPGD has been established with several generations of MM-PICOSEC prototypes:
- ❖ Large-area (10 cm × 10 cm) and multi-channel (100 pads) prototype ➔ < 20 ps with MIPs and ~50 ps with single photon (laser)
- ❖ R&D on PICOSEC technologies is part of DRD1 WP7➔ strong connection (i.e., beam test campaign and GDD lab at CERN)

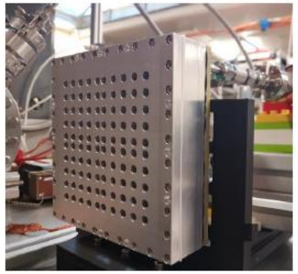
- 1-ch (ϕ1cm)
- Proof of concept
- Resistive and non-resistive prototypes.

- 7-ch (1cm)
- Signal sharing
- Resistive prototype



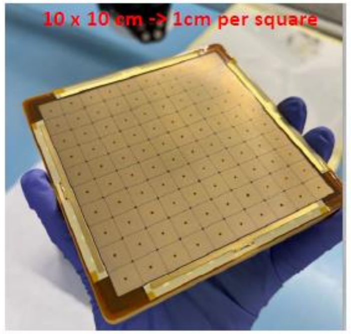
- 19-ch (ϕ3.6cm)
- Signal sharing.

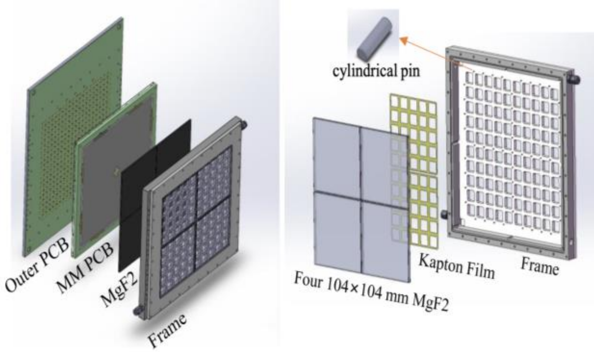
- 100-ch (10 cm x10 cm)
- Tileable
- Hybrid ceramic substrate MM
- MM decoupled from housing with spring-loaded pins



- 100 ch (10 cm x10 cm)
- MgF2 mechanically decoupled

- 100 ch (10 cm x10 cm)
- Sealed Ti housing
- Increased fill factor





20×20 Resistive PICOSEC MM from USTC

- Bortfeldt *et al.*, Nuclear Inst. and Methods in Physics Research, A 903 (2018) 317–325, https://doi.org/10.1016/j.nima.2018.04.033
- Aune *et al.*, Nuclear Inst. and Methods in Physics Research, A 993 (2021) 165076, https://doi.org/10.1016/j.nima.2021.165076
- A. Utrobicic *et al.*, 2023 JINST 18 C07012, https://doi.org/10.1088/1748-0221/18/07/C07012
- Y. Meng, USTC, MPGD2024

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μRWELL-PICOSEC: New addition to PICOSEC family

μRWELL-PICOSEC:

- ❖ Is an alternative MM-PICOSEC with strong synergies btw the two μRWELL and Micromegas technologies
- ❖ The R&D effort started as the Jefferson Lab Laboratory Directed Research and Development (LDRD) Program in 2023
- ❖ Development of μRWELL-PICOSEC technologies is included in the CPAD RDC6 as well as CERN DRD1 WP7 (Timing Detectors).

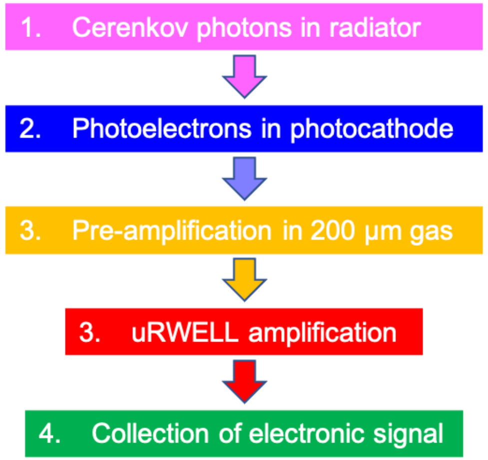
Potential applications for future HEP and NP experiments:

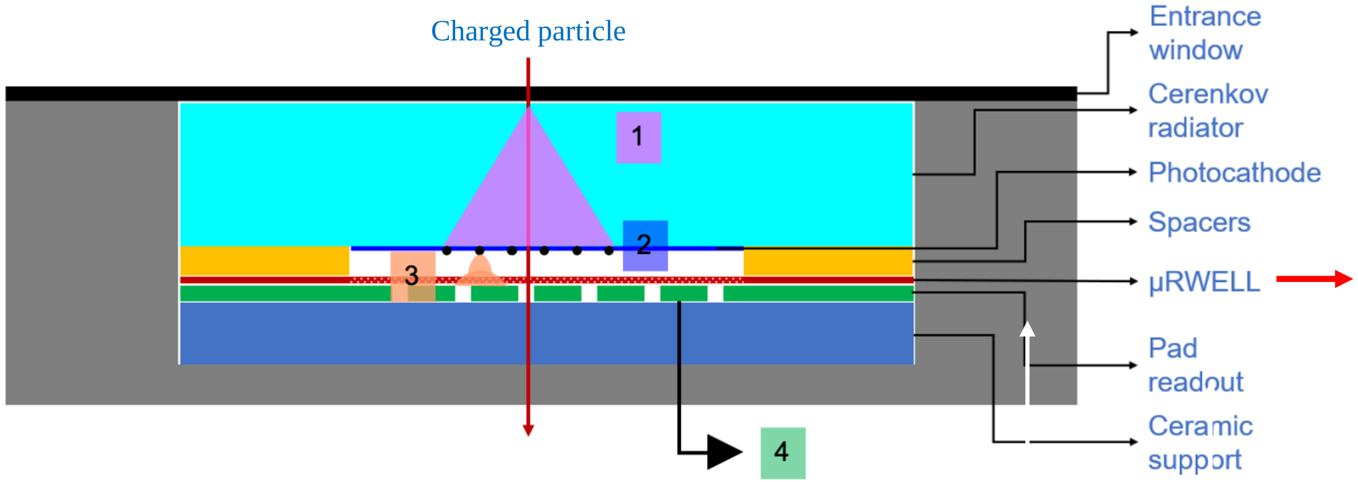
- ❖ μRWELL-PICOSEC is attractive for Time-Of-Fight (TOF) detectors of charged particles and photosensors readout for RICH detectors.
- ❖ The technology could be used in future Electron Ion Collider (EIC) Detector II, ePIC upgrade or future experiments at Jefferson Lab
- ❖ Potential application in medical instrumentation such as for TOF-PET devices will be explored.

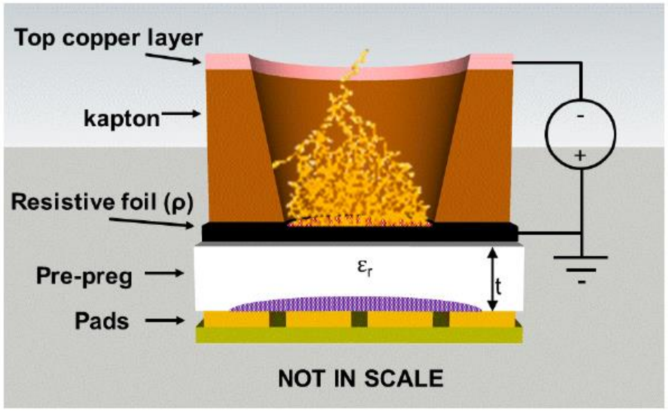
µRWELL-PICOSEC Concept

Concept of µrPICOSEC: fast timing gaseous detector using µRWELL amplification ➔ time resolution of ~10s ps

1. Cherenkov photons: relativistic charged particle creates Cerenkov photons ➔ prompt photons i.e. good timing.
2. Photoelectrons: convert the Cerenkov photons into electrons, all created at the location ➔ good timing
3. Pre-amplification: First amplification of electrons ~100 µm gas in high drift field region (~20 kV/cm)
4. Amplification: Final electron amplification in µRWELL gain structure ➔ high electric field (~40 kV/cm)
5. Electronic Signal: Arrival of the amplified electrons to the anode creates a signal.



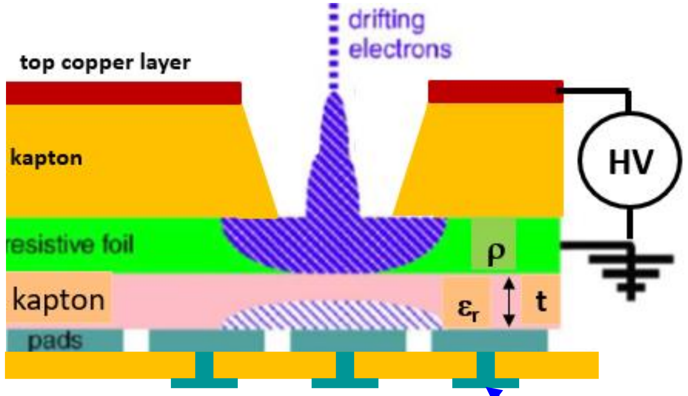




µRWELL PCB

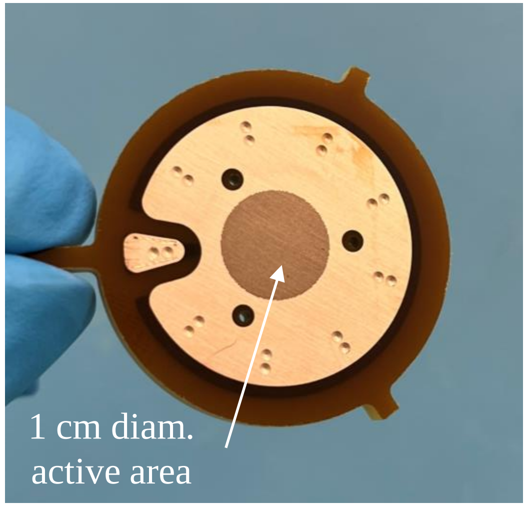
Typical gas mixture for Gaseous PICOSEC Neon : C_2H_6 : CF_4 = 80 : 10 :10 (at ambient pressure)

μRWELL-PICOSEC: Small prototype

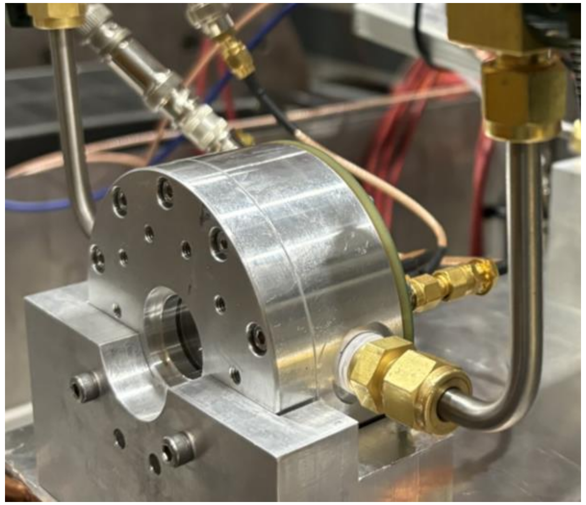


μRWELL PCB

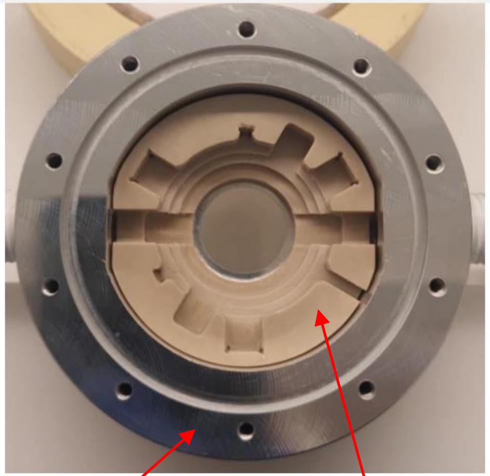
Readout pad contact



μRWELL PCB front side

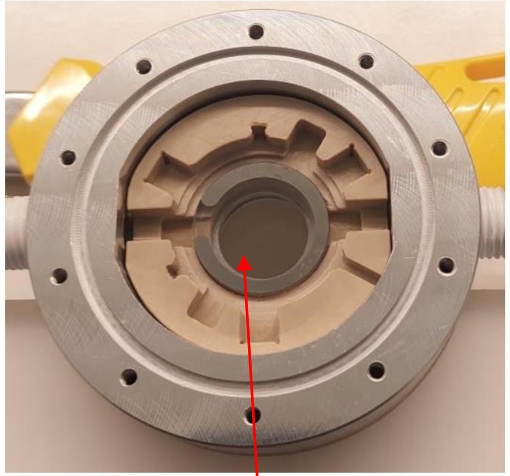


Prototype in Al chamber

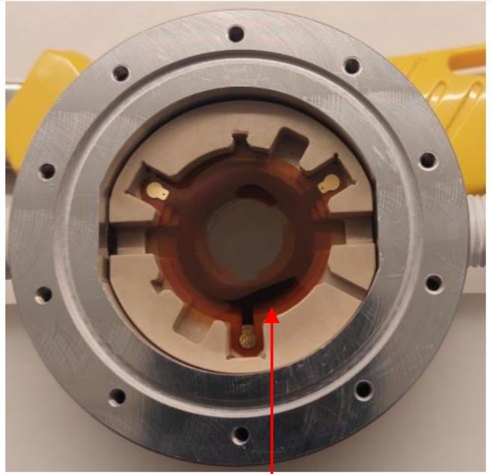


Al chamber

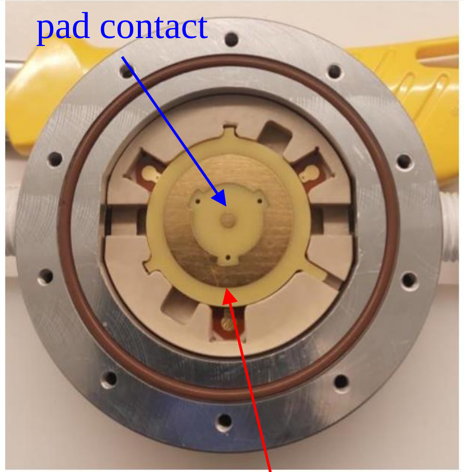
PEEK insert



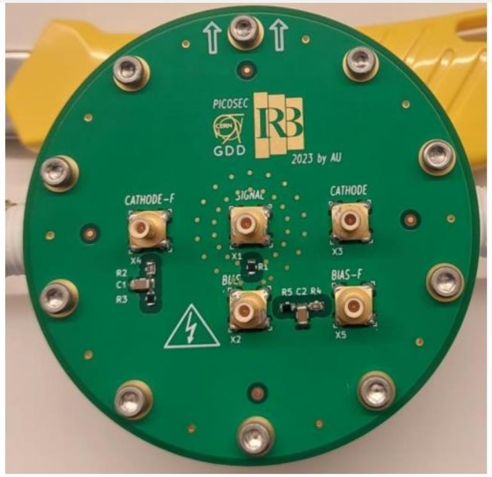
3mm MgF_2 crystal with 18nm CsI / 2nm DLC photocathode



Spacer / cathode contact



μRWELL PCB back side

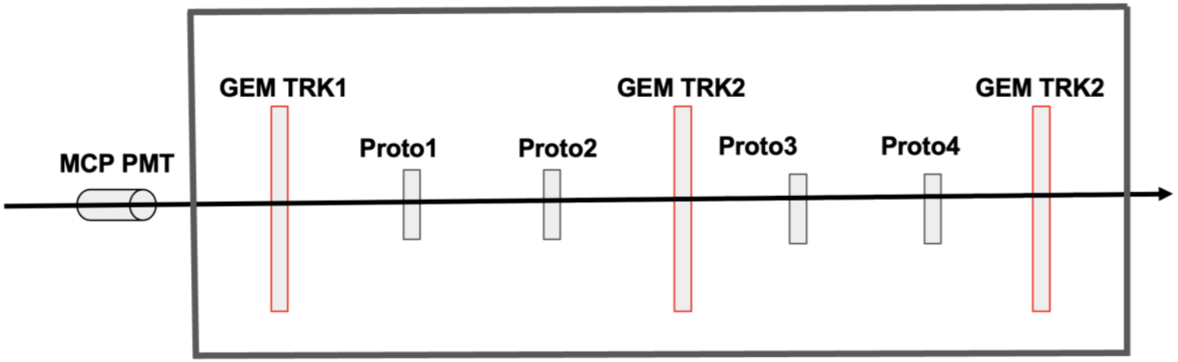


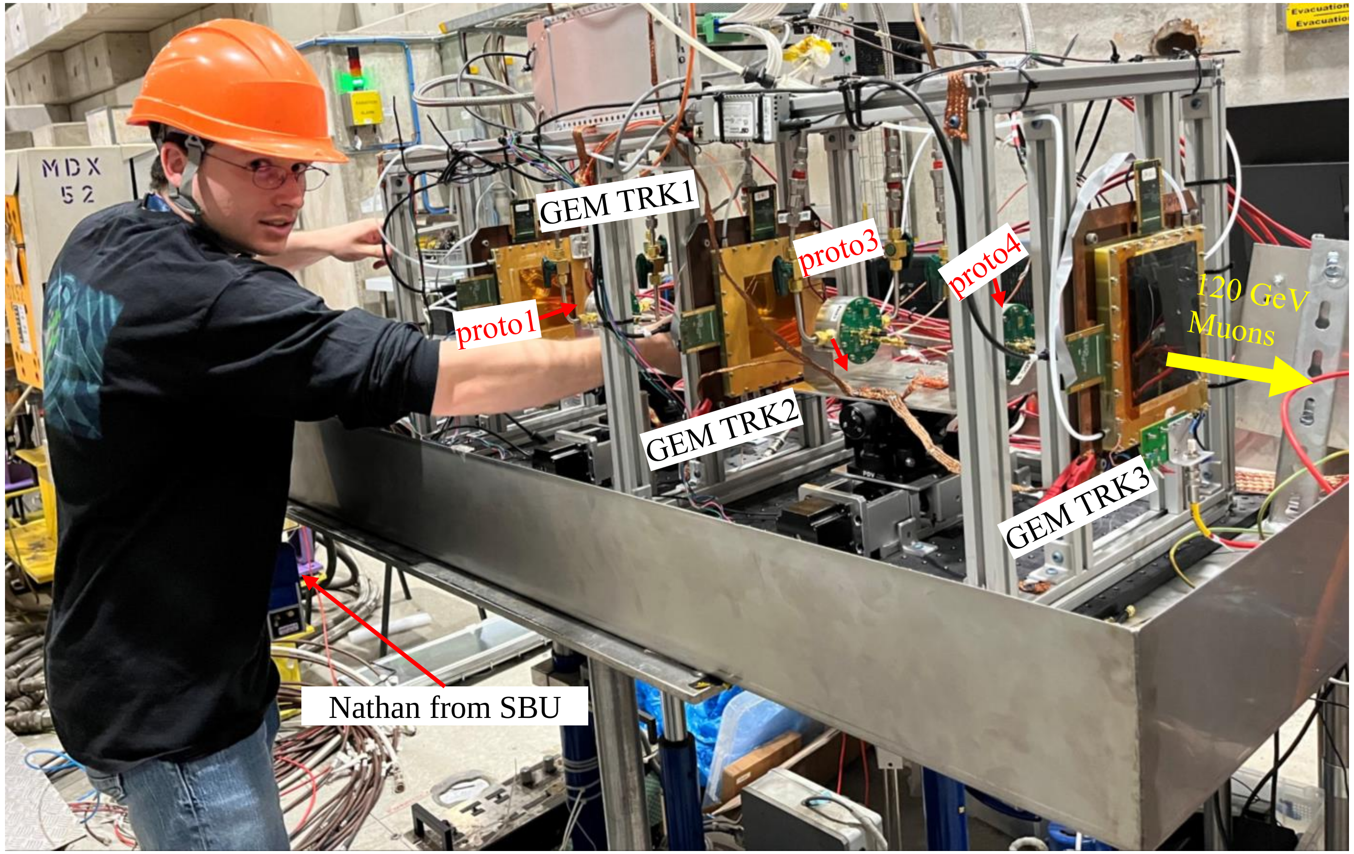
Outer board

µRWELL-PICOSEC: Beam test setup with small prototypes

The setup of small prototypes at the Summer 2024 :CERN bean test is a telescope composed of:

- **Prototypes:** 4 single-pad µRWELL-PICOSEC
- **Reference timing detector:** MCP-PMT ~4 ps resolution
- **Tracking:** 3 triple-GEMs + APV25-SRS ~70 µm
- **Preamplifier:** CIVIDEC or fast custom preamplifier
- **DAQ / readout:** high resolution oscilloscope





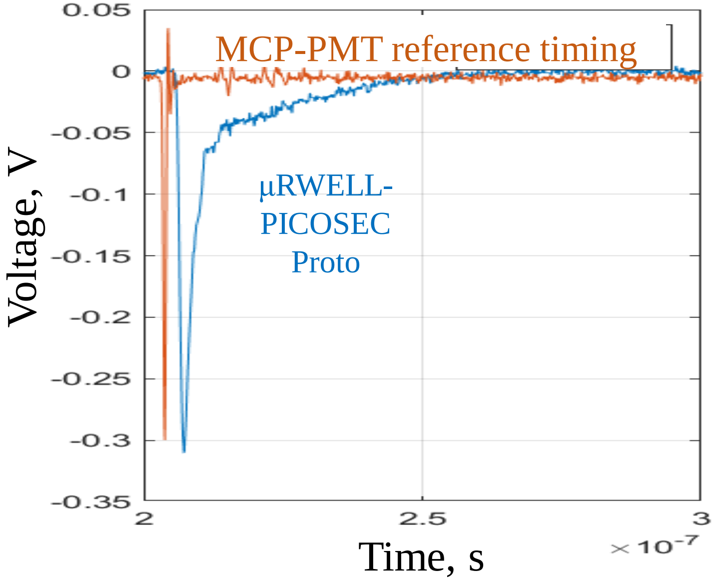
µRWELL-PICOSEC Telescope used in April and July 2024 test beam at CERN

Several small prototypes with different characteristics and parameters where tested on this setup

- µRWELL holes parameter (pitch, diameter, shapes) ➔ studies impact of geometry
- Thickness of the prepreg layer between µRWELL and pd layer and pad geometry ➔ impact of detector capacitance
- Photocathode materials (CsI and DLC)

Analysis of PICOSEC data

MCP-PMT & μRWELL-PICOSEC signals with 150 GeV/c muons.



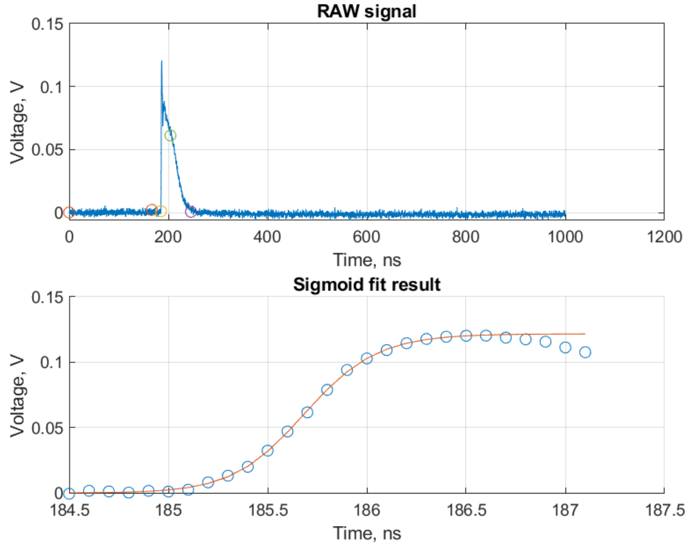
Time difference = (t_{proto} - t_{ref}) - t_{walk}

Time resolution of MCP PMT ~4ps

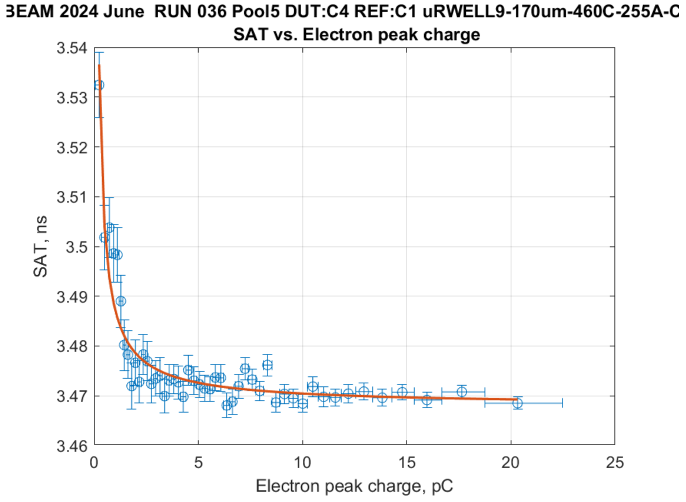
t_{ref} = Time of MCP PMT

t_{proto} = Time of μRWELL-PICOSEC

Constant Fraction (CF) analysis



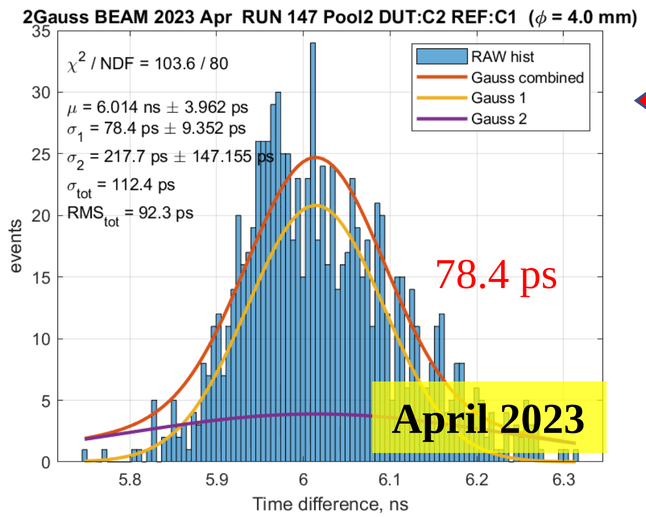
Sigmoid fit of signal



t_{walk} = Time walk correction

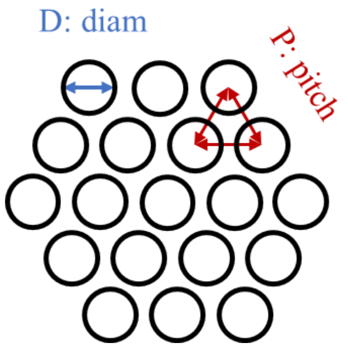
- A sigmoid function is fitted to the leading edge of the electron-peak to minimize noise contribution
- The time corresponding to a 20% CF method applied to the sigmoid fit
- Time walk correction is applied before subtracting from the reference time
- Cuts used to obtained final time difference distribution:

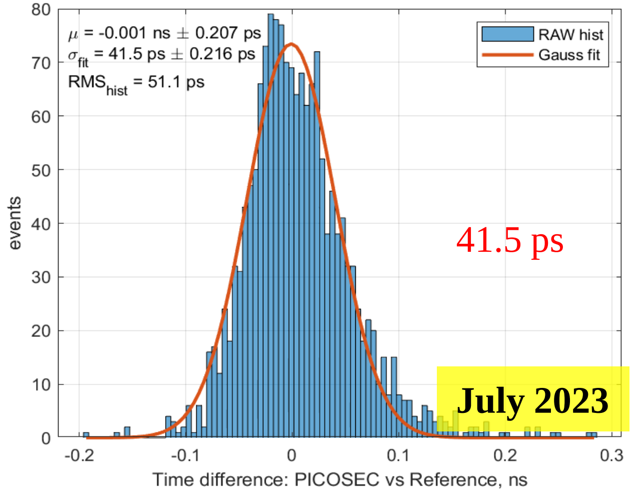
µRWELL -PICOSEC: One year of optimization



Std µRWELL proto – old housing

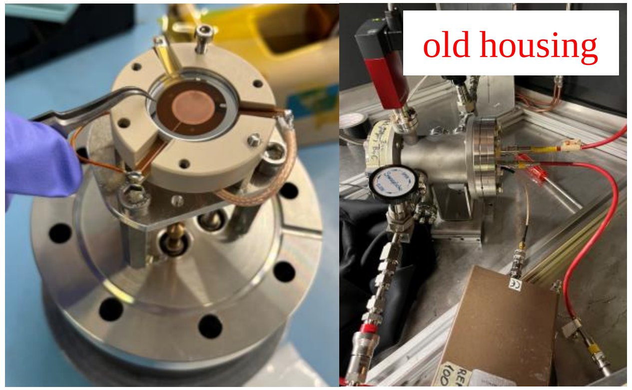
Standard µRWELL: Pitch 140 µm, outer diam 70 µm, inner diam. 50 µm





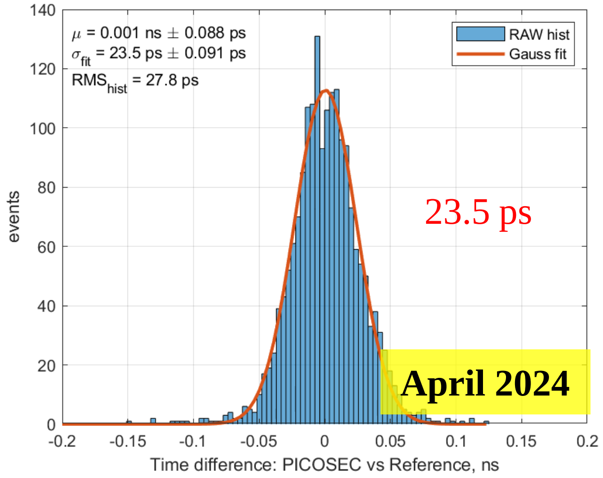
New µRWELL proto – old housing

- New Alu housing
- New prototype Pitch 120 µm, outer diam 100 µm, inner diam. 80 µm



Old detector housing with wire connection to electrodes ➔ increase capacitance

- New round of prototypes - different µRWELL geometries ➔ change pitch and diameter
- Best result: Pitch 120 µm, outer diam 85 µm, inner diam. 65 µm



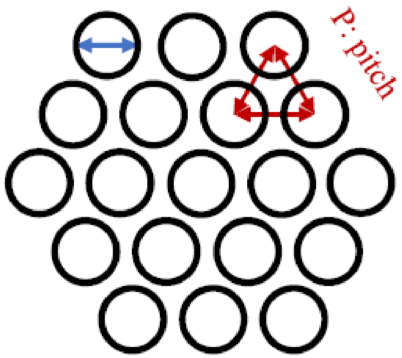
Newer µRWELL proto – new housing

Comparison of µRWELL hole shape

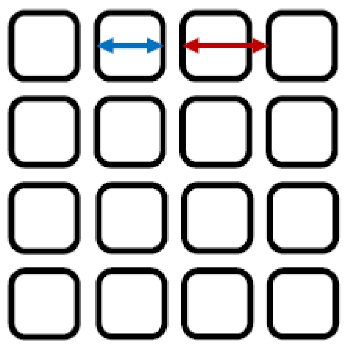
Study the impact of µRWELL hole geometry on timing

- In general, round hole geometry shows improved timing resolution (25.2 ps vs. 28 ps) for 3 µRWELL HV settings (245V, 250V, 255V)
- For the lowest µRWELL HV setting (240V), hole prototype is slightly better at 29 ps compared to 33 ps for the round

Caveat: Different photocathode samples were used in different prototypes so the results might also be affected by the quality of the photocathode



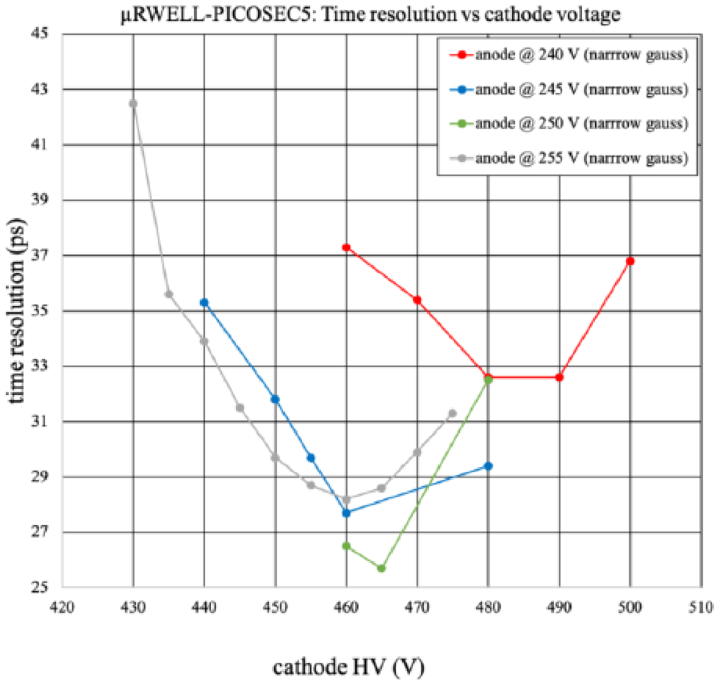
Round hole

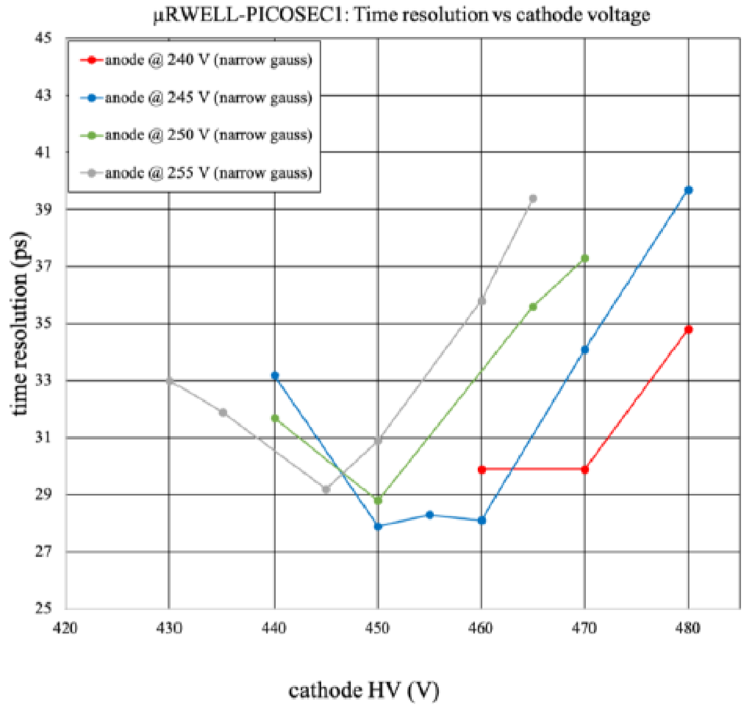


Square hole

Hole geometries

Parameters	µRWELL5	µRWELL1
Pitch (µm)	120	120
Hole(o) (µm)	100	100
Hole(i) (µm)	80	80
Hole shape	Round	Square
Readout	Plain	Plain
Spacer (µm)	170	170
Photocathode	CsI	CsI

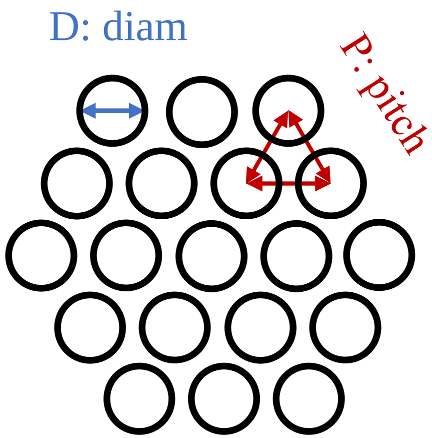


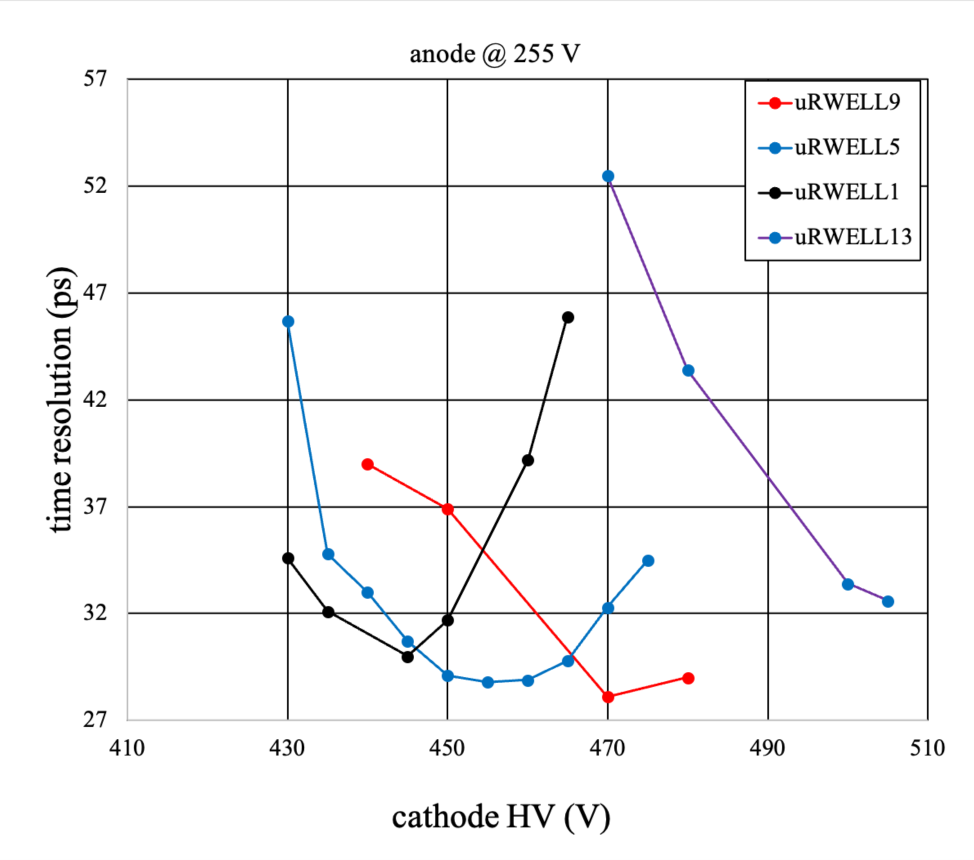


Comparison of µRWELL hole pitch

Study the impact of µRWELL hole pitch on timing

- Best performance with µRWELL9 (100 µm pitch and 80 µm hole diameter)
- Larger pitch µRWELL5 and smaller pitch µRWELL13 gives slightly worst timing but more data needed for definite conclusion





Caveat: Different photocathode samples were used in different prototypes so the results might also be affected by the quality of the photocathode

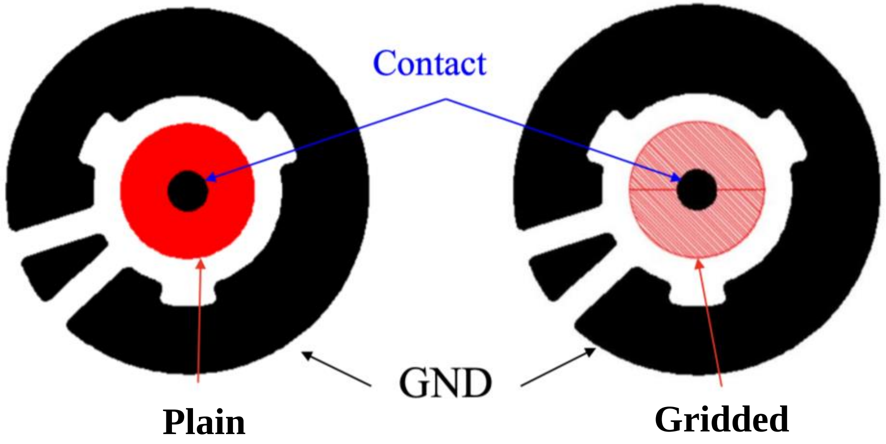
	µRWELL5	µRWELL1	µRWELL9	µRWELL13
Pitch (µm)	120	120	100	80
Hole(o) (µm)	100	100	80	60
Hole(i) (µm)	80	80	60	40
Hole shape	Round	Square	Round	round
Readout	Plain	Plain	Plain	Plain
Spacer (µm)	170	170	170	170
Photocathode	CsI	CsI	CsI	CsI

Comparison of detector capacitances

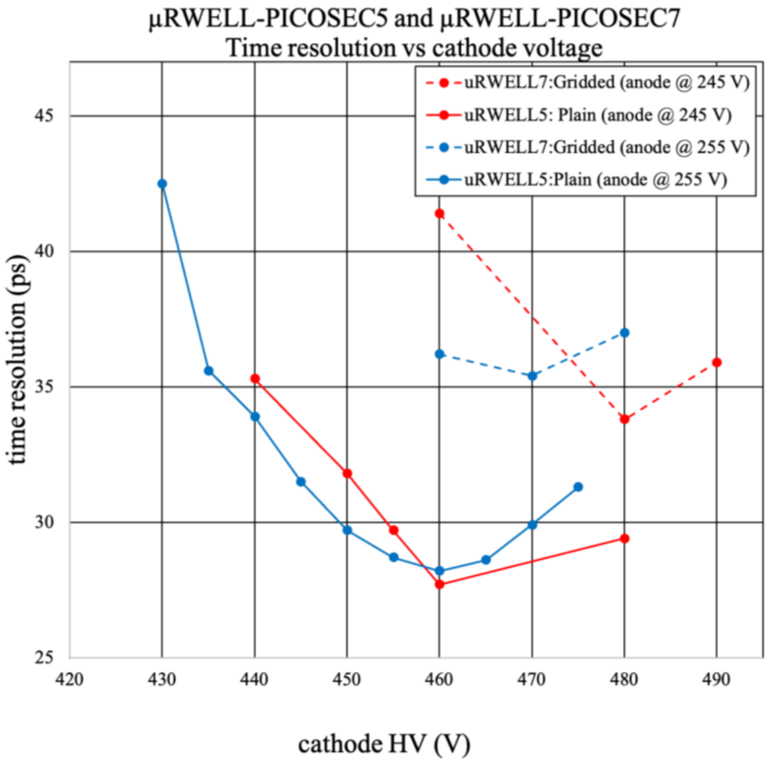
We also looked at the impact of the pad area on detector capacitance and timing resolution

- ❖ Prototype featuring a plain readout demonstrates improved timing resolution compared to the prototype with a grided readout scheme.
- ❖ This is mostly because the signal collection with the gridded pad readout is twice smaller ➔ so we could expect some improvement with larger gain

Caveat: Different photocathode samples were used in different prototypes so the results might also be affected by the quality of the photocathod



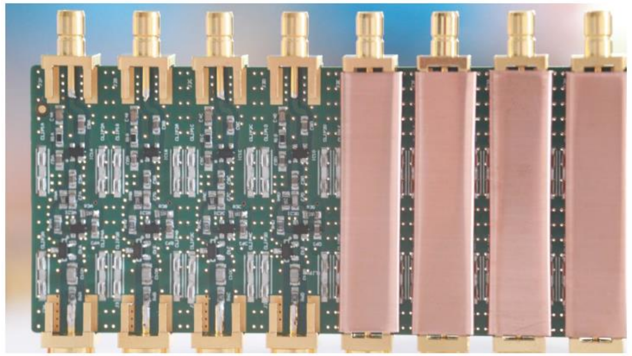
Parameters	μRWELL5	μRWELL7
Pitch (μm)	120	120
Hole(o) (μm)	100	100
Hole(i) (μm)	80	80
Hole shape	Round	Round
Readout	Plain	Gridded
Spacer (μm)	170	170
Photocathode	CsI	CsI



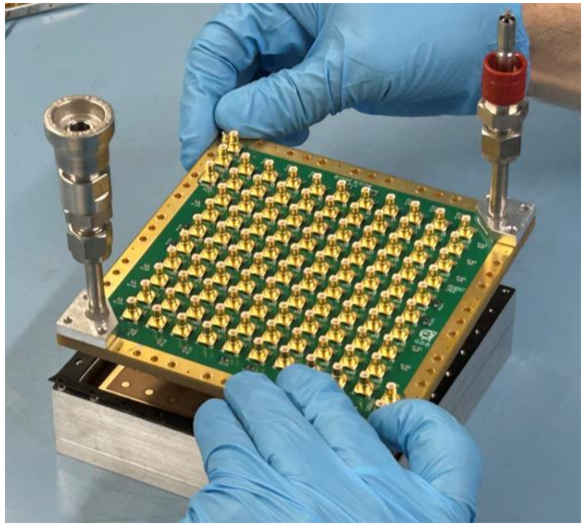
Large (10 cm × 10 cm) μRWELL-PICOSEC prototype

Large (10 cm×10 cm) μRWELL-PICOSEC prototype 100-pads readout

- 100-pads μRWELL-PICOSEC with **120** μm pitch, **100** μm outer diameter and **80** μm inner diameter assembled
- The back of the large μRWELL-PCB connect to outer readout PCB through pogo pins
- Instrumented with fast electronics based on custom fast preamplifiers coupled with the multi channel SAMPIC digitizer readout & DAQ

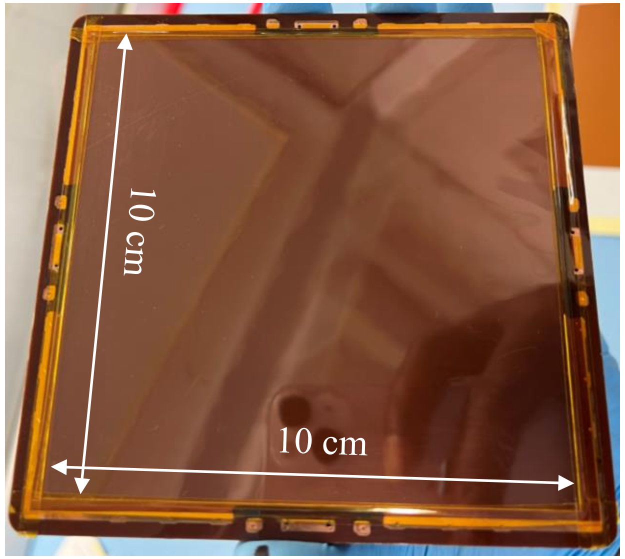


10-channel fast preamplifier card

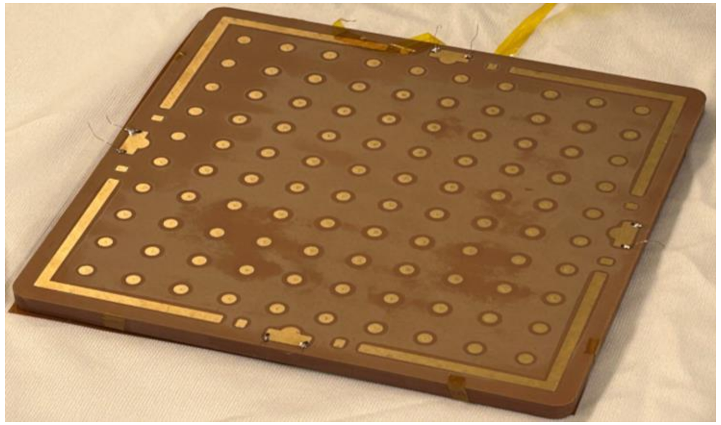


Prototype in Al housing, closed by outer readout PCB

64-channels SAMPIC



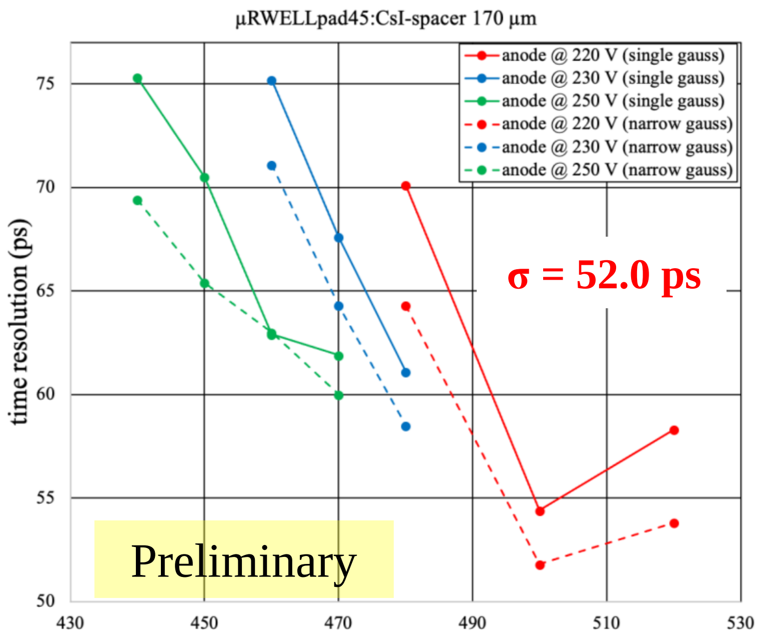
Top side of the μRWELL-PCB



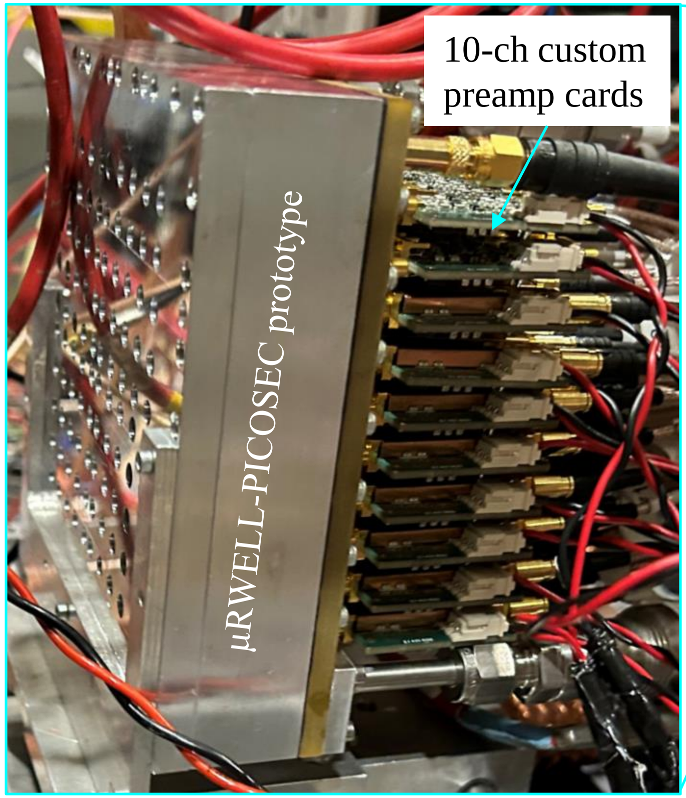
Back side of the μRWELL PCB

Large μRWELL-PICOSEC prototype: in beam @ CERN

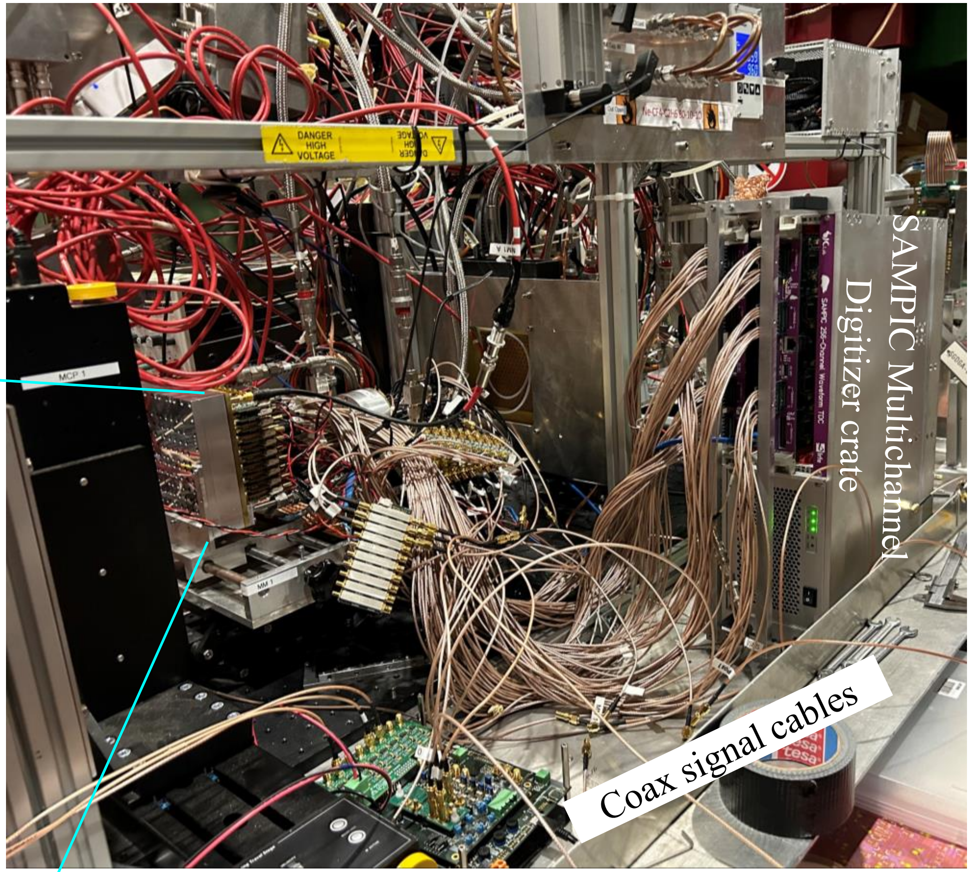
- The large (10 cm × 10 cm) μRWELL-PICOSEC tested in beam July 2024
- Runs with all 100 pads connected to custom preamp cards + SAMPIC digitizer
- **Position scan of full area (all 100 pads) ➔ dedicated SAMPIC runs**
- HV scan on pad45 to determine optimal voltage setting
- Detector run flawlessly but planarity is poor ➔ will affect timing performance



Time resolution vs. cathode HV scan



Zoomed view of large prototype



Large prototype in beam test setup at CERN (July 2024

- preliminary test beam results on individual pads give time resolution ~52 ps ➔ Gap non uniformity and poor quality CsI photocathode
- Analysis is still ongoing

Summary

- Fast timing µRWELL-PICOSEC technology with picosecond timing resolution is fast emerging field for Time of Flight (TOF) PID applications in HEP and NP field.
- Preliminary beam test results with small µRWELL-PICOSEC prototypes show timing resolution of 23 ps after optimization of µRWELL PCB geometry and features.
- The results suggested that further optimization possible to reach < 20 ps resolution with MIPs.
- Large area 10 cm × 10 cm µRWELL-PICOSEC prototype was also successfully tested with encouraging results for large and cost effective fast timing detector technologies.
- We will explore funding opportunities to develop application as TOF PID options for future detector such as a potential EIC detector II or for future FCC detector.

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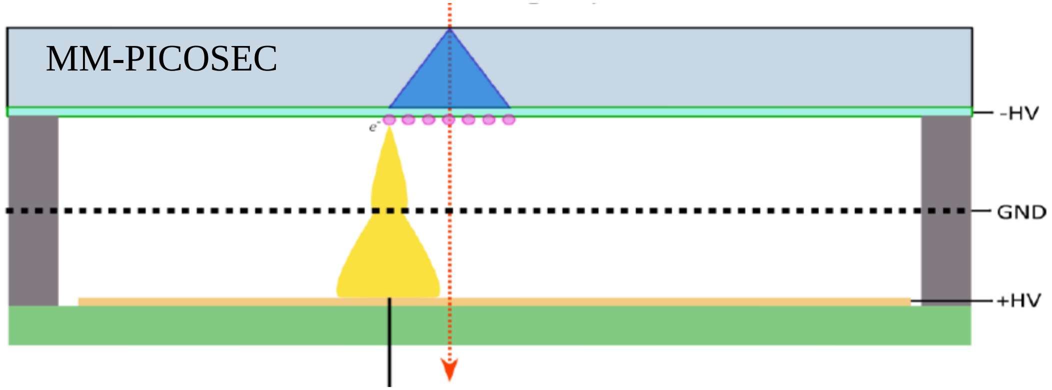
LDRD @ Jefferson Lab

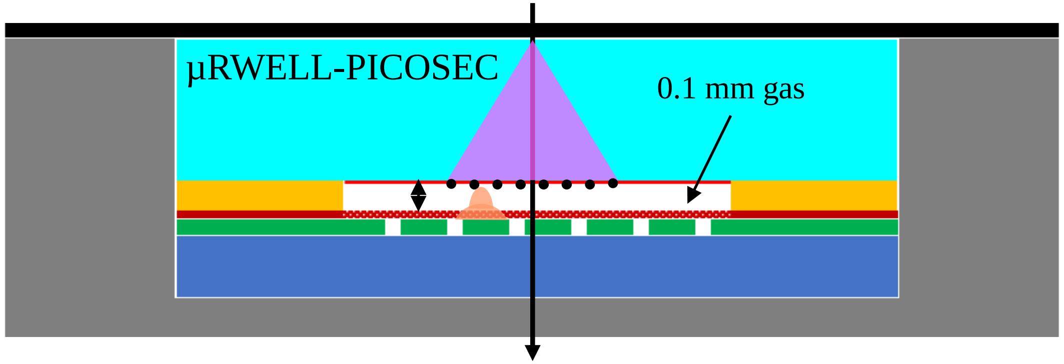
Back-up

Comparison of MM-PICOSEC and µRWELL-PICOSEC

- µRWELL-PICOSEC and MM-PICOSEC belongs to the MPGD-based fast timing detector family
- Difference in amplification structure allows different type of optimization of the technologies in term of operation stability and performance
- Parallel development of will mutually benefit the two technologies and offer options for applications

	MM-PICOSEC	µRWELL-PICOSEC	Comments
Radiator & photocathode	Same for both devices		common R&D
Readout structure	Same for both devices		common R&D
Amplification structure	Metallic mesh 128µm ✓ ➔ (low capacitance) but woven mesh ➔ non uniform gap ×	Standard µRWELL foil has large capacitance ×	But lot of flexibility for optimization (thickness, pitch and hole geometry …)
Resistive vs. metallic	Both options available ✓	Only resistive ✓	Resistive ➔ HV stability
Mechanical structure	Mesh tensioning challenging for large area	no pillar, no stretching ✓	
Segmentation MPGD	Segmentation of the mesh will be challenging	µRWELL Cu-electrode can be segmented ✓	Improve rate capabilities for resistive





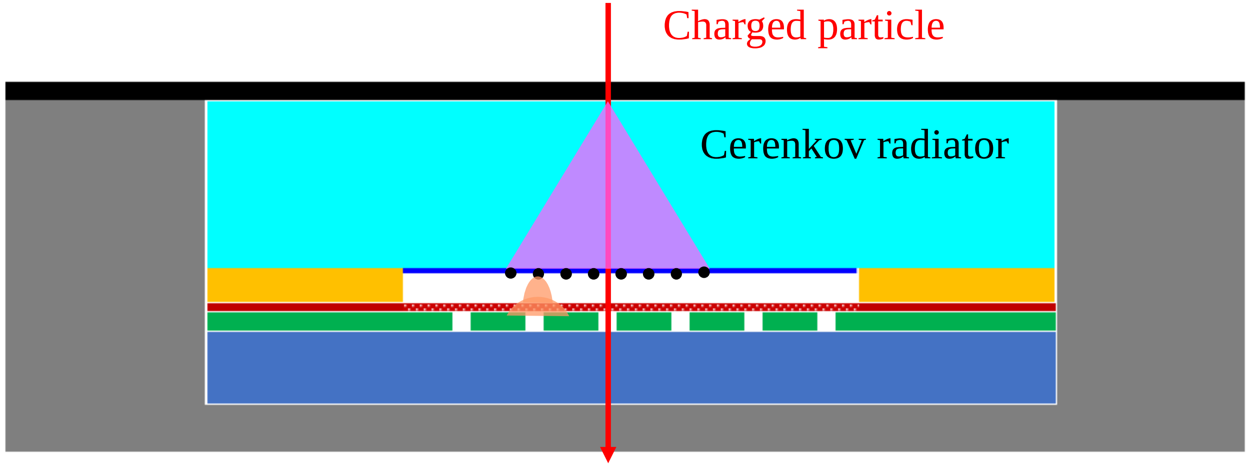
µRWELL-PICOSEC: TOF or Single Photon Detector

Timing detector for relativistic charged particles:

- Cerenkov radiator crystal transparent in VUV region
- High quantum efficiency (QE) photocathode in VUV medium ~ 7 photoelectrons for 3 mm MgF2
- Goal for timing resolution (~25 ps)

Applications:

- Time of Flight detector
- T0 detector

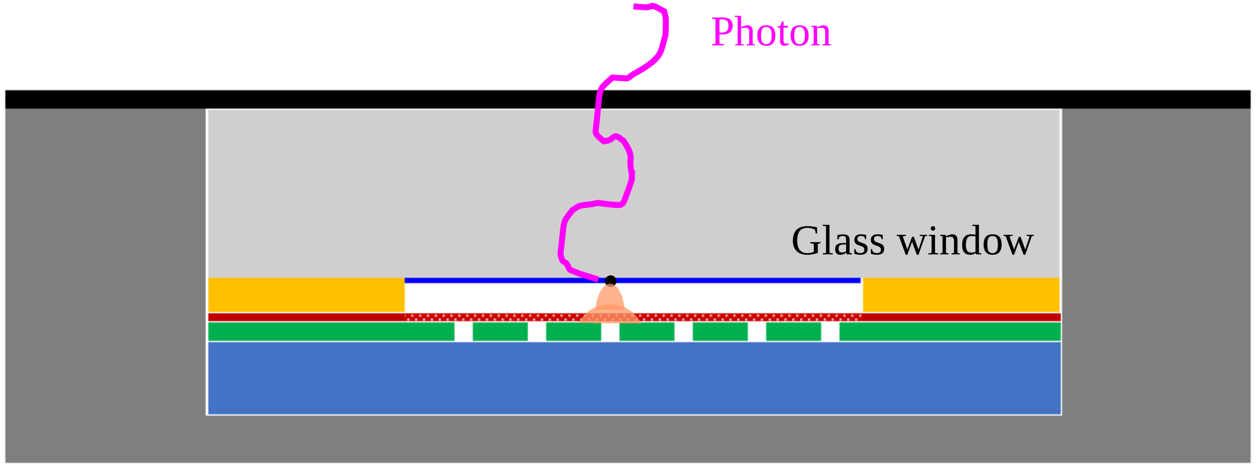


Single photon photodetector:

- High quantum efficiency (QE) photocathode in (VUV) medium which is most radiated by any radiator medium
- Window transparent to Cerenkov radiation
- High gain for single photon timing goal of ~50 - 70 ps

Applications:

- Photosensor for RICH detectors
- T0 tagger at neutrino detector (liquid Ar scintillator light)



µRWELL-PICOSEC vs. Alternative Technologies

This R&D target

Time of Flight (TOF) detectors

	MRPCs	AC-LGAD	µrPICOSEC
Time resolution (ps)	20 – 70 ✓	20 ✓	25 ✓
Rate (MHz / cm^2)	0.05 ×	N/A	> 1 ✓
Position resolution (mm)	~ 10 ×	0.030 ✓ (claim)	< 1mm ✓
Performance in high B-field	Yes	Yes	Yes ✓
module size	20 × 20 cm^2 ✓	N/A	20 × 20 cm^2 ✓
Cost ($ M / m^2)	0.2 – 0.4 ✓	High ×	0.2 – 0.4? ✓

This R&D target

Photosensors for Cerenkov detectors

	SiPMs	MCP-PMTs	LAPPDs	µrPICOSEC
Time resolution (ps)	< 100	< 100	50 ✓	50 ✓
Position resolution (mm)	> 1 ×	1 ×	0.3 – 1 ✓	< 1 ✓
Performance in high B-field	Yes	Limited	Limited	Yes ✓
Radiation hardness	dark current ×	N/A	N/A	Yes ✓
Cost ($ M / m^2)	0.8 – 1 ×	> 1 ×	0.8 – 1 ×	0.2 – 0.4 ✓

Timing analysis

uRWELL PICOSEC signal	fast electron-peak (electrons) →	**Timing Analysis**
	Slow component (ion drift)	

Electron peak: the difference between the highest point of the waveform and the baseline

For the timing measurement, a **Constant Fraction** (CF) method based on a sigmoid function is used to minimize the contribution of the noise

A sigmoid function is fit to the leading edge of the electron-peak:

$$V(t) = \frac{P_0}{1 + \exp\left(-P_2 \times (t - P_1)\right)} + P_3$$

where P_0 and P_3 respectively the maximum and the minimum values, P_1 is the inflection time (i.e. where the slope changes derivative), and P_2 quantifies the speed of the sigmoid change (i.e. is correlated to the signal risetime).

The time corresponding to a 20% CF is calculated as follows:

$$t_z = P_1 - \frac{1}{P_2} \log\left[\frac{P_0}{0.2 \times V_{max} - P_3} - 1\right]$$

Now above time is calculated for both uRWELL and MCP PMT and then difference of them gives time resolution.

Cuts used to obtained final time difference distribution:

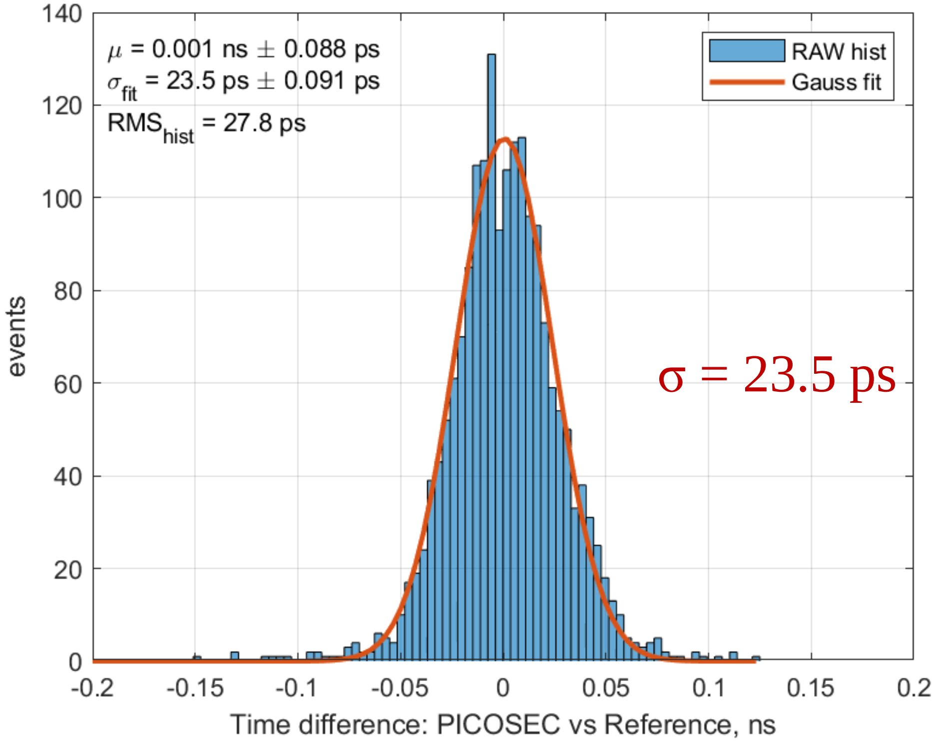
1. Time window cut applied to select events within pm300 ps of the median time difference of all triggered events.
2. Min and maximum signal amplitude cut
3. Geometrical cut: central pad only (to avoid partial loss of photoelectrons outside center pad region)

J. Bortfeldt, F. Brunbauer, C. David, D. Desforge, et al. NIM A 903 (2018) 317–325. doi:https://doi.org/10.1016/j.nima.2018.04.033.

Comparison of different photocathodes

CsI photocathode

- Npe ~7 ➔ excellent timing resolution ✓
- Handling in vacuum x
- Hygroscopic x
- Ion bombardment x
- High rate limitation x



DLC photocathode

- Npe ~2-3 ➔ worse timing resolution x
- Very stable material ✓
- No hygroscopic ✓
- Ion bombardment ✓
- High rate ✓