Precise timing with gaseous detectors

Florian M. Brunbauer
(CERN, PICOSEC MM)

florian.brunbauer@cern.ch

Innovative Detector Technologies and Methods, September 13, 2023

Outline

Precise timing requirements

Overcoming timing limitations in gaseous detectors

Precise timing with PICOSEC Micromegas

- Detector concept & timing performance
- Robust photocathodes and resistive Micromegas
- Multi-pad detector modules
- Scalable readout electronics

Precise timing needs

Good timing resolution is highly important for future applications of gaseous detector

Identified needs for applications in muon systems, PID detectors, calorimeters and TOF systems in ECFA Detector R&D roadmap for future facilities

Varying requirements for timing resolutions from tens of ps to sub-ns

		DRDT	< 2030						2030-2035						2035-2040	2040-2045			>2045		
			SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E,...)	Neutrino near detectors (DUNE)	Large ton dual-phase[1]	Light dark matter...[2]	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments[3]	R&D ton scale 0nbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟠	🟠		🟠			🟢	🟠	🟢		🟠	🟠	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_0	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟠		🟠						🟠				🟢	🟠	🟢	🟠			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟠	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	1.4				🟢	🔴	🔴					🔴	🔴							

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

http://cds.cern.ch/record/2784893/files/

Precise timing in DRD1

WP7: Timing Detectors

Work in progress

Work package currently being defined in context of future DRD1 collaboration

Clustering groups working on common R&D developments of gaseous detectors for precise timing applications

Two WP projects:

- **High-rate, high-granularity precise timing with MPGDs**
- **High-rate, large, precise timing (M)RPC**

Defined tasks and deliverables for 2024-2026

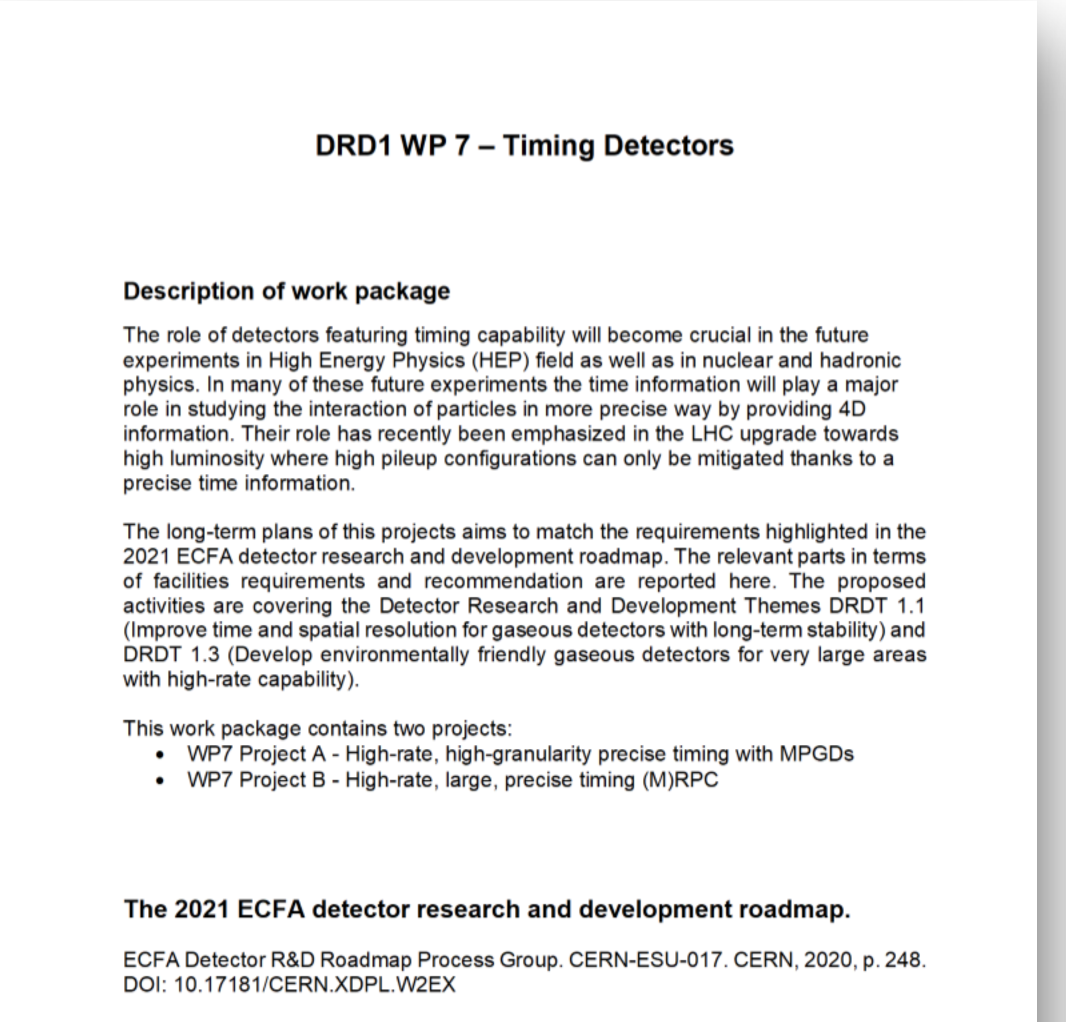
Institutes participate with existing FTE and non-FTE resources and/or intend to request additional resources

Participation of >20 institutes

https://drd1.web.cern.ch/wp/wp7

Tasks:

- T1: Optimize the amplification technology towards large-area detectors
- T2: Enhance timing performance
- T3: Enhance rate capability
- T4: Spatial resolution and readout granularity
- T5: Stability, robustness and longevity
- T6: Material studies
- T7: Gas studies for precise timing applications
- T8: Modelling and simulation of timing detectors
- T9: Readout electronics for precise timing
- T10: Precision mechanics and construction techniques
- T11: Common framework and test facilities for precise timing R&D



DRD1 WP 7 – Timing Detectors

Description of work package

The role of detectors featuring timing capability will become crucial in the future experiments in High Energy Physics (HEP) field as well as in nuclear and hadronic physics. In many of these future experiments the time information will play a major role in studying the interaction of particles in more precise way by providing 4D information. Their role has recently been emphasized in the LHC upgrade towards high luminosity where high pileup configurations can only be mitigated thanks to a precise time information.

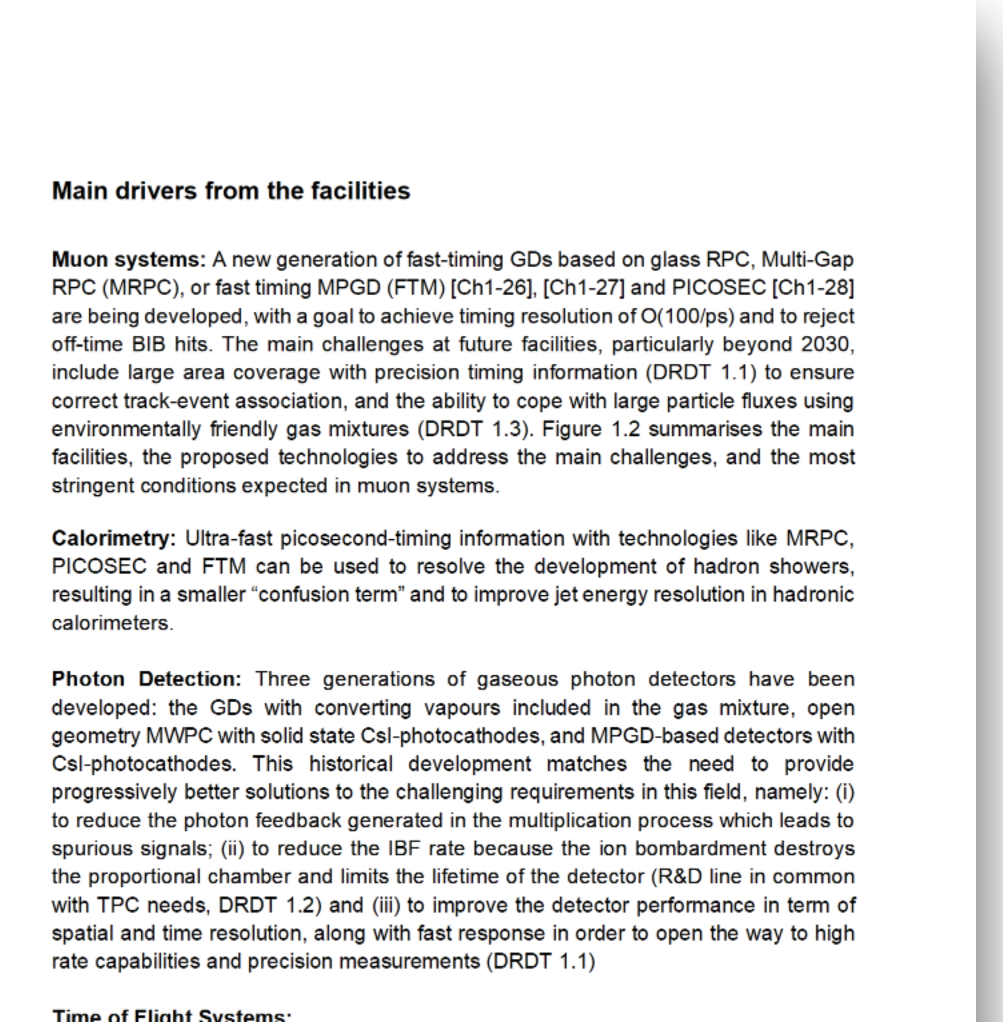
The long-term plans of this projects aims to match the requirements highlighted in the 2021 ECFA detector research and development roadmap. The relevant parts in terms of facilities requirements and recommendation are reported here. The proposed activities are covering the Detector Research and Development Themes DRDT 1.1 (Improve time and spatial resolution for gaseous detectors with long-term stability) and DRDT 1.3 (Develop environmentally friendly gaseous detectors for very large areas with high-rate capability).

This work package contains two projects:

- WP7 Project A - High-rate, high-granularity precise timing with MPGDs
- WP7 Project B - High-rate, large, precise timing (M)RPC

The 2021 ECFA detector research and development roadmap.

ECFA Detector R&D Roadmap Process Group. CERN-ESU-017. CERN, 2020, p. 248. DOI: 10.17181/CERN.XDPL.W2EX



Main drivers from the facilities

Muon systems: A new generation of fast-timing GDs based on glass RPC, Multi-Gap RPC (MRPC), or fast timing MPGD (FTM) [Ch1-26], [Ch1-27] and PICOSEC [Ch1-28] are being developed, with a goal to achieve timing resolution of O(100/ps) and to reject off-time BIB hits. The main challenges at future facilities, particularly beyond 2030, include large area coverage with precision timing information (DRDT 1.1) to ensure correct track-event association, and the ability to cope with large particle fluxes using environmentally friendly gas mixtures (DRDT 1.3). Figure 1.2 summarises the main facilities, the proposed technologies to address the main challenges, and the most stringent conditions expected in muon systems.

Calorimetry: Ultra-fast picosecond-timing information with technologies like MRPC, PICOSEC and FTM can be used to resolve the development of hadron showers, resulting in a smaller "confusion term" and to improve jet energy resolution in hadronic calorimeters.

Photon Detection: Three generations of gaseous photon detectors have been developed: the GDs with converting vapours included in the gas mixture, open geometry MWPC with solid state CsI-photocathodes, and MPGD-based detectors with CsI-photocathodes. This historical development matches the need to provide progressively better solutions to the challenging requirements in this field, namely: (i) to reduce the photon feedback generated in the multiplication process which leads to spurious signals; (ii) to reduce the IBF rate because the ion bombardment destroys the proportional chamber and limits the lifetime of the detector (R&D line in common with TPC needs, DRDT 1.2) and (iii) to improve the detector performance in term of spatial and time resolution, along with fast response in order to open the way to high rate capabilities and precision measurements (DRDT 1.1)

Time of Flight Systems:

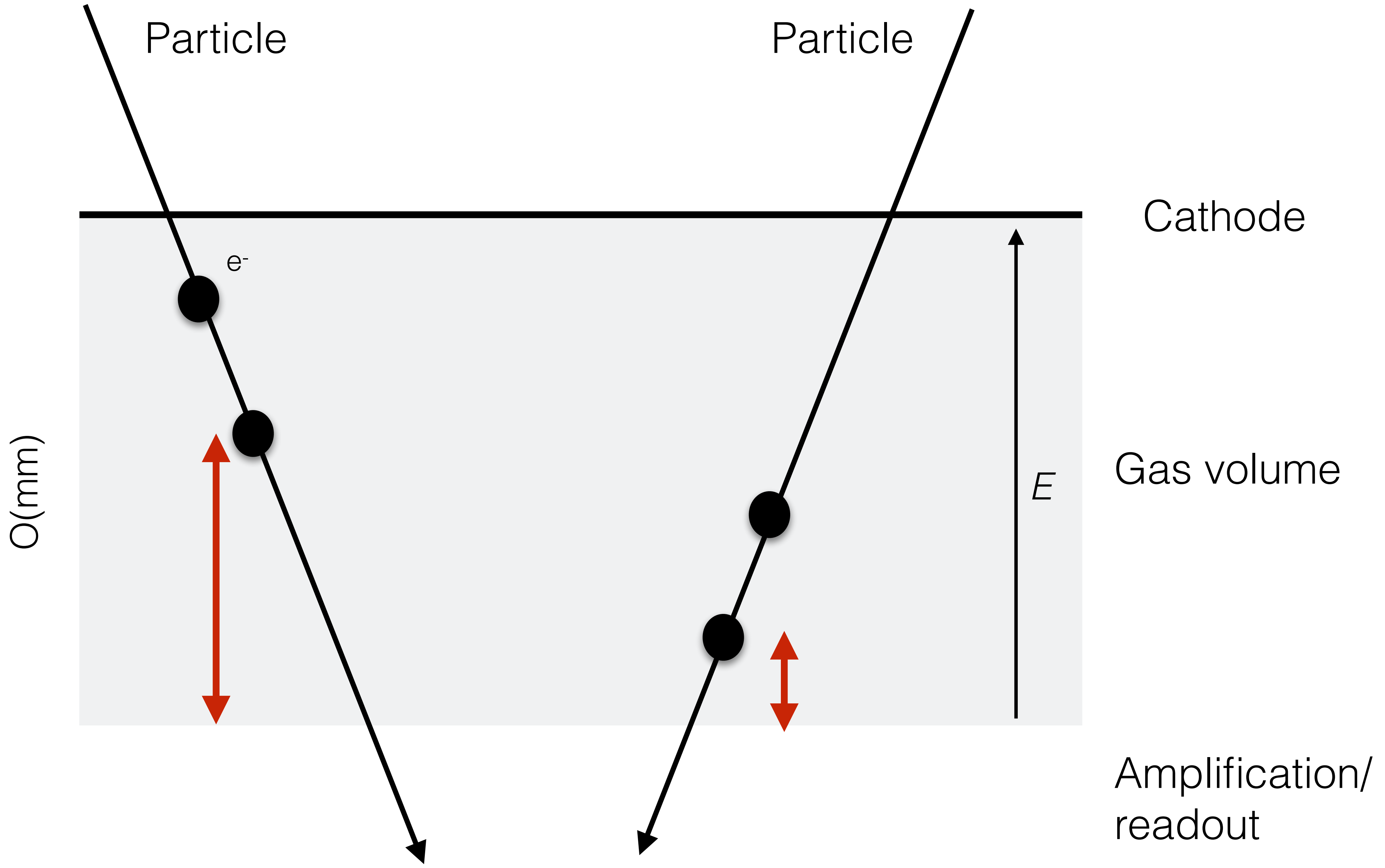
Timing limitations of gaseous detectors

Conventional gaseous detectors

Ionisation of gas in active volume

Primary electrons produced by ionisation along particle trajectory in drift region

Drift distance differences on the order of millimetres
→ **Timing jitter of ≈ ns**



Schematic not drawn to scale

Timing with (M)RPC

- Hundreds of ps achieved with RPCs
- Tens of ps with MRPCs

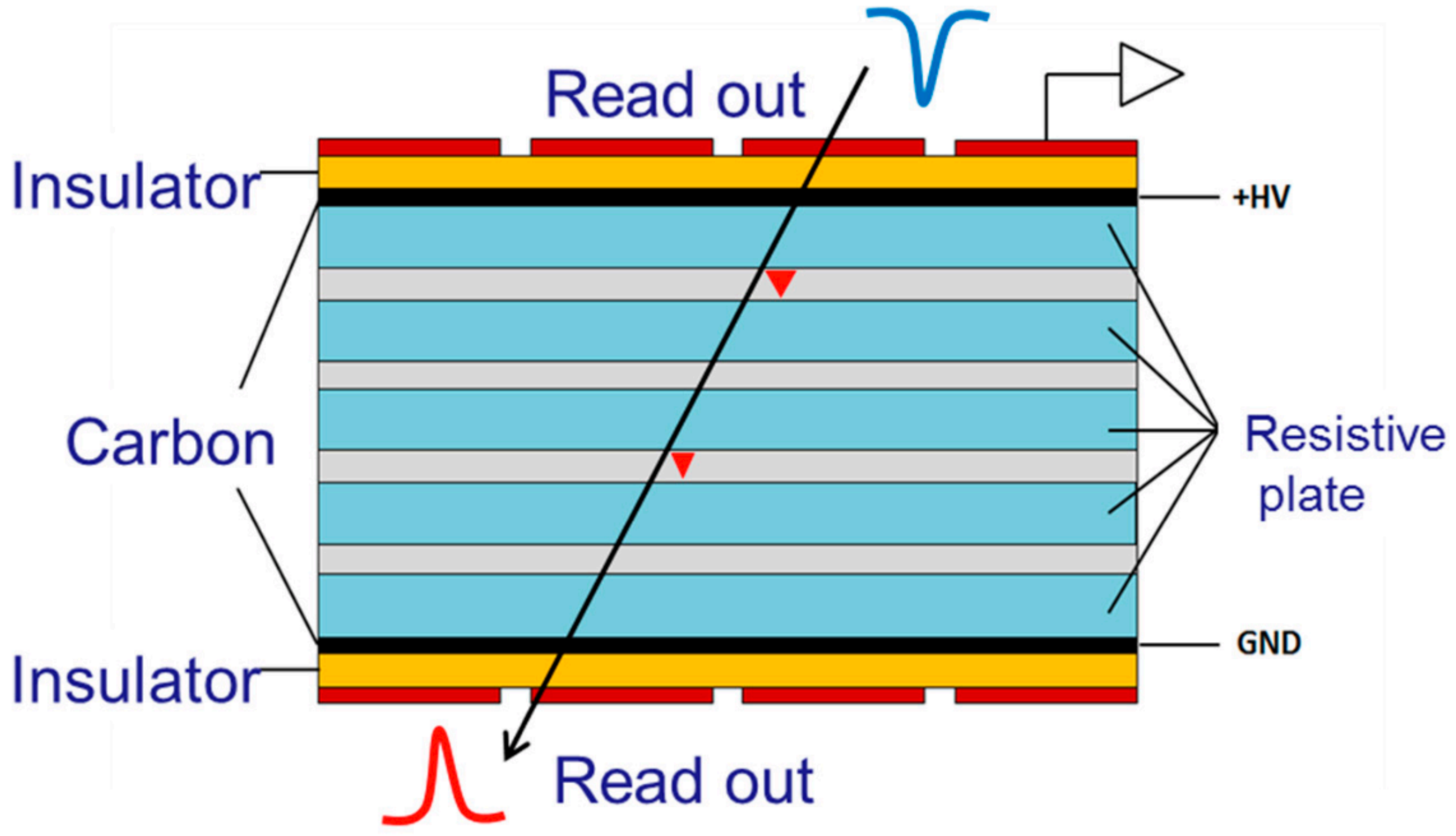
Cluster statistics, multiplication in gaps and noise contributions limited achievable timing resolution

Developments to improve timing resolution:

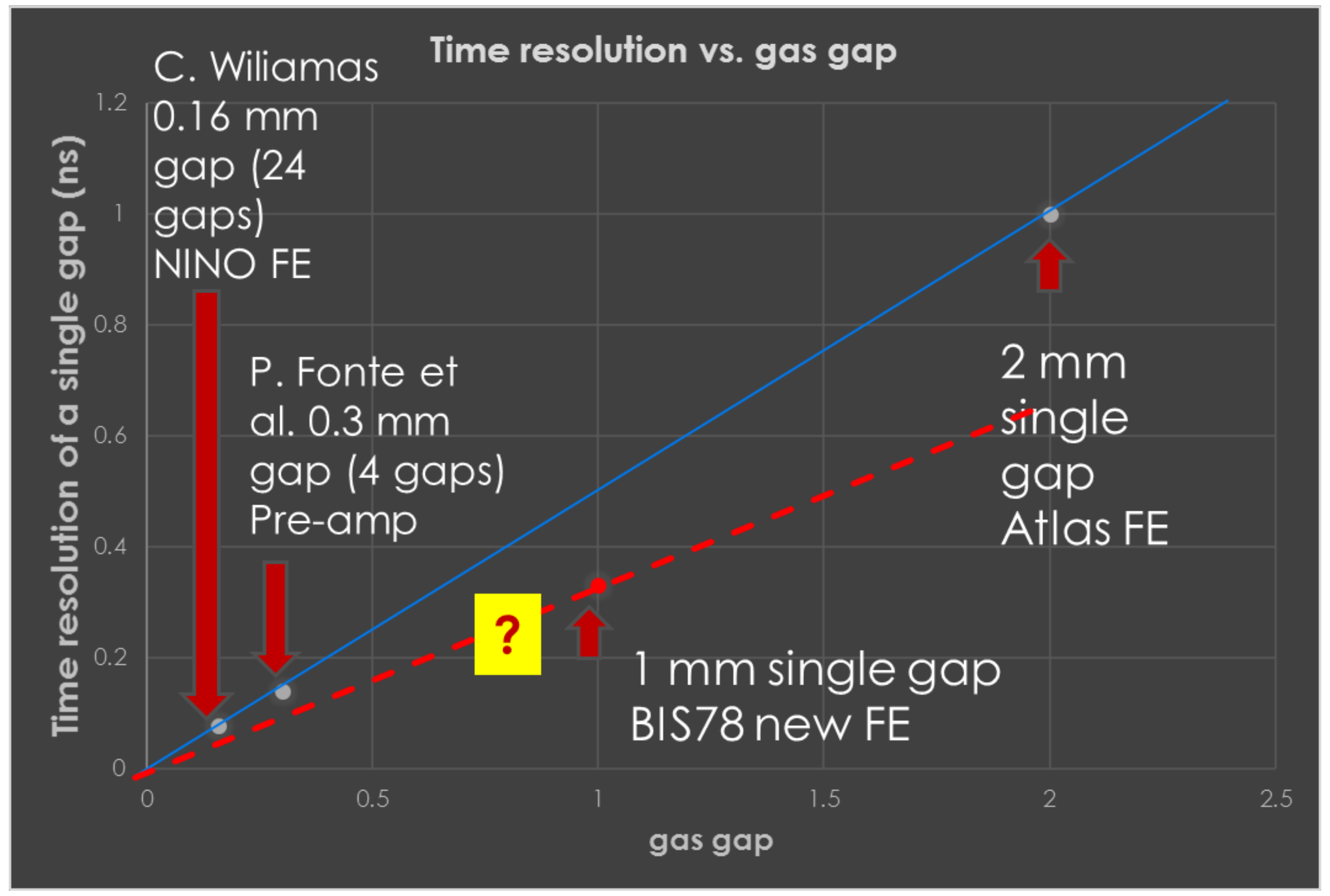
- Increased number of gaps
- Smaller gaps to operate at higher electric fields
- Thinner electrodes for increased SNR
- Low-noise FEE

→ New developments in timing RPCs, A. Blanco

→ Eco-friendly Resistive Plate Chambers for HL-LHC and beyond, M. Abbrescia



https://doi.org/10.3390/app11010111



https://indico.cern.ch/event/999799/

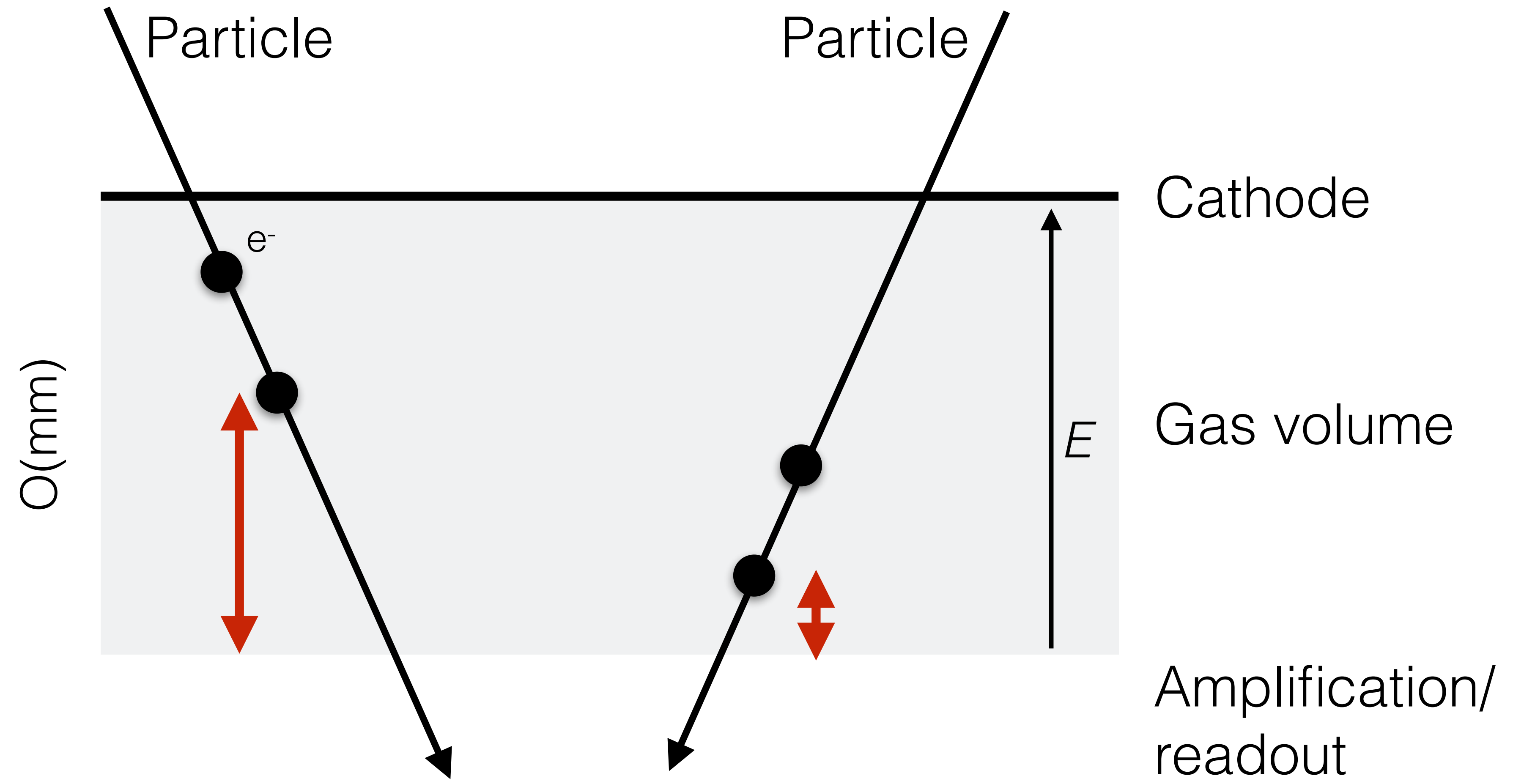
Giulio Aielli, ECFA TF1 Symposium, 2021,
https://indico.cern.ch/event/999799/

Timing limitations of gaseous detectors

Conventional gaseous detectors

Ionisation of gas in active volume

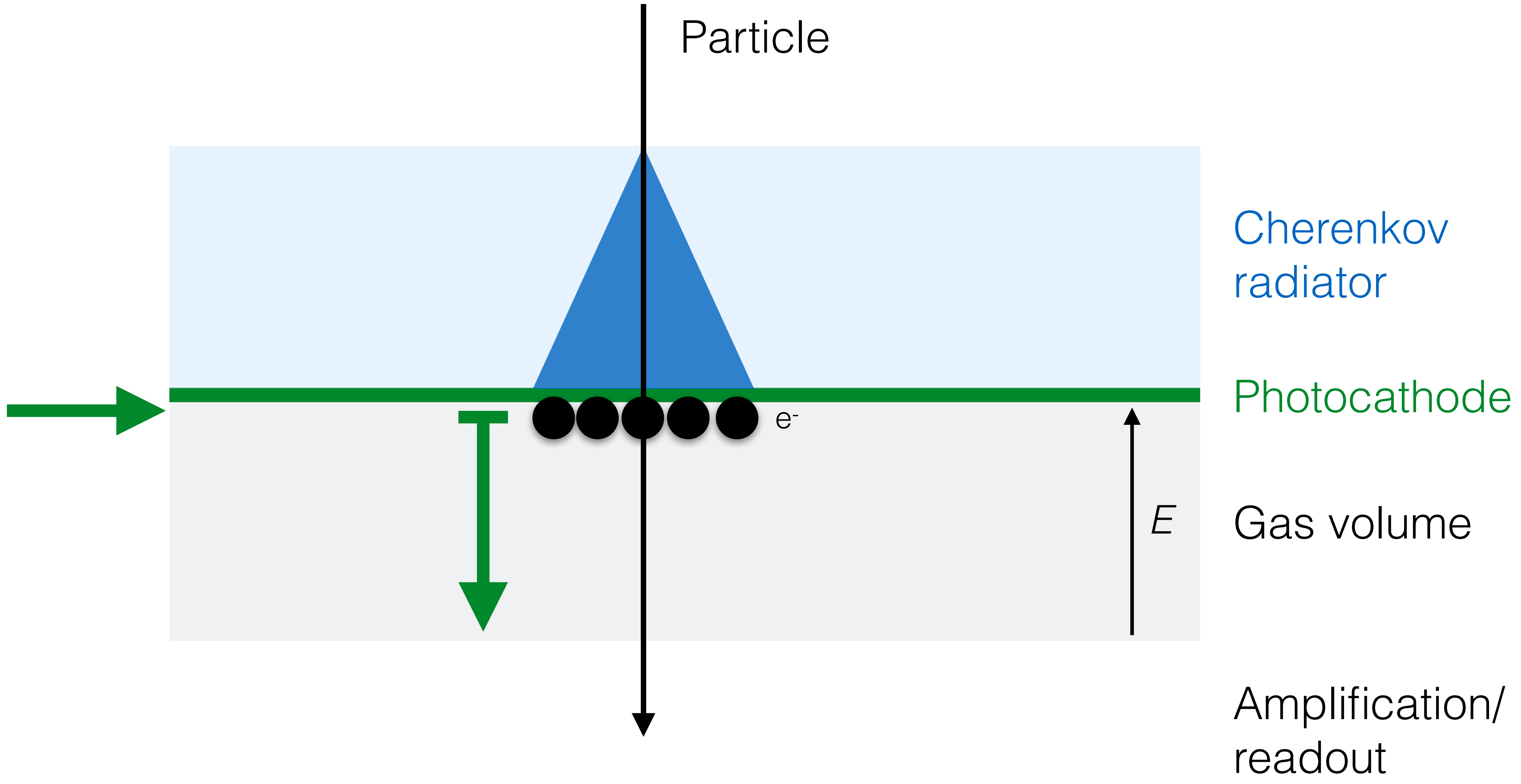
→ Timing jitter of ≈ ns



MPGD precise timing detectors: PICOSEC Micromegas

Cherenkov light emission + photocathode
or solid secondary converter layer

Primary electrons at **well-defined location & time**
→ Timing jitter of ≈ tens of ps

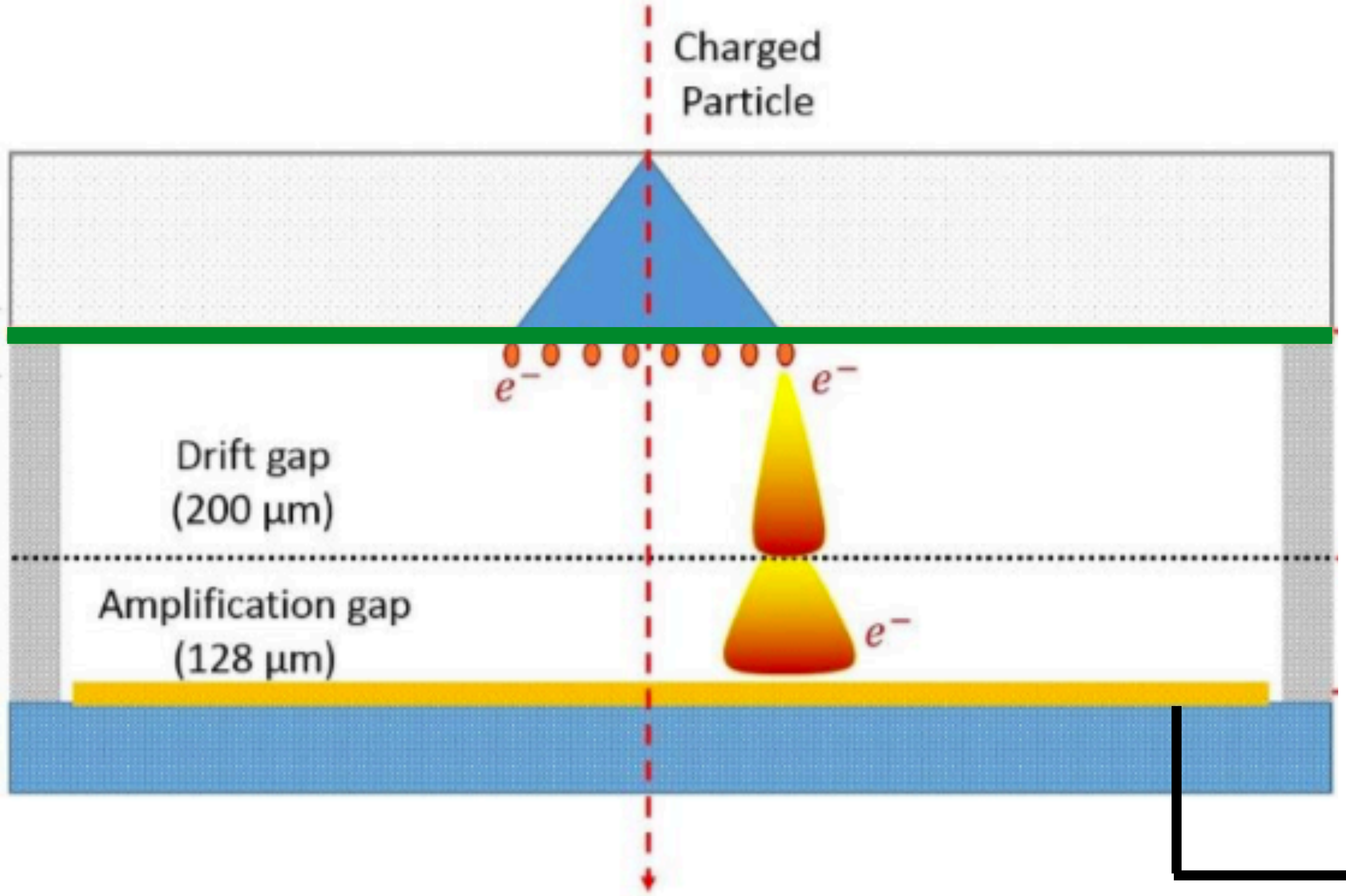


Schematic not drawn to scale

PICOSEC detection concept

Precise timing with Micromegas

PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector
J. Bortfeldt et. al. (RD51-PICOSEC collaboration), NIM A (903), 2018, https://doi.org/10.1016/j.nima.2018.04.033



Cherenkov radiator
(3 mm MgF_2)

Light to charge conversion
Photocathode (CsI)

Preamplification
Drift gap

Amplification
Micromegas

2-stage amplification

Induced signal readout

Gas mixture: 80% Ne + 10% C_2H_6 + 10% CF_4
at ambient pressure

Schematic not drawn to scale

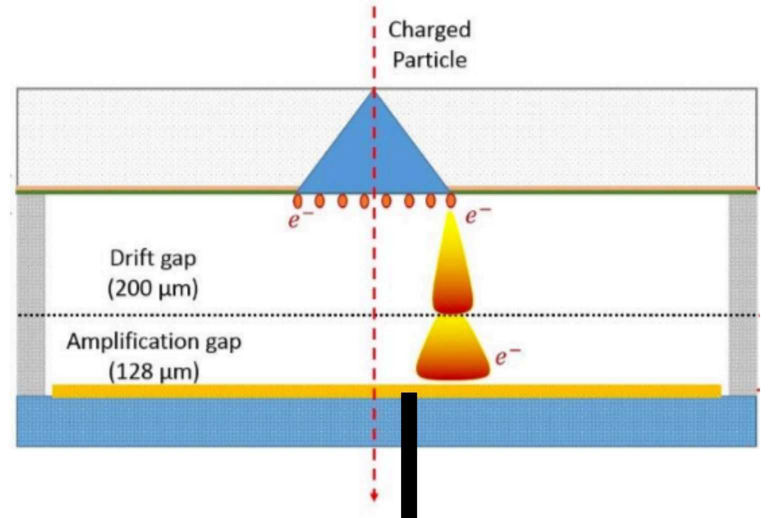
X. Wang et al., Study of DLC photocathode for PICOSEC detector, RD51 collaboration meeting, October 2018

PICOSEC detection concept

Precise timing with Micromegas

Induced signals are recorded from anode pads, amplified and digitised

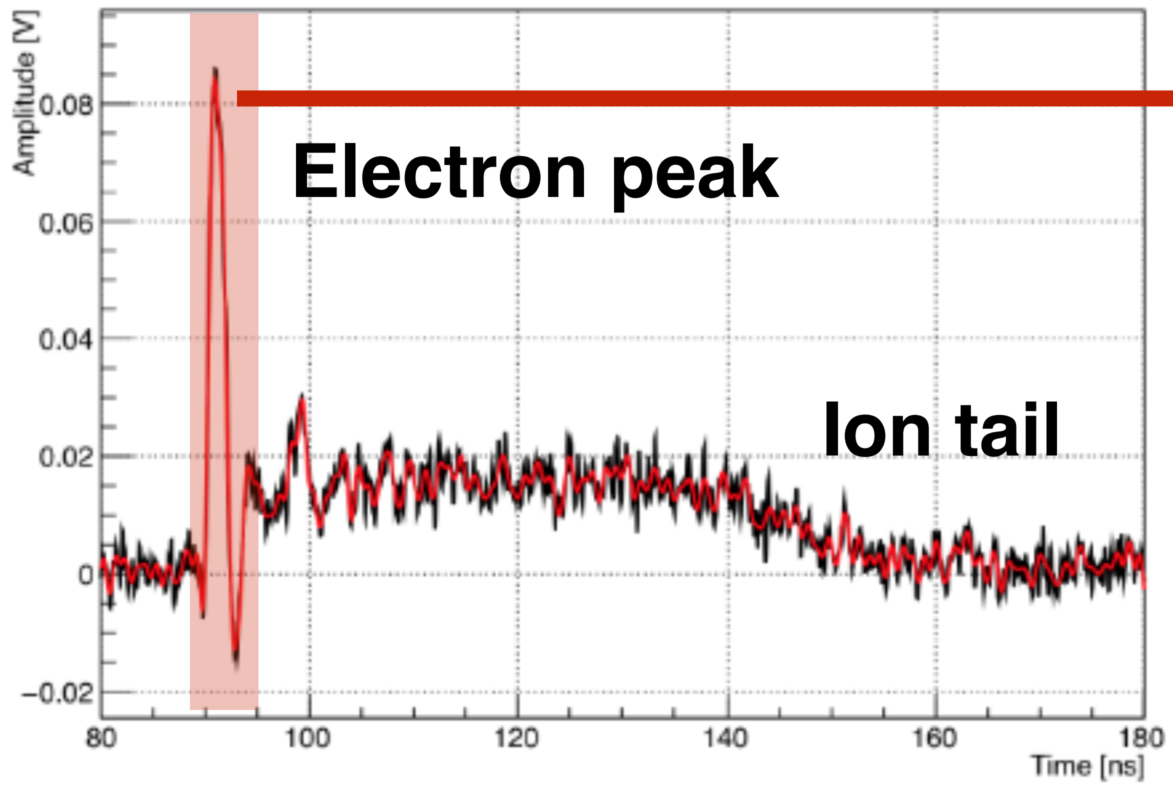
Rising edge of fast electron peak is used for timing measurements with CFD to account for time walk



Preamplification of induced signal

Digitized by high-bandwidth oscilloscope @ 20GSamples/s

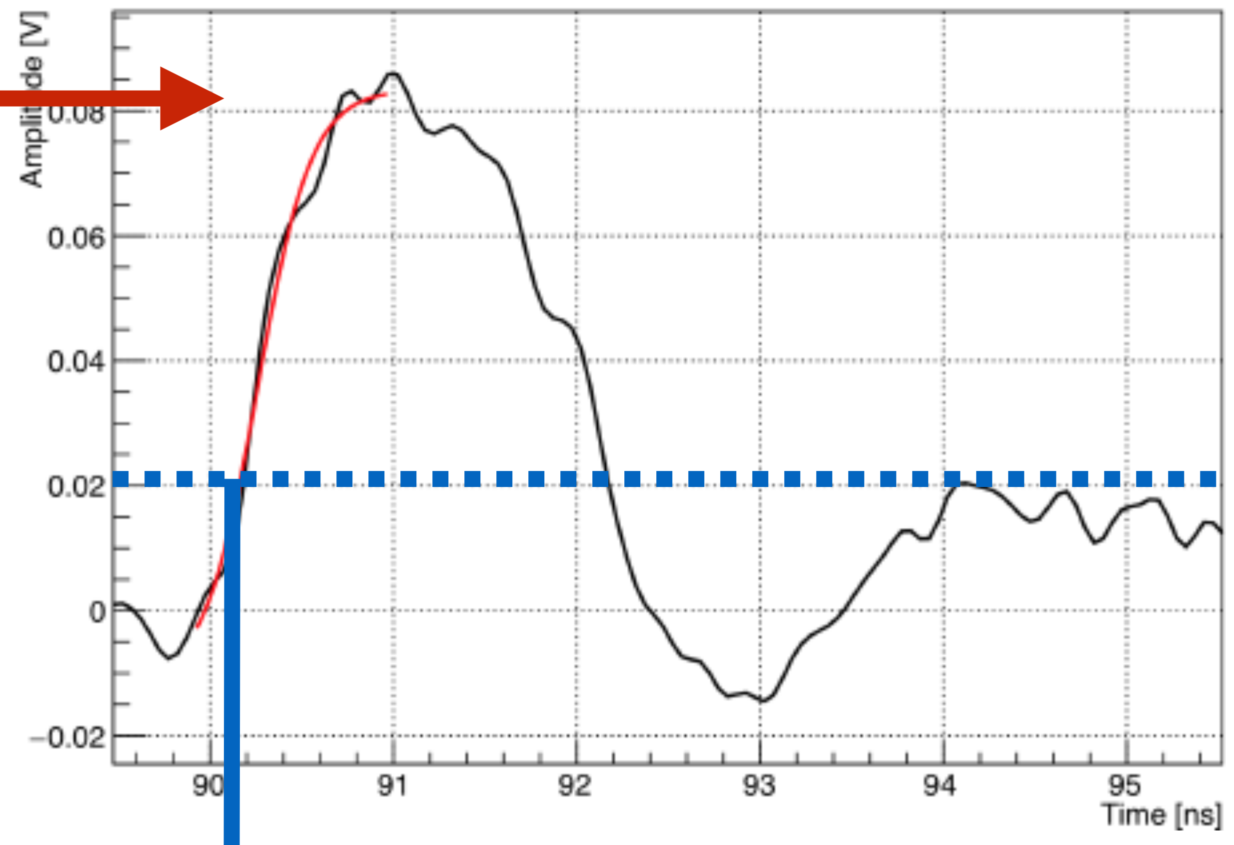
Recorded waveform



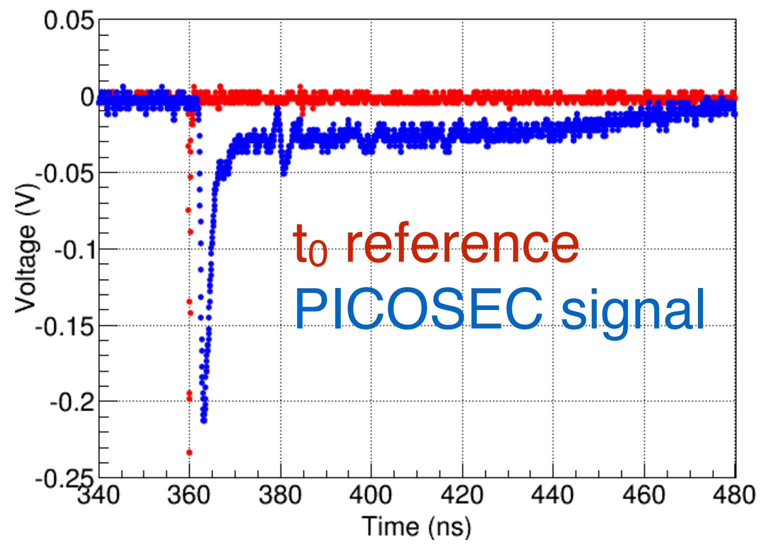
Signal with two distinct components:

- Electron peak: fast (≈0.5 ns)
- Ion tail: slow (≈100 ns)

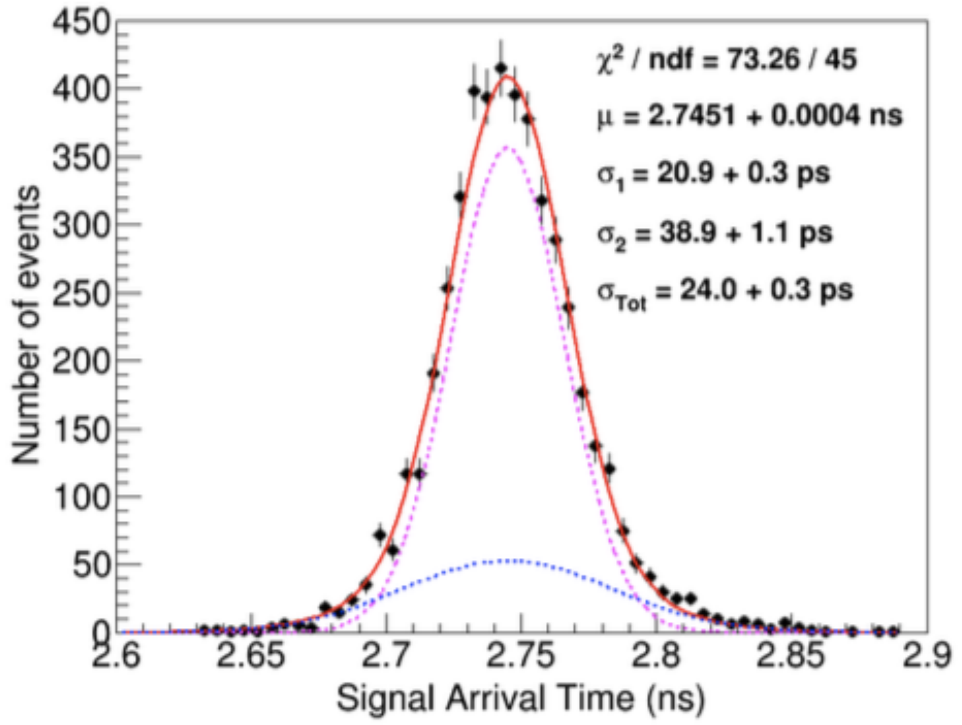
Zoom: electron peak



Constant Fraction Discrimination (**CFD**) at 20% on the fitted noise-subtracted e-peak



Time difference between signal and reference



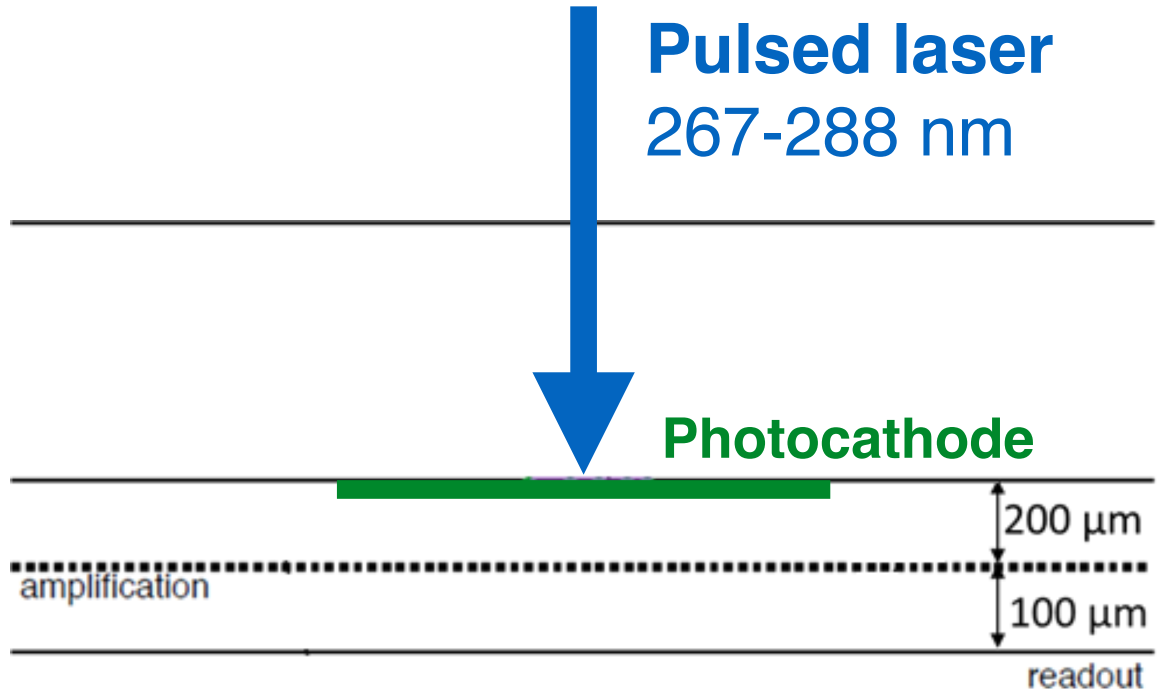
24 ps timing resolution (for MIPs)

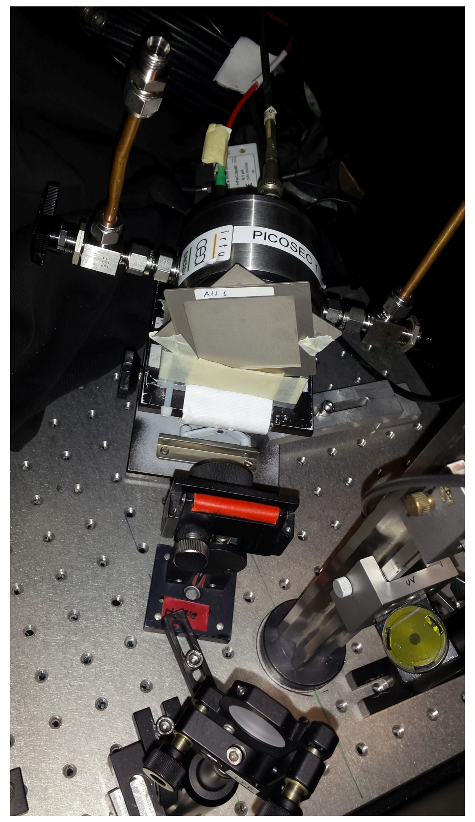
Schematic not drawn to scale

Measurements of timing performance

Achievable timing resolution is measured with pulsed laser for single photoelectron signals and in test beam campaigns for Minimum Ionising Particle (MIP) timing response

Laser tests





Pulsed laser at IRAMIS facility (CEA Saclay)

Fast photodiode (<5 ps resolution) as **timing reference**.

Detailed detector response studies in well-controlled conditions: direct production of **single photoelectrons** at photocathode.

L. Sohl, Overview on recent PICOSEC-Micromegas developments and performance tests, RD51 Mini-Week February 2020, https://indico.cern.ch/event/872501/contributions/3726013/

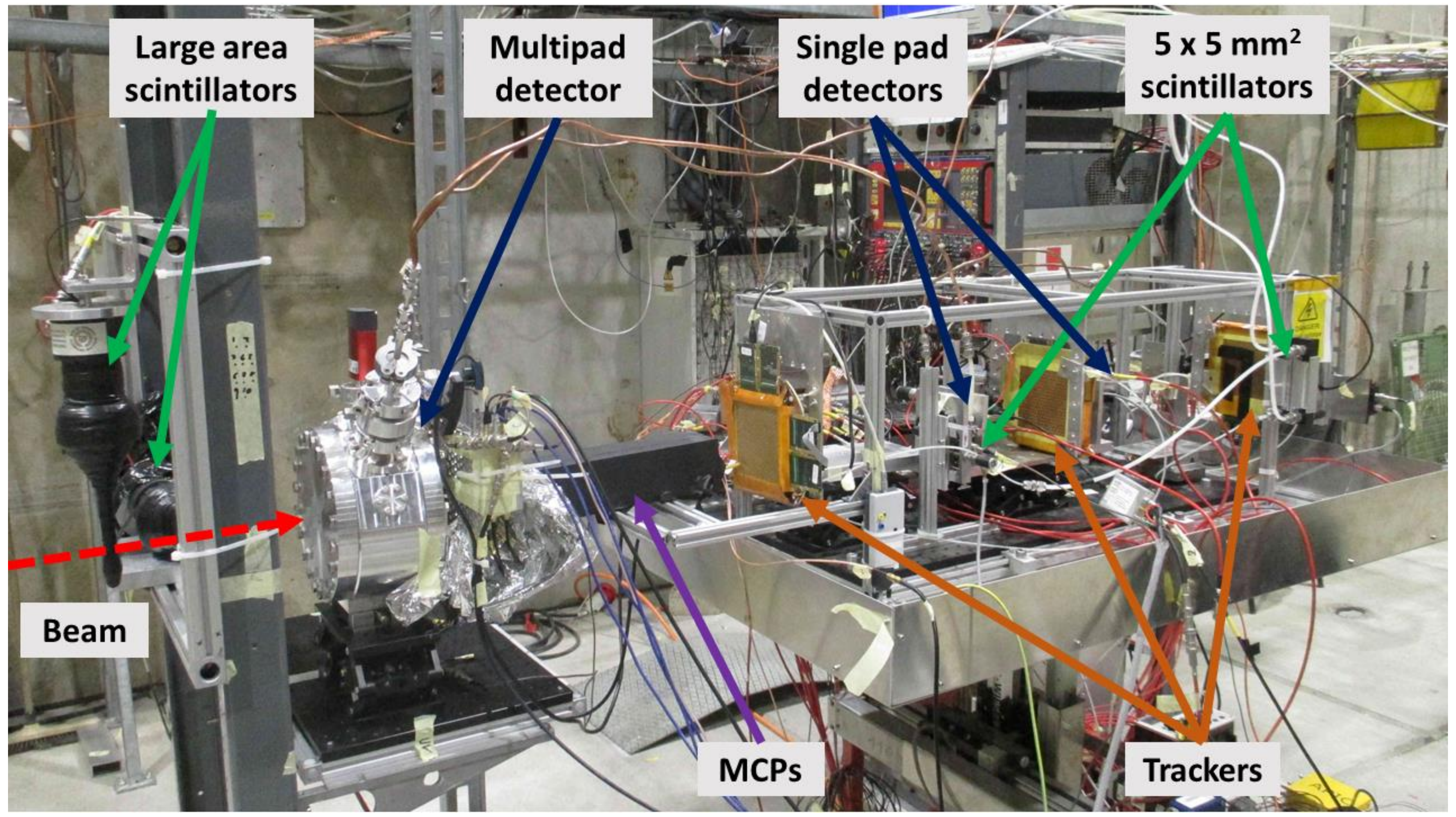
Schematic not drawn to scale

MIP test beam campaigns

150 GeV muons and pions from SPS

Two **MCP-PMTs** used as timing reference (<5 ps resolution)

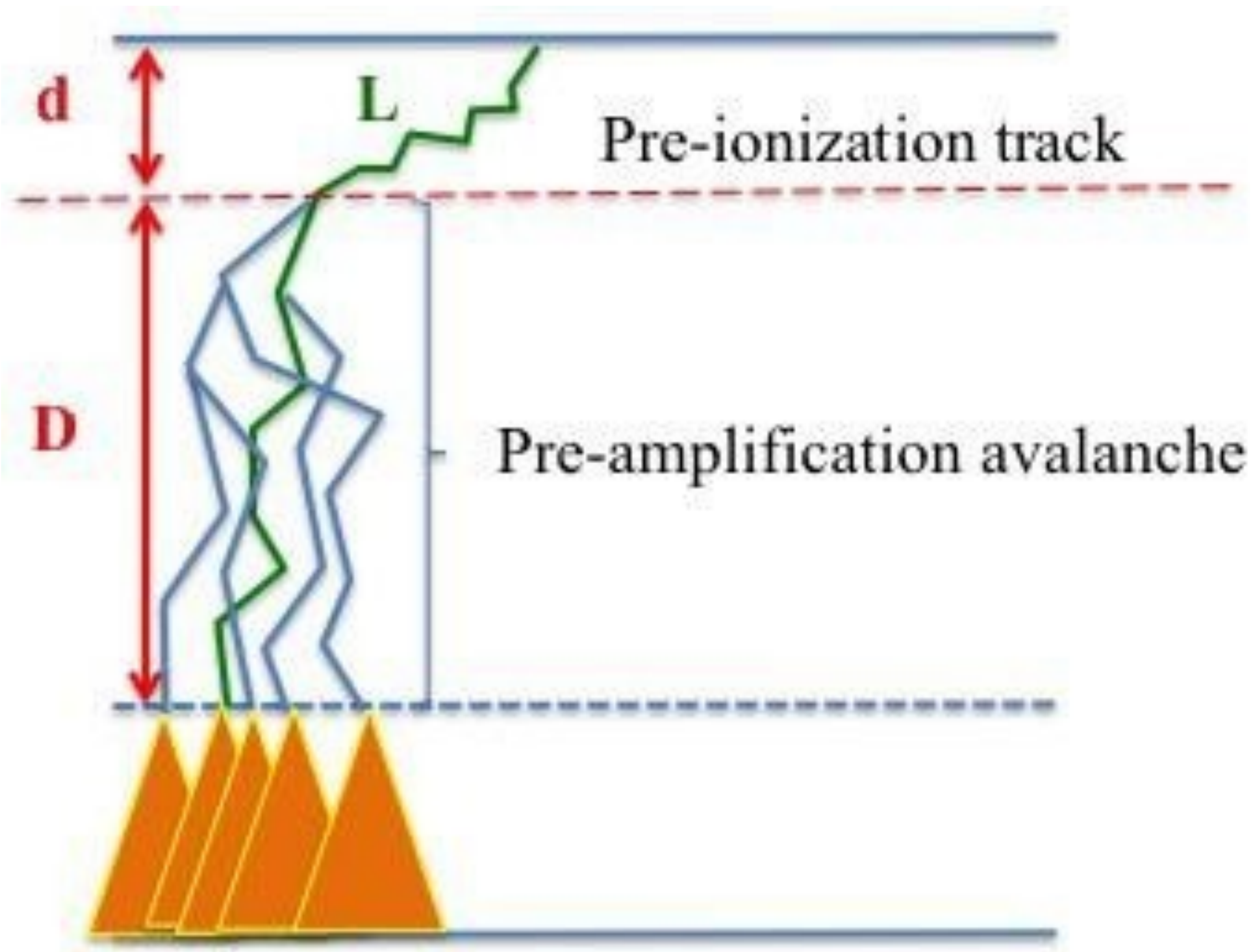
Detector response to MIP (higher number of photoelectrons) and stability



Detector response

Time resolution depends primarily on e-peak charge

SAT depends on e-peak size:
- bigger pulses → lower SAT
- higher drift field → lower SAT

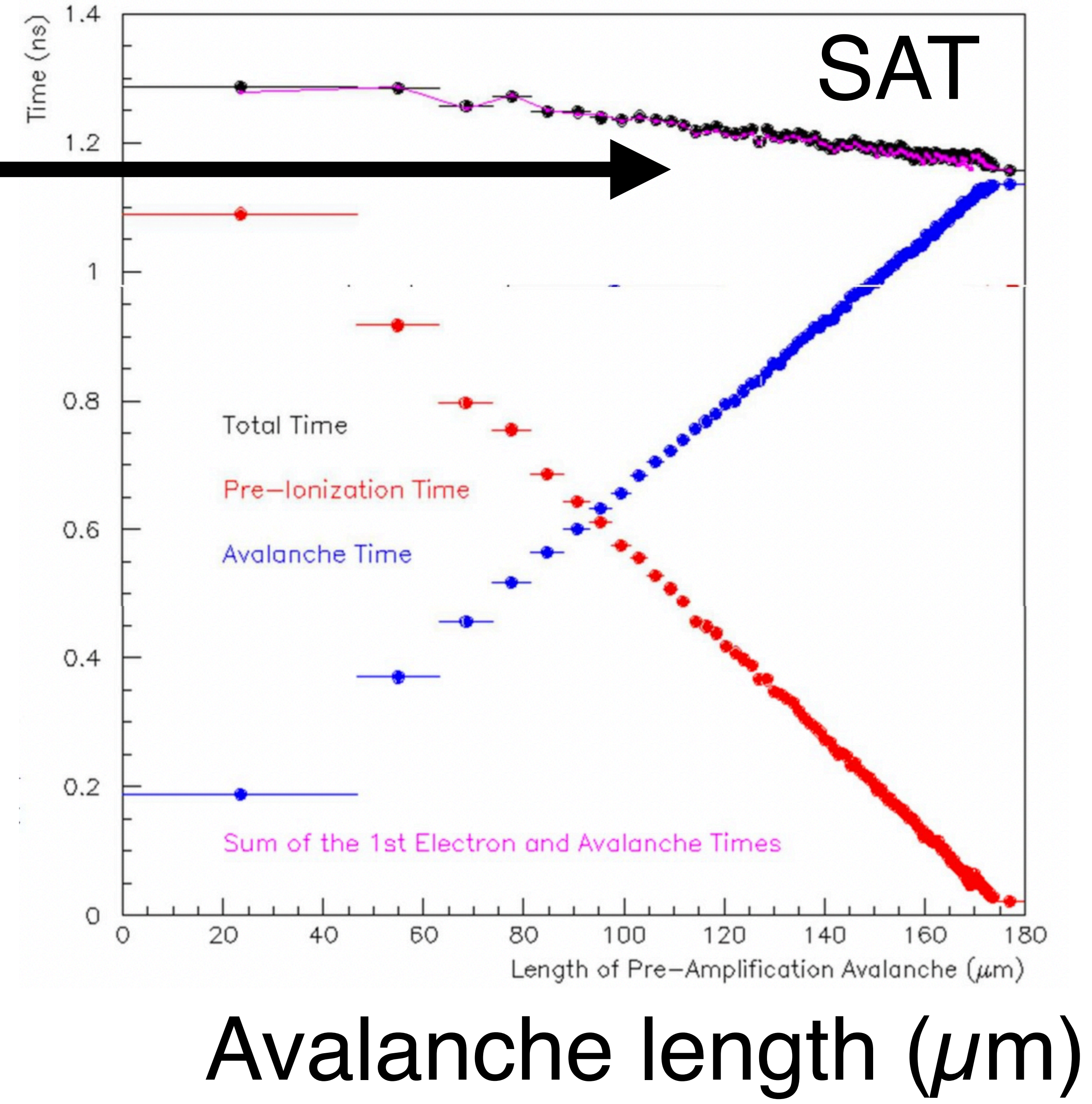


Location of first ionisation determines length of avalanche

Longer avalanches result in bigger e-peak charge
SAT reduces with e-peak charge

Short pre-ionisation track → larger e-peak charge → better time resolution

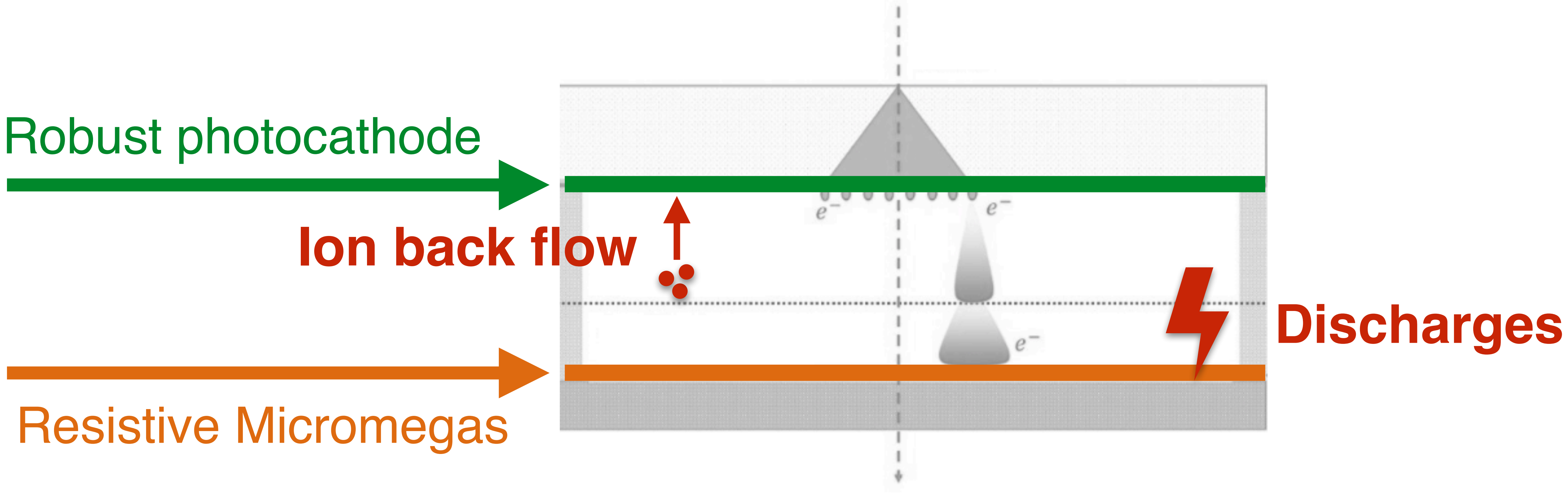
K. Kordas, Progress on the PICOSEC-Micromegas Detector Development: towards a precise timing, radiation hard, large-scale particle detector with segmented readout, VCI2019 - The 15th Vienna Conference on Instrumentation
https://indico.cern.ch/event/716539/contributions/3246636/



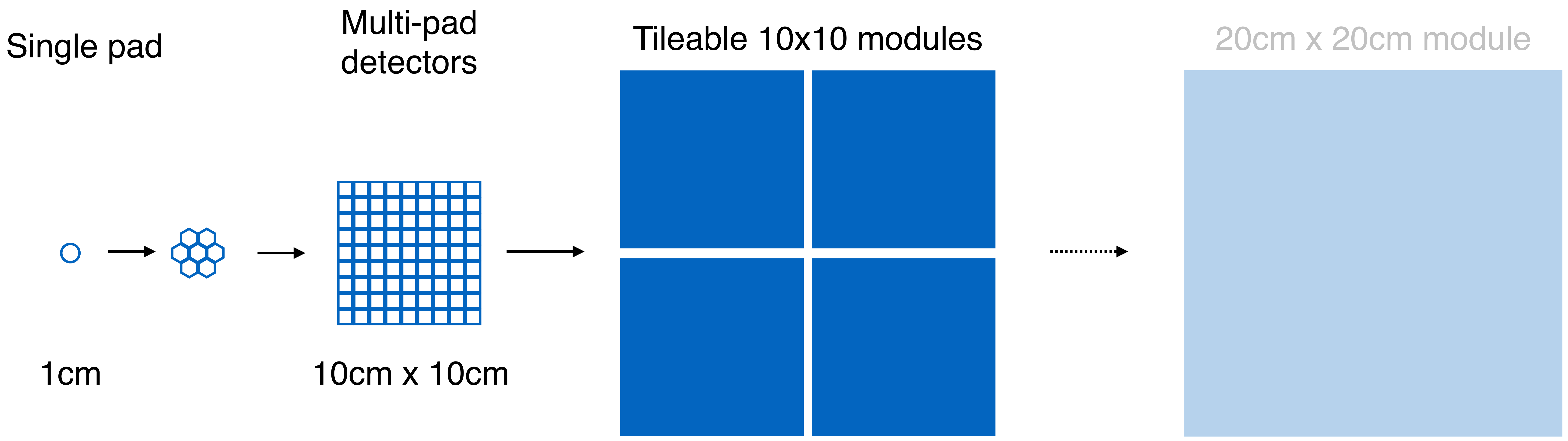
Towards a robust, large-area detector

Robustness

- Resistive Micromegas
- Robust photocathodes

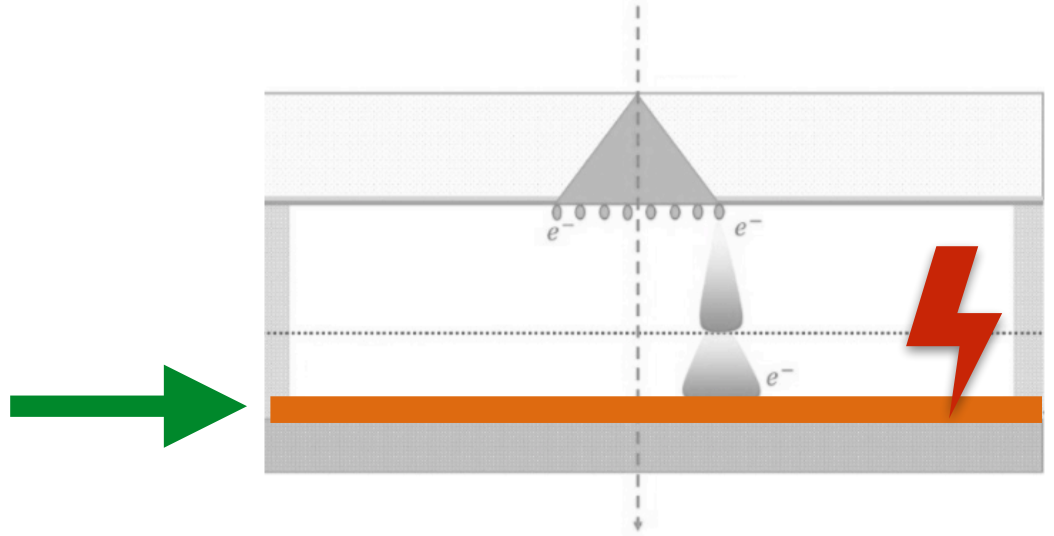


Tileable detector modules



Schematic not drawn to scale

Resistive Micromegas

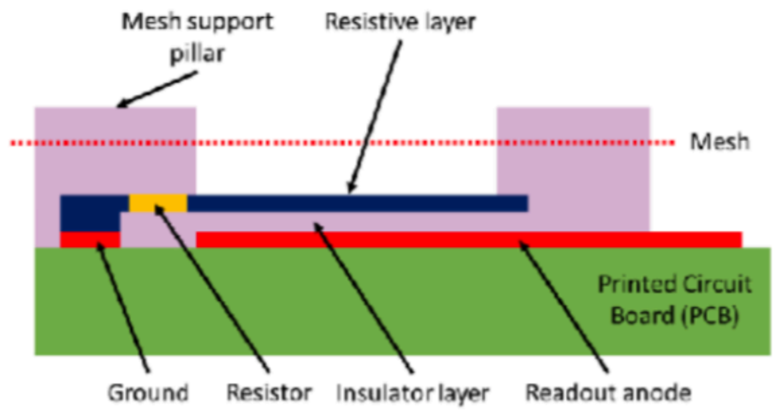


Resistive elements (layer, discrete resistors) to limit destructive effect of discharges by limiting energy released

Sufficiently high resistivity
→ Protect Micromegas by limiting discharge energy
→ Minimise impact on signal rising edge

Sufficiently low resistivity
→ Avoid voltage drop resulting from current through resistive layer
→ Exploit signal spreading for improved spatial resolution

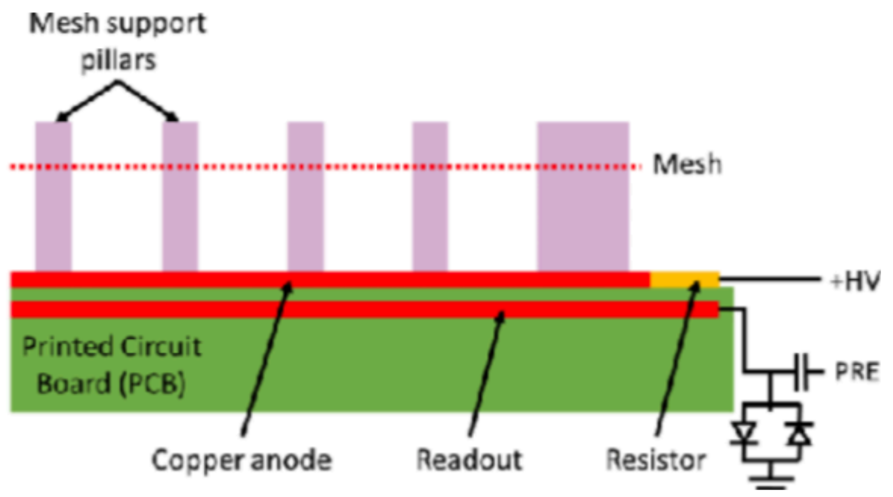
Resistive strips (MAMMA)



T. Alexopoulos et al., NIMA **640** (2011) 110-118

σ = 41 ps

Floating strips (COMPASS)

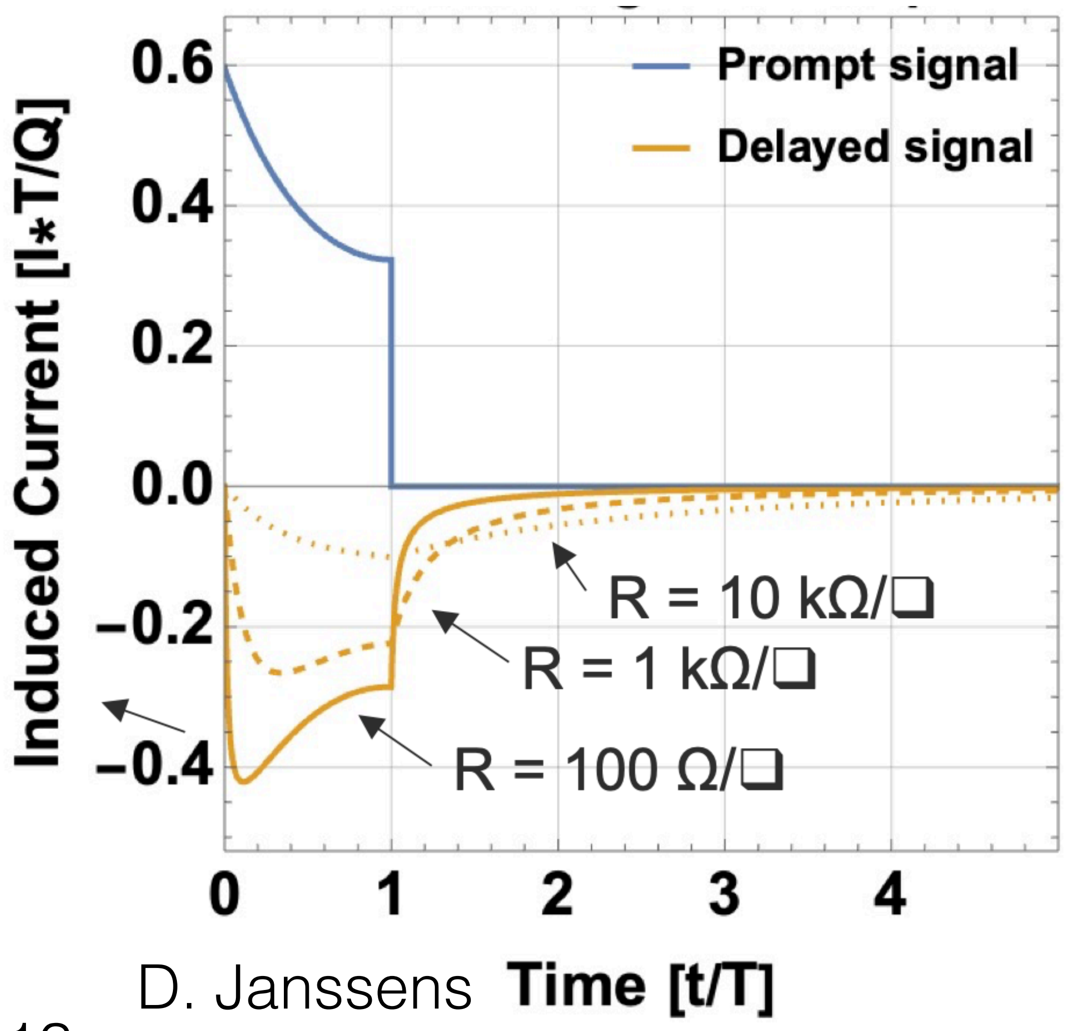


σ = 28 ps

L. Sohl, "Progress of the PICOSEC Micromegas concept towards a robust particle detector with segmented readout" 9th Symposium on large TPCs for low-energy rare event detection", 2018, https://indico.cern.ch/event/715651

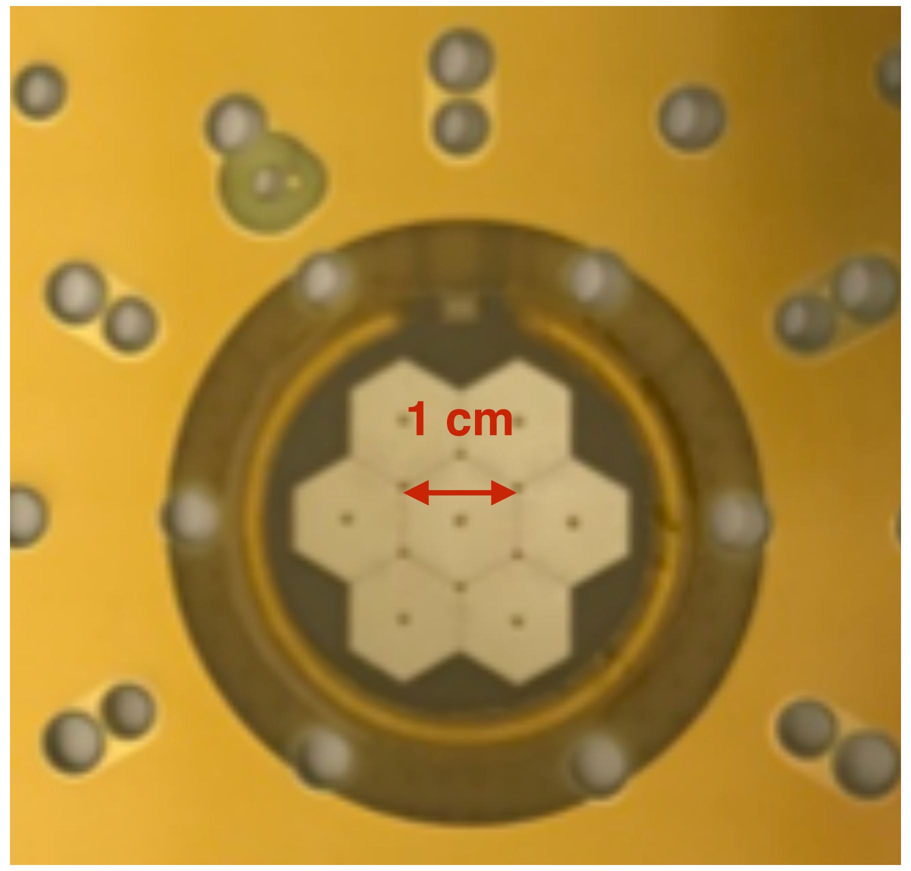
Schematic not drawn to scale

Simulation of signals induced in resistive detectors



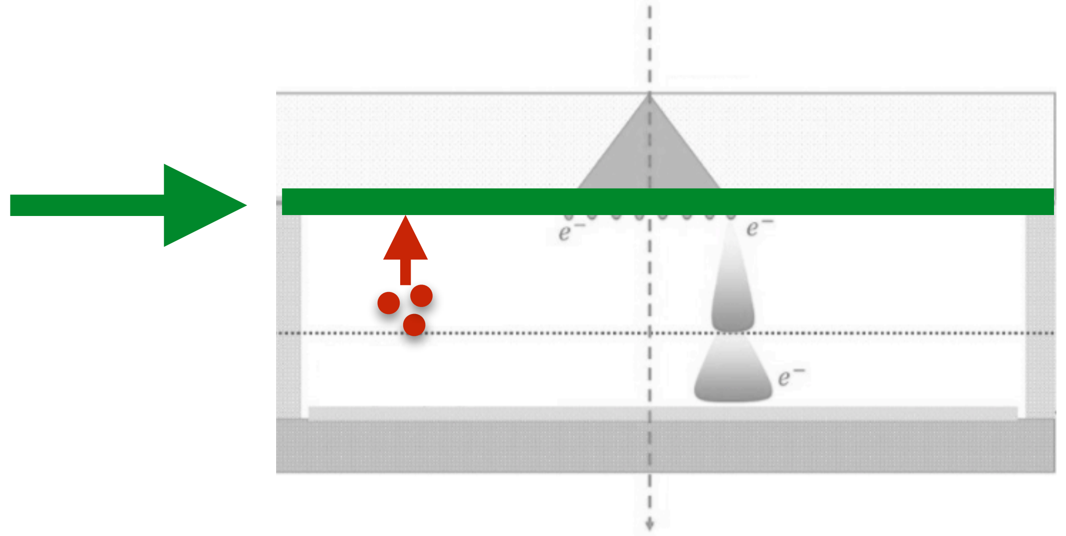
D. Janssens

Systematic study of **different resistivities** in **multi-pad** PICOSEC prototype



T. Papaevangelou,
L. Sohl, CEA Saclay

Photocathode robustness

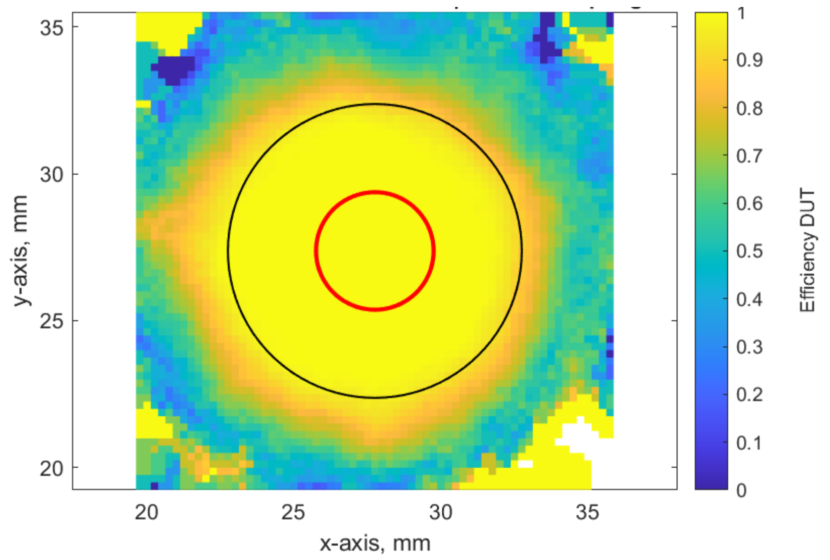


Robustness of photocathode is important to preserve QE and thus full detection efficiency and timing resolution during prolonged operation.

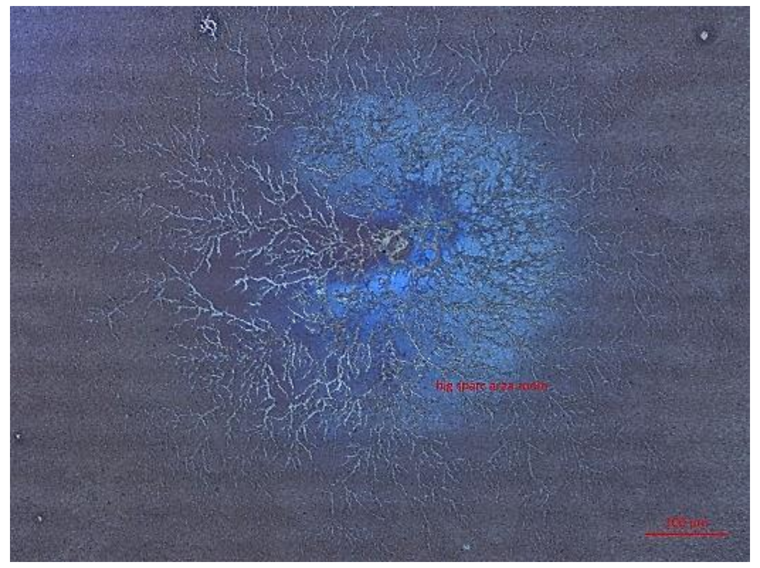
Standard PICOSEC photocathode: 18 nm CsI + 3 nm Cr → ≈10 p.e. / MIP

CsI sensitive to humidity, ion backflow and sparks

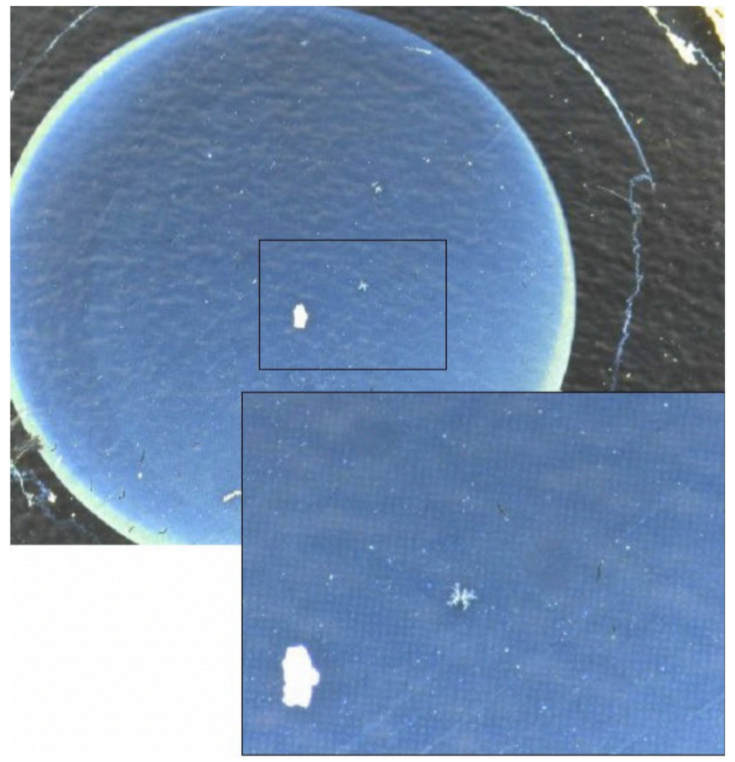
Efficiency map with CsI



CsI after spark

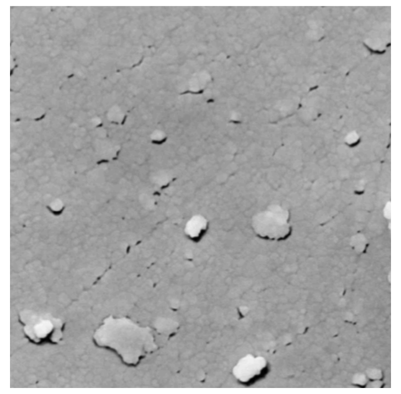


Ion backflow on CsI

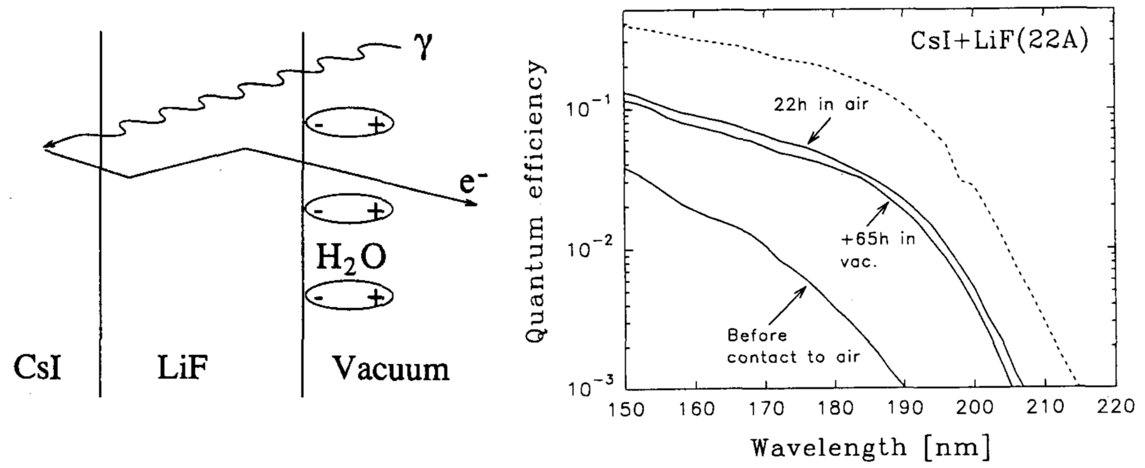


Making CsI more robust

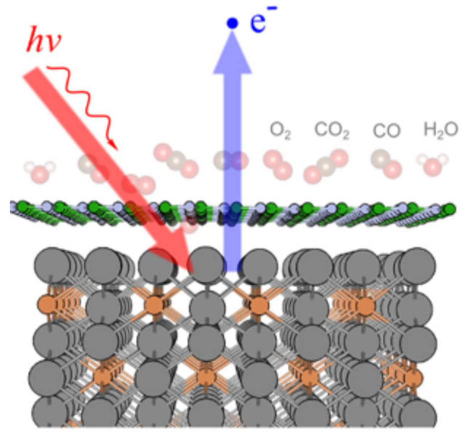
- Minimise effect of ion back flow while preserving QE
- Protection layers (MgF_2, LiF, graphene, …)



10.1016/ j.nima.2009.05.179



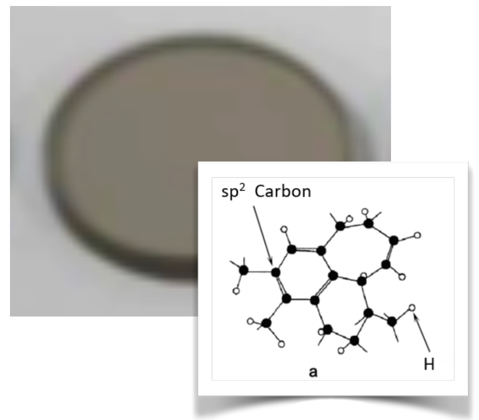
CsI + LiF_2, A. Breskin et al., 10.1109/23.467832



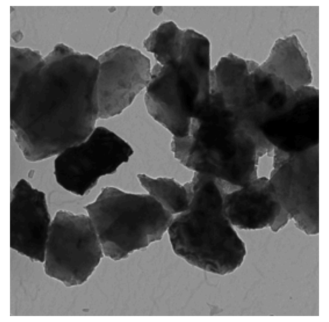
Graphene passivation, G. Wang et al

Alternative photocathodes

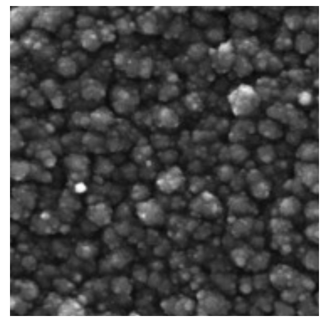
- Inherently robust materials (with possible lower QE)
- Metallic, DLC, B_4C, nano diamonds, CVD diamond, GaN, …



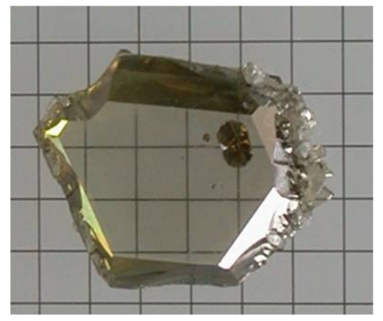
DLC, Y. Zhou et al.



ND, L. Velardi et al.



B_4C, 10.1016/ j.jnucmat.2015.01.015



GaN crystal

Picosec detector modules

Scaling up to tileable modules for larger area coverage

Detector → Preamplifier → Digitisation

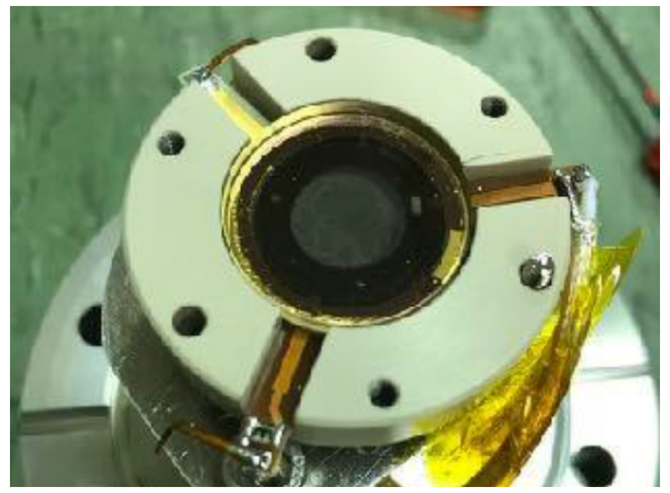
Several variants of multi-channel PICOSEC prototypes in development / under test to address challenges associated with scaling to larger areas:

Integration

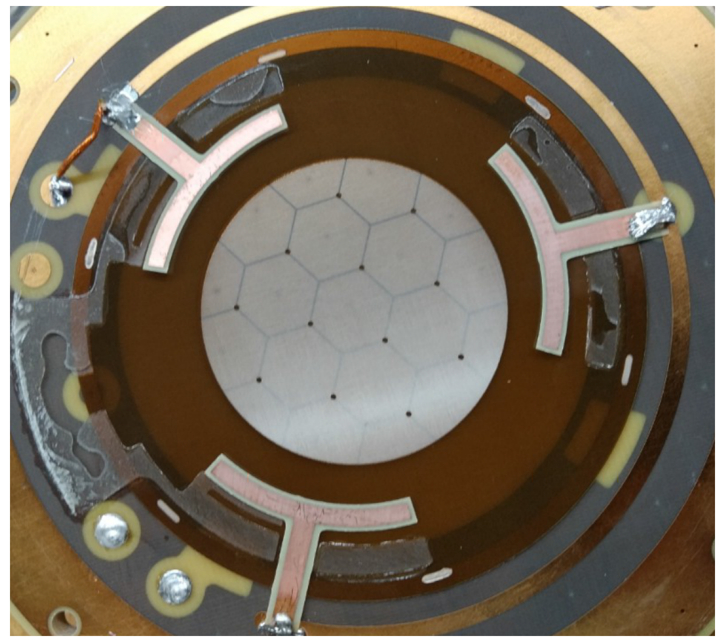
- Mechanics to preserve precise gaps
- Tileing & compact detector vessel

Electronics

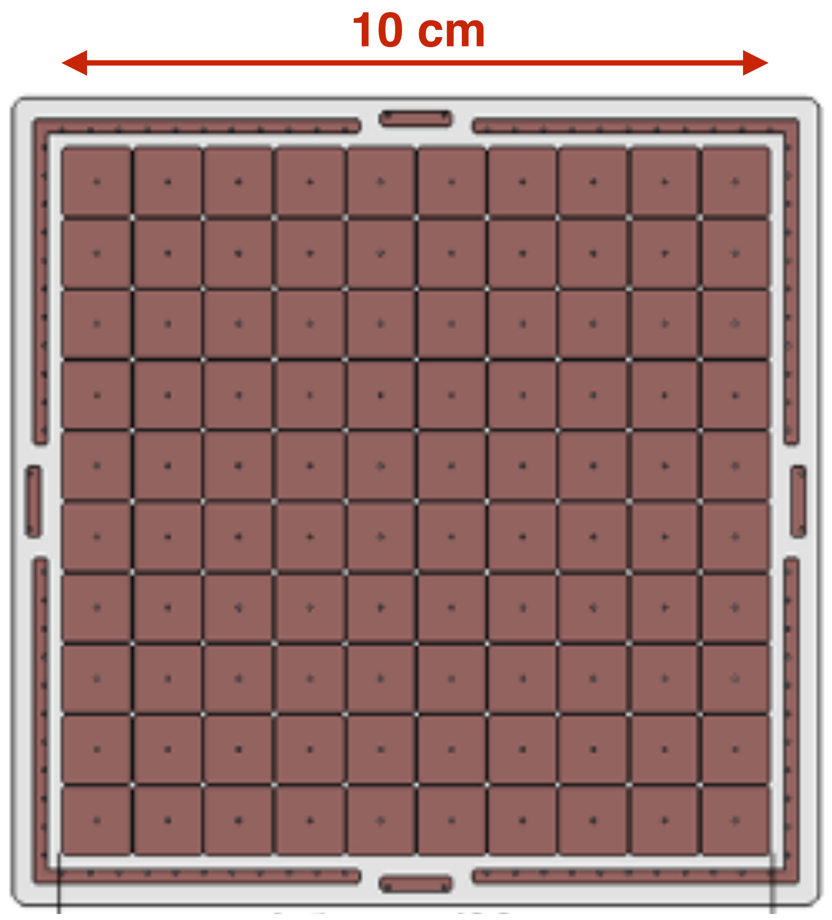
- Signal sharing between pads
- Premplifiers and multi-channel digitisers



Single pad (2016)
ø1 cm



Multi pad (2017)
⬡ 1 cm

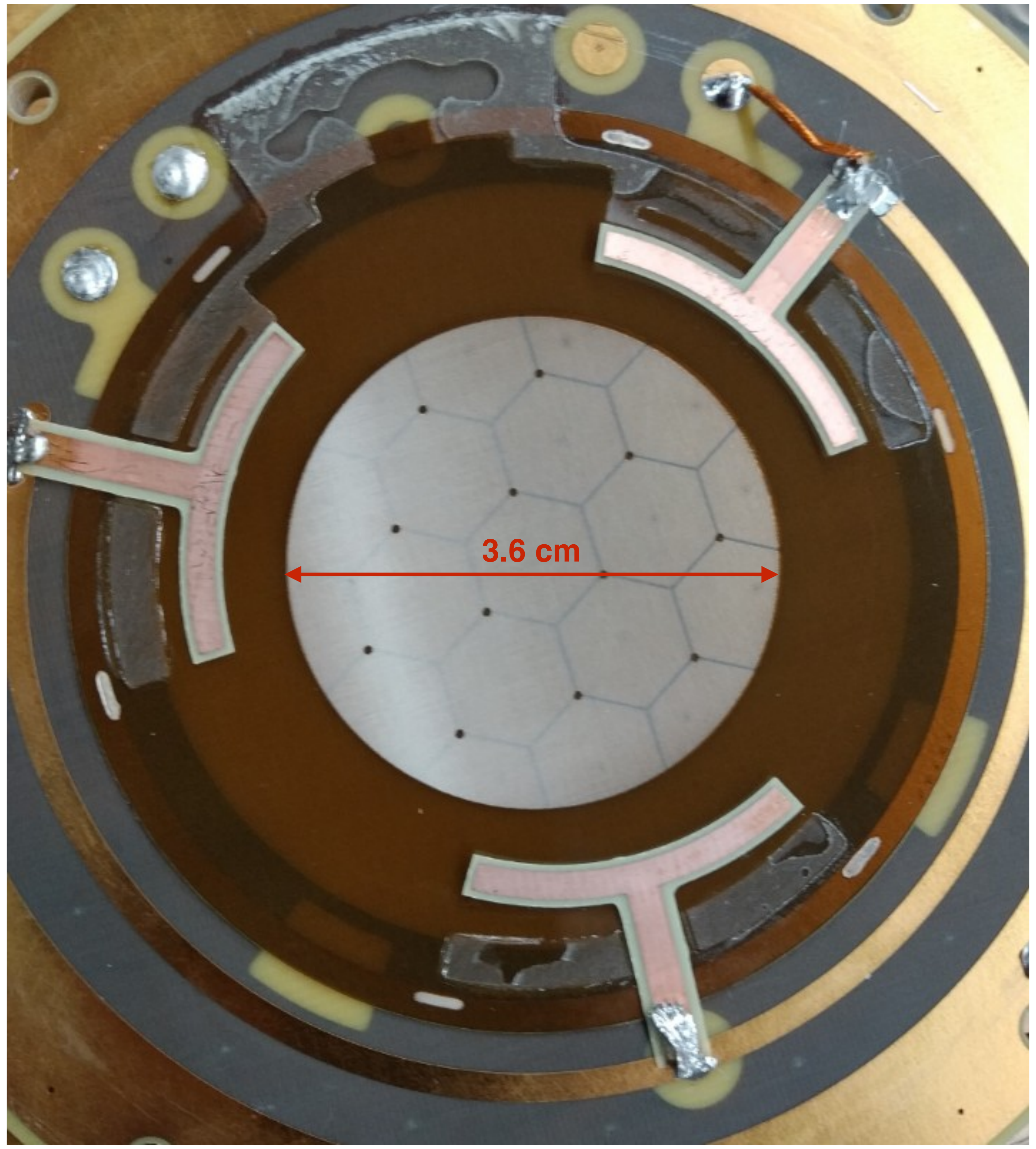


10x10 module
◻ 1 cm

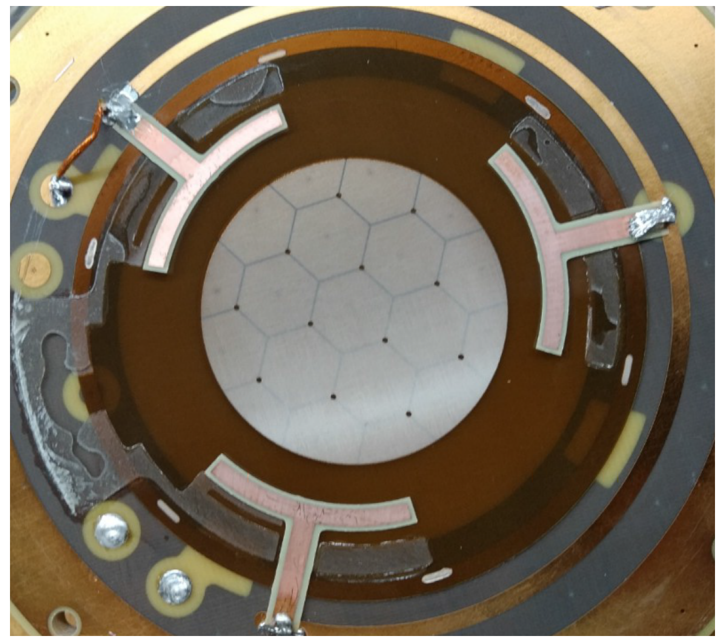
Large-area coverage

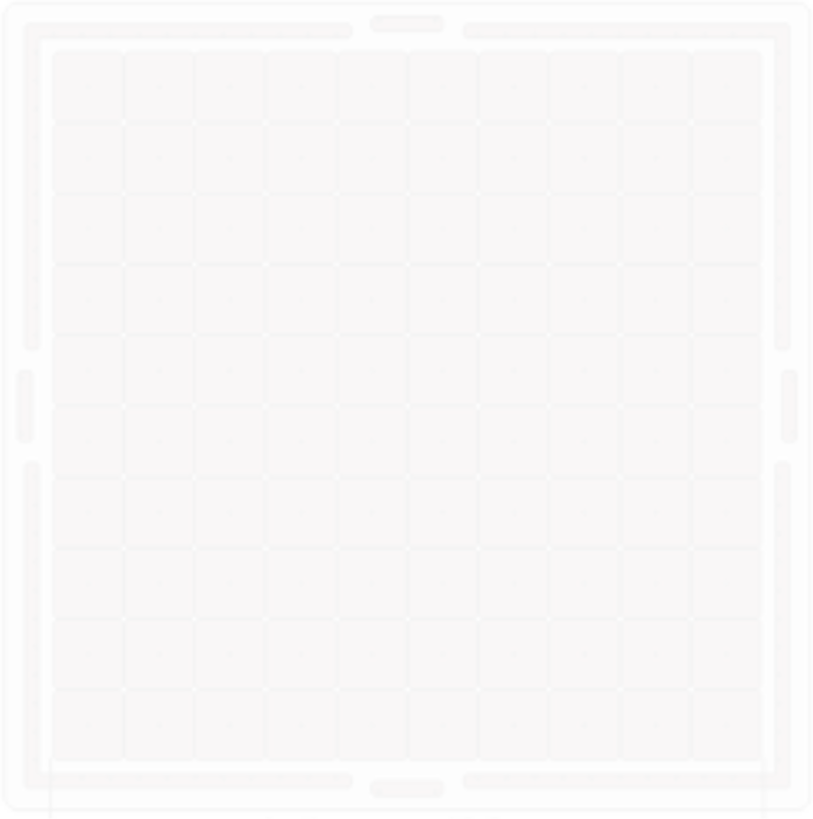
Scaling up multi-channel PICOSEC

Multi-pad prototype was evaluated in test beam campaigns to study achievable time resolution for **signal shared across multiple pads**



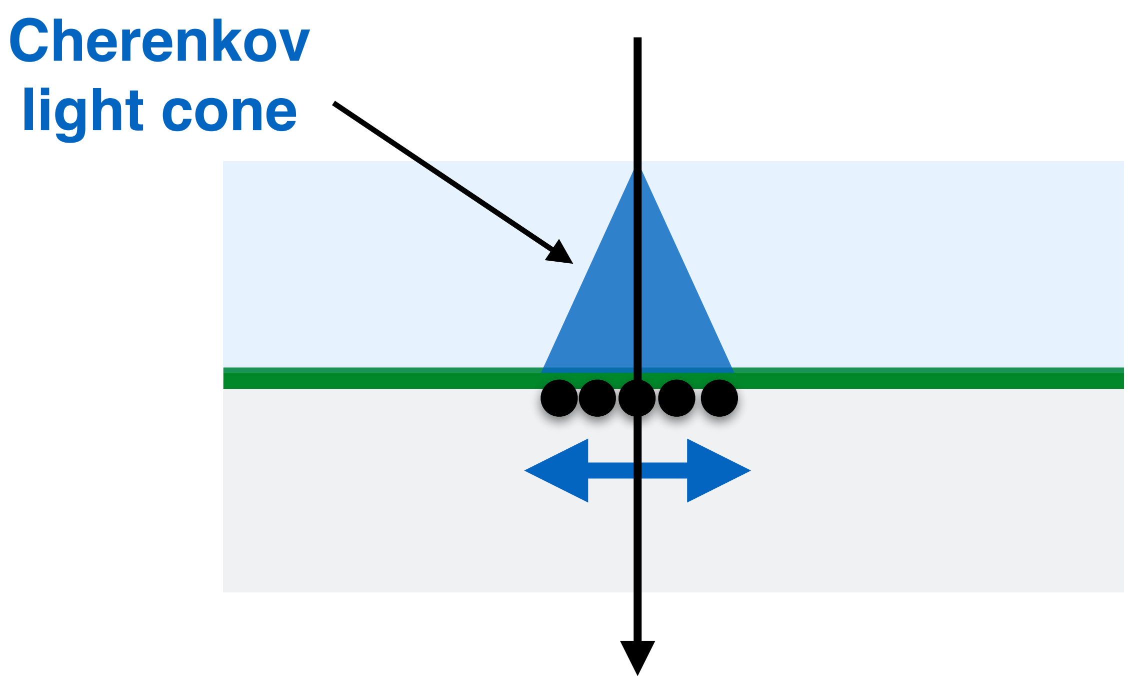

Single pad (2016)
⌀1 cm

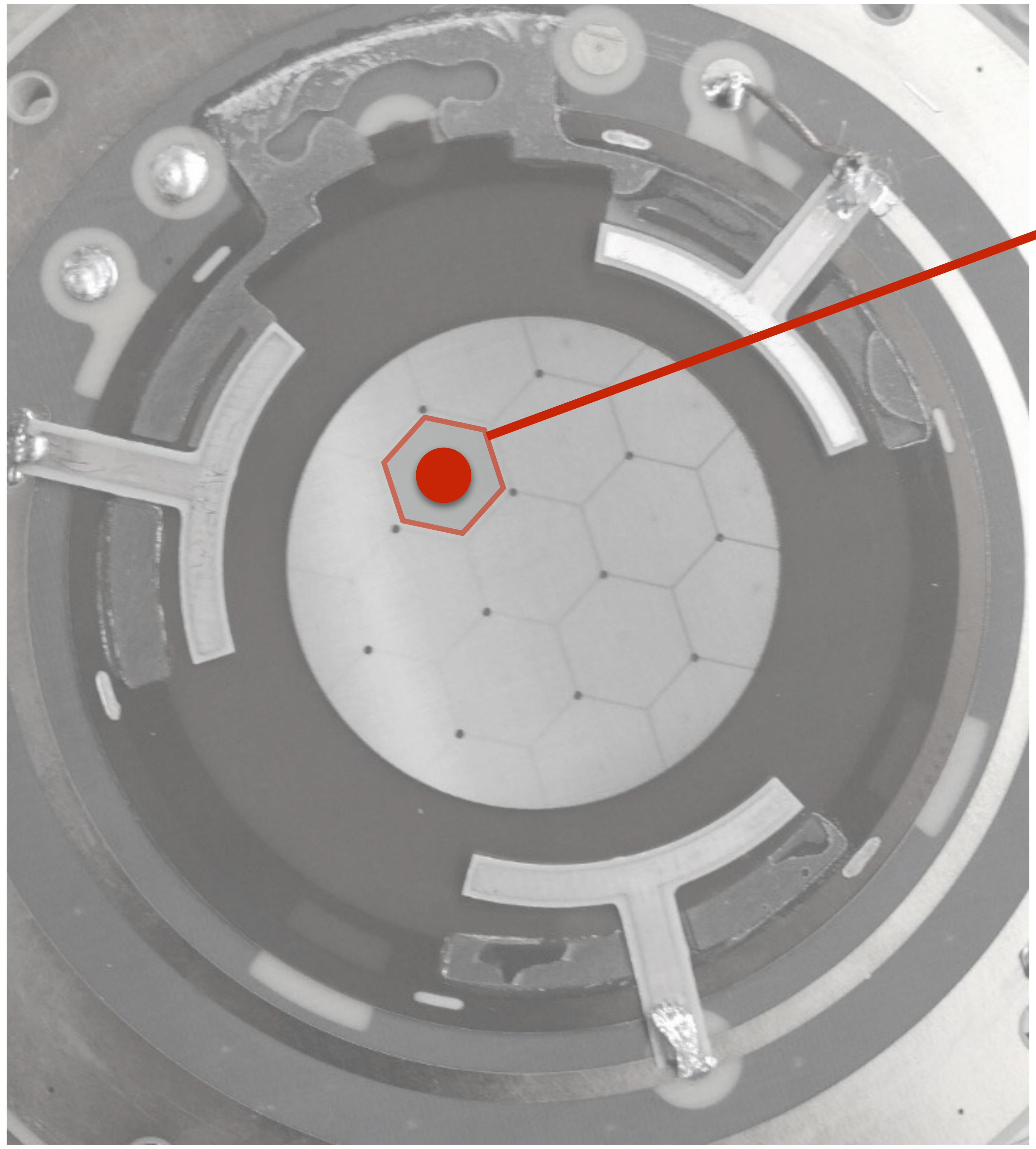

Multi pad (2017)
⬡ 1 cm

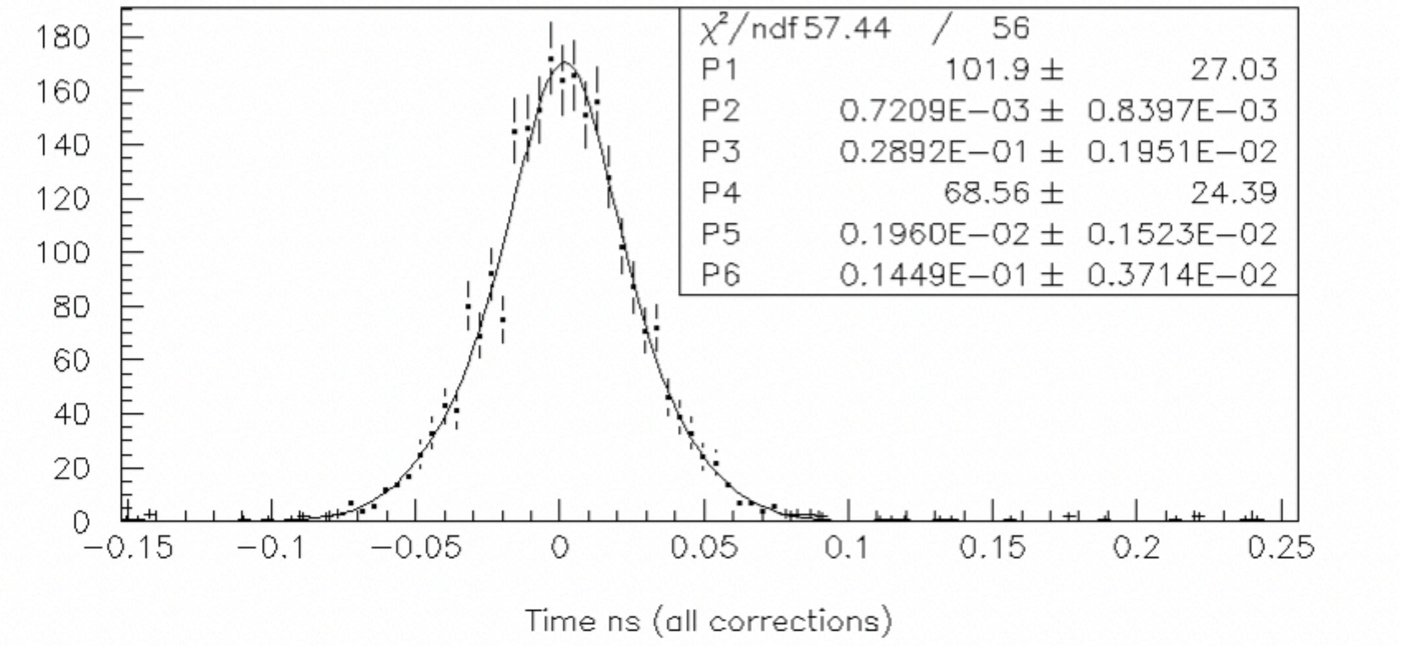

10x10 module
□ 1 cm

Large-area coverage

Scaling up multi-channel PICOSEC





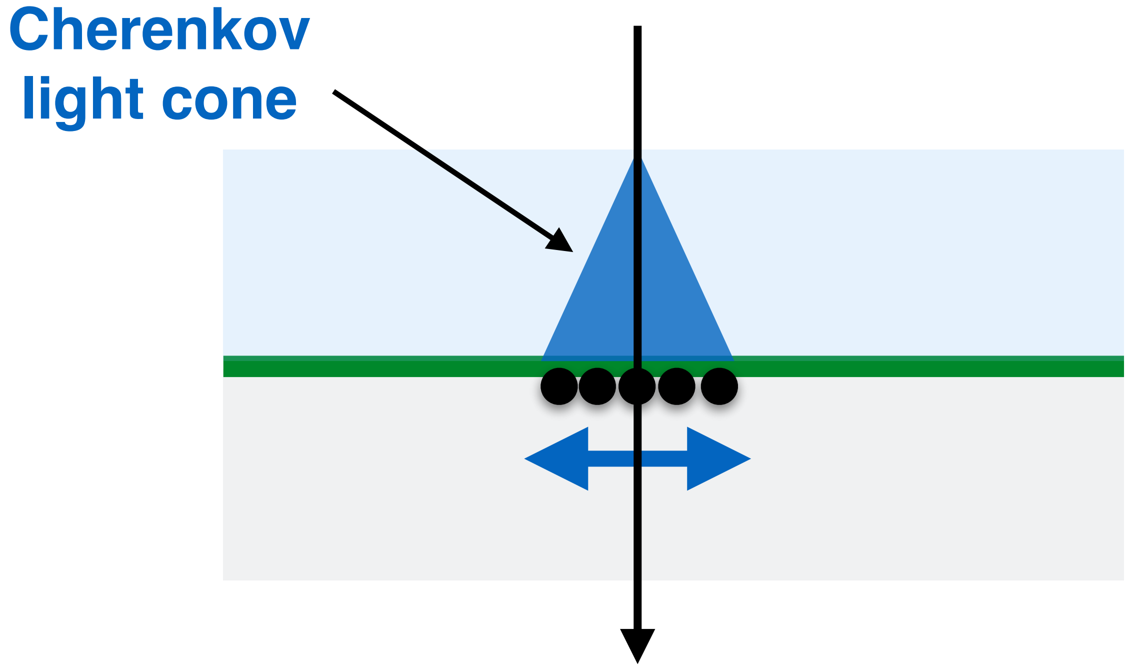


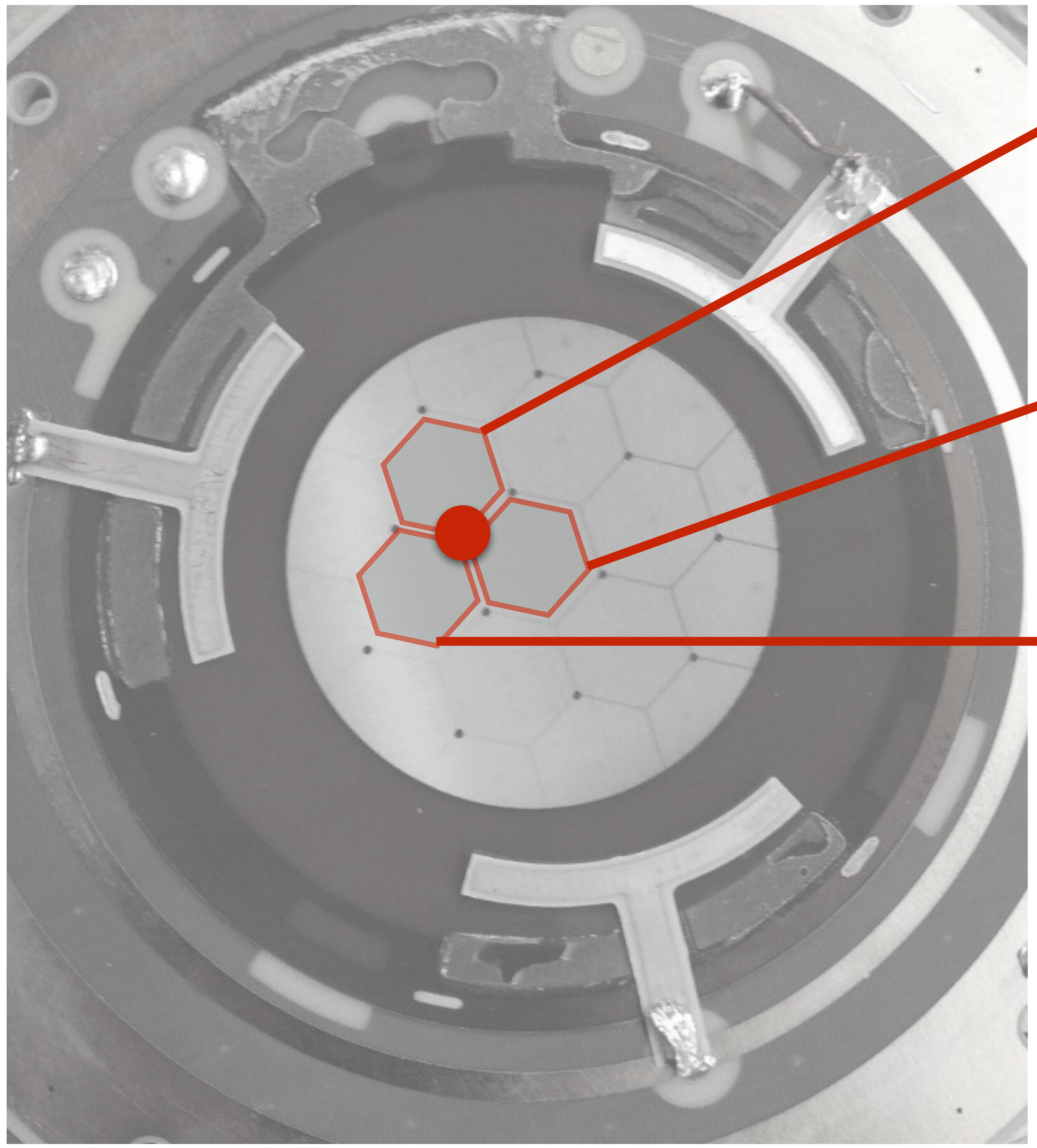
Single pad hit:
25 ps timing resolution for all pads

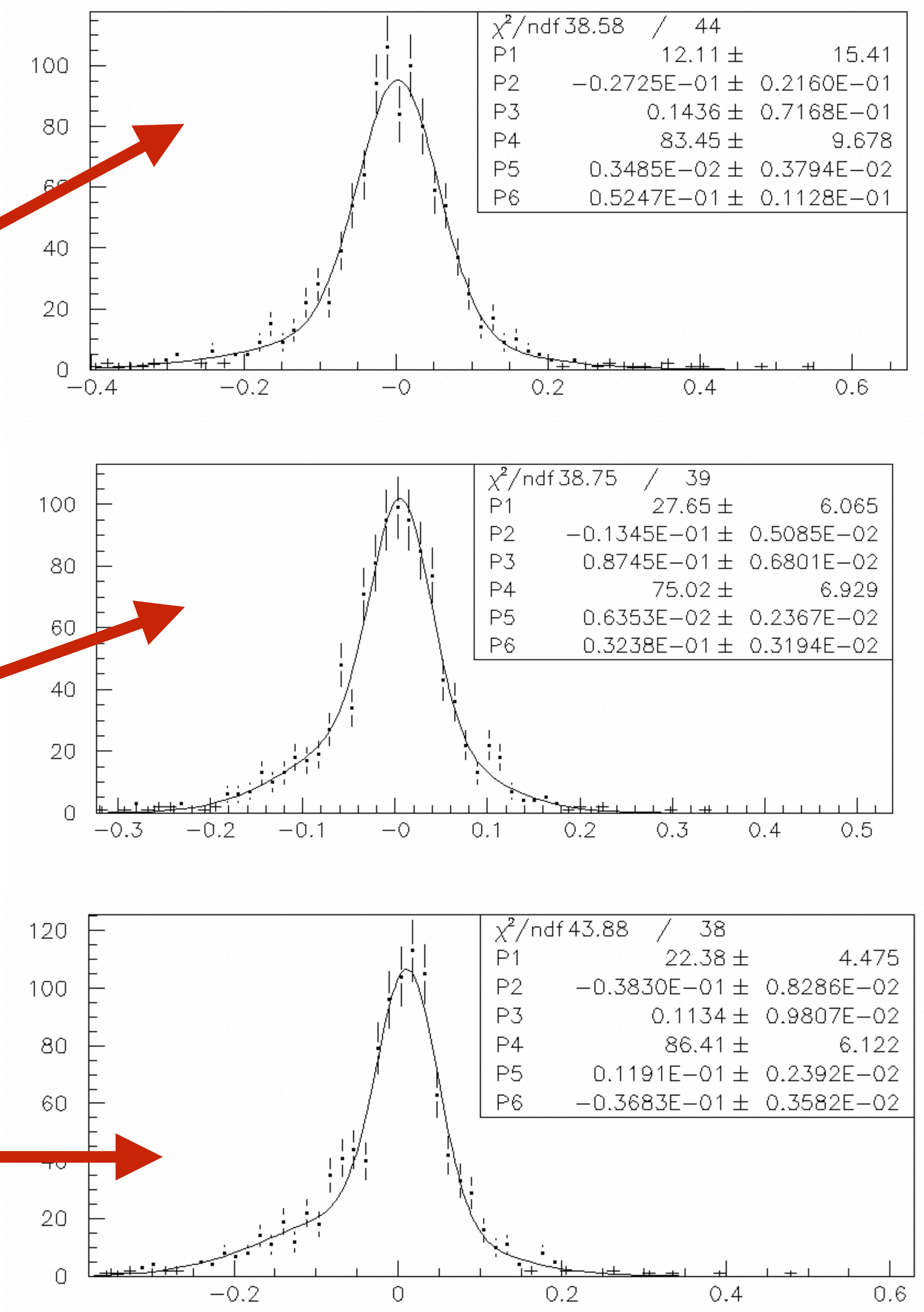
S. Aune et al., "Timing performance of a multi-pad PICOSEC-Micromegas detector prototype", NIM A (993), 2021, https://doi.org/10.1016/j.nima.2021.165076

Large-area coverage

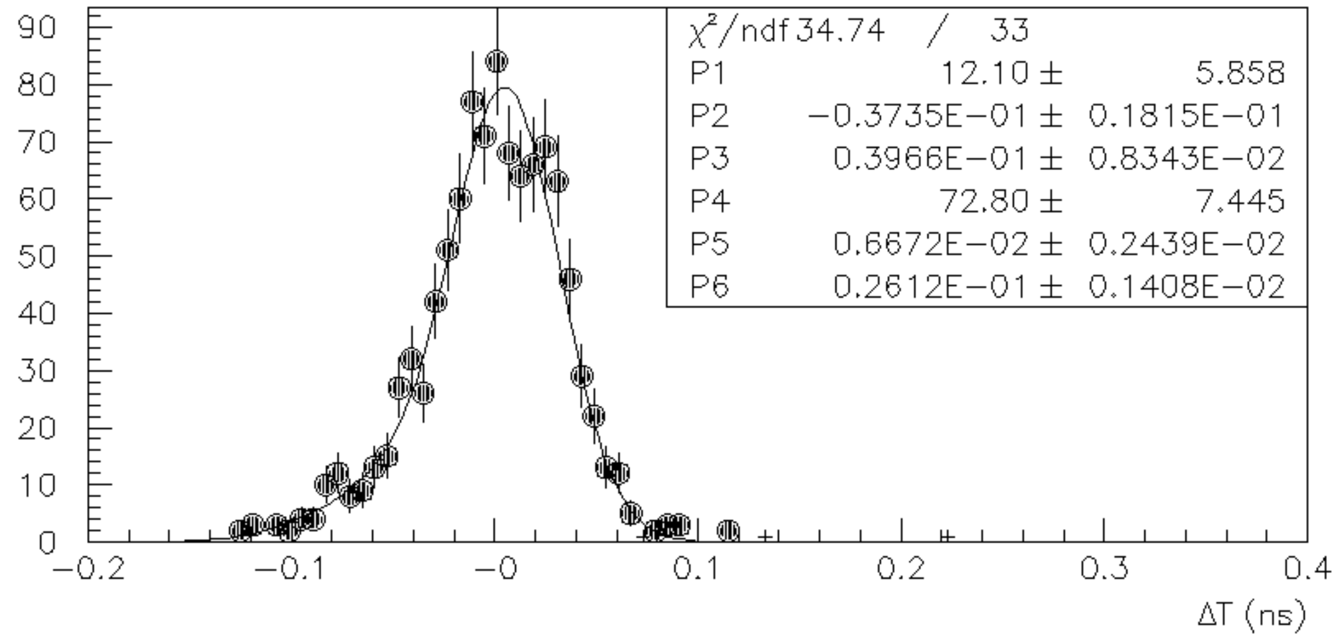
Scaling up multi-channel PICOSEC







Multiple pads hit:
70 ps / 86 ps / 81ps
timing resolution



Combined:
31 ps timing resolution

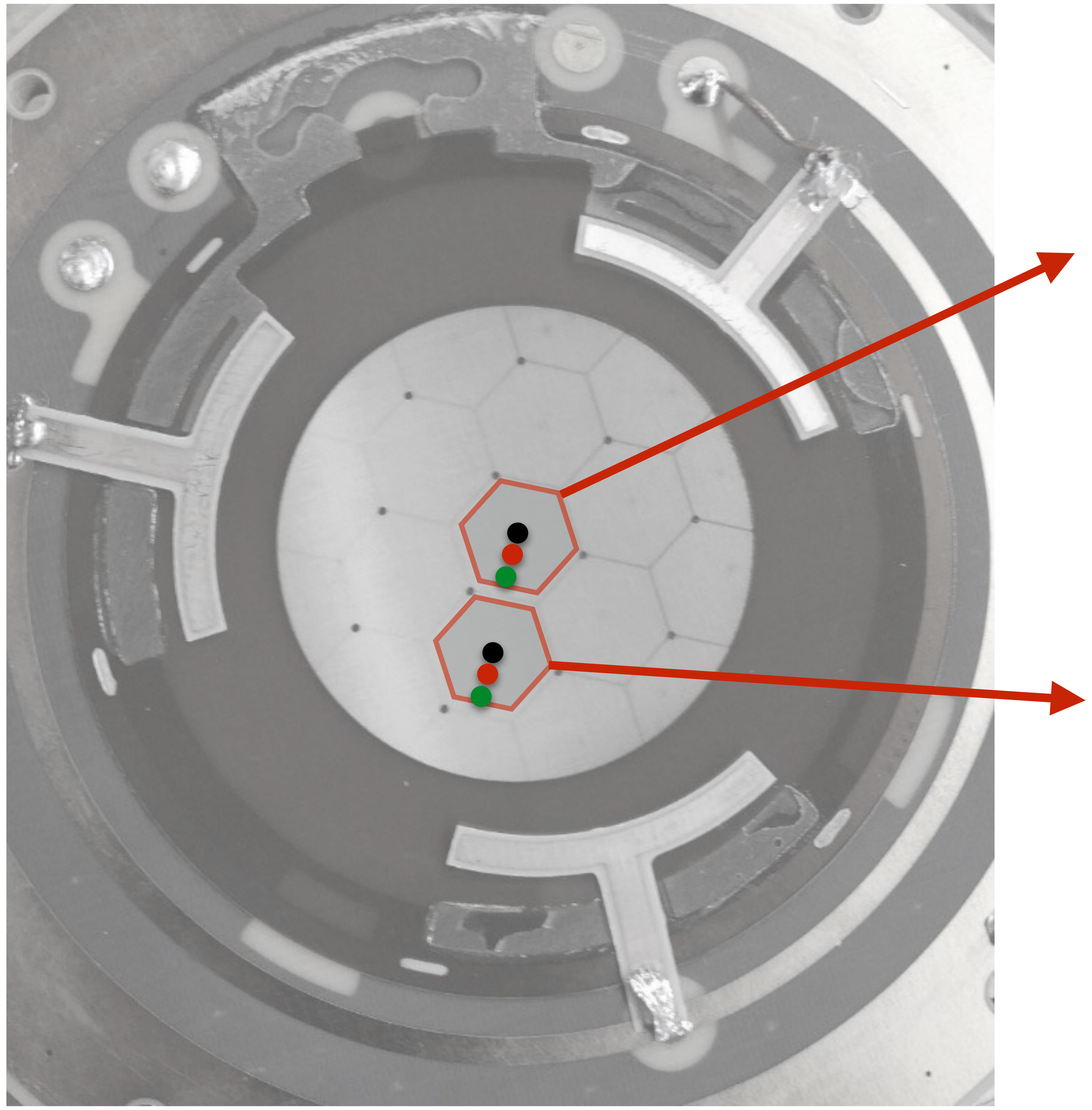
$$\chi^2 = \sum_{i=1,4} \frac{\left(\left[t_i - \{\langle SAT\rangle(R_i,\theta_i) - \langle SAT\rangle(R_i,90^\circ)\} - \{SL(Q)\} - \hat{t}\right]\right)^2}{\left(\mathrm{Res}(Q_i)\right)^2}$$

S. Aune et al., "Timing performance of a multi-pad PICOSEC-Micromegas detector prototype", NIM A (993), 2021, https://doi.org/10.1016/j.nima.2021.165076

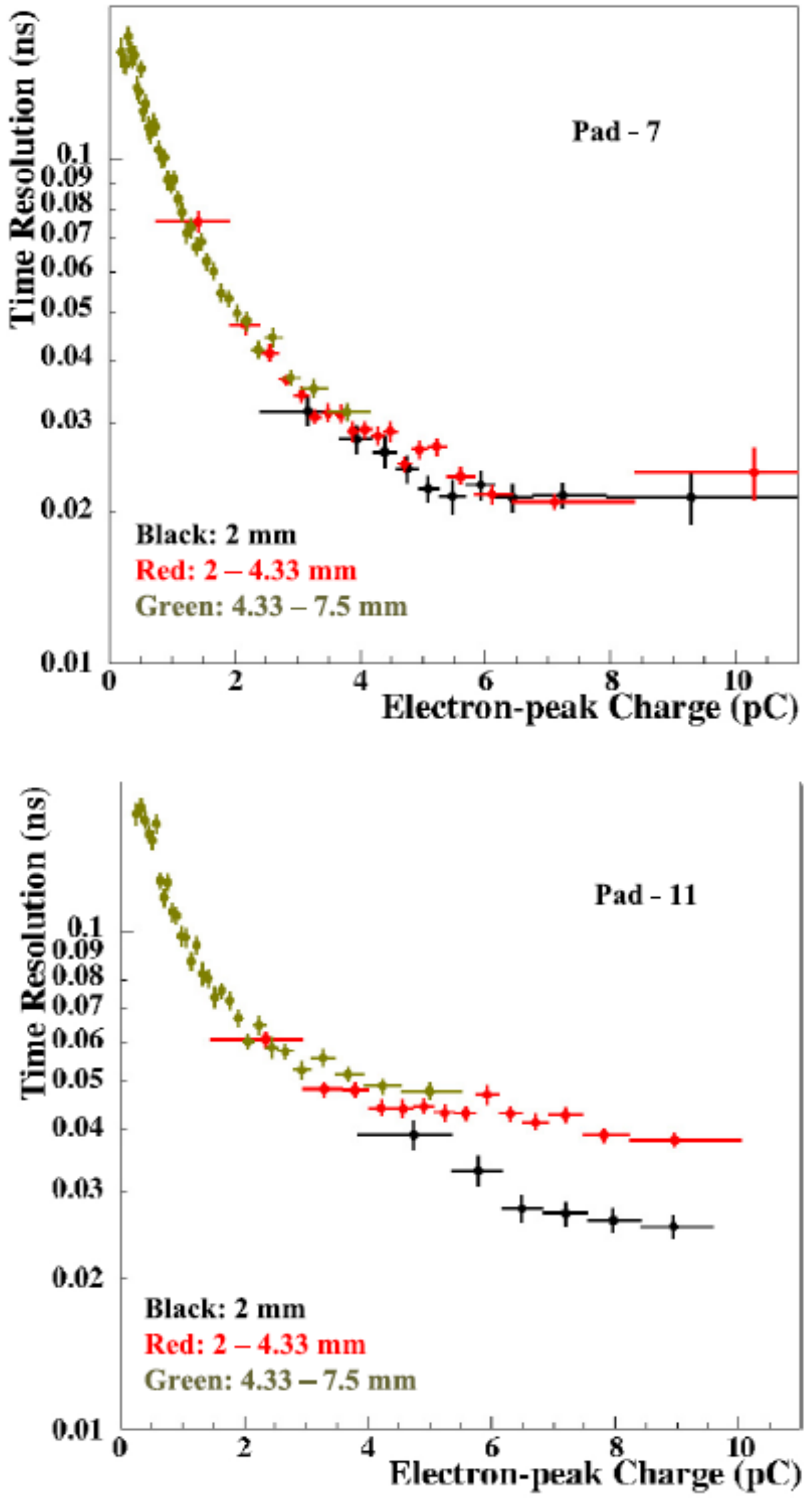
Large-area coverage

Scaling up multi-channel PICOSEC

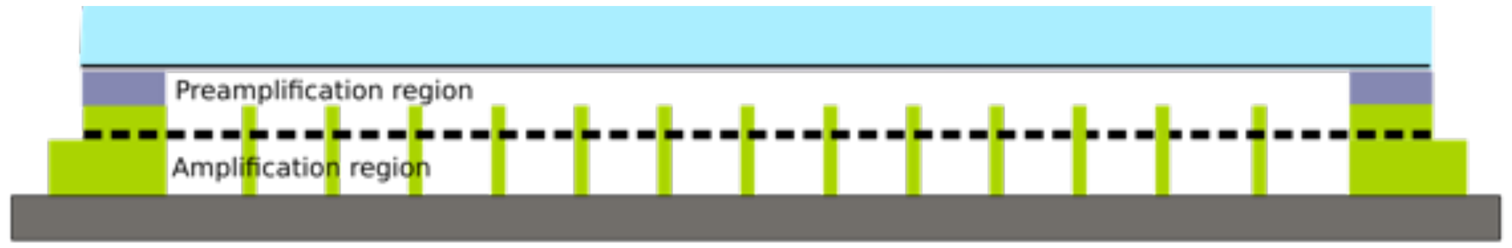
Using tracking information, dependence of time resolution on hit location within pads (center vs. periphery) was observed:
→ **non-uniform pre-amplification gap** from mechanical deformation
→ lower pre-amplification field → lower SAT, wider distribution



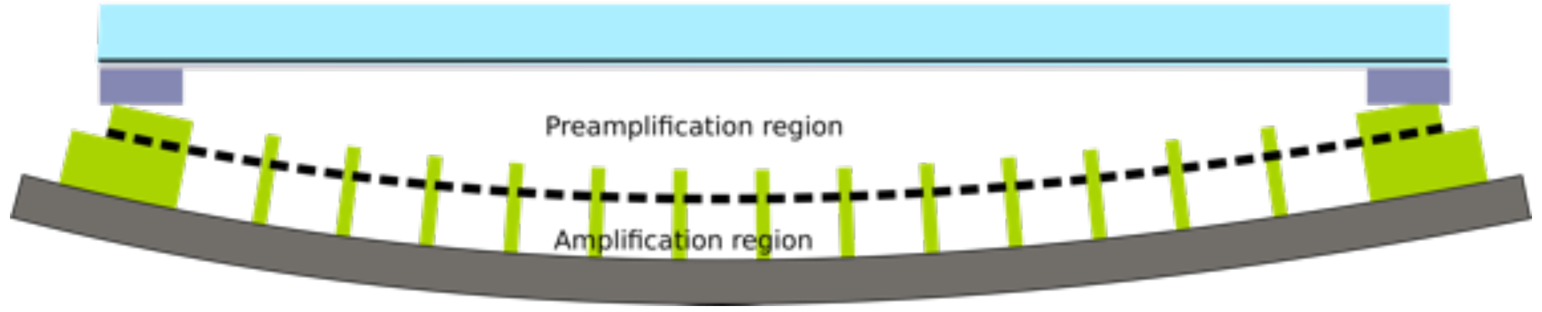
Schematic hit locations not drawn to scale



Ideal, uniform preampfification gap

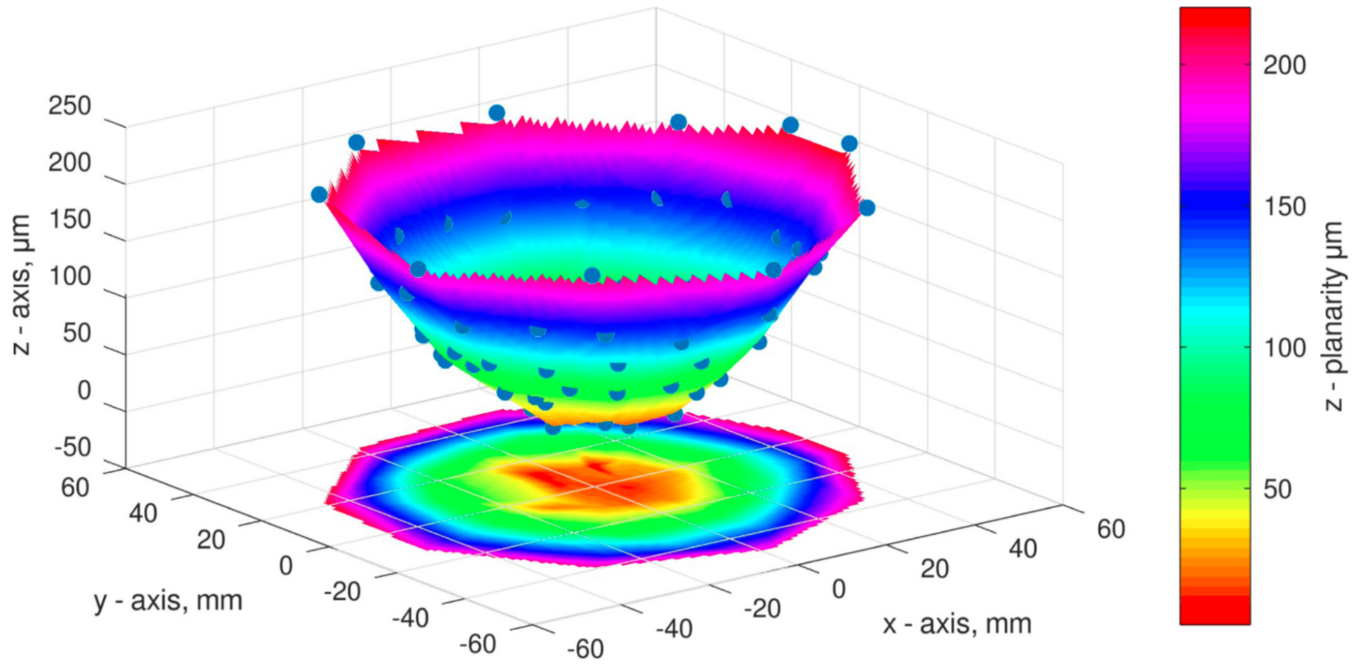


Observed, deformed preamplification gap



Schematic not drawn to scale

Measured mechanical deformation

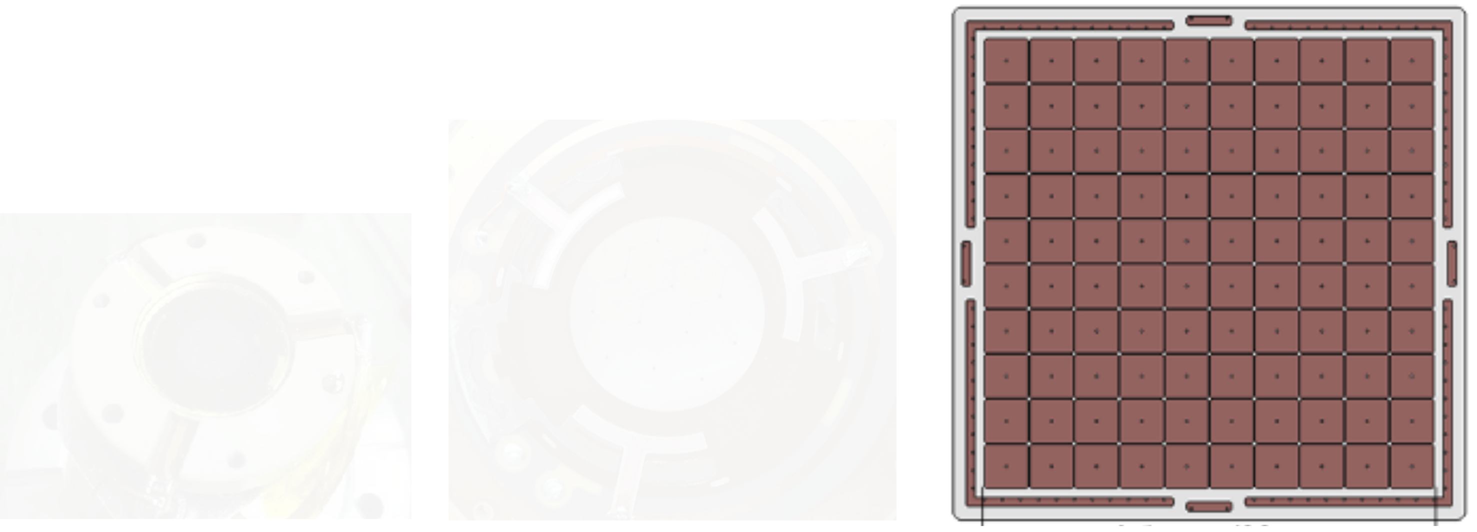


Challenge for scaling up to larger detectors

- Non-planarity of PCB?
- Tension of Micromegas mesh?
- Bending from gas pressure?
- Bending from mechanical fixation?

S. Aune et al., NIM A (993), 2021, https://doi.org/10.1016/j.nima.2021.165076

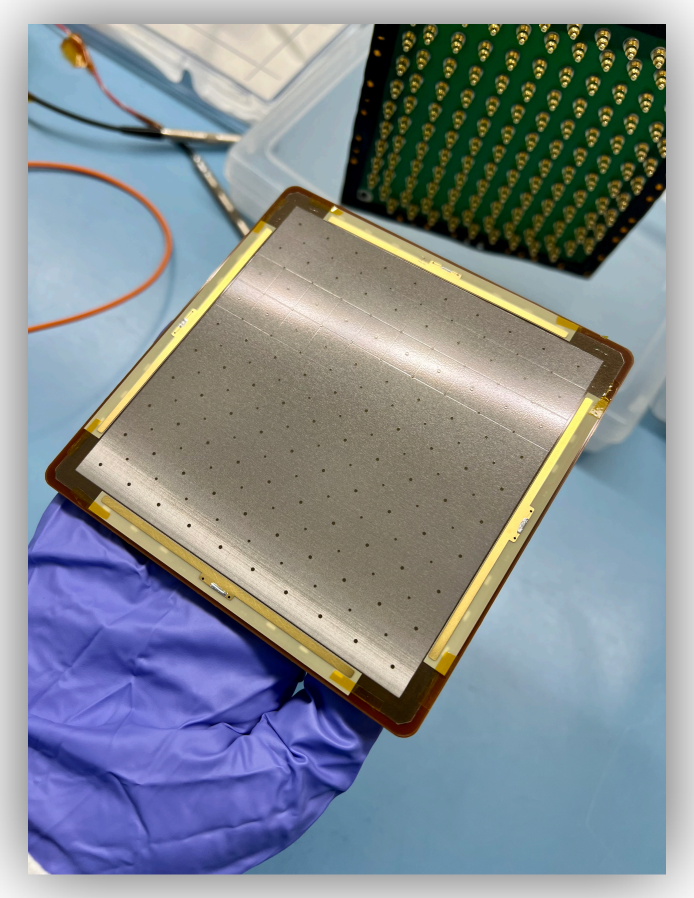
PICOSEC 10cm x 10cm module



10x10 module
◻ 1 cm pads

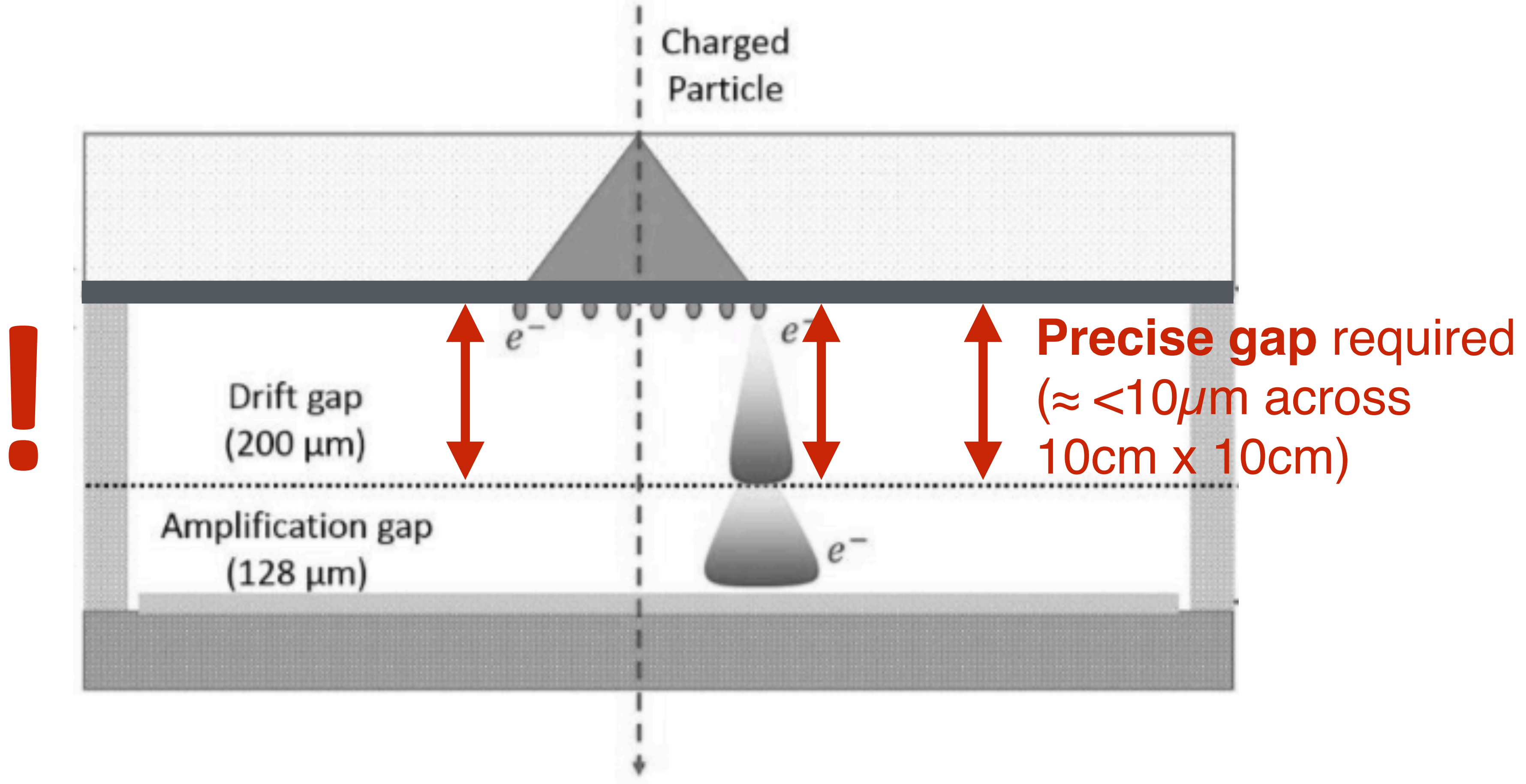
Uniform pre-amplification gap thickness crucial for timing performance (<10μm across tens of cm)

- Stress from stretched micro mesh tension → **rigid ceramic PCB**
- Mechanic stress → **decoupled Micromegas** from housing
- with low spring force contacts



Substrate polishing and planarity survey during production at CERN MicroPattern Technologies workshop

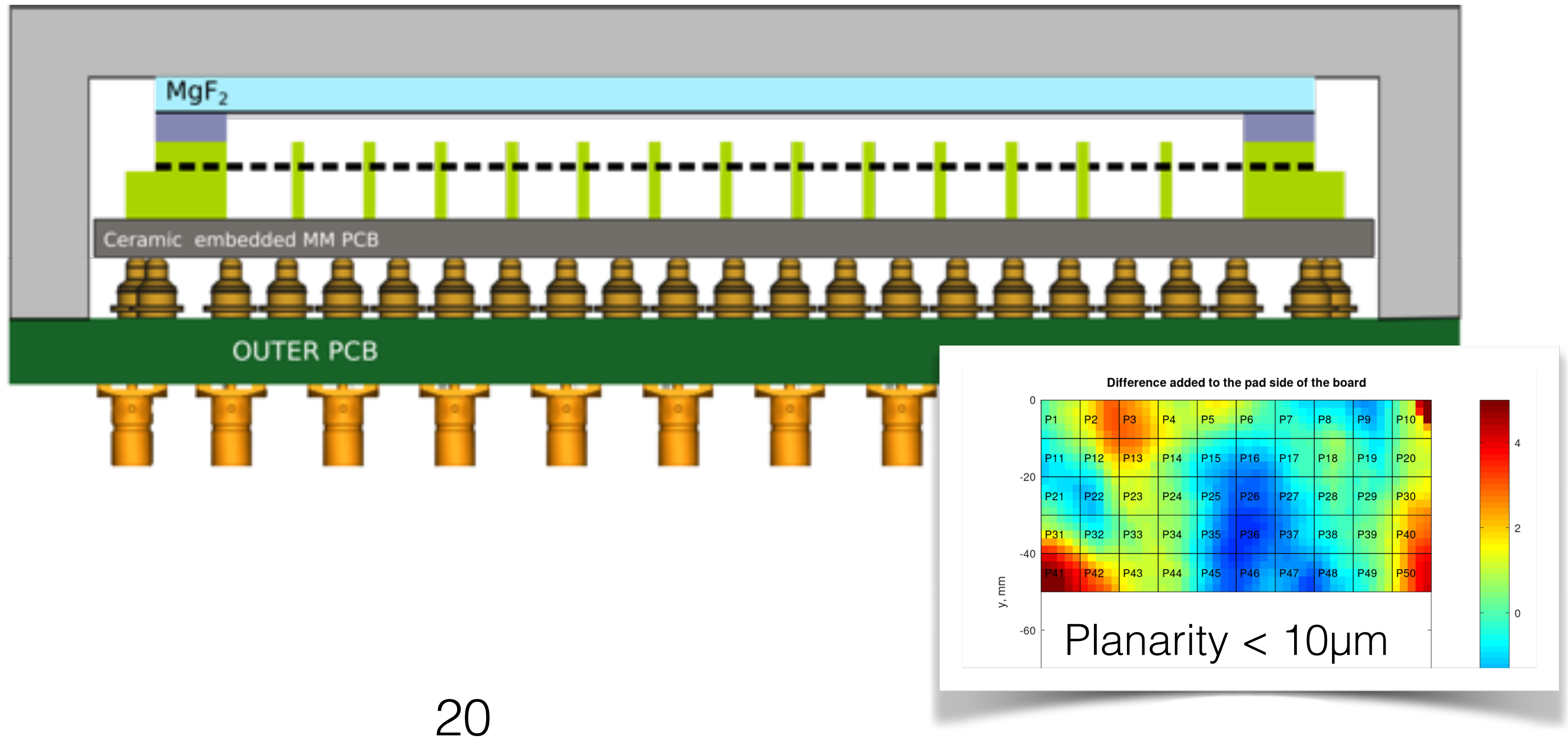
Uniform detector gain across active area



Precise gap required (≈ <10μm across 10cm x 10cm)

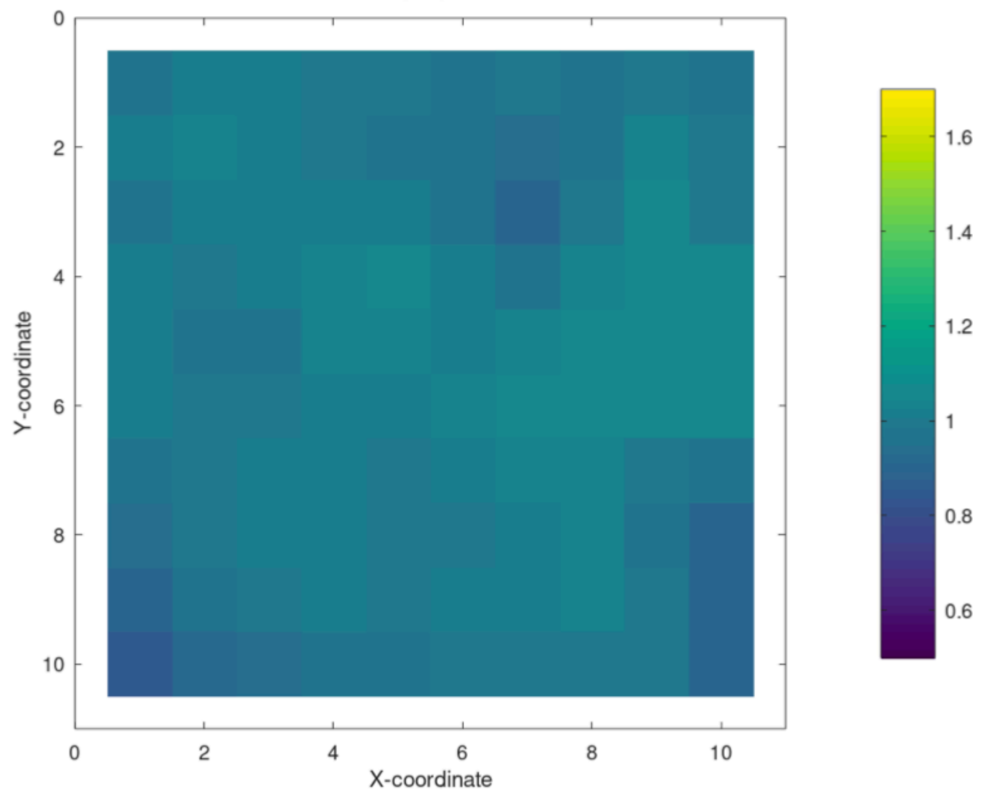
Schematic not drawn to scale

Cross-section

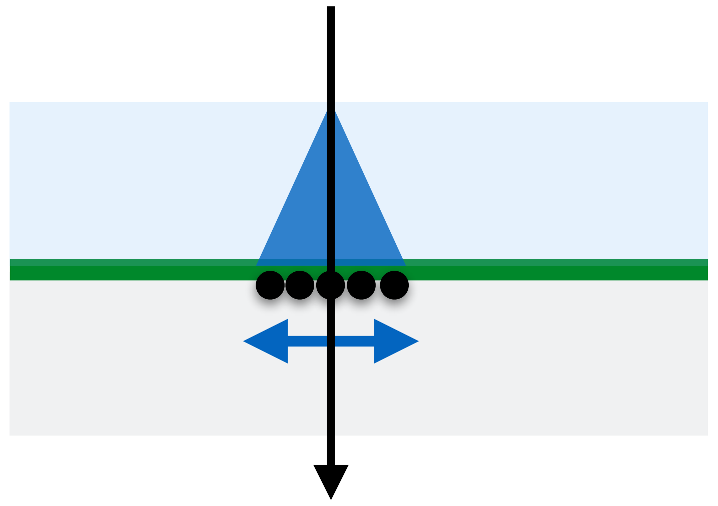


Planarity < 10µm

Gain uniformy σ = 3.9 %



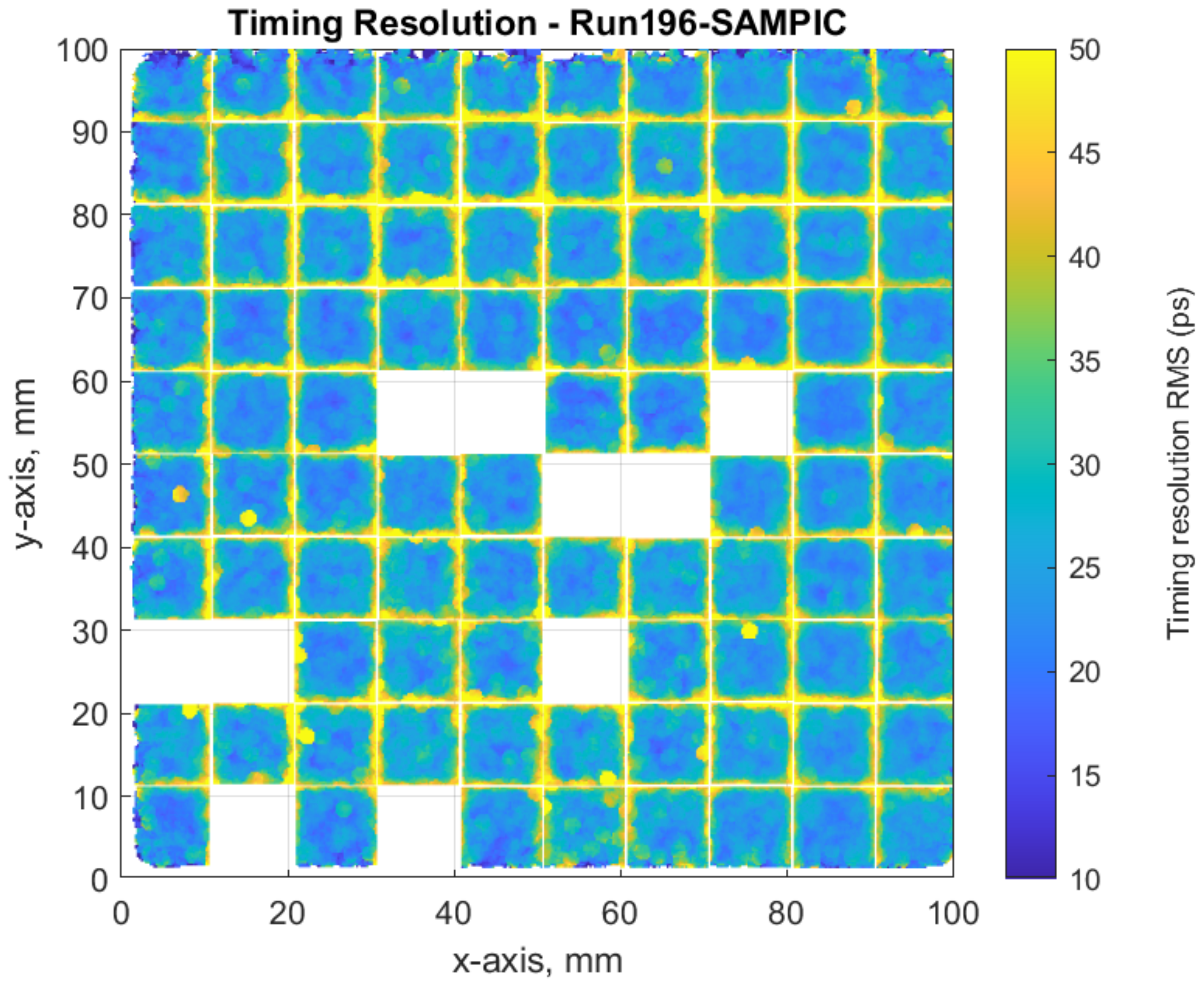
Picosec detector module

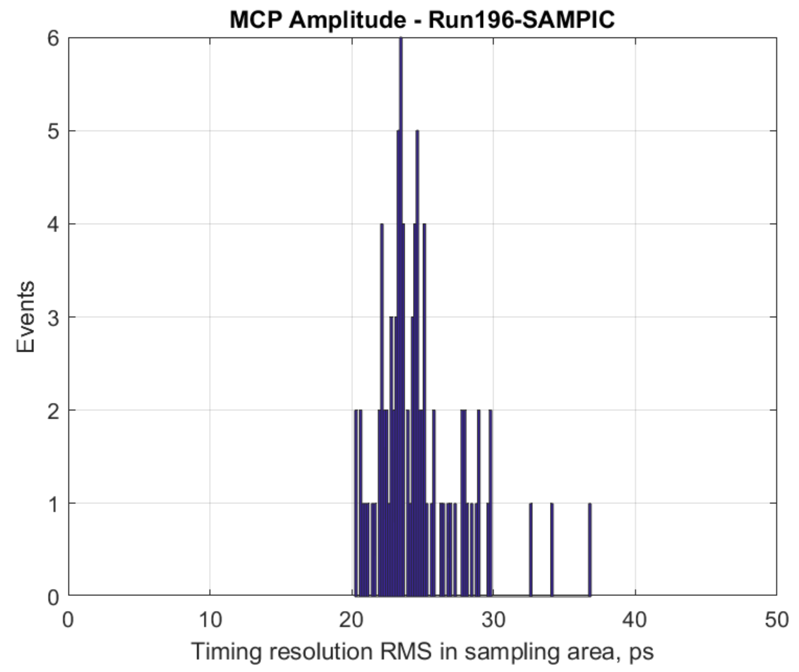


10cm x 10cm detector module prototype with 100 channels characterised in MIP test beam campaigns

Detector shows uniform response and different anode pads exhibit the same trend of signal-arrival-time as function of electron peak charge → **universal time walk correction**

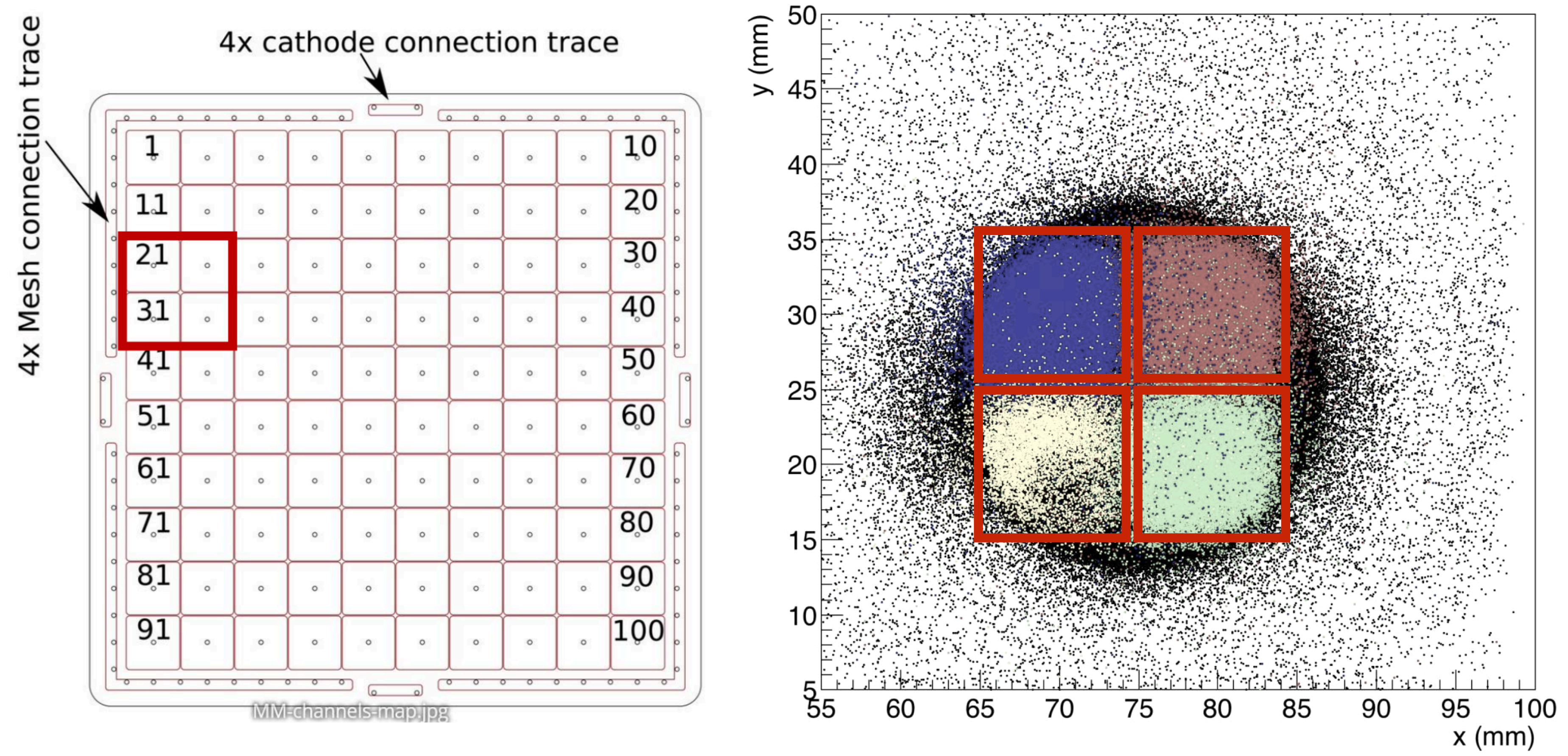
Uniform time resolution response across 10cm x 10cm active area





Pads provide 20-25ps time resolution

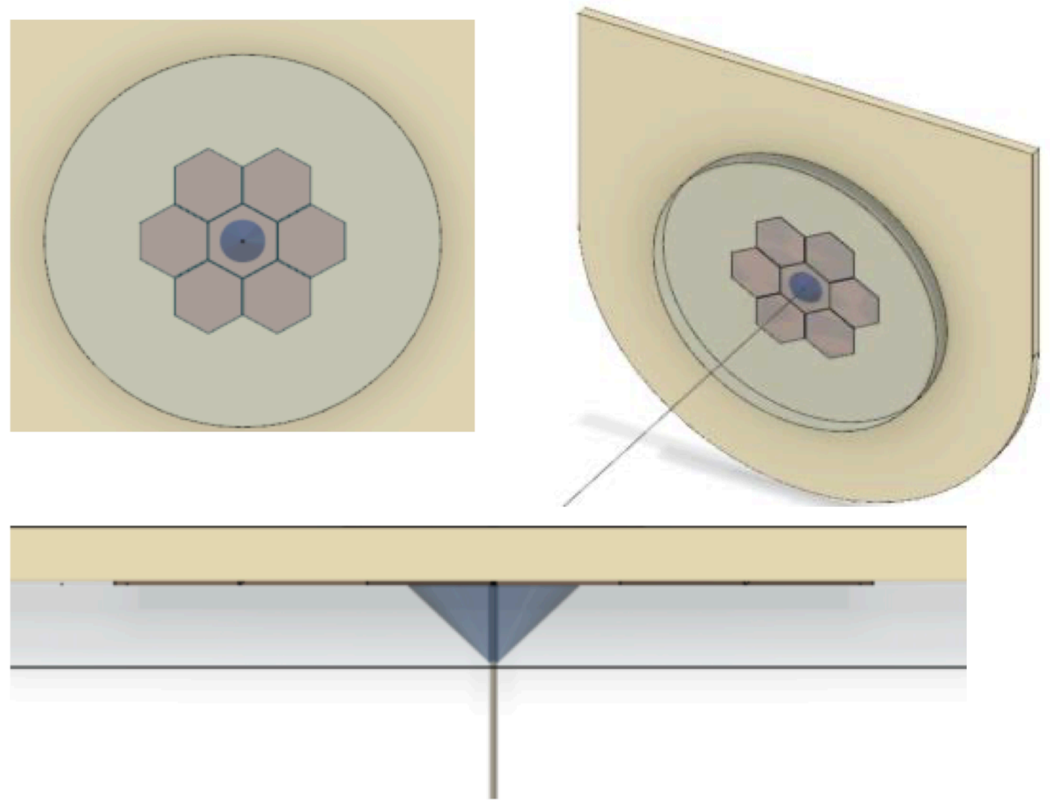
Signals shared across multiple pads can be combined to achieve a combined time resolution of σ **<30 ps**



A. Kallitsopoulou, First results in signal sharing with multi-pad Picosec module prototypes, RD51 Collaboration Meeting Nov 2021, https://indico.cern.ch/event/1071632/contributions/4607166/

Schematic not drawn to scale

Signal sharing and spatial resolution

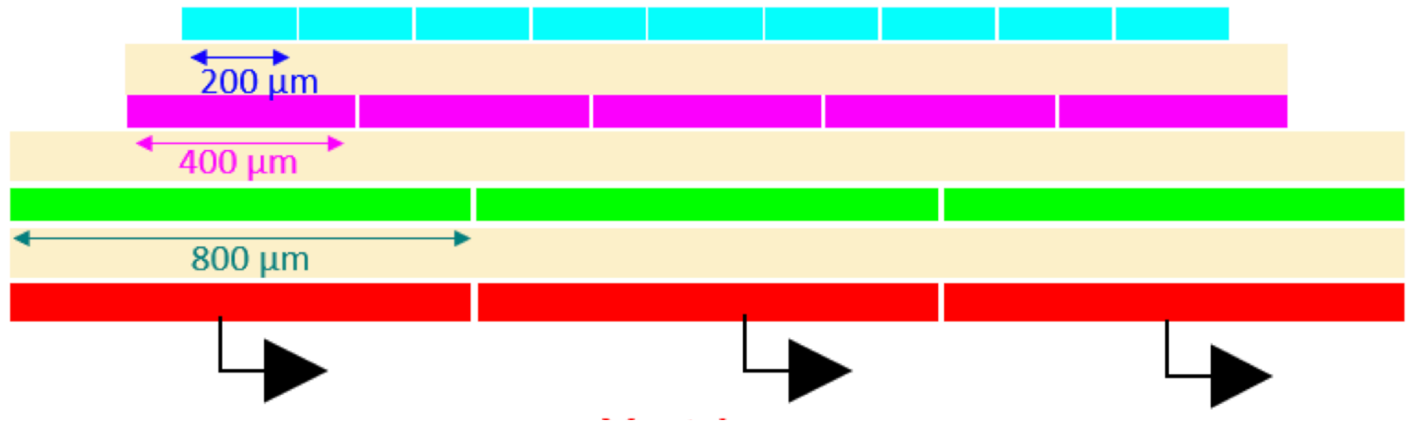


Signals can be **shared across multiple readout pads** by size of Cherenkov cone (3mm thick radiator -> 6mm diameter light cone)

Signal sharing can be increased by **resistive layers** with sufficiently low resistivity

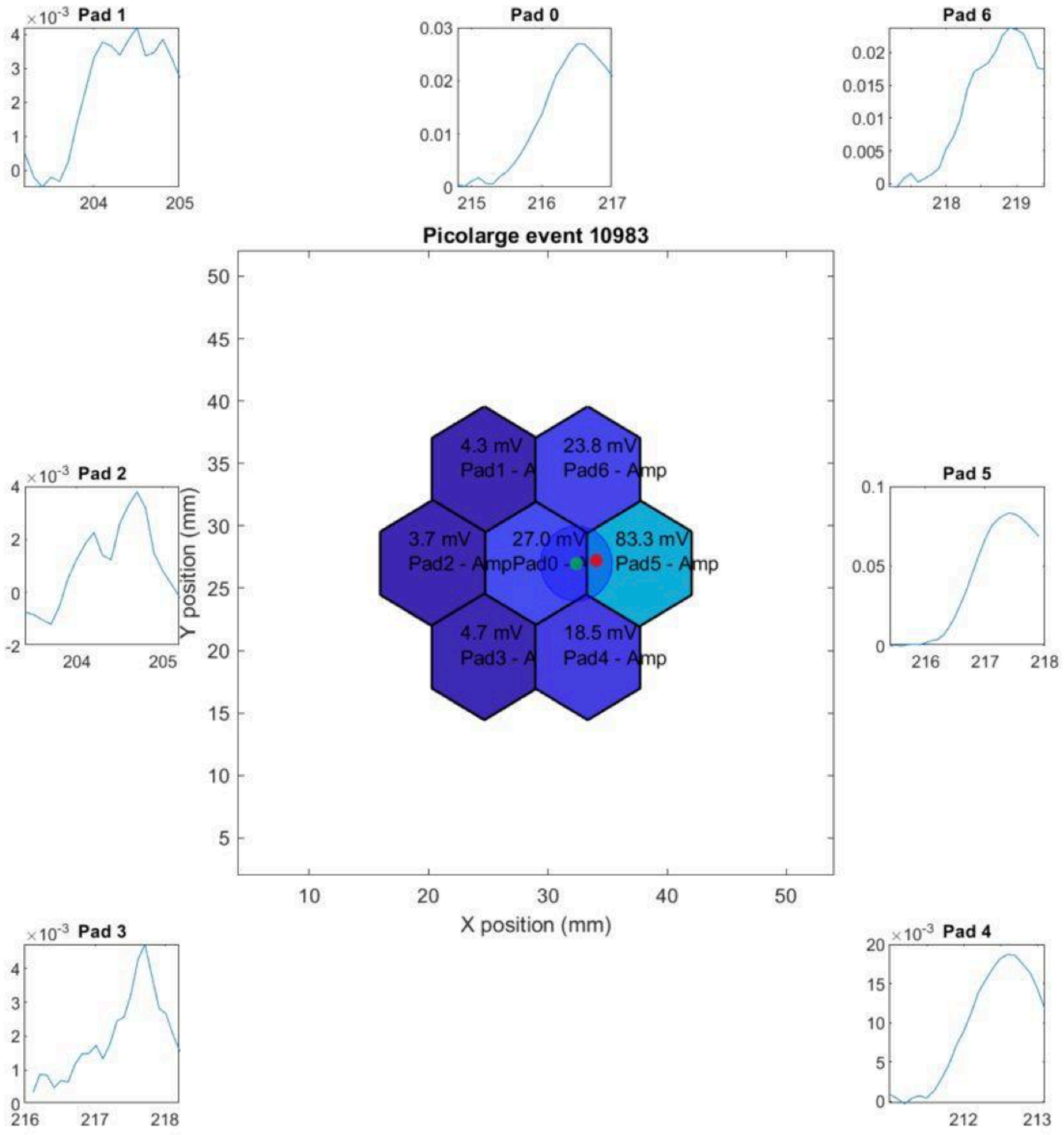
Alternatively, **capacitive sharing** can be used to spread signals to multiple readout pads

Kondo Gnanvo,
https://indico.cern.ch/event/889369/contributions/4042739/attachments/2119963/3567713/20201009_KG_RD51_Coll_Meeting.pdf



Preliminary

Reconstructing hit position by COG in 7-pad resistive Picosec detector
Red: true hit position (external tracker)
Green: reconstructed hit position



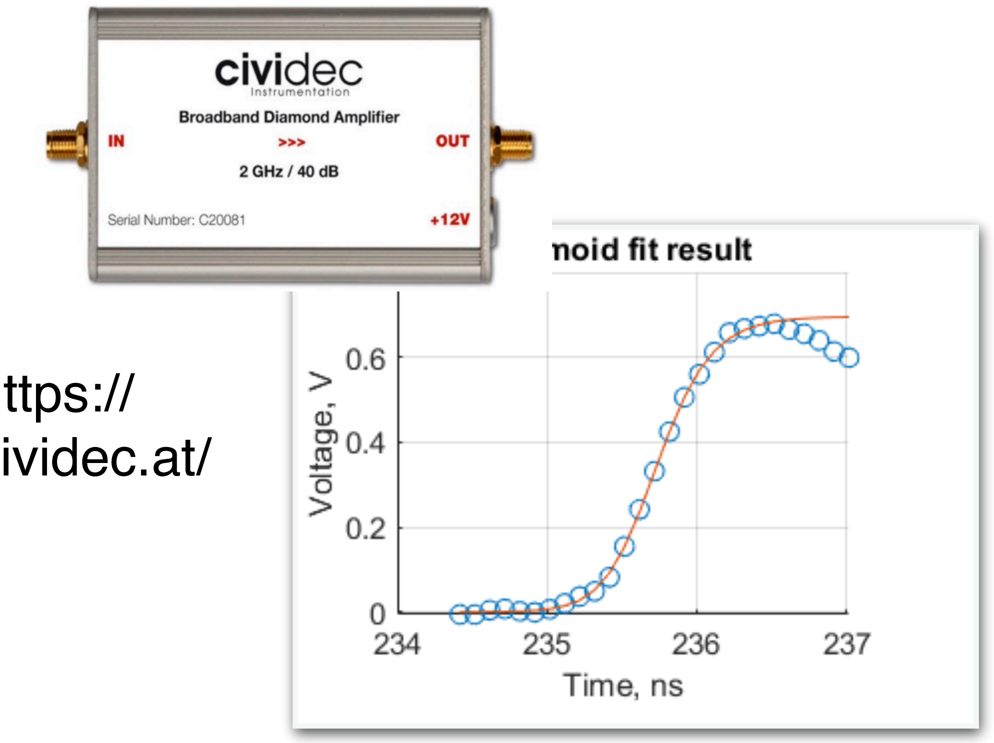
Readout electronics

Require **readout electronics** solution that preserves **excellent timing resolution** and is **scalable to 100s of channels** for tileable Picosec modules.

Detector → **Preamplifier** → Digitisation

Proprietary Cividec preamp

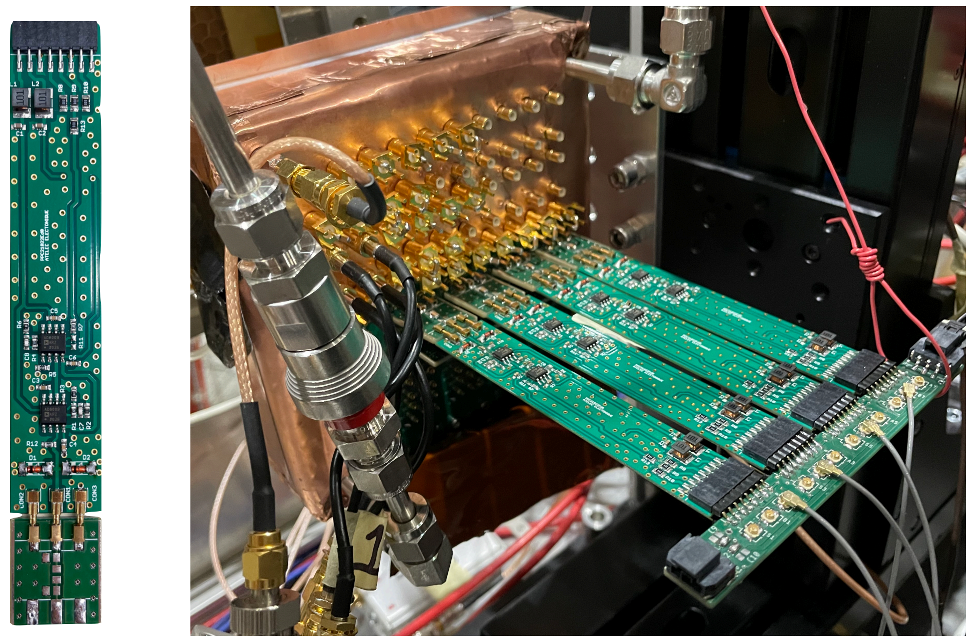
- Single channel
- High-bandwidth, 40db gain



https://cividec.at/

Custom preamplifiers (P. Legou, CEA Saclay)

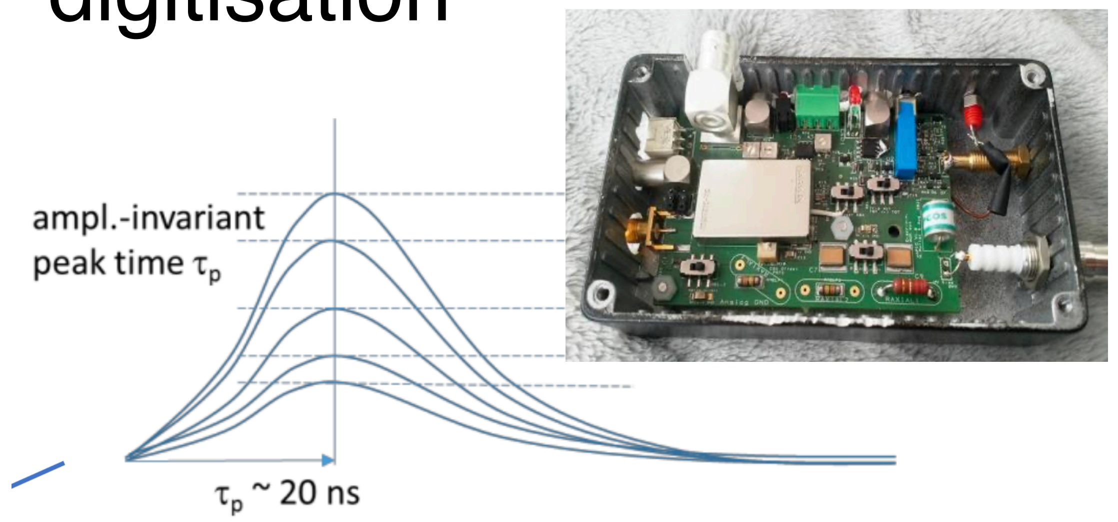
- Fast risetime, low noise, moderate gain
- Good timing resolution



Preamp card, 10x10 module

Alternative approach: CSA-shaper macro uAPIC

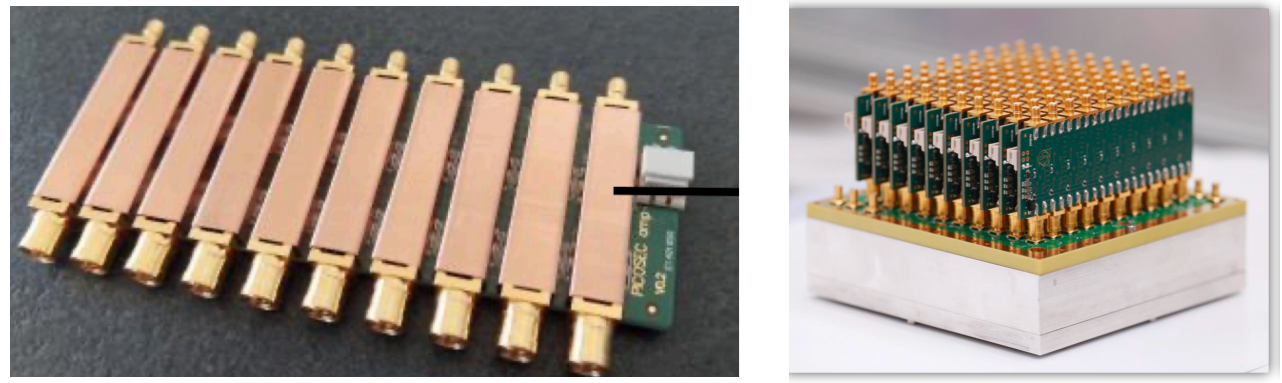
- O(10ns) shaper without time walk
- Release requirements on digitisation



CSA-shaper, H. Muller, CERN

Dedicated custom preamplifier cards

- High bandwidth, high gain
- Input protection circuit
- Optimised for signal coupling to PICOSEC MM



A. Utrobicic, MPGD 2022, https://indico.cern.ch/event/1219224/contributions/5130511/attachments/2565926/4423657/PICOSEC_MM100ch_A.pdf

Experience with different preamp circuits as input for new, optimised implementation for 100 channel PICOSEC modules

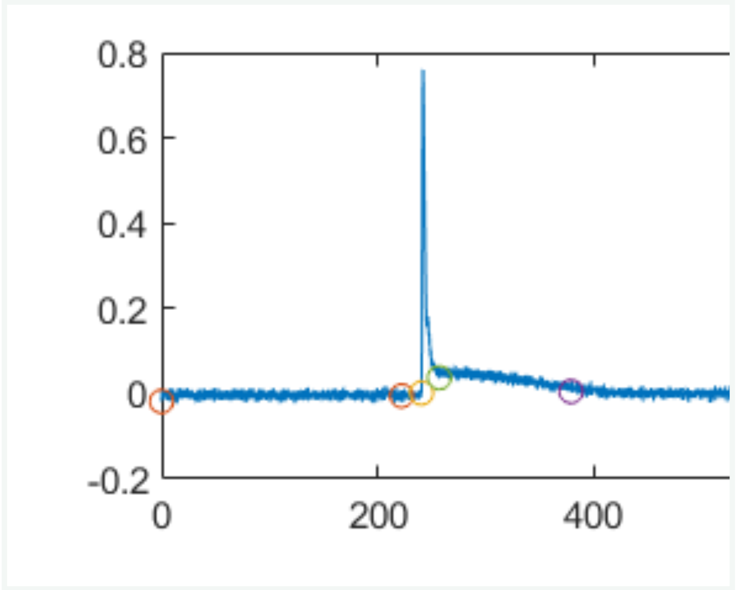
Readout electronics

Require **readout electronics** solution that preserves **excellent timing resolution** and is **scalable to 100s of channels** for tileable Picosec modules.

Detector → Preamplifier → **Digitisation**

10 GS/s sampling with oscilloscope

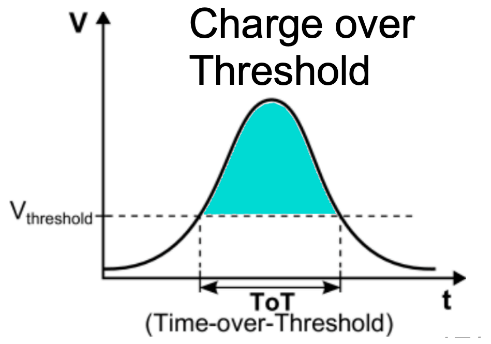
- Record full waveform (electron + ion)
- Detector R&D, response studies
- Not scalable



Alternative approaches:

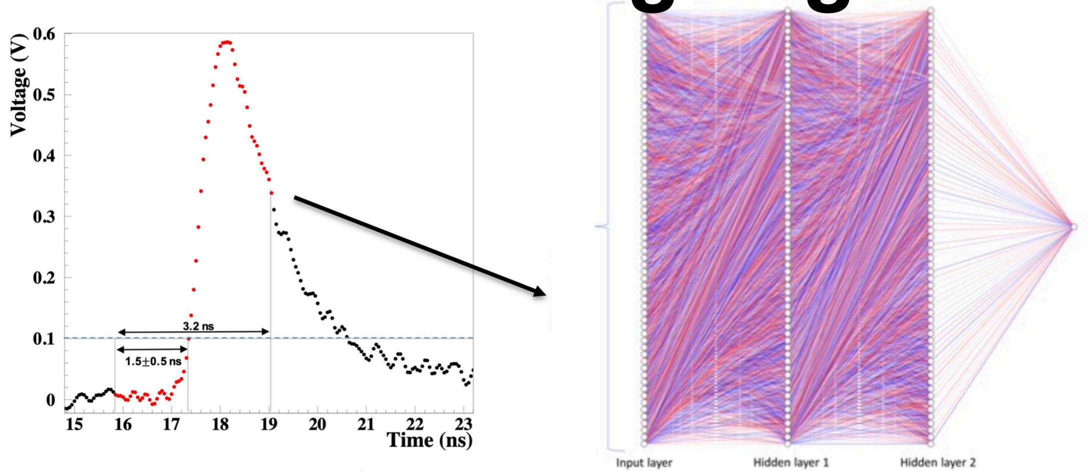
Single threshold timing with time walk correction from multi-threshold ToT

S.E. Tzamarias et al., to be published, Ioannis Manthos, PSD12



Preliminary

Artificial NN to extract time from rising edge



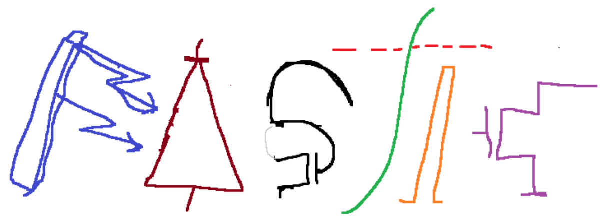
A. Tsiamis, PSD 12

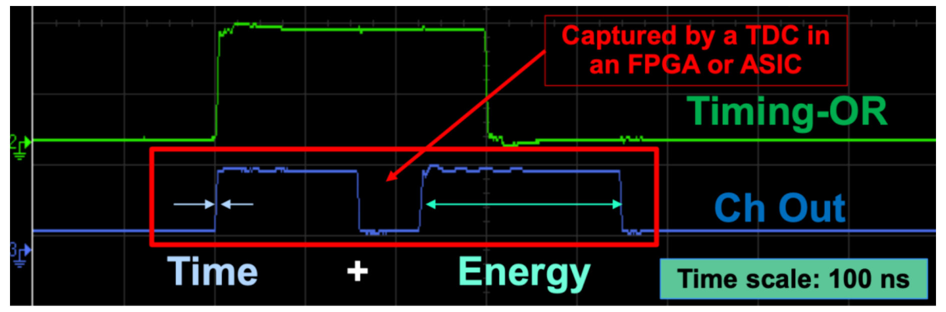
→ 64 samples as input, ≈reproduce time resolution with only **5 GS/s**

Integrated precise timing ASIC

Evaluating FastIC with timing at threshold + energy information for time walk correction

May be used with TDC

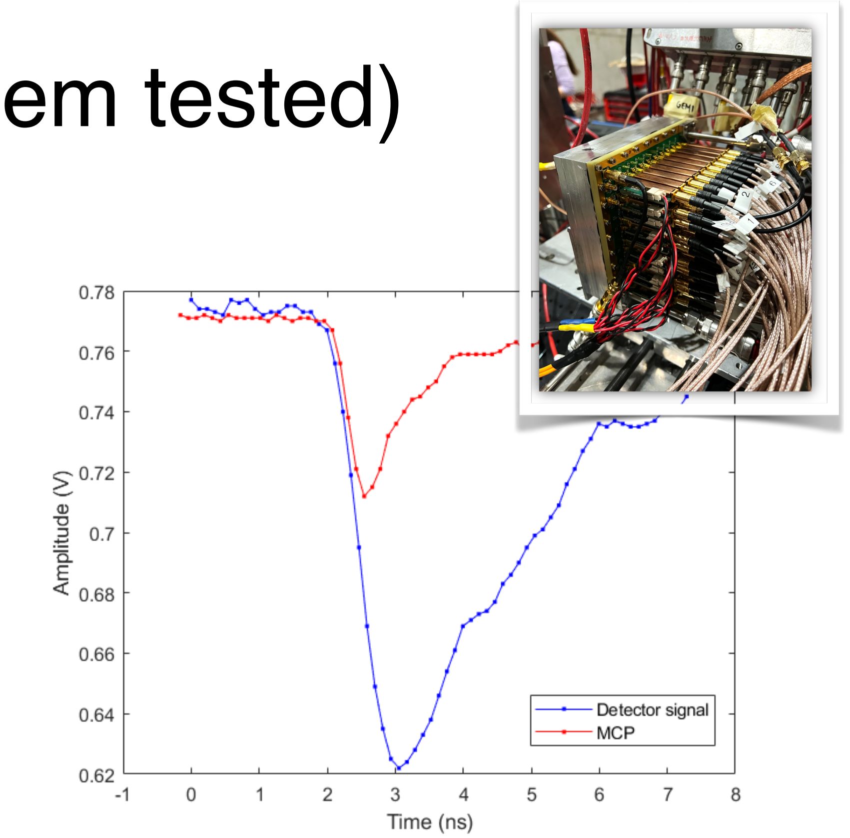




SAMPIC Waveform TDC

- Waveform sampling of rising edge of electron peak and time extraction with sigmoid fit and 20% CFD
- Up to 8.5 GS/s sampling frequency with 64 samples
- Scalable (128CH system tested)

16 channel SAMPIC (D. Breton, J. Maalmi et al.)



Waveforms recorded at 8.5 GS/s

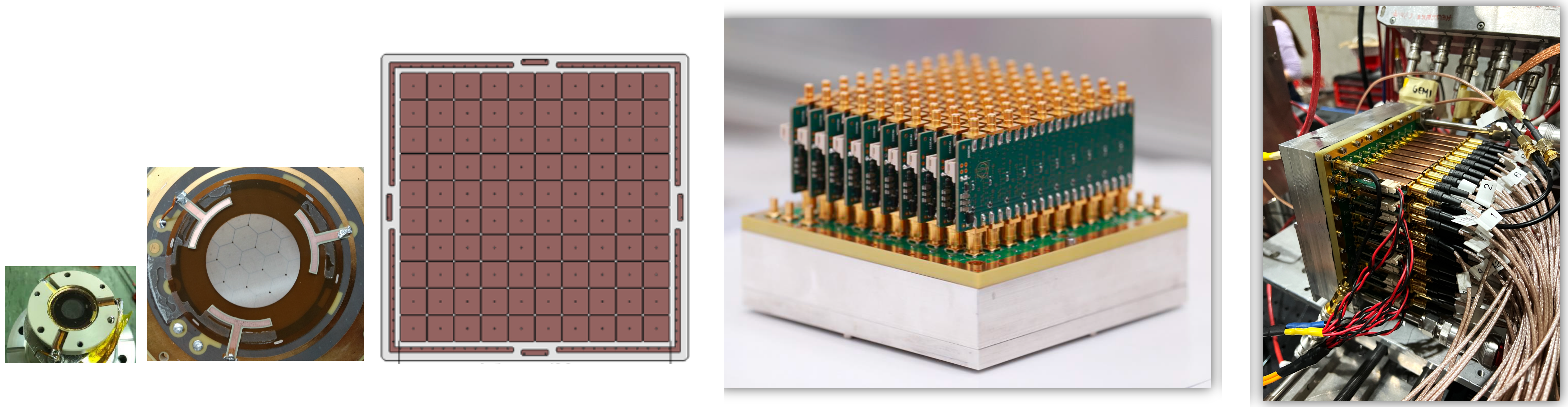
Summary

Time resolution limitations of conventional gaseous detectors are overcome by **MRPCs** with multiple thin gaps or **PICOSEC Micromegas** utilising Cherenkov radiators and tens of ps resolution is achieved.

The **PICOSEC detection concept** overcomes timing limitations of gaseous detectors and achieves high timing precision of < 25 ps for MIPs.

Tileable 10x10 pad detector modules have been tested in MIP test beams and provide good timing resolution also for signals shared across pads.

Robust converter layers (photocathodes, secondary emitters), **resistive detectors** and scalable readout electronics are implemented for scaling detectors to larger detection areas.



Future perspectives

Amplification structure: optimised double/single gaps, mesh geometries/ technologies, μRWELL

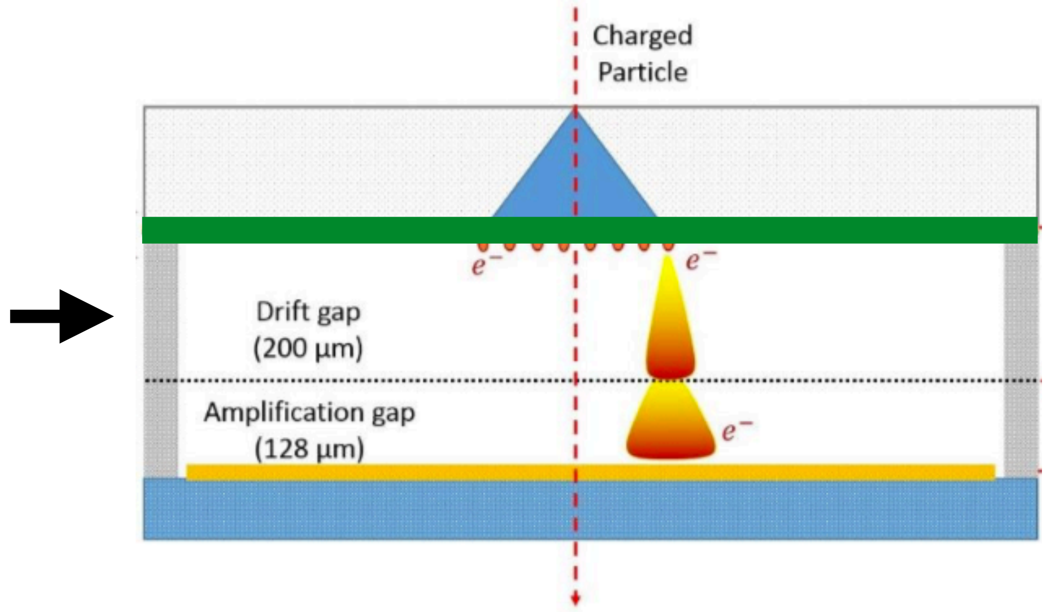
Spatial resolution: adjusting pad size, charge sharing (resistive / capacitive)

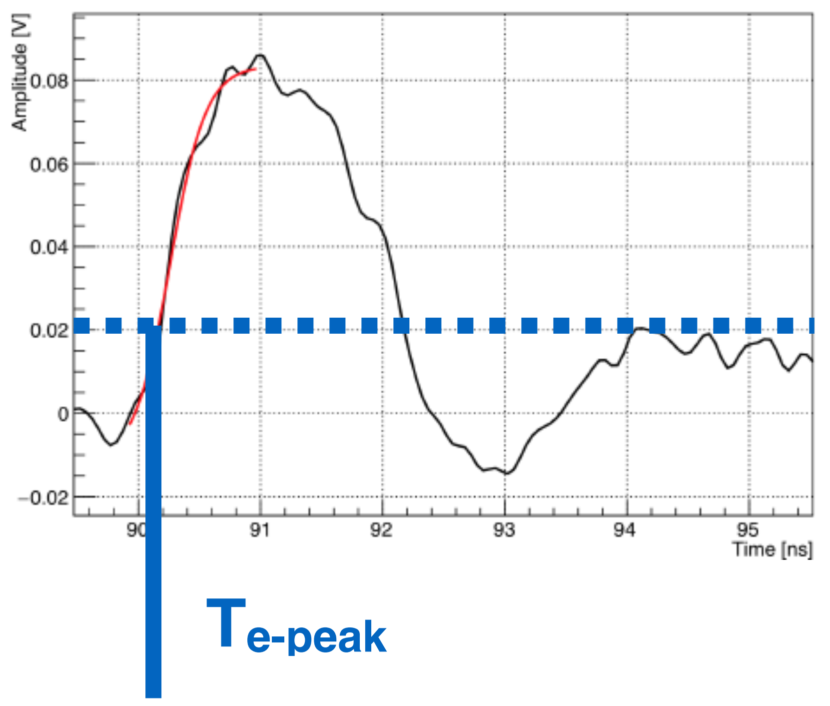
Secondary emitters: minimise material budget

Electronics: waveform digitisation vs. threshold based timing + integrated TDC

?

Detector response





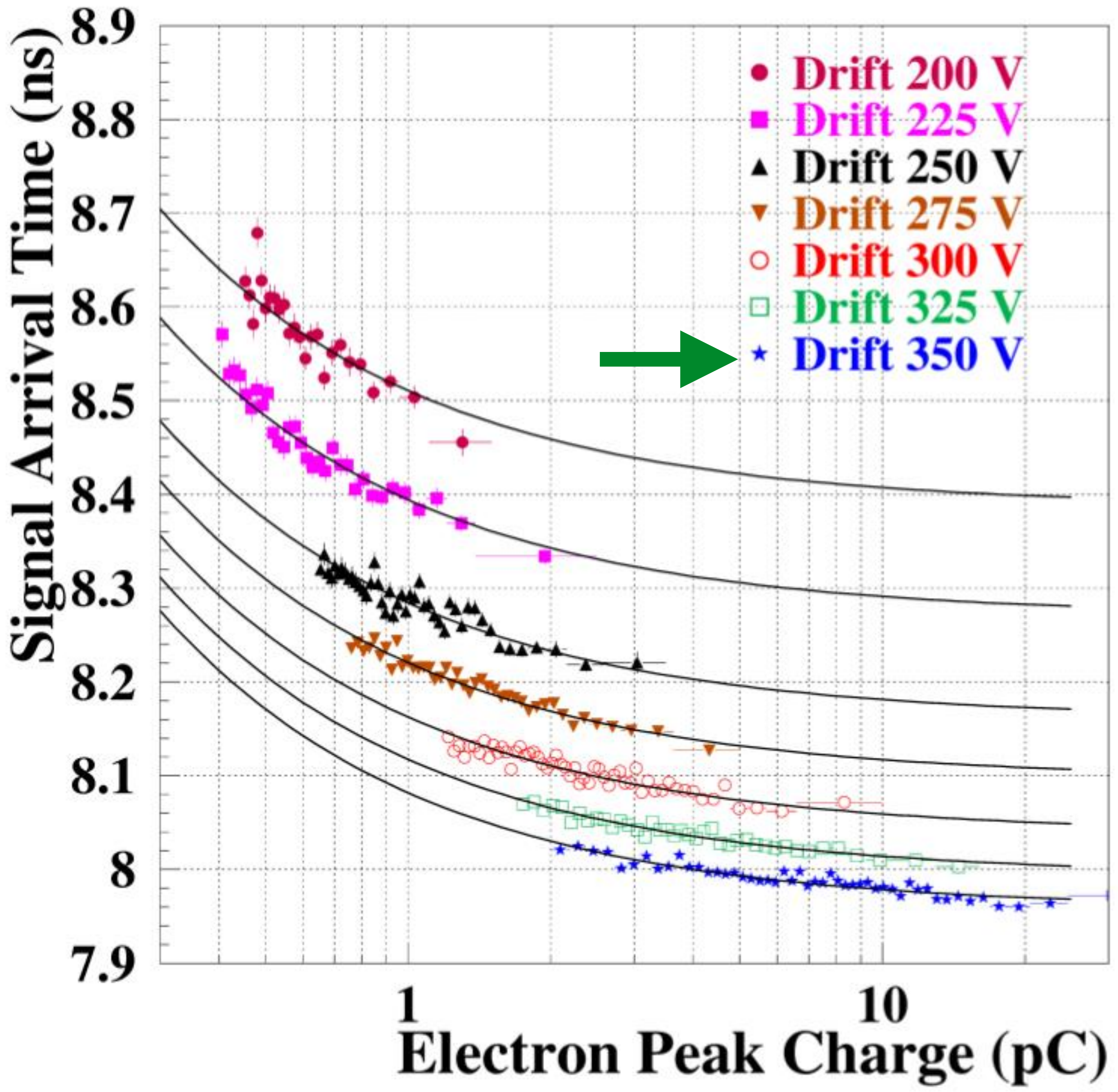
Correlation of signal arrival time and pulse amplitude

Time resolution depends primarily on e-peak charge

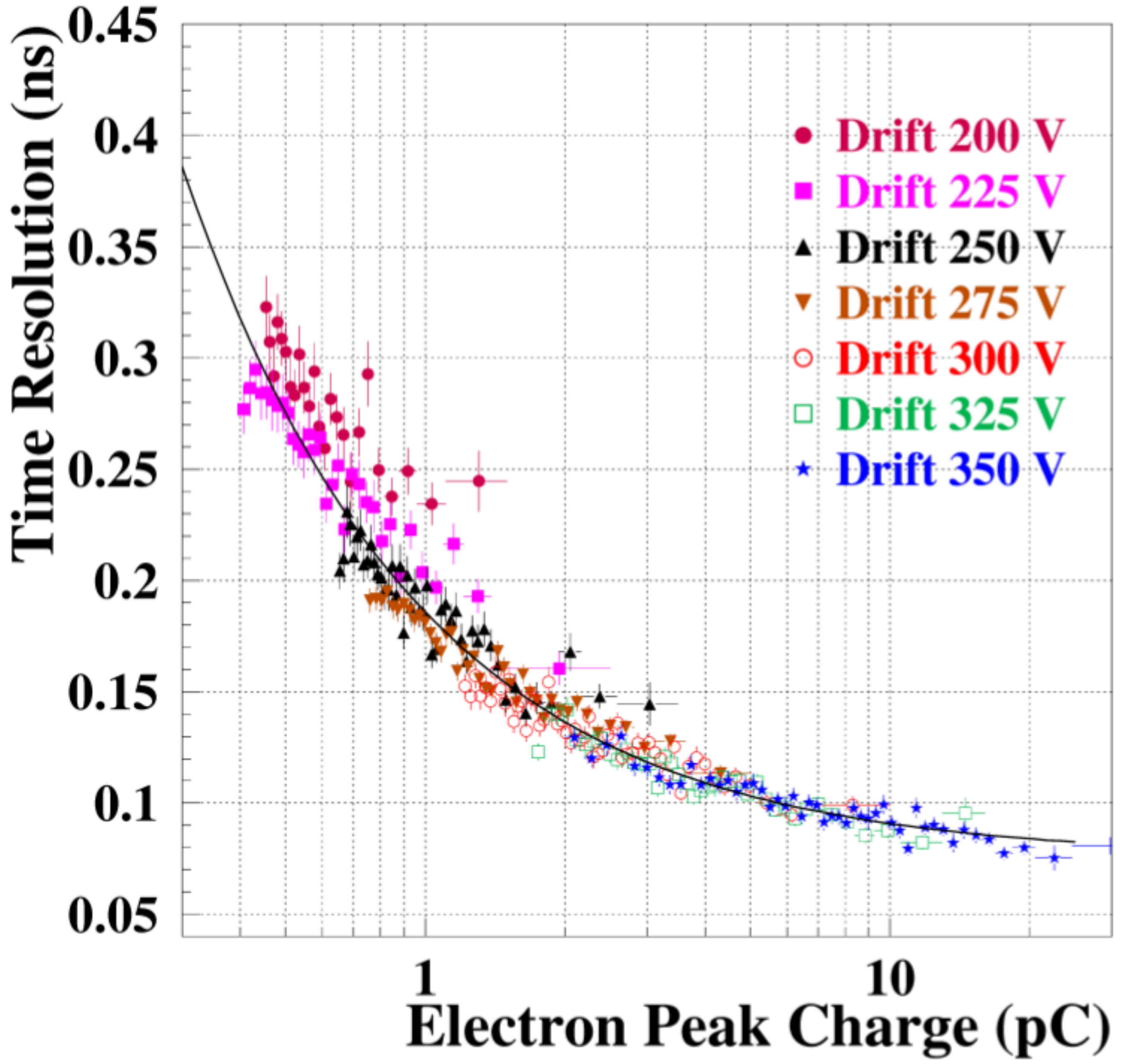
Signal arrival time (SAT) = <$T_{e\text{-peak}}$>

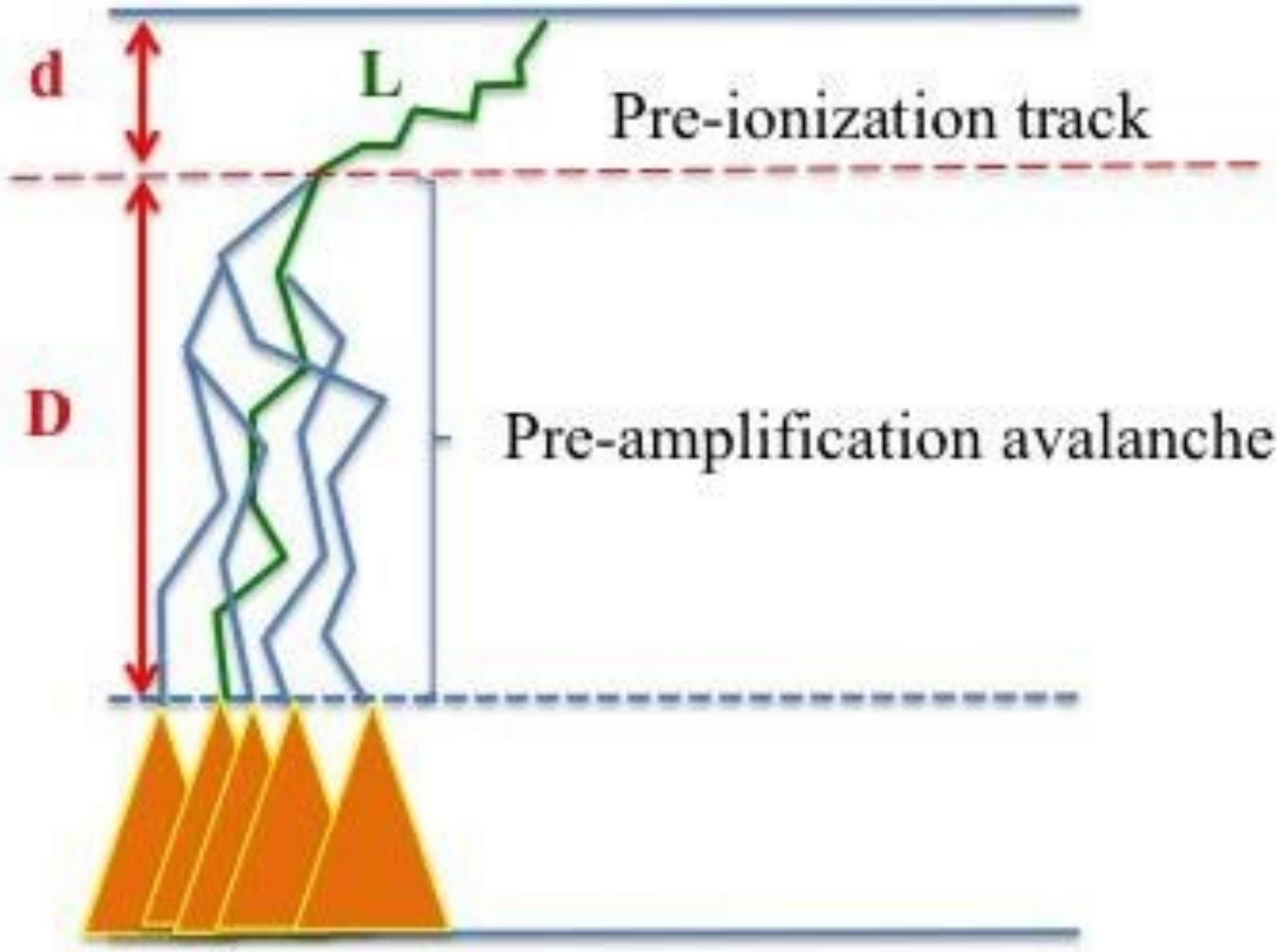
Time resolution = RMS ($T_{e\text{-peak}}$)

Signal arrival time



Time resolution





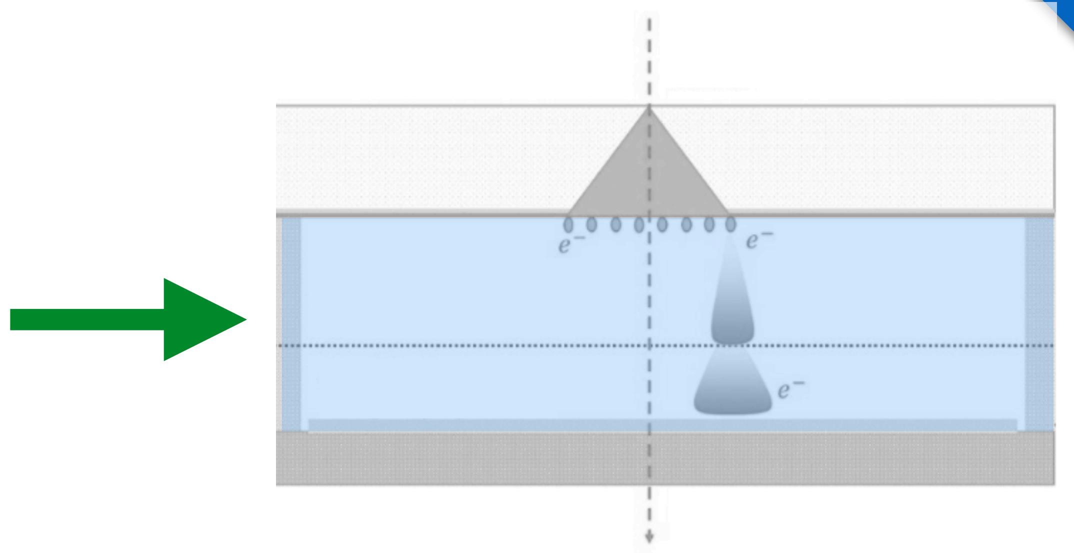
https://indico.cern.ch/event/716539/contributions/3246636/

Better time resolution for shorter pre-ionisation track ⇒ thinner gap

J. Bortfeldt et. al. (RD51-PICOSEC collaboration), NIM A (903), 2018, https://doi.org/10.1016/j.nima.2018.04.033
https://indico.cern.ch/event/716539/contributions/3246636/

Preliminary

Alternative gases



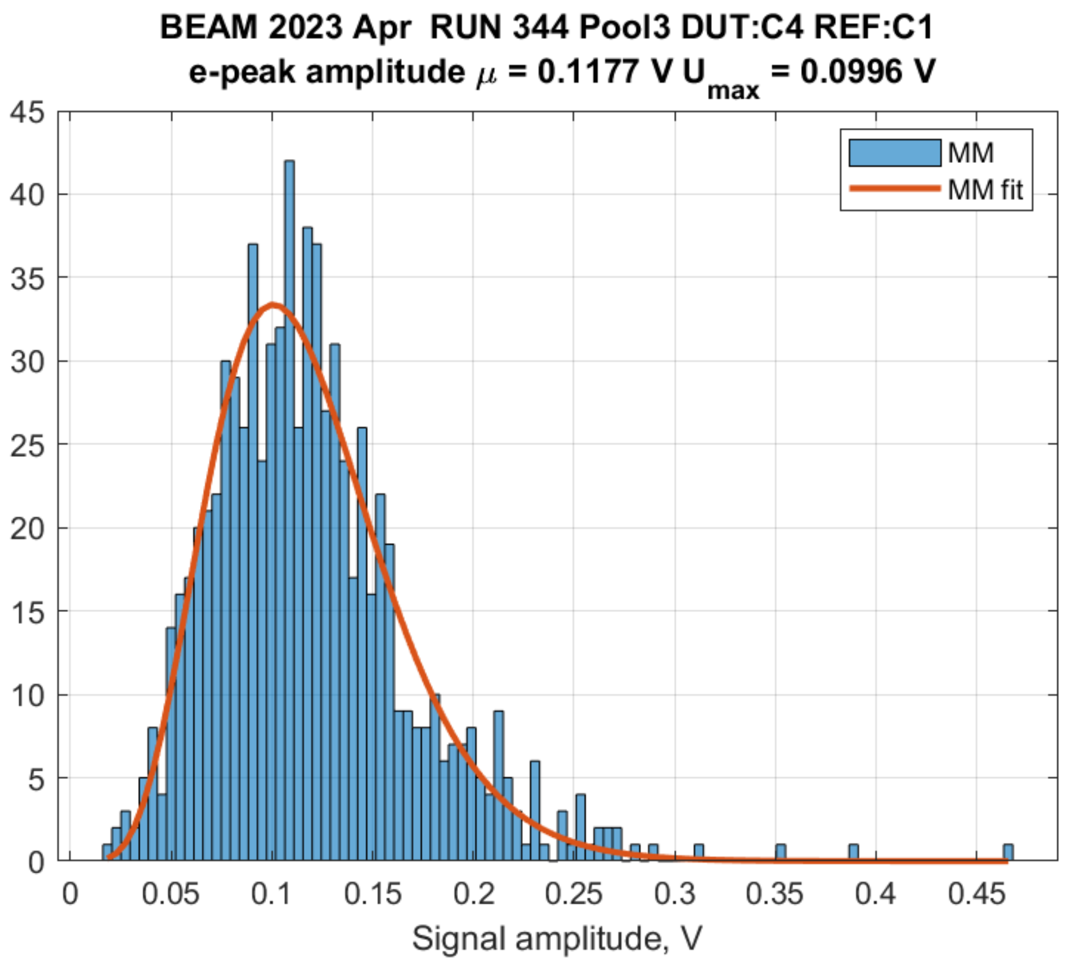
Standard gas mixture: 80% Ne + 10% C_2H_6 + 10% CF_4 (COMPASS gas) at ambient pressure

Investigation of alternative gas mixtures:

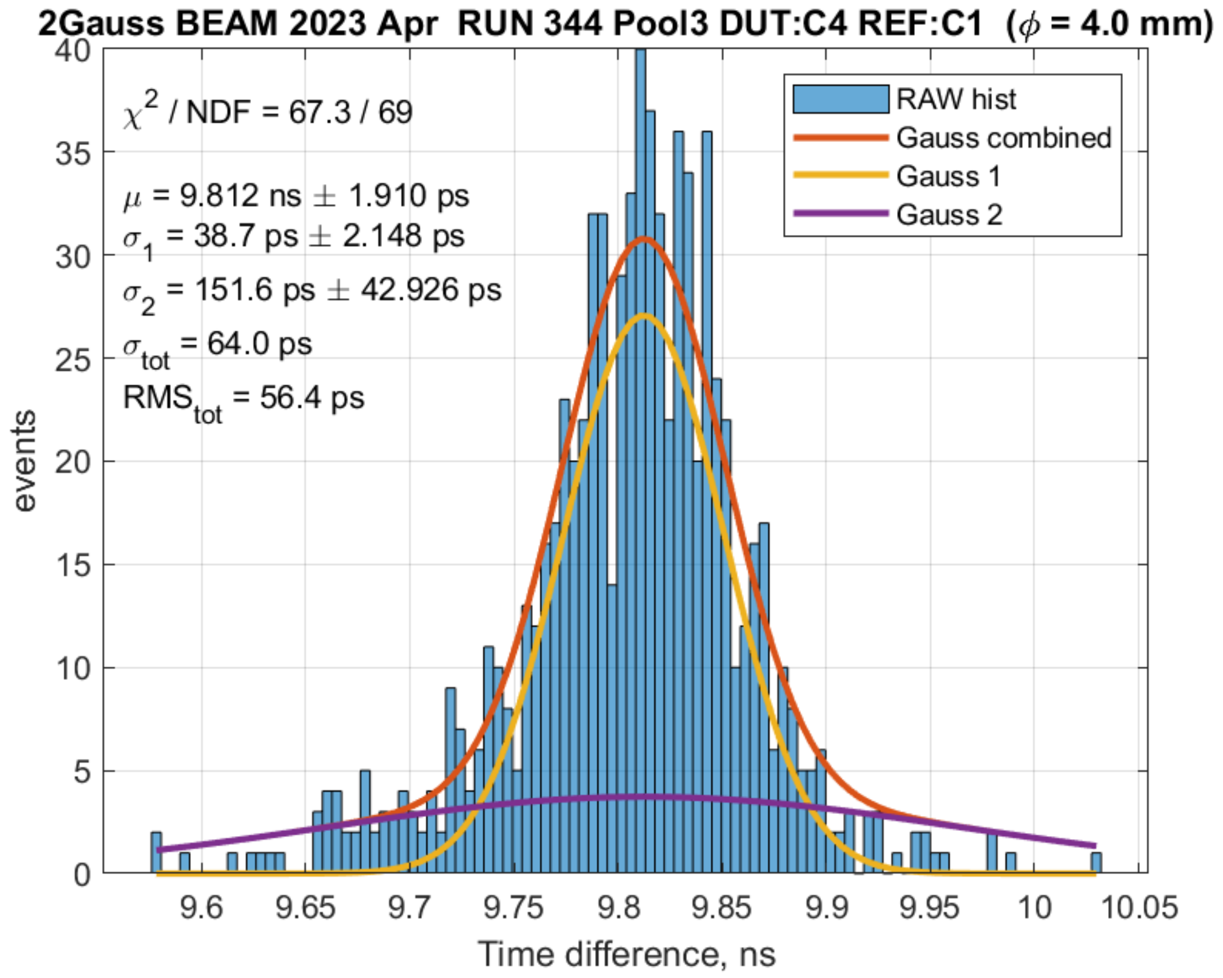
- Without CF4
- Non-flammable

Standard mixture:
Ne/ethane/CF4 (80/10/10%)
540/275V

Signal amplitude

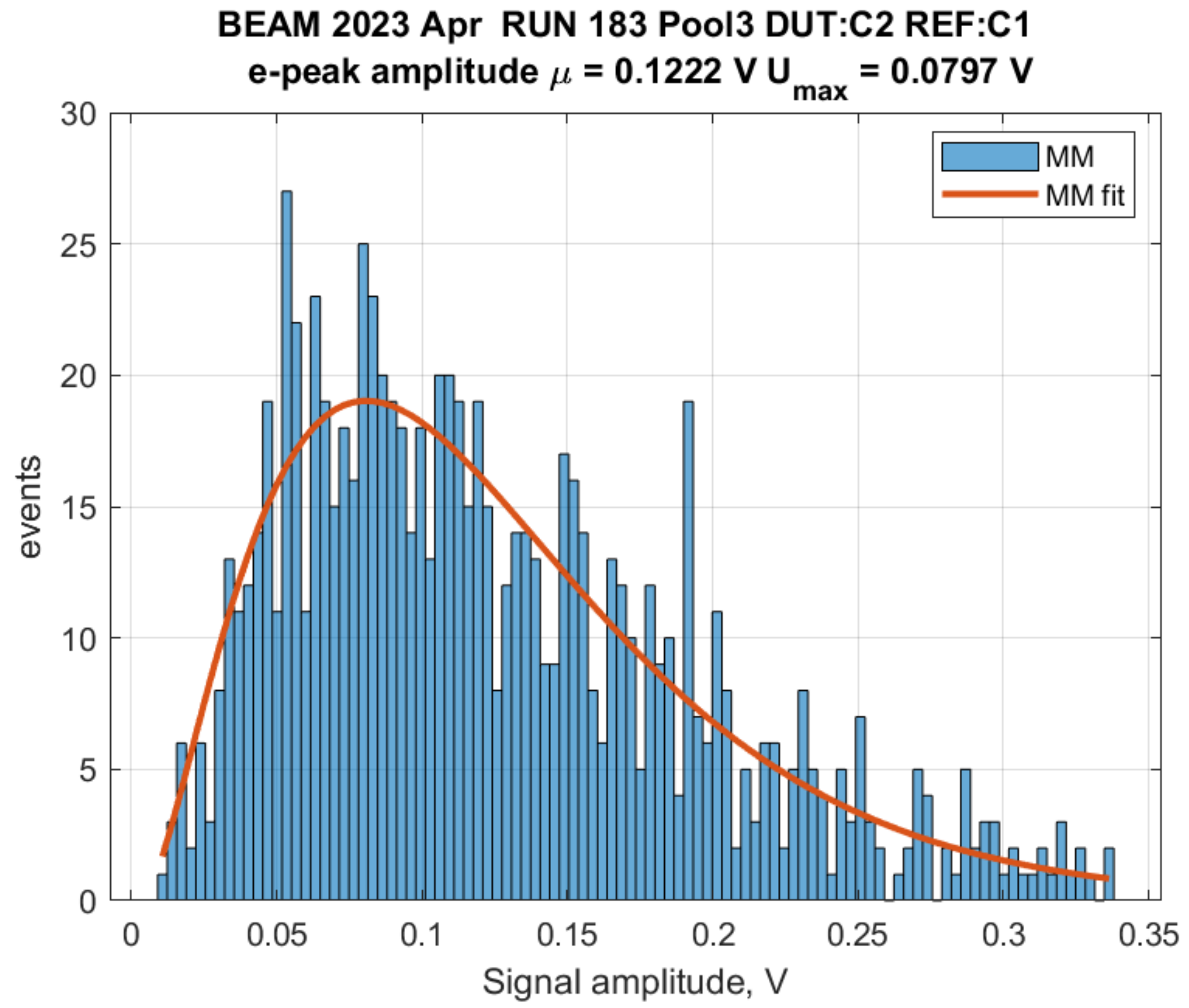


Time resolution

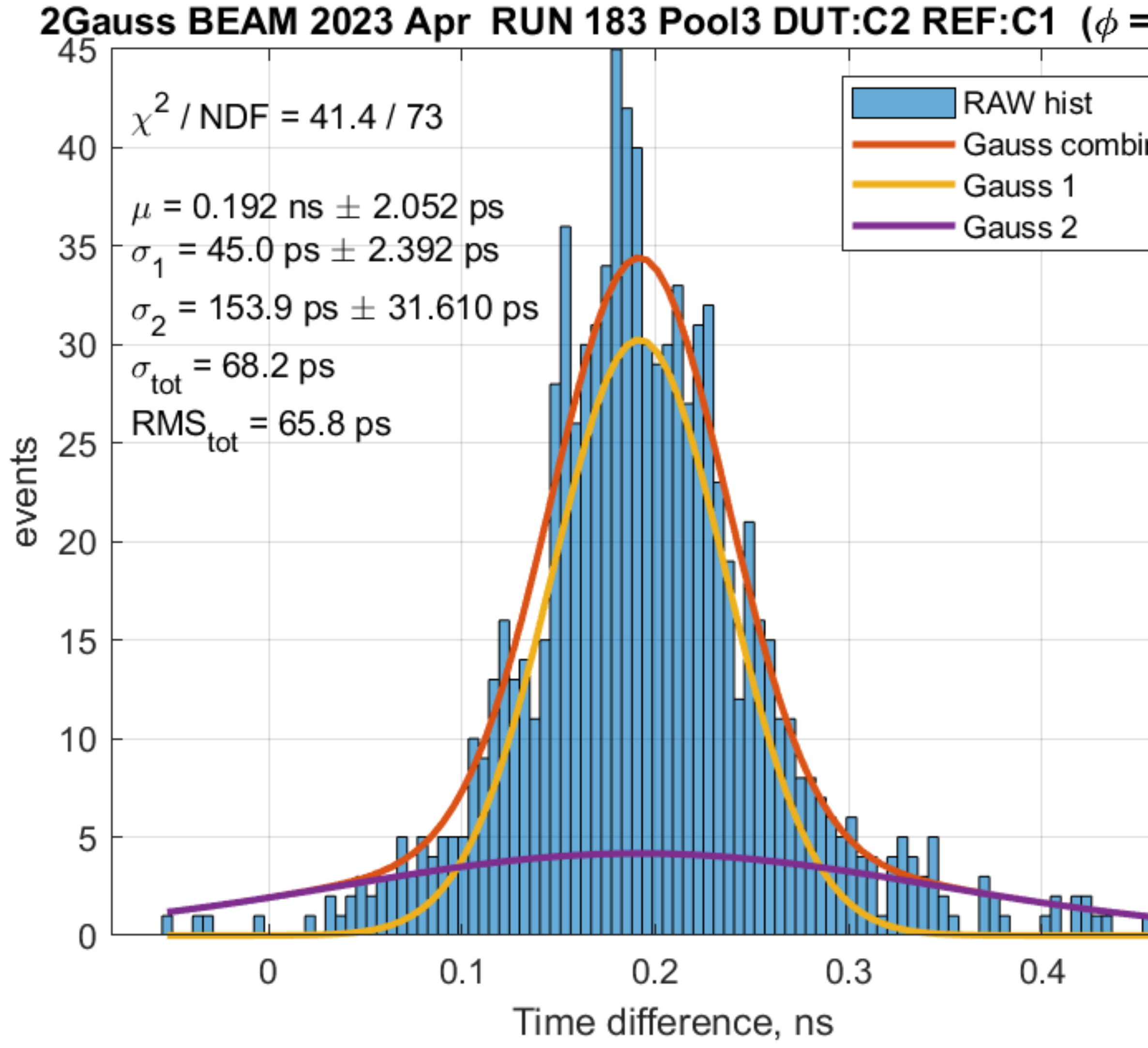


Alternative gas mixture:
Ne/iC4H10 (94/6%)
450/300

Signal amplitude



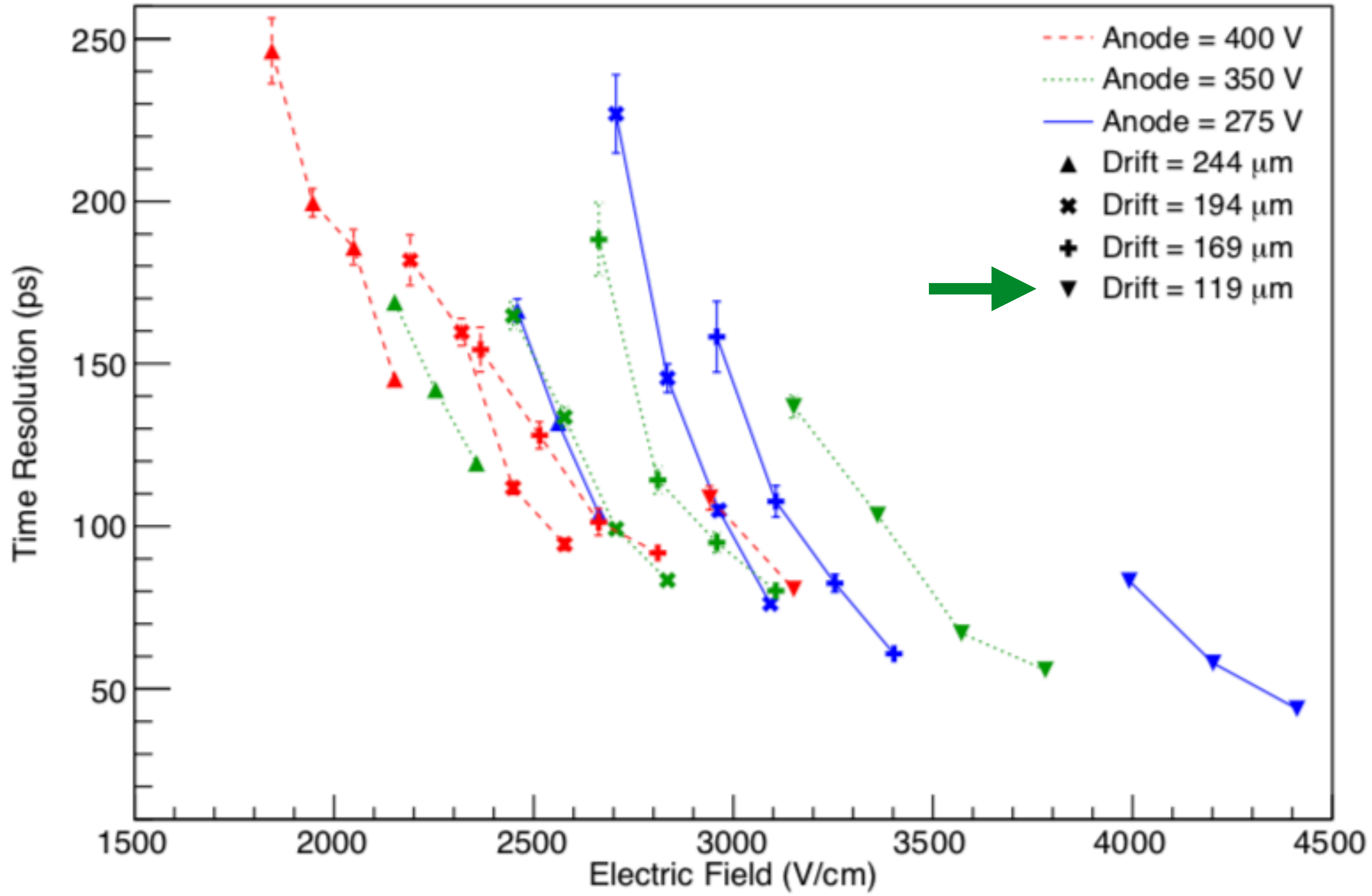
Time resolution



D. Fiorina (INFN-PV)

Thin gap Picosec

Systematic tests of electric field configurations (drift / amplification fields), drift gaps and gas mixtures performed in laser facility

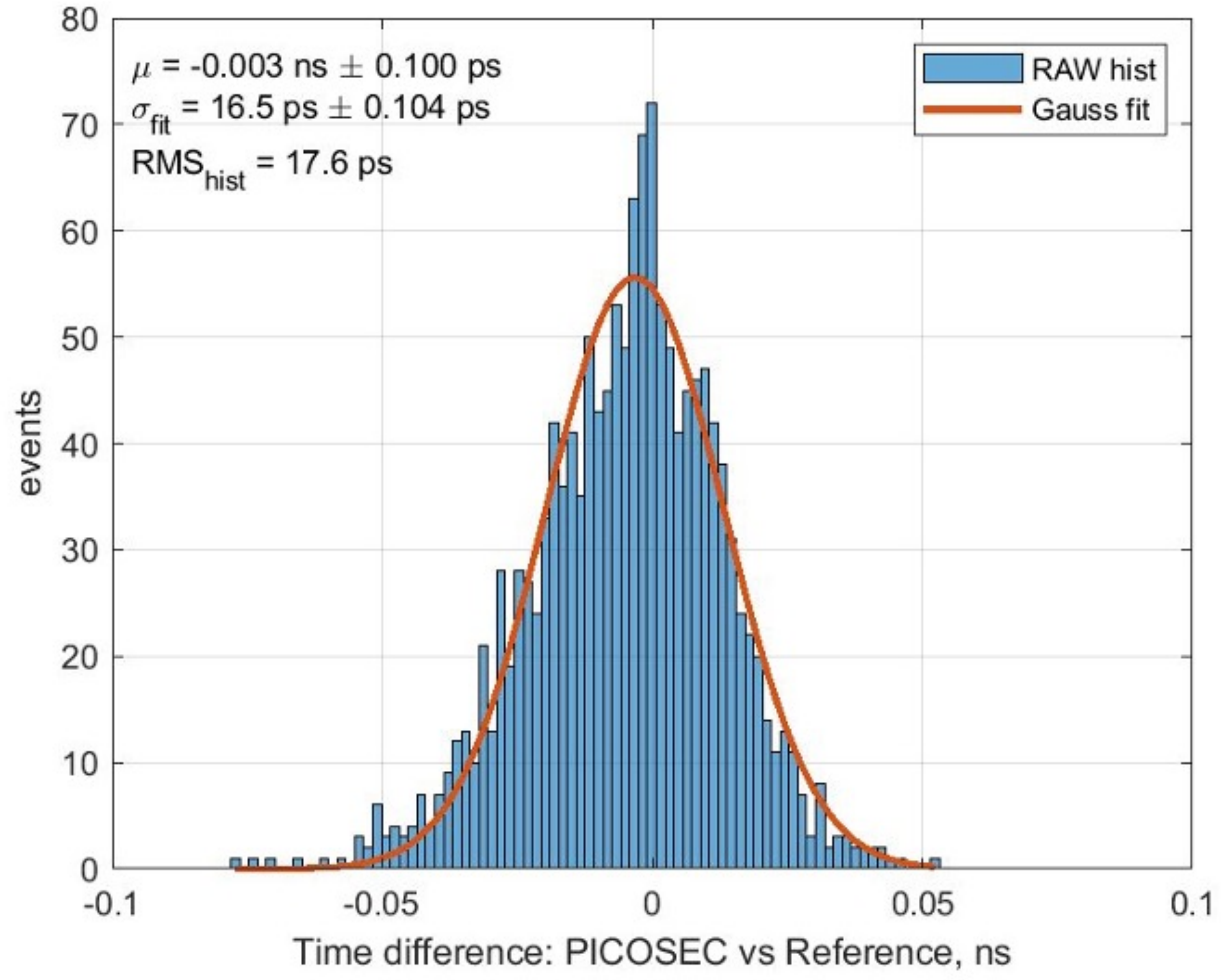


L. Sohl, et al., Single photoelectron time resolution studies of the PICOSEC-Micromegas detector, JINST Proc. of the 15th Topical Seminar on Innovative Particle and Radiation Detectors 2019, InPress (2020)

Smaller drift gap has better performance at same gain
(Shorter drift time of the first electron)

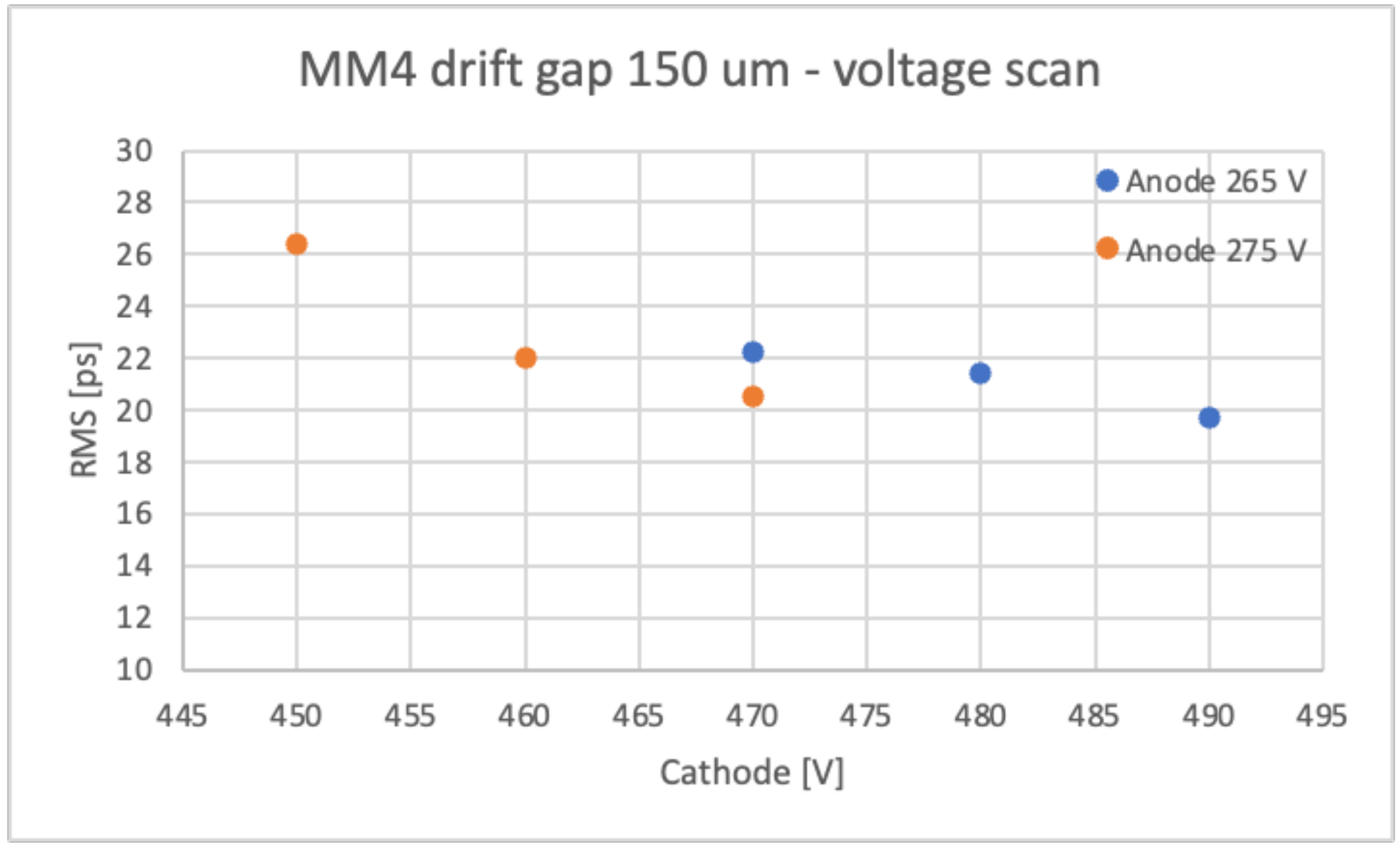
Excellent timing performance confirmed in MIP test beam

<20ps timing resolution achieved with **thin gap Picosec** (≈120-170μm drift gap)

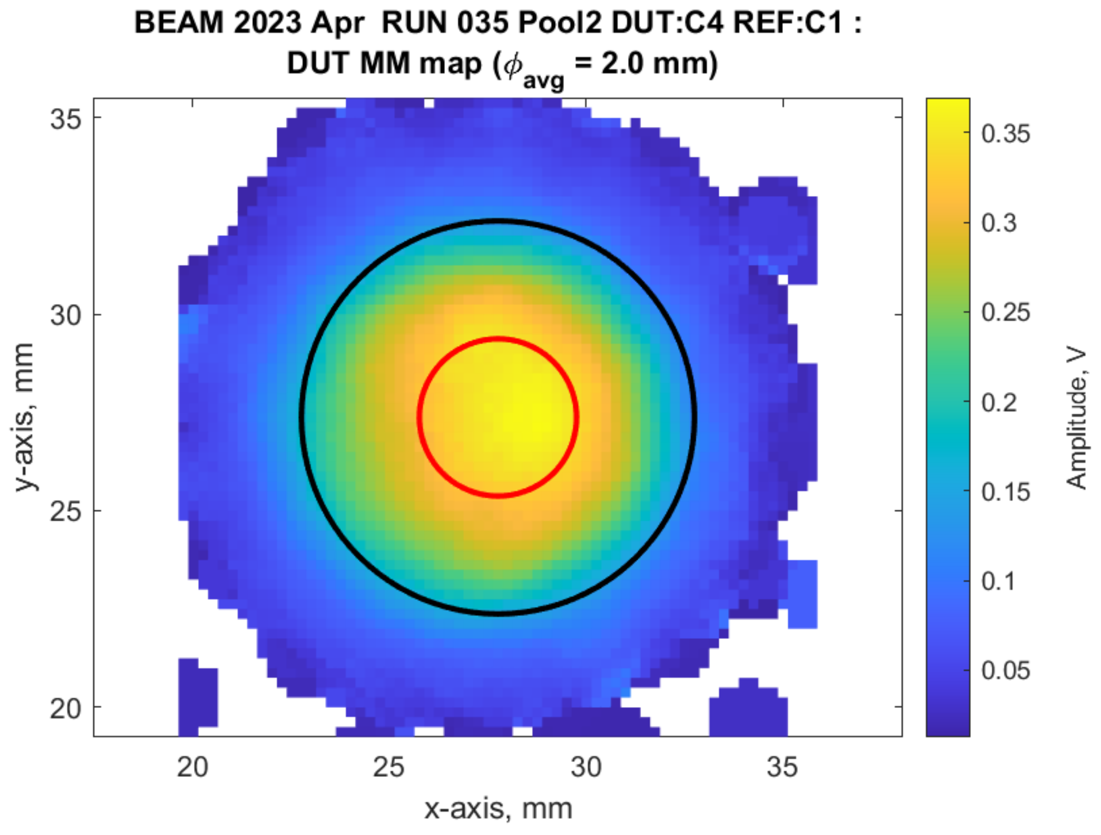


CsI

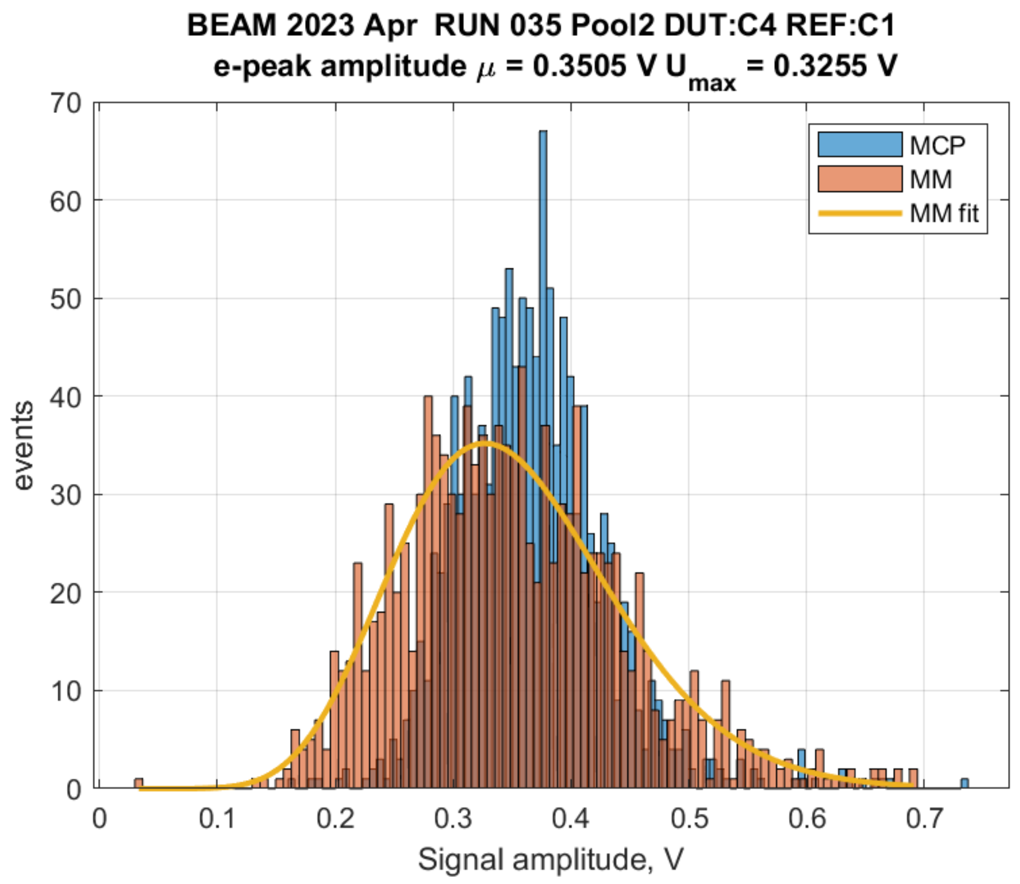
Single pad detector, sealed operation
82M resistive Micromegas, 150µm preampfification gap



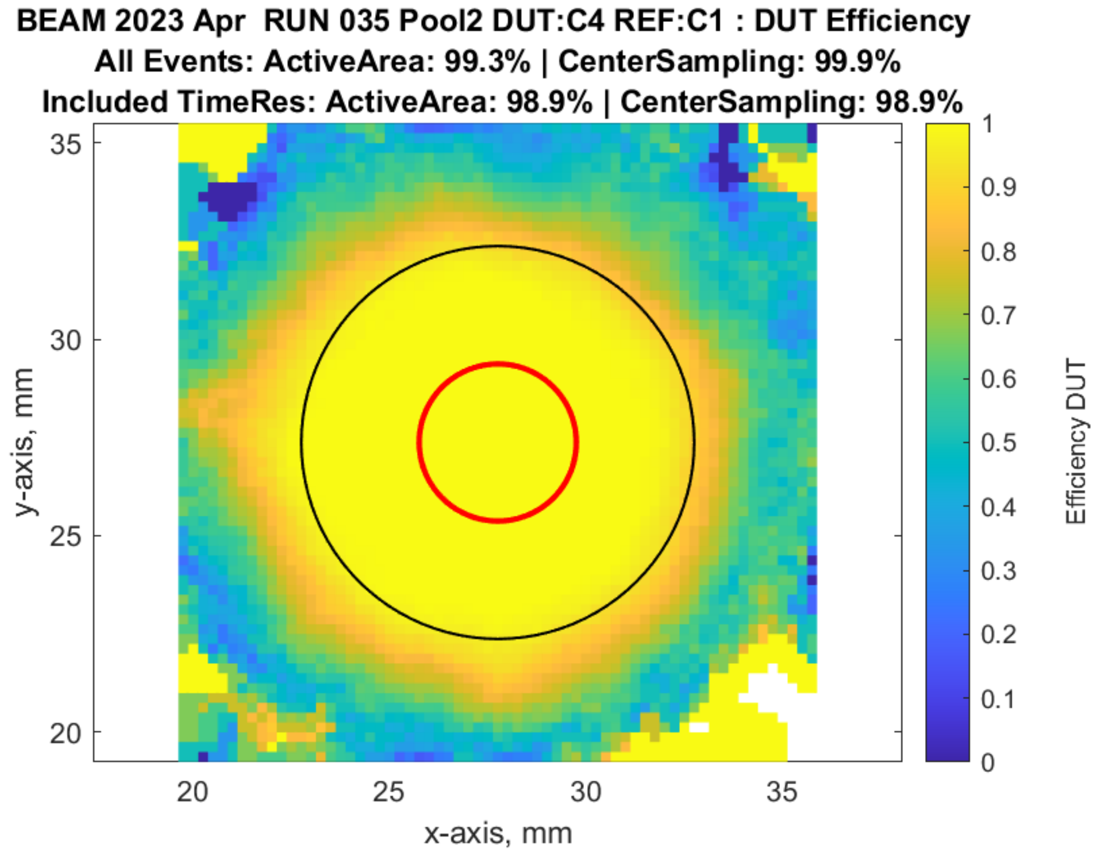
2D amplitude map



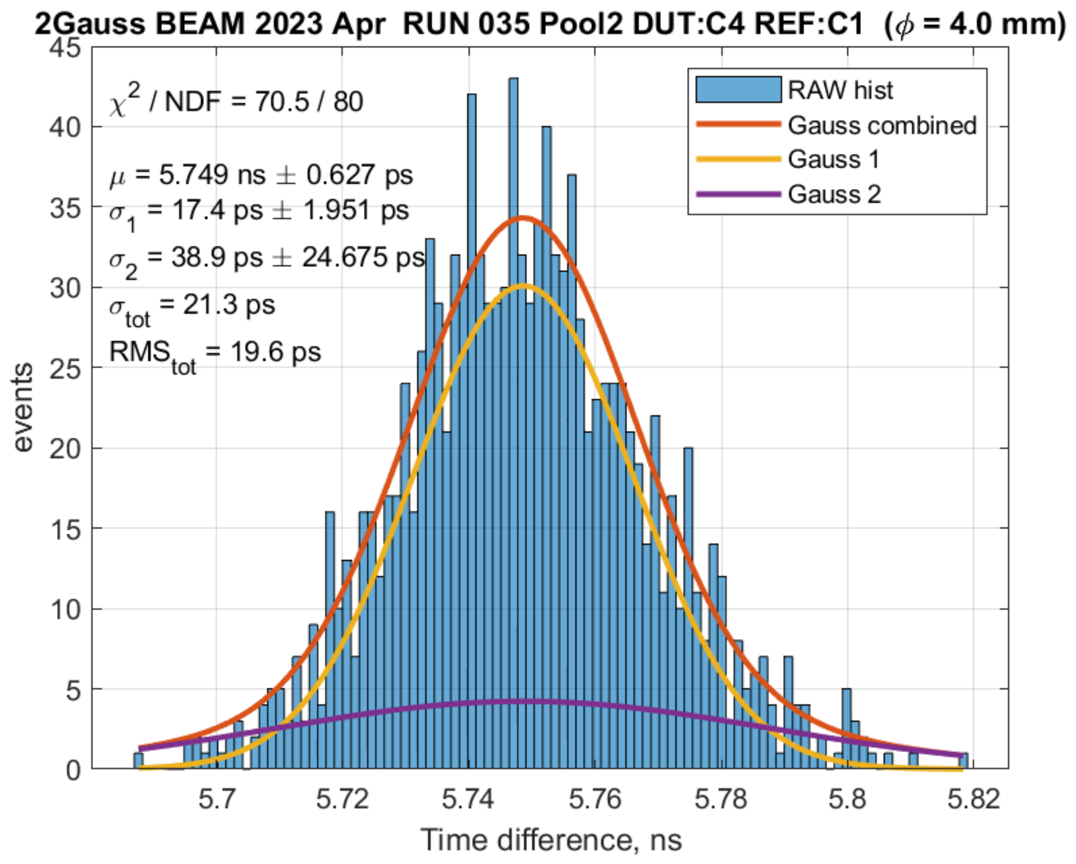
Amplitude distribution



Efficiency map



Time resolution <20ps



Picosecond timing

Timing requirements on the level of tens of ps set by increasing luminosity and precision measurements. Examples of requirements at future facilities include:

Mitigate pileup in high multiplicity environments to distinguish event and mitigate background

Precise **Time-of-Flight (ToF)** measurements for Particle Identification (PID) at level of ≈20 ps/MIP can offer Pion/Kaon and Kaon/Proton separation for a wide momentum range

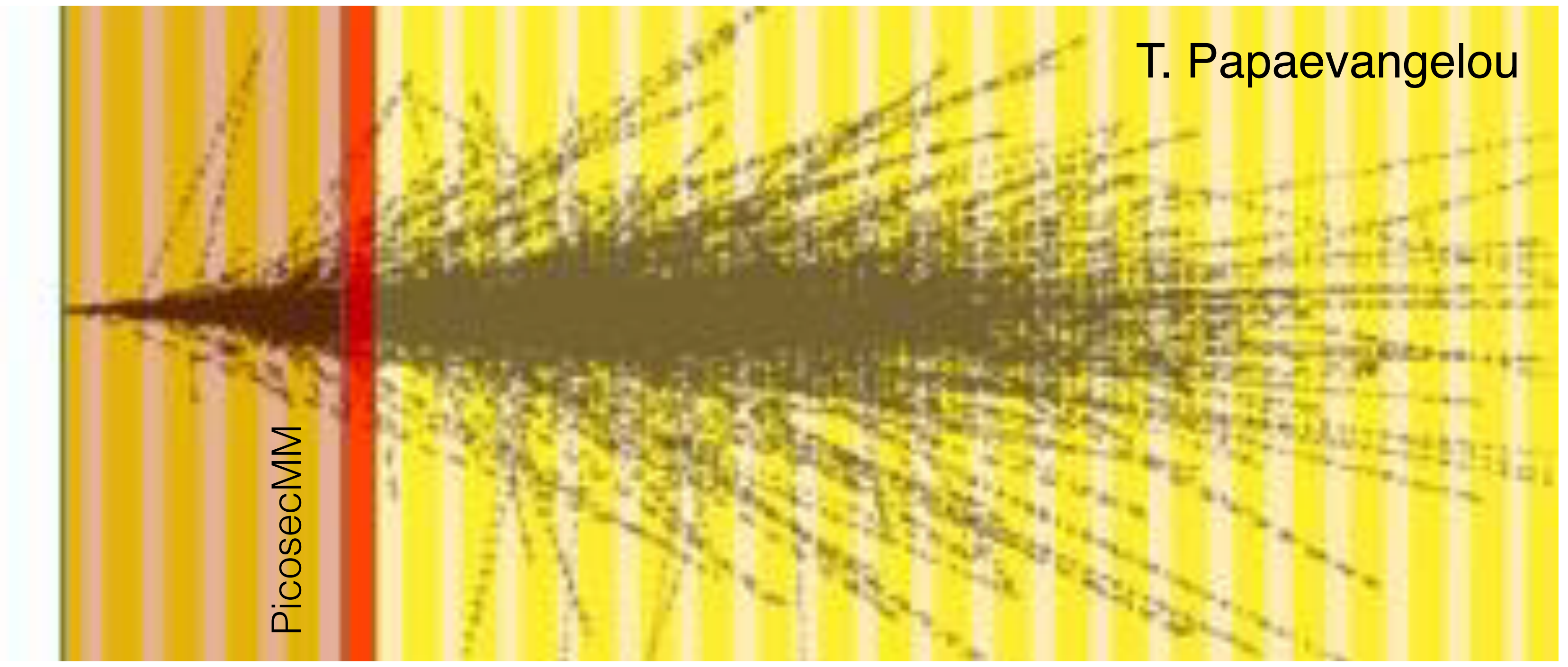
Tagged neutrino beam (time and flavour of tagging) for event-by-event decay measurements (ENUBET)

$$K^+ \rightarrow \pi^0 e^+ \nu_e$$

Photodetectors with high timing resolution

Timing detector requirements:
- Tens of ps timing precision
- Large surface coverage
- Resistance against ageing

J. Va'vra, https://dx.doi.org/10.1016/j.nima.2017.02.075



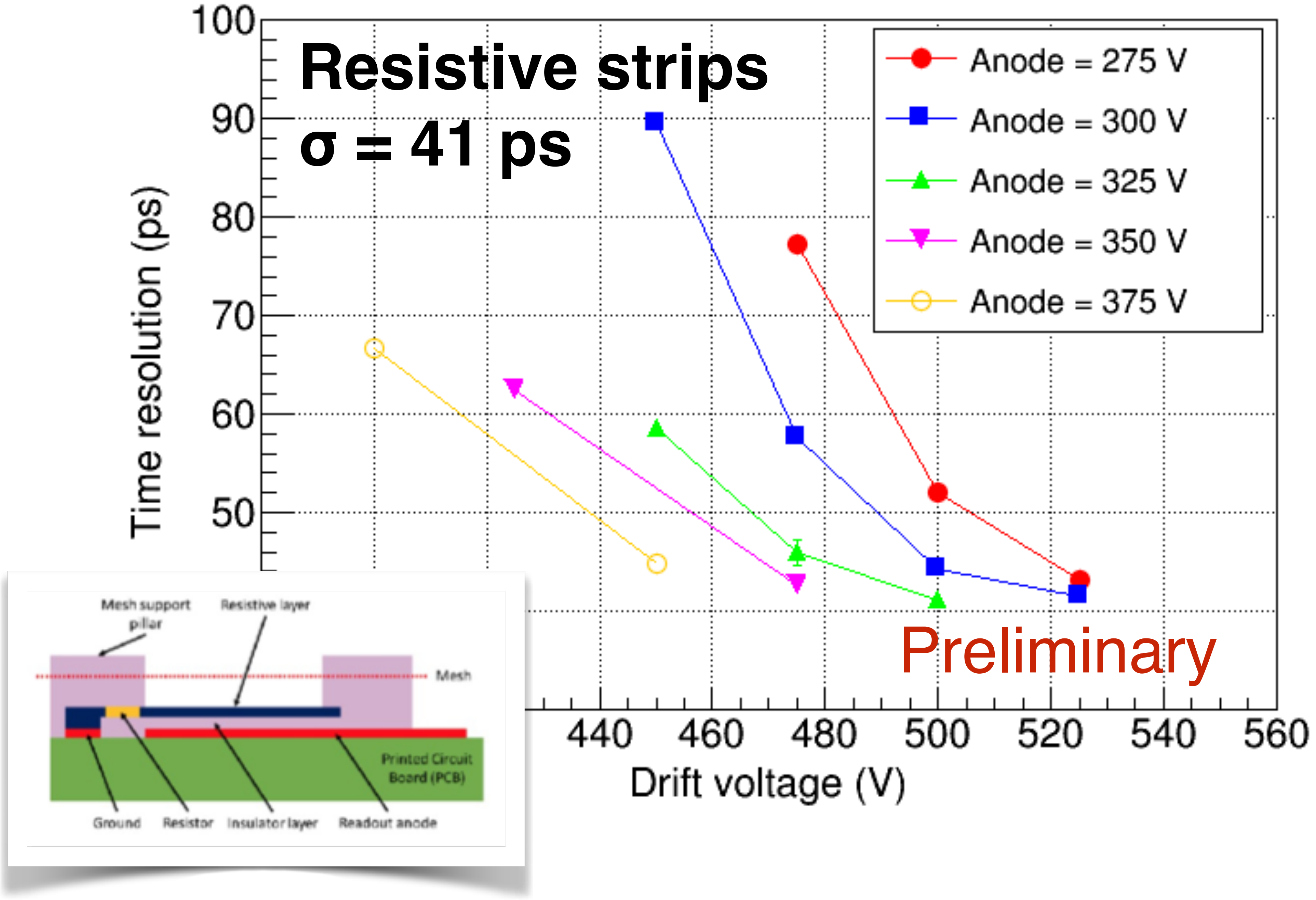
Embedding a PICOSEC Micromegas layer into an Electromagnetic Calorimeter (EMC)

Detector stability

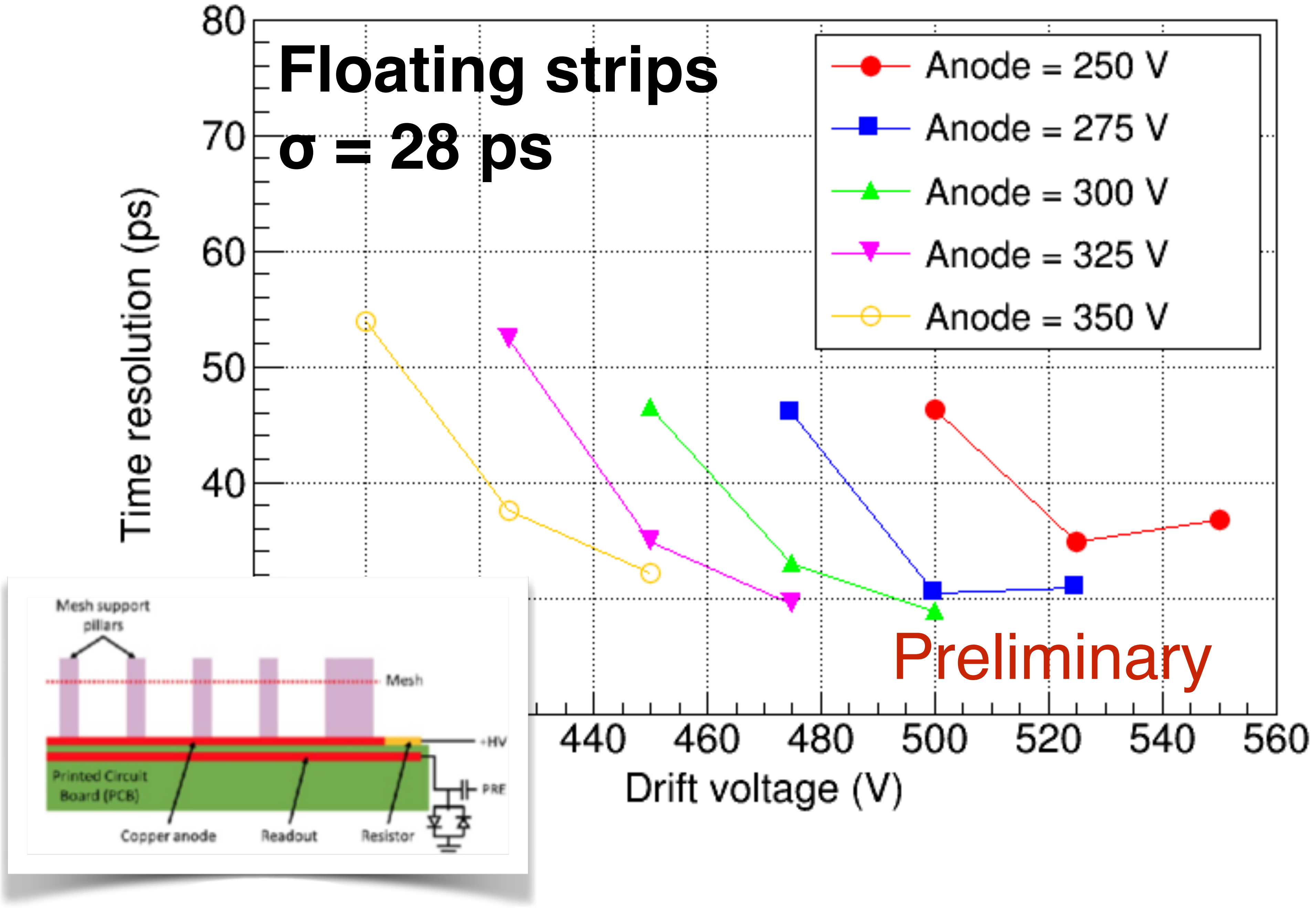
Resistive Micromegas

Achieved time resolution close to PICOSEC bulk readout.

Stable operation in intense pion beam



41 MΩ/sq



25 MΩ

Photocathode robustness

Alternatives tested during test beam campaigns

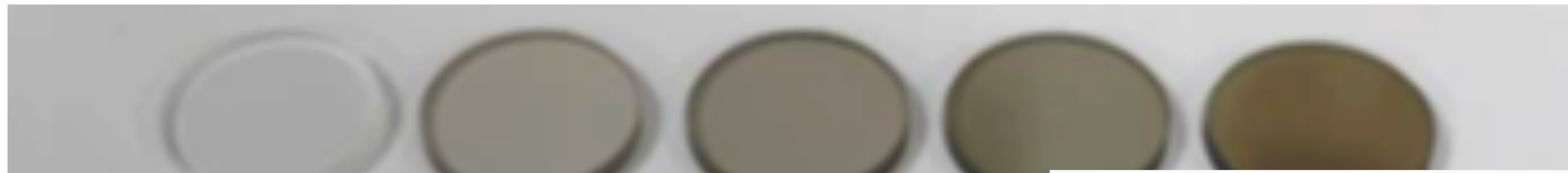
Photocathode	$N_{ph.e.}$ / muon
Cr +18 nm CsI	10.4 ± 0.4
20 nm Cr	0.66 ± 0.13
6 nm Al	1.69 ± 0.01
10 nm Al	2.20 ± 0.05
Cr + 5nm diamond	1.85

Photocathode	$N_{ph.e.}$ / muon
CsI + LiF	<1
CsI + MgF_2	3.55 ± 0.08

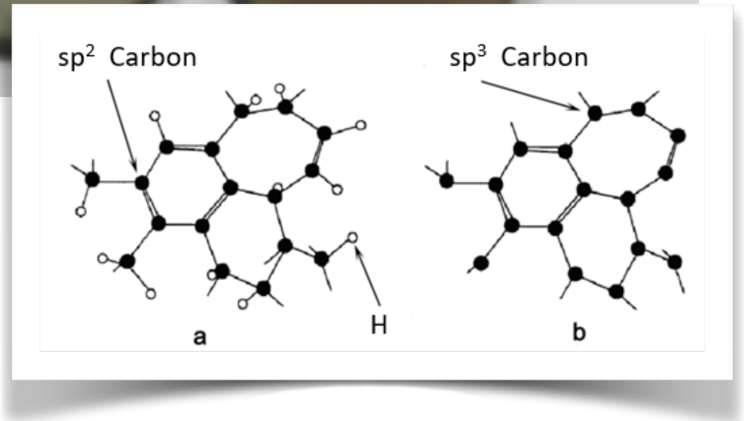
DLC thickness	$N_{ph.e.}$ / muon
2.5nm	3.7
5nm	3.4
7.5nm	2.2
10nm	1.7

Diamond-like carbon (DLC)

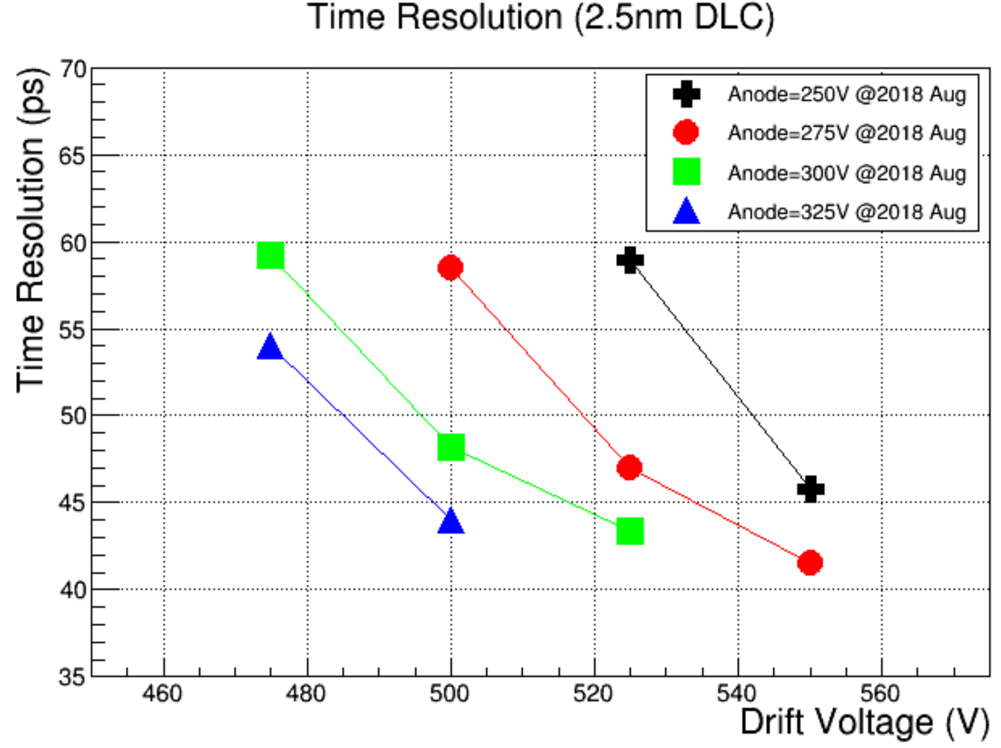
Robust material used for resistive electrodes and with promising properties as photocathode.

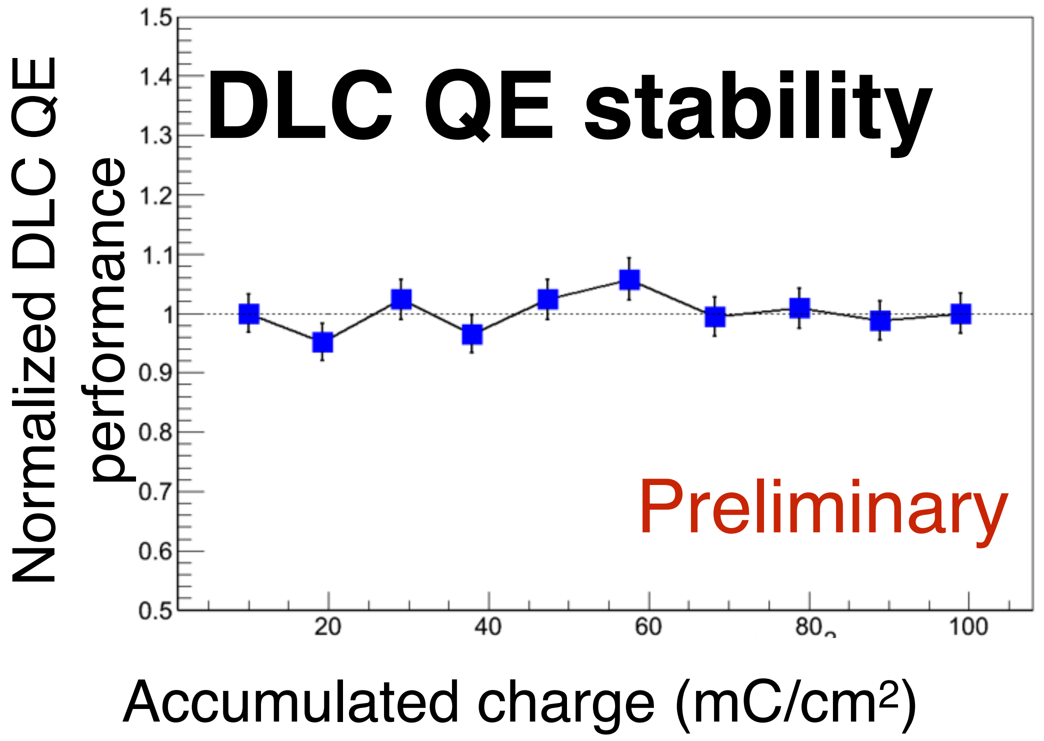


https://indico.cern.ch/event/709670/contributions/3012912/attachments/1671364/2681277/DLC-photo-cathode.pdf



First beam tests show **≈3.5 pe/muon** and 40-45 ps achievable time resolution

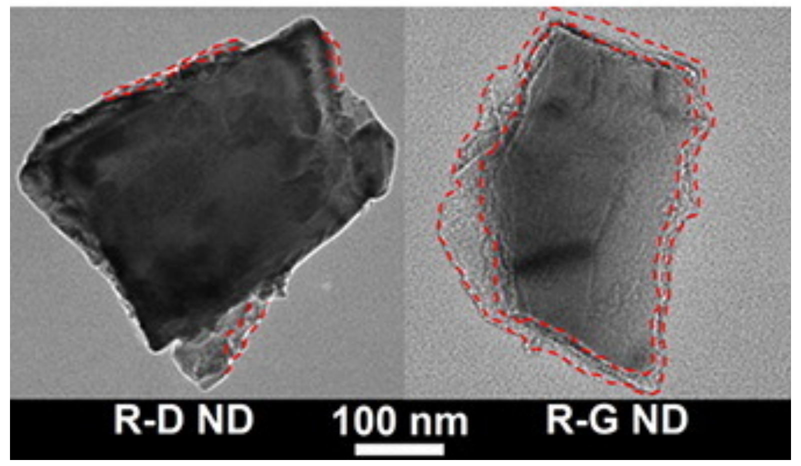


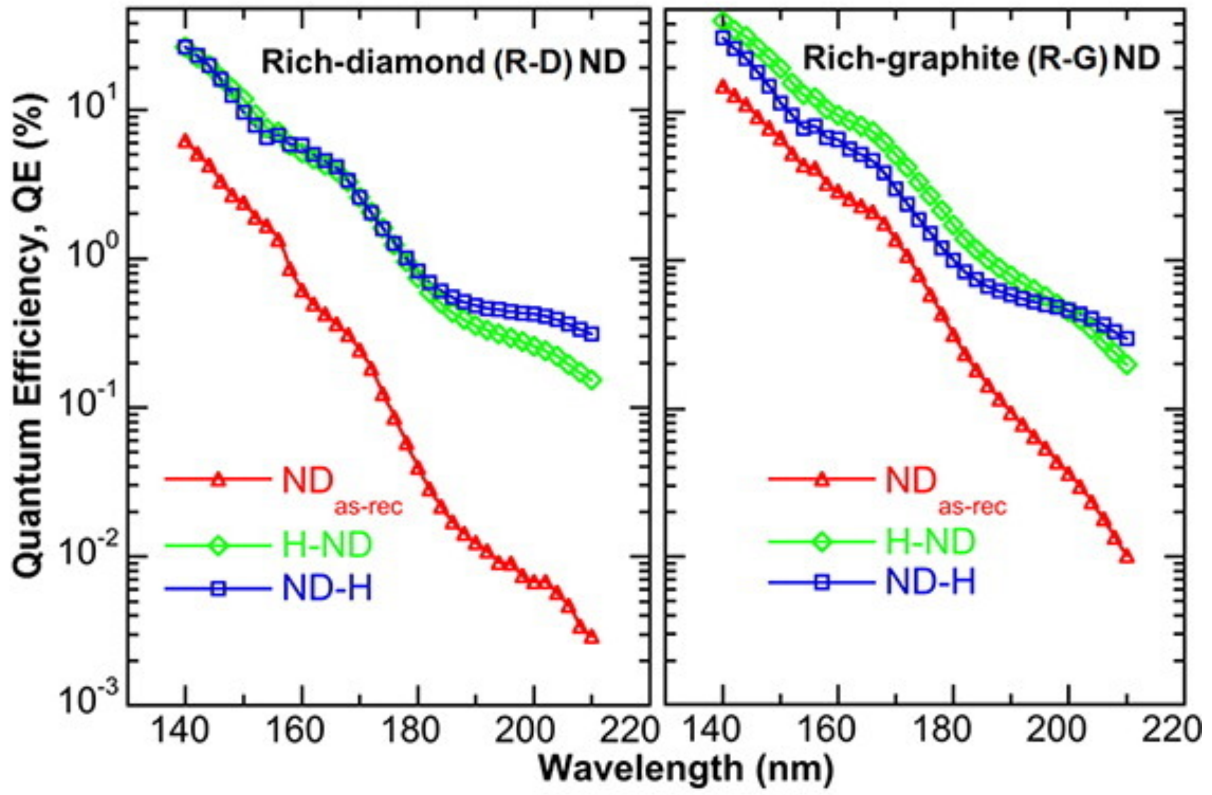


X. Wang, Recent photocathode and sensor developments for the PICOSEC Micromegas detector, MPGD 2019 https://indico.cern.ch/event/757322/contributions/3387110

Nanodiamond (ND) powder

Based on ≈100nm diamonds particles deposited by spray technique, good QE

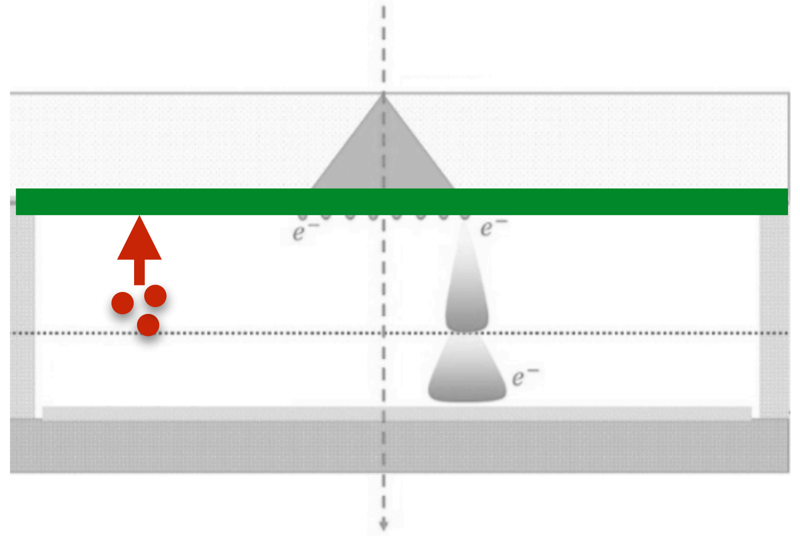




Velardi et al., https://doi.org/10.1016/j.diamond.2017.03.017
C. Chatterjee et al 2020 J. Phys.: Conf. Ser. 1498 012008
https://iopscience.iop.org/article/10.1088/1742-6596/1498/1/012008/pdf

Photocathode robustness

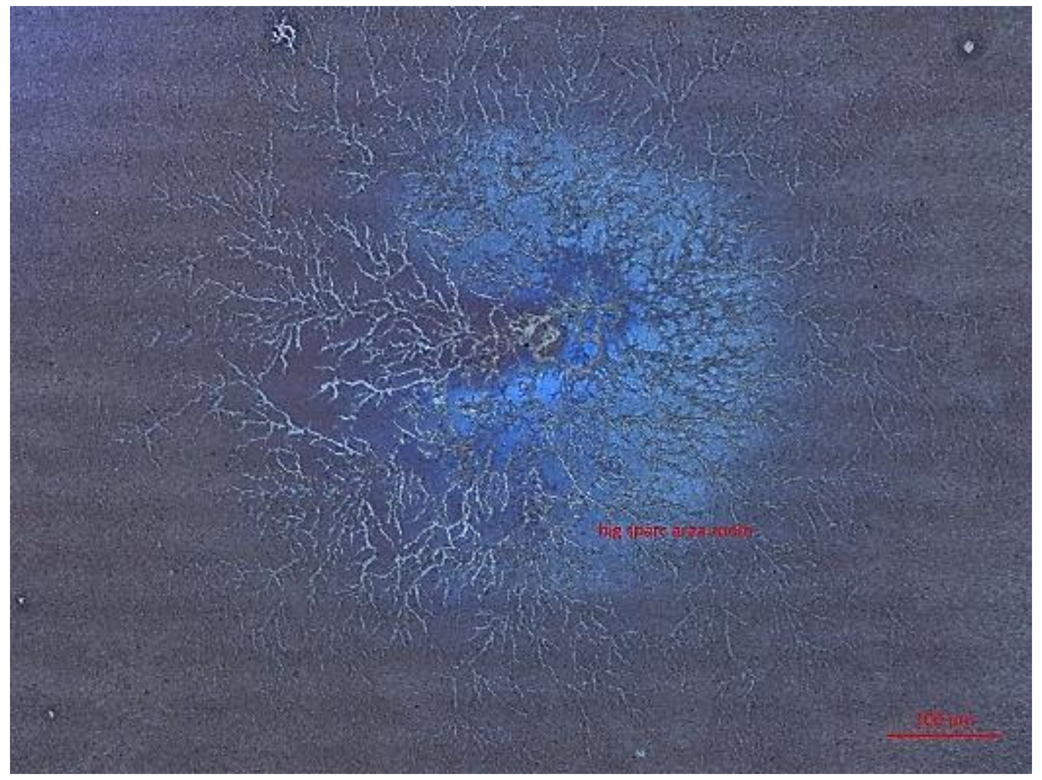
Limitations of CsI



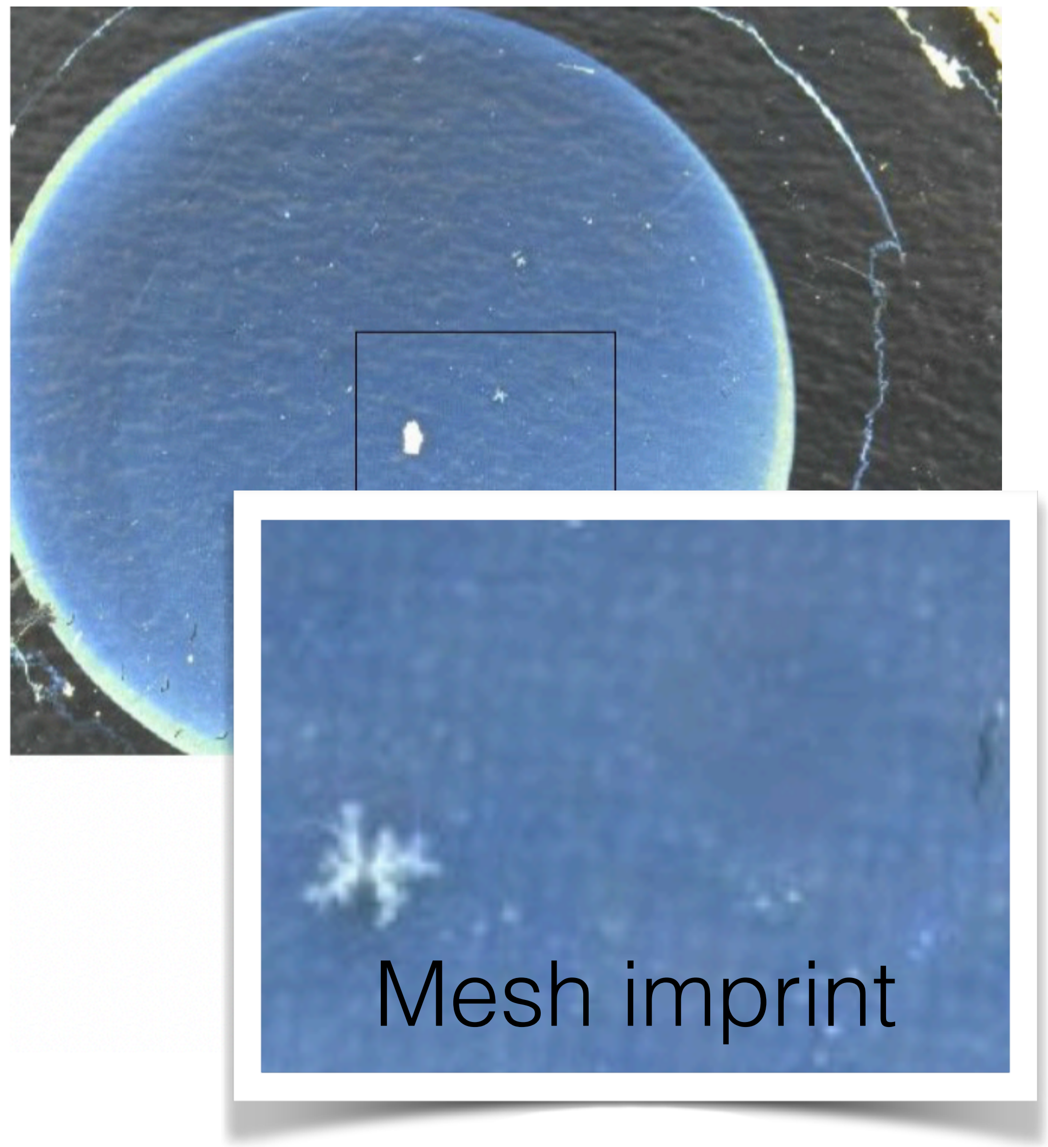
Standard PICOSEC photocathode: 18 nm CsI + 3 nm Cr → ≈10 p.e. / MIP

CsI sensitive to humidity, ion backflow and sparks

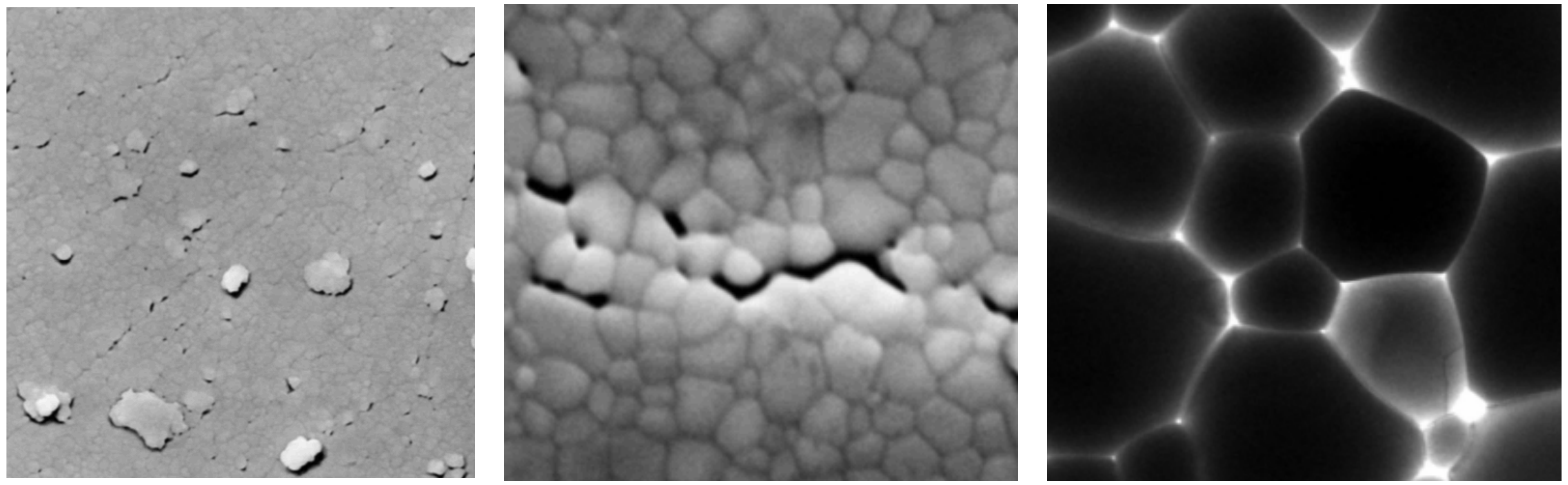
CsI photocathode after spark



Ion backflow on CsI



Scanning electron microscope images of CsI morphology



CsI: deposited

After VUV exposure

Humidity exposure

https://doi.org/10.1016/j.nima.2009.05.179

https://doi.org/10.1016/j.nima.2011.10.019

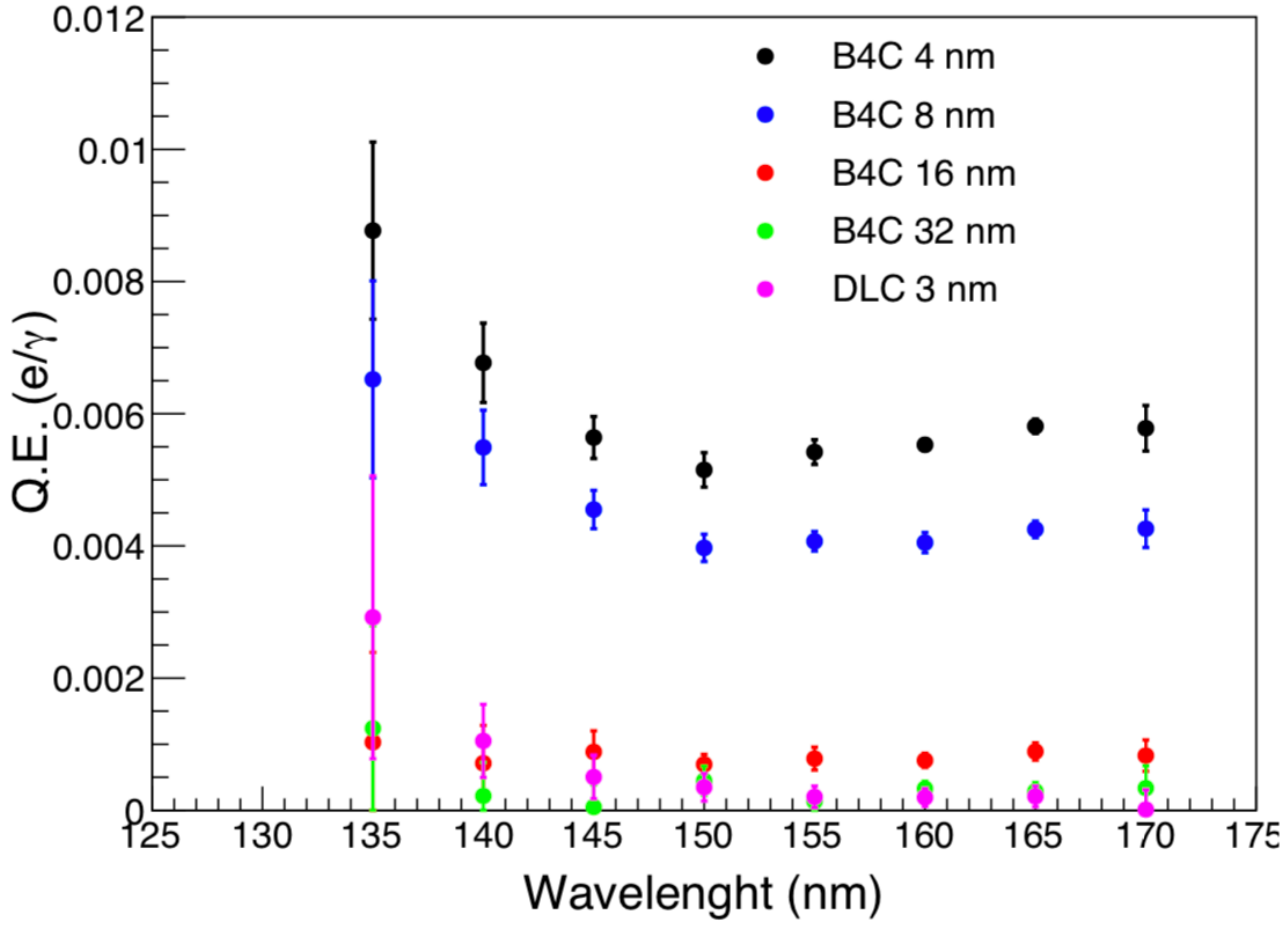
Photocathode studies with ASSET

Tested **CsI** samples and protection layers produced by TFG lab (M. van Stenis, T. Schneider)

Measurements of **B_4C, DLC** and **nano diamond** photocathodes with visiting RD51 groups

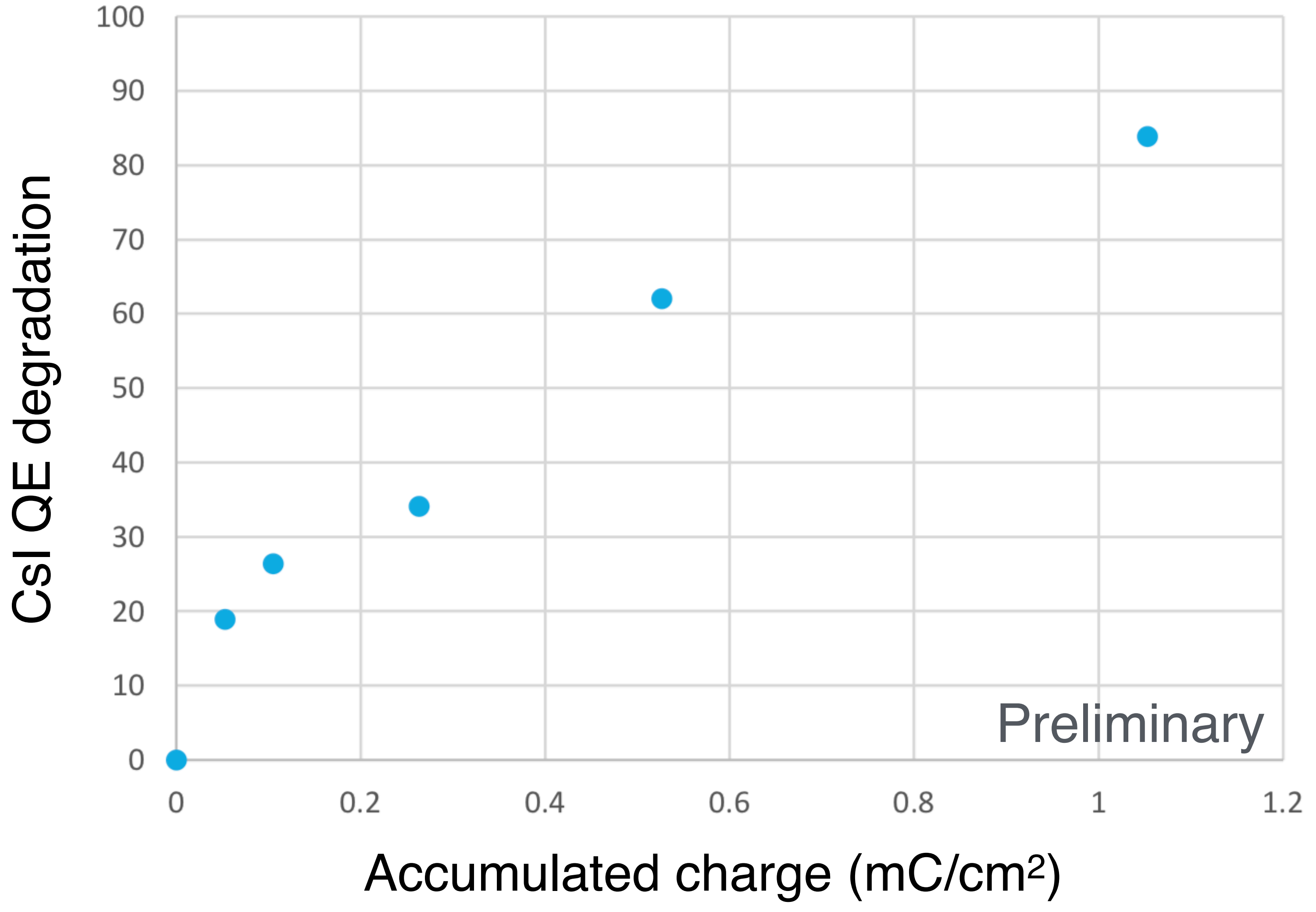
Reflective/transmissive QE, ion bombardment degradation and VUV transparency measurements

B_4C / DLC transmission QE

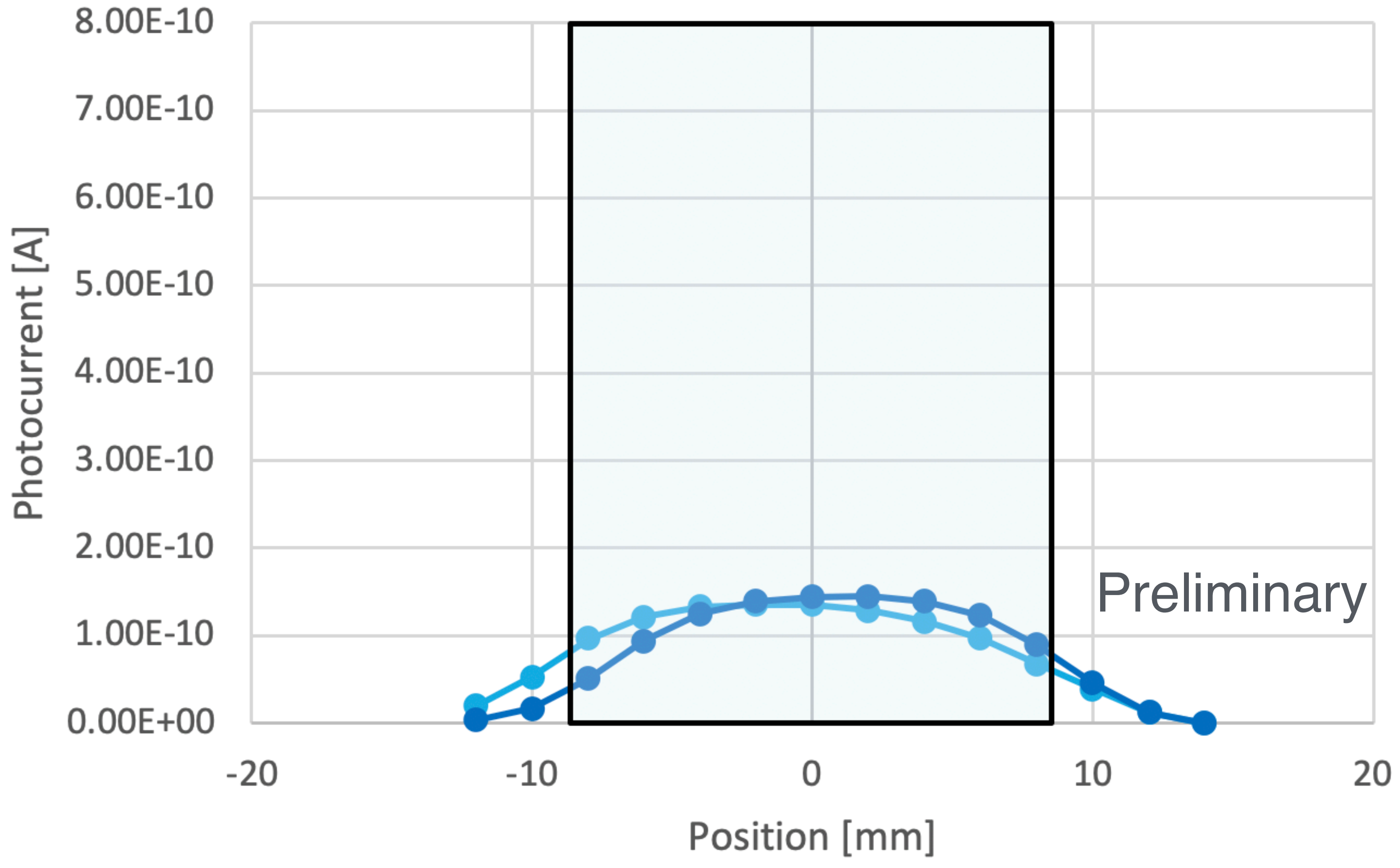


L. Sohl, Overview on recent PICOSEC-Micromegas developments and performance tests, RD51 Mini-Week February 2020, https://indico.cern.ch/event/872501/contributions/3726013/

CsI degradation under ion bombardment



QE uniformity scan of nano diamond photocathode



M. Lisowska, ASSET - Photocathode characterisation device, RD51 Mini-Week February 2020, https://indico.cern.ch/event/872501/contributions/3726017

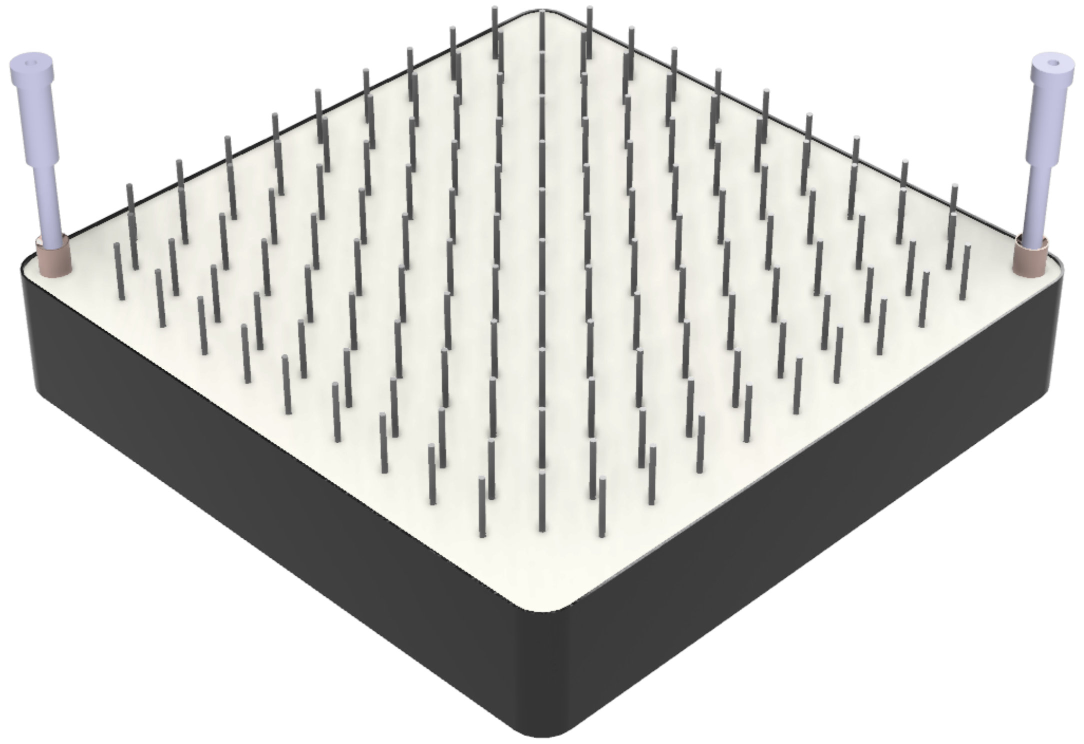
Sealed detector

10cm x 10cm detector module towards tiling with increased fill factor

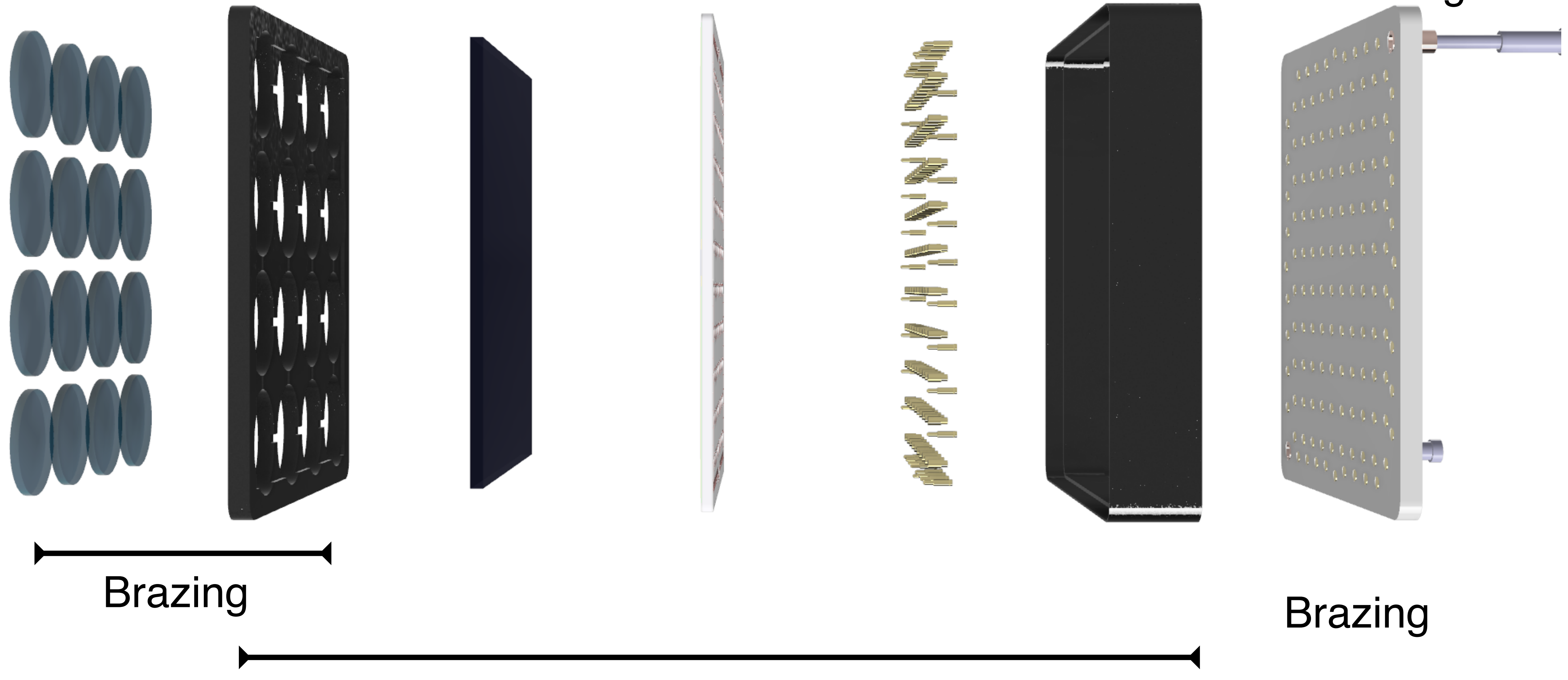
Use of **low outgassing** components in detector (ceramic PCBs) and **sealing** techniques (brazing, electron beam welding) for minimal contamination and hermetic sealing.

- **Simplified services**: no need for continuous (flammable) gas flow
- **High fill-factor:** minimised dead area due to replacement of o-rings with welds
- **Cleanness for photocathode**

3D model



During assembly



Sapphire windows

Ti flange

MgF_2

Micromegas

Ti housing

Brazed feedthroughs

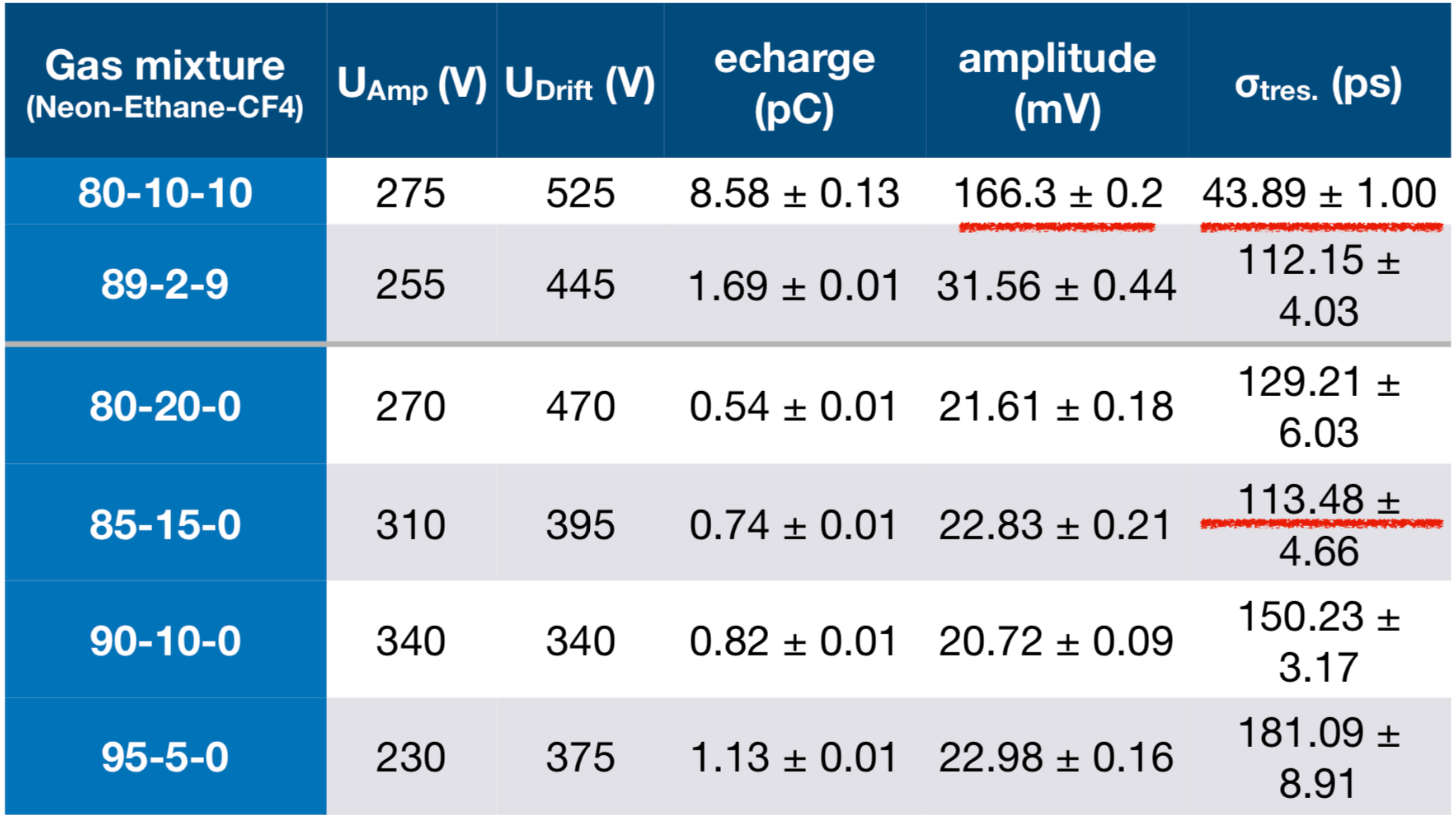
Brazing

Brazing

Electron beam welding

M. Lisowska

Gas studies

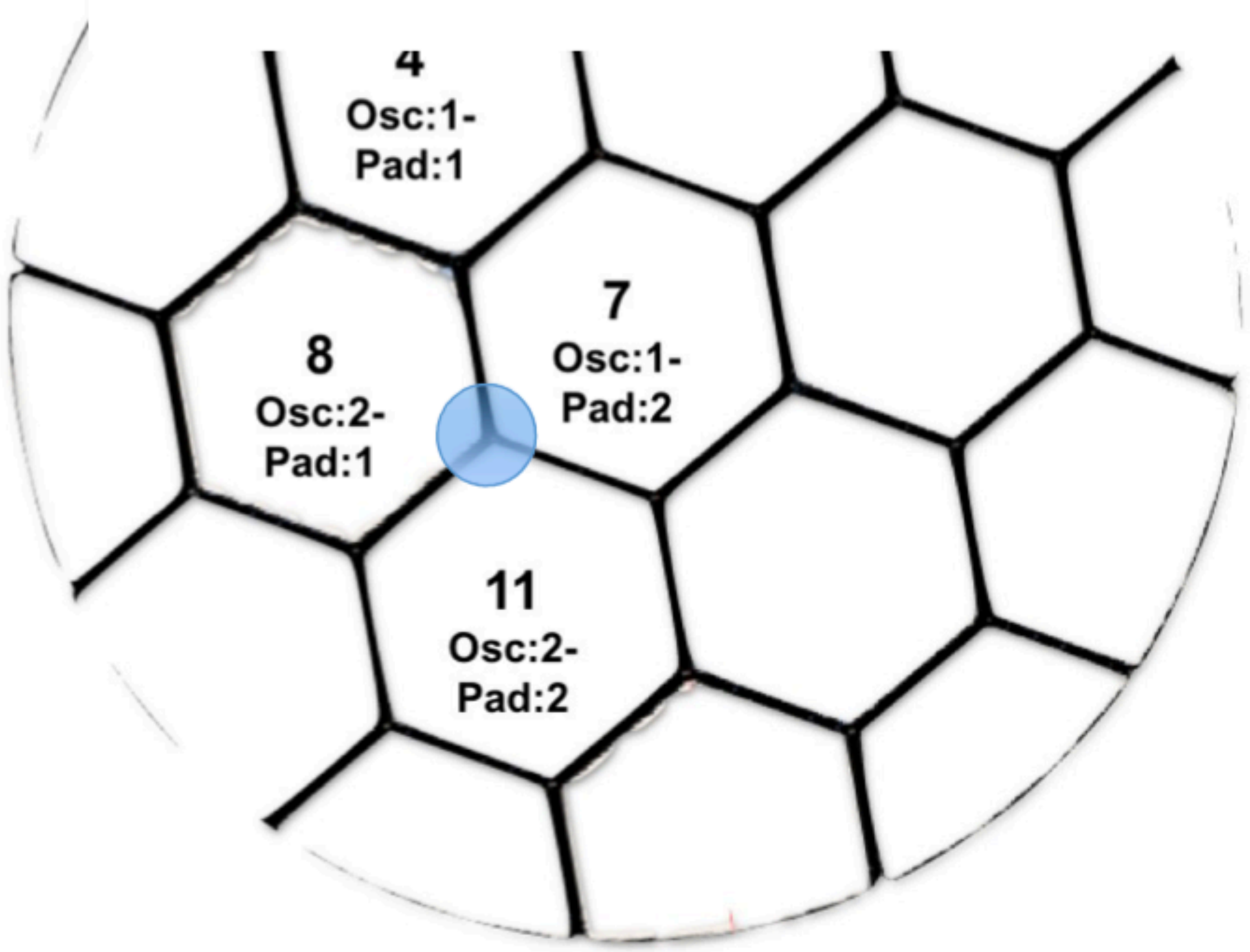


Gas mixture (Neon-Ethane-CF4)	U_{Amp} (V)	U_{Drift} (V)	echarge (pC)	amplitude (mV)	$\sigma_{tres.}$ (ps)
80-10-10	275	525	8.58 ± 0.13	166.3 ± 0.2	43.89 ± 1.00
89-2-9	255	445	1.69 ± 0.01	31.56 ± 0.44	112.15 ± 4.03
80-20-0	270	470	0.54 ± 0.01	21.61 ± 0.18	129.21 ± 6.03
85-15-0	310	395	0.74 ± 0.01	22.83 ± 0.21	113.48 ± 4.66
90-10-0	340	340	0.82 ± 0.01	20.72 ± 0.09	150.23 ± 3.17
95-5-0	230	375	1.13 ± 0.01	22.98 ± 0.16	181.09 ± 8.91

L. Sohl, Overview on recent PICOSEC-Micromegas developments and performance tests, RD51 Mini-Week February 2020, https://indico.cern.ch/event/872501/contributions/3726013/

Combining multi-pad hits

$$\chi^2 = \sum_{i=1,4} \frac{\left(\left[t_i - \left\{\langle SAT\rangle(R_i,\theta_i) - \langle SAT\rangle(R_i,90^o)\right\} - \left\{SL(Q)\right\} - \hat{t}\,\right]\right)^2}{\left(\mathrm{Re}\,s(Q_i)\right)^2}$$



S. Aune et al., “Timing performance of a multi-pad PICOSEC-Micromegas detector prototype”, NIM A (993), 2021, https://doi.org/10.1016/j.nima.2021.165076

RD51 PICOSEC-Micromegas Collaboration

CEA Saclay (France): D. Desforge, I. Giomataris, T. Gustavsson, C. Guyot, F.J.Iguaz[1], M. Kebbiri, P. Legou, O. Maillard, T. Papaevangelou, M. Pomorski, P. Schwemling, L.Sohl

CERN (Switzerland): J. Bortfeldt, F. Brunbauer, C. David, D. Janssens, M. Lisowska, M. Lupberger, H. Müller, E. Oliveri, F. Resnati, L. Ropelewski, T. Schneider, P. Thuiner, M. van Stenis, A. Utrobicic, R. Veenhof[2], S.White[3]

USTC (China): J. Liu, B. Qi, X. Wang, Z. Zhang, Y. Zhou

AUTH (Greece): A. Kallitsopoulou, K. Kordas, I. Maniatis, I. Manthos[4], K. Paraschou, D. Sampsonidis, A. Tsiamis, S.E. Tzamarias

NCSR (Greece): G. Fanourakis

NTUA (Greece): Y. Tsipolitis

LIP (Portugal): M. Gallinaro

HIP (Finland): F. García

IGFAE (Spain): D. González-Díaz

1) Now at Synchrotron Soleil, 91192 Gif-sur-Yvette, France

2) Also MEPhI & Uludag University.

3) Also University of Virginia.

4) Now at University of Birmingham