Precise timing with PICOSEC Micromegas

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on behalf of the PICOSEC Micromegas collaboration

10th symposium on large TPCs for low-energy rare event detection, December 17, 2021

Outline

PICOSEC detection concept: precise timing with Micromegas

Timing studies & detector physics: single photoelectron and MIP beam tests

Towards a robust large-area detector: resistive Micromegas, photocathodes, tileable modules and scalable readout electronics

Picosecond timing needs

Timing requirements on the level of tens of ps set by increasing luminosity and precision measurements

Mitigate pileup
e.g. at High Luminosity Upgrade of LHC with ATLAS/CMS expecting ~150 vertexes/crossing

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

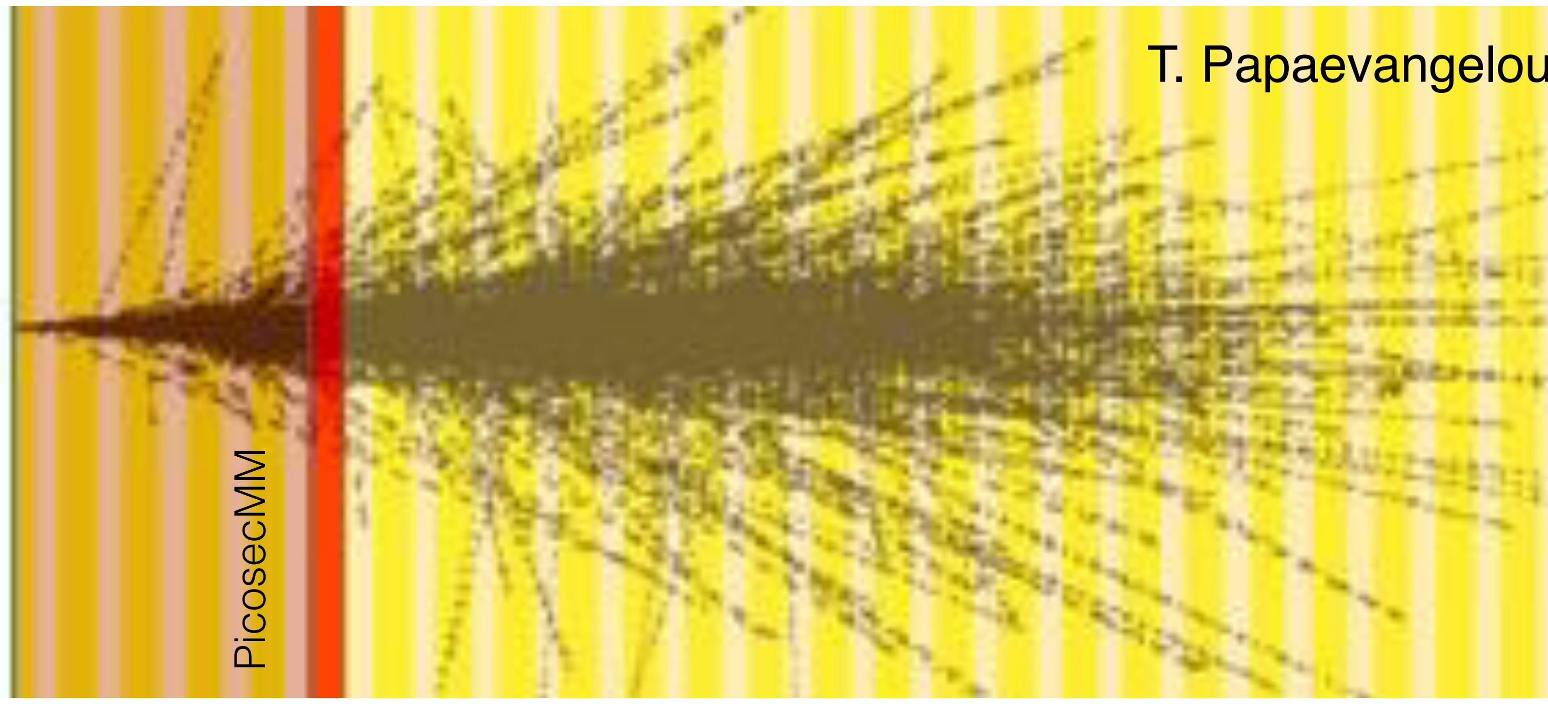
Tagged neutrino beam (time and flavour of tagging) for event-by-event decay measurements (ENUBET)

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

Precise 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



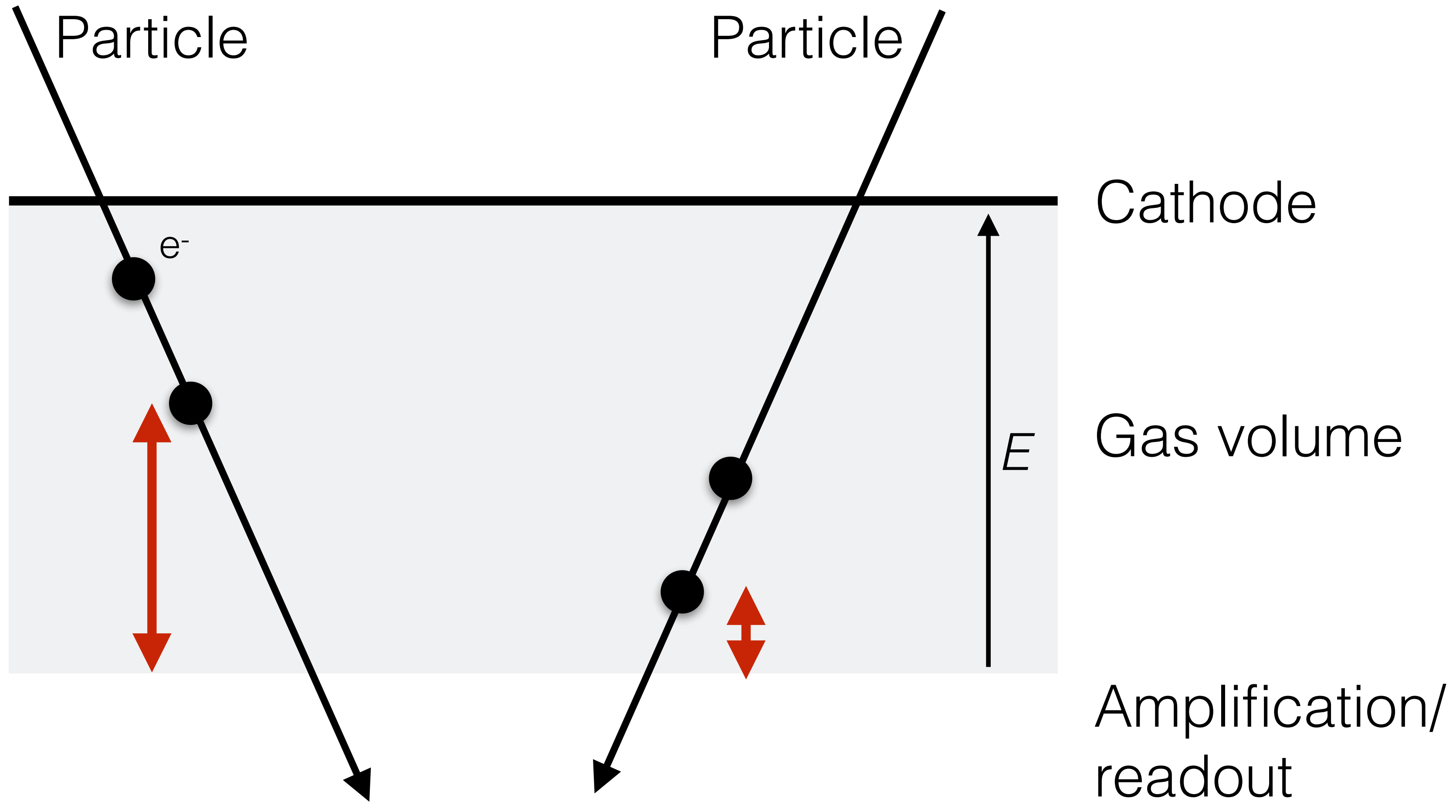
Embedding a PICOSEC Micromegas layer into an Electromagnetic Calorimeter (EMC)

Timing limitations of gaseous detectors

Ionisation of gas in active volume

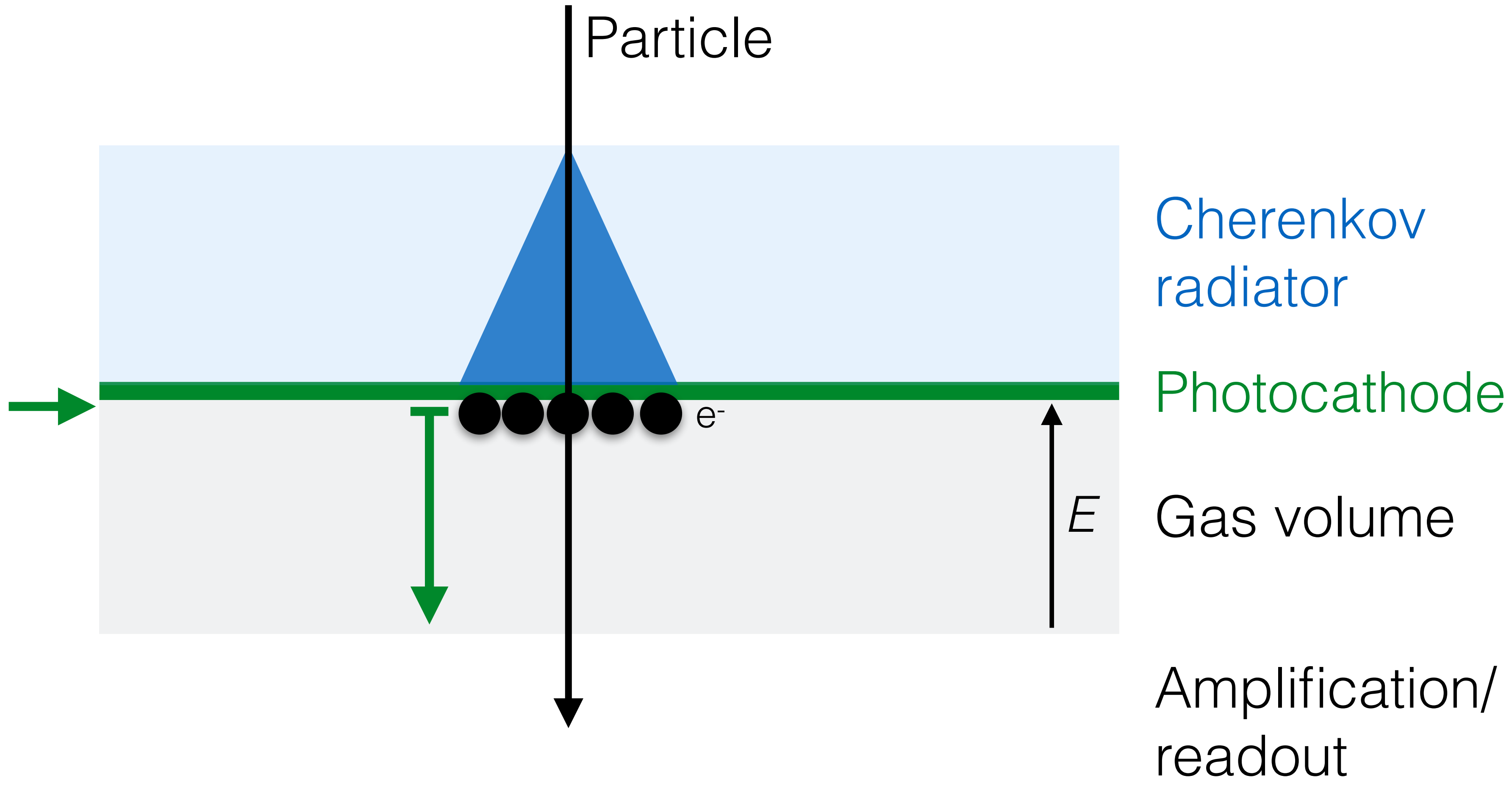
Primary electrons produced by ionisation along particle trajectory in drift region

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



Cherenkov light emission + photocathode
or solid secondary converter layer

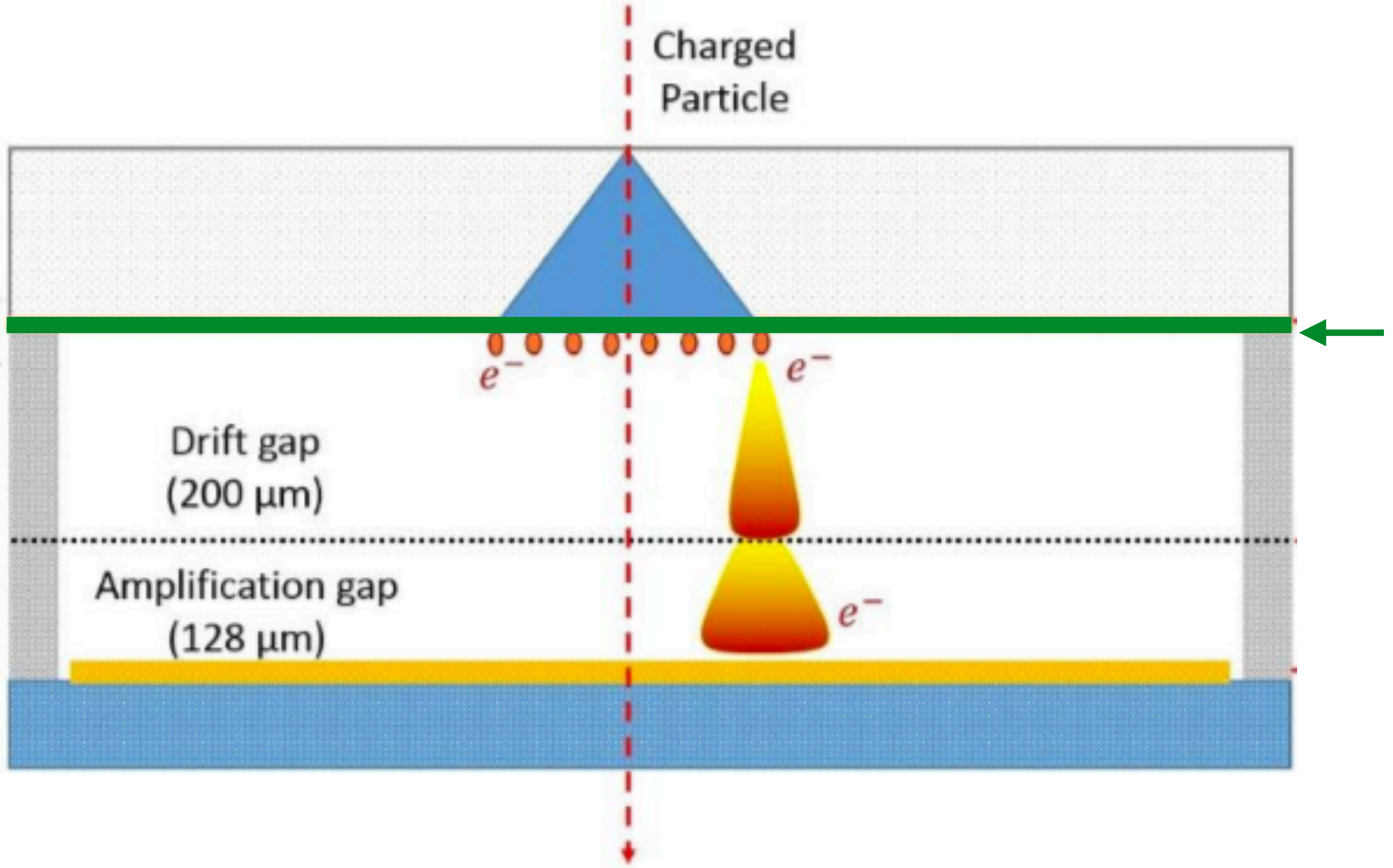
Primary electrons at **well-defined location & time**
→ **Timing jitter of ≈ tens of ps**



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



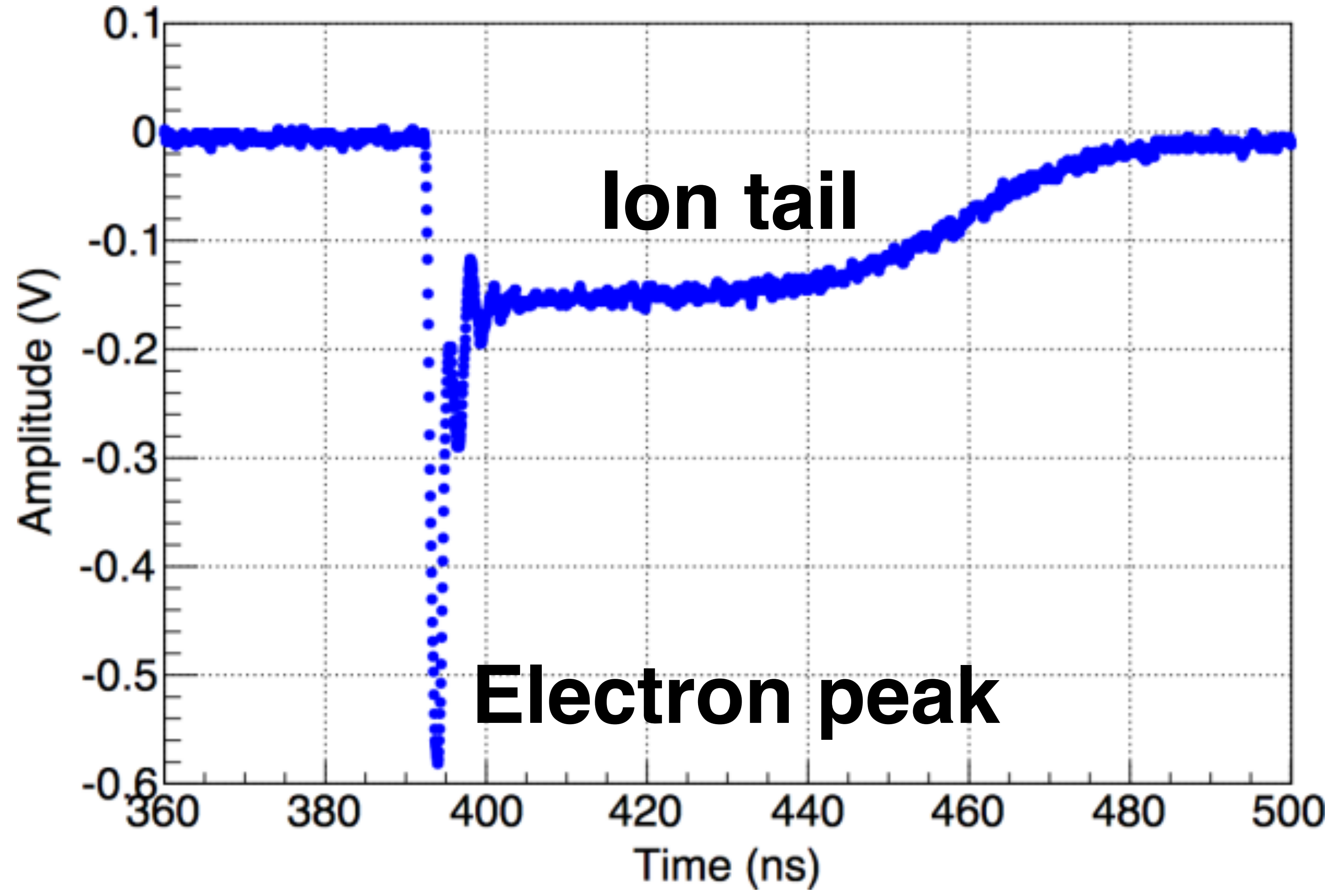
Cherenkov radiator
(3 mm MgF_2)

Photocathode
(3 nm Cr + 18 nm CsI)

Drift gap
(Pre-amplification)

Micromegas
(Amplification)

Gas mixture: 80% Ne + 10% C_2H_6 + 10% CF_4
(COMPASS gas)



- **Signal with two distinct components:**
  Electron peak: fast (≈0.5 ns)
- Ion tail: slow (≈100 ns)

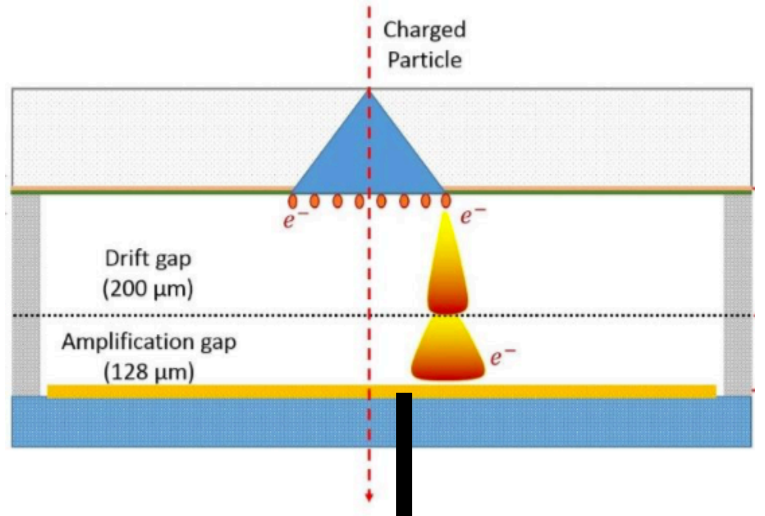
Schematic not drawn to scale
X. Wang et al., Study of DLC photocathode for PICOSEC detector, RD51 collaboration meeting, October 2018

PICOSEC detection concept

Precise timing with Micromegas

Signals are recorded from anode pads, amplified and digitised

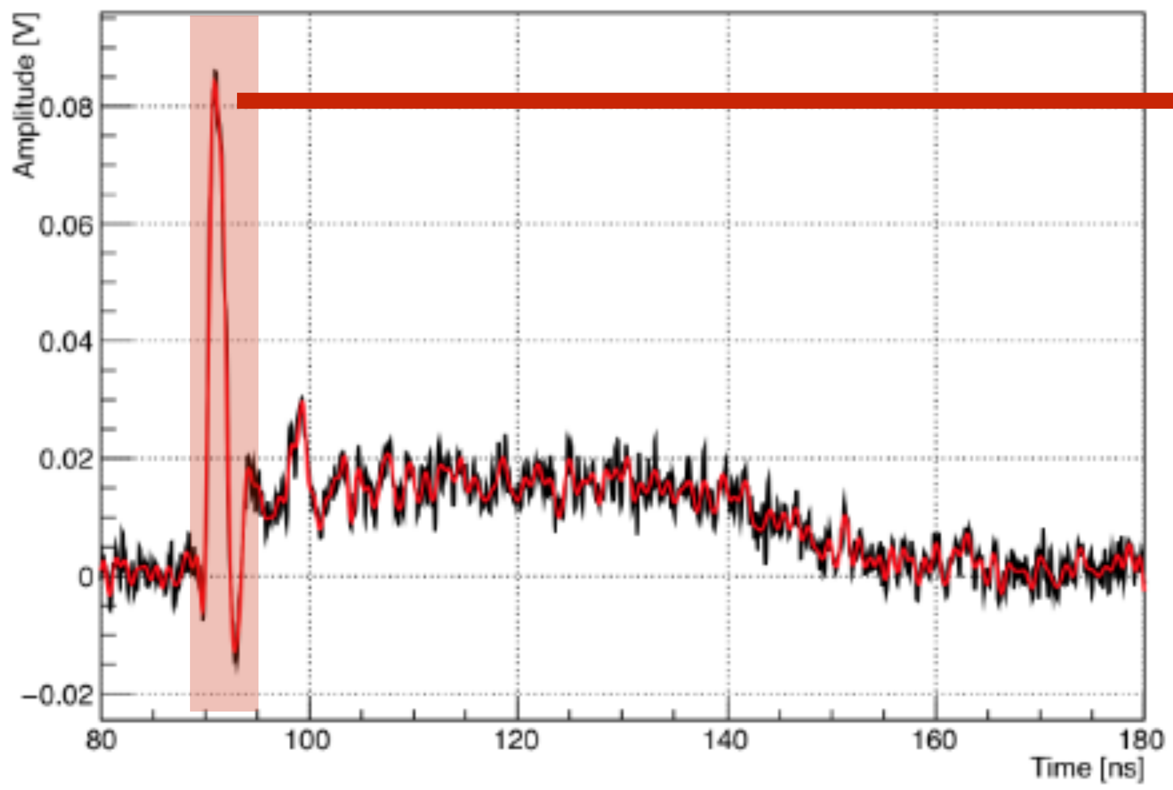
Rising edge of fast electron peak is used for timing measurements with Constant Fraction Discrimination to account for time walk



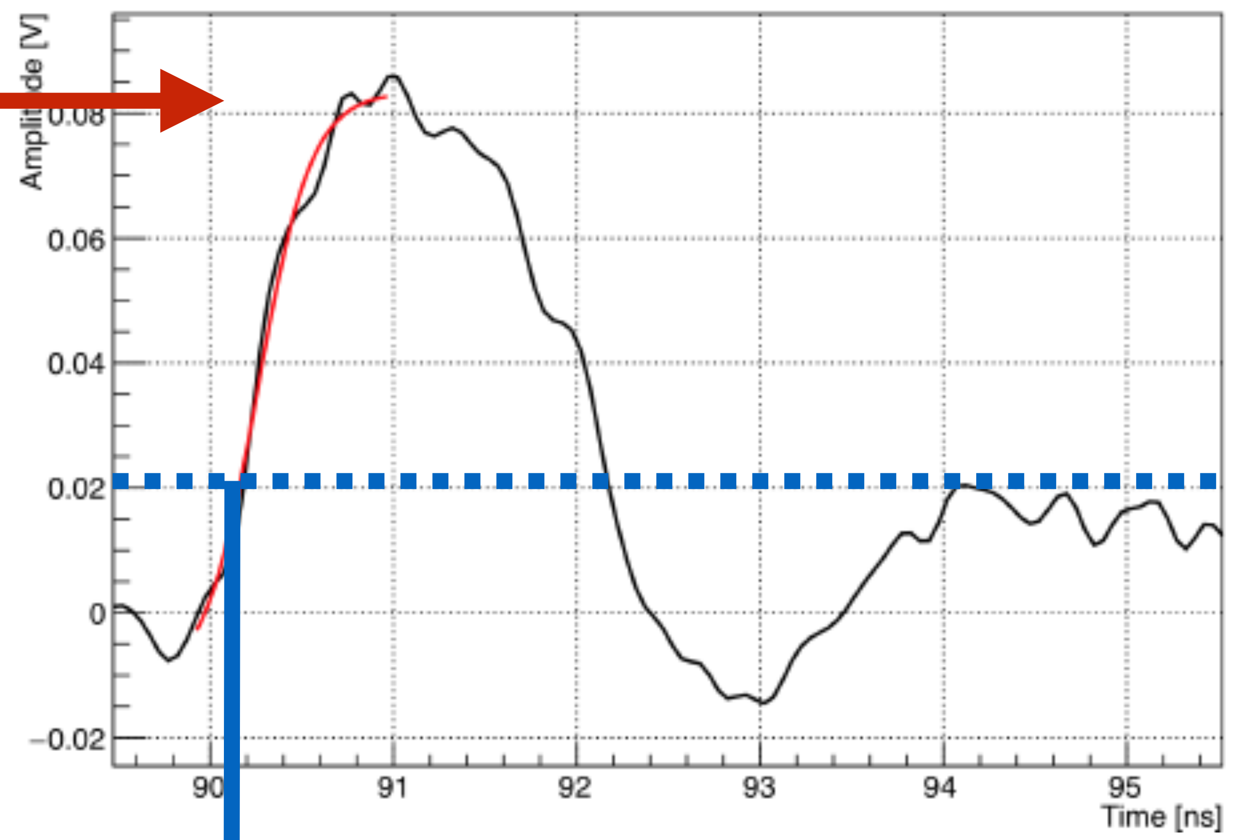
Preamplification of induced signal

Digitized by high-bandwidth oscilloscope @ 20GSamples/s

Recorded waveform

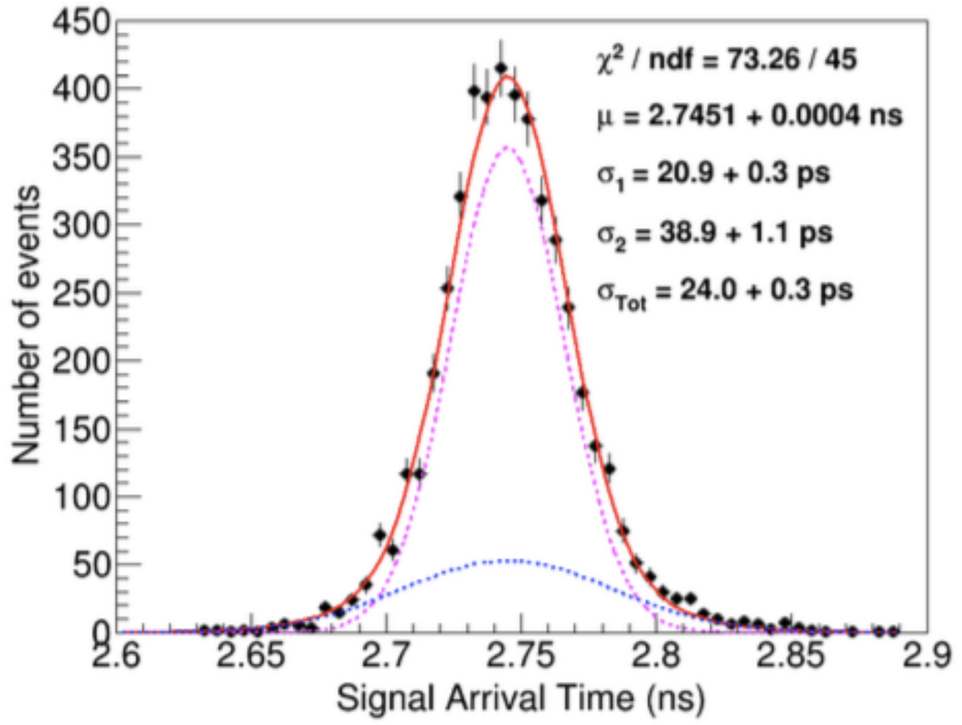


Zoom: electron peak



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

24 ps timing resolution (for MIPs)



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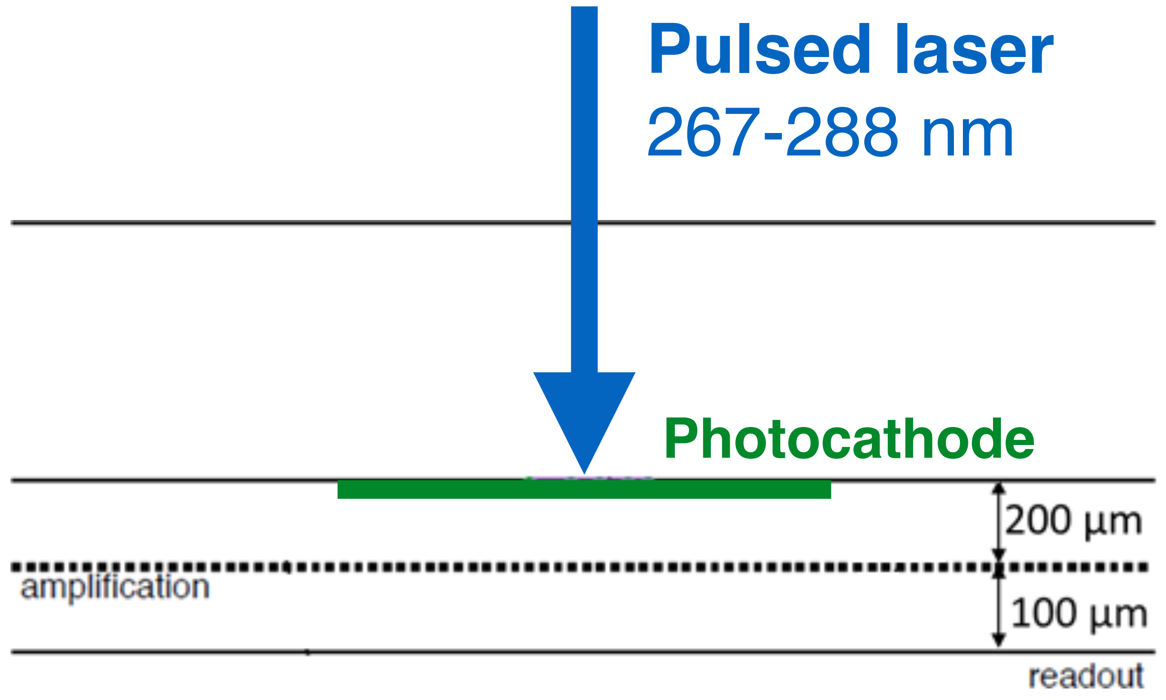
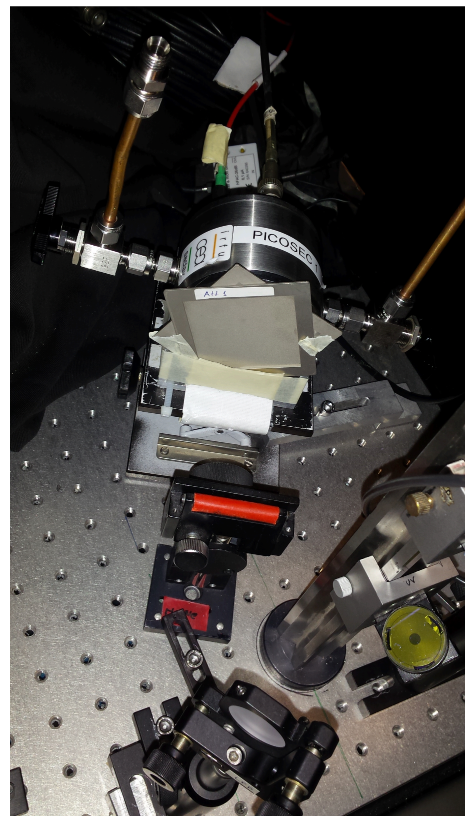
Measurements of timing performance

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/

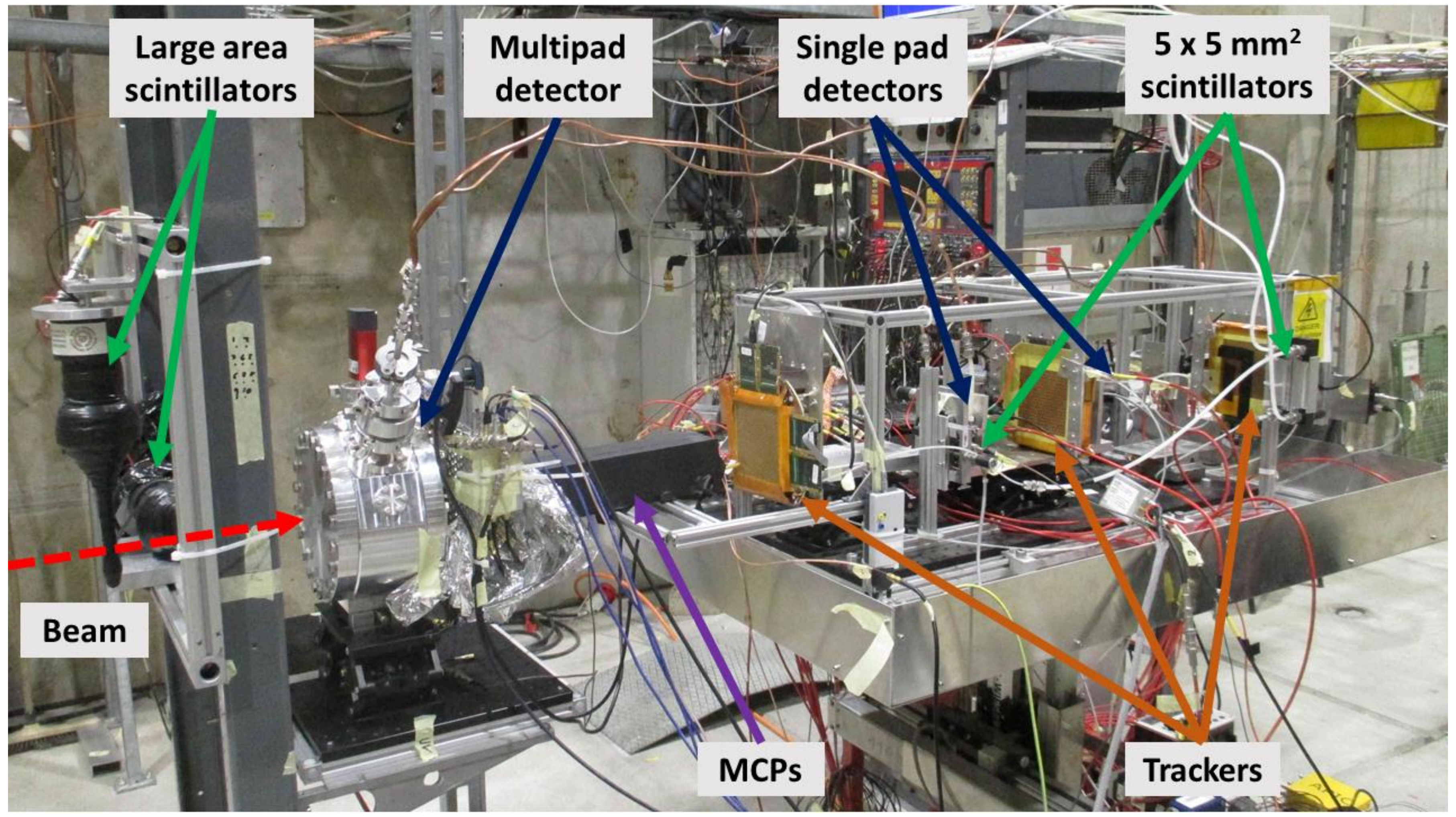
Schematic not drawn to scale

MIP test beam campaigns

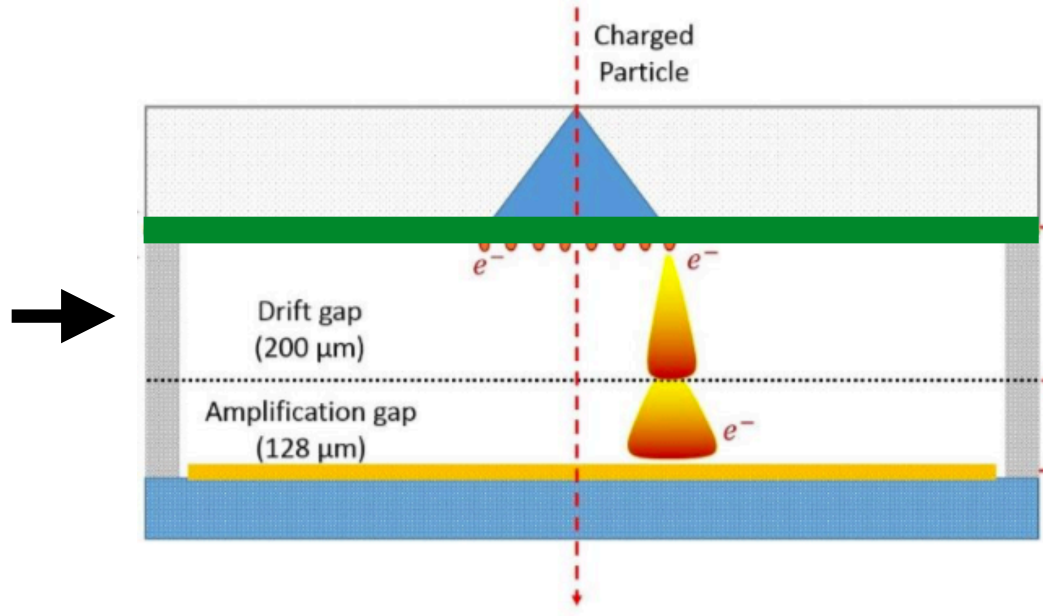
150 GeV muons and pions from SPS

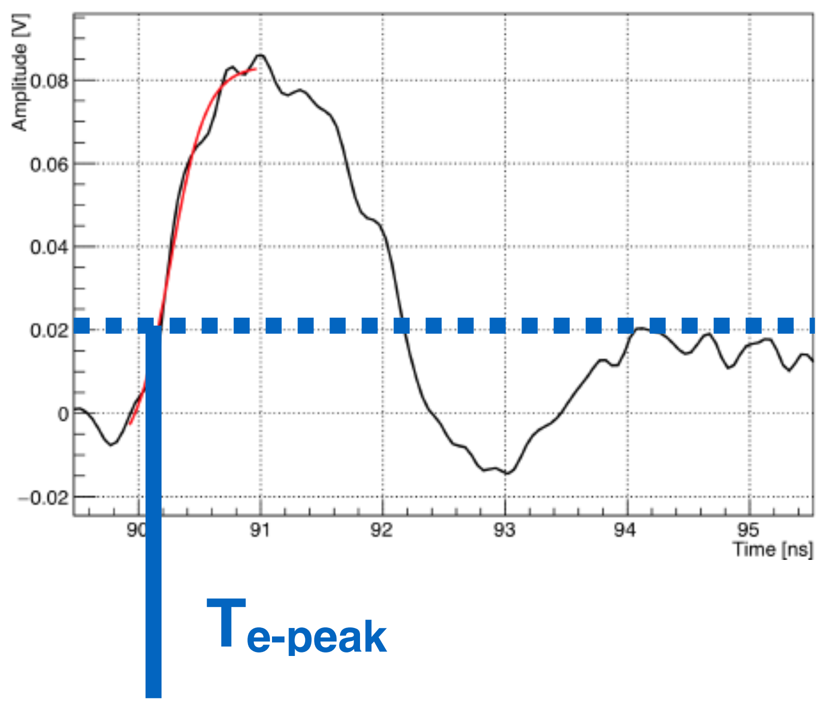
Two **MCP-PMTs** used as timing reference (<5 ps resolution)

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



Detector response





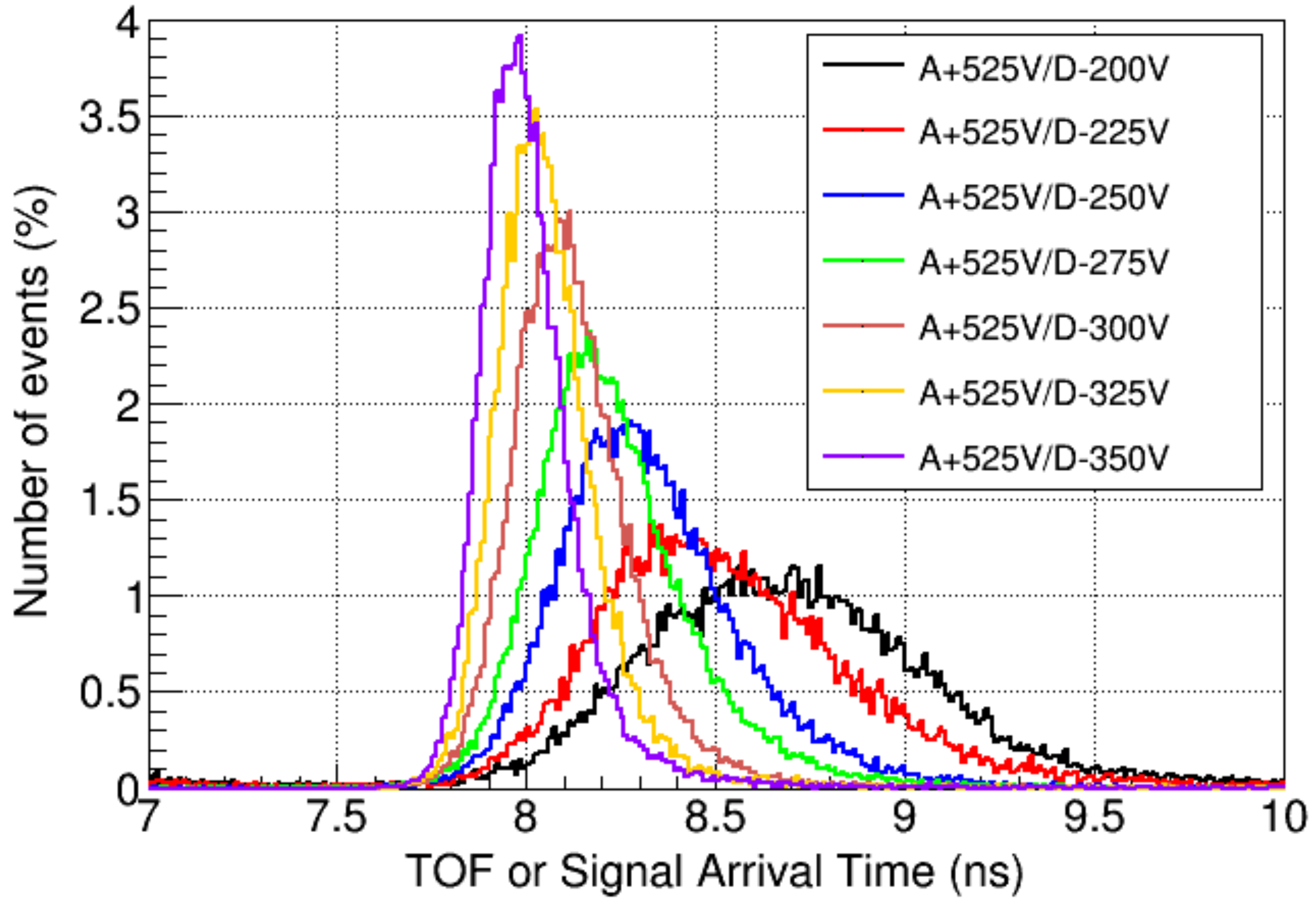
Correlation of signal arrival time and pulse amplitude

Time resolution depends primarily on e-peak charge

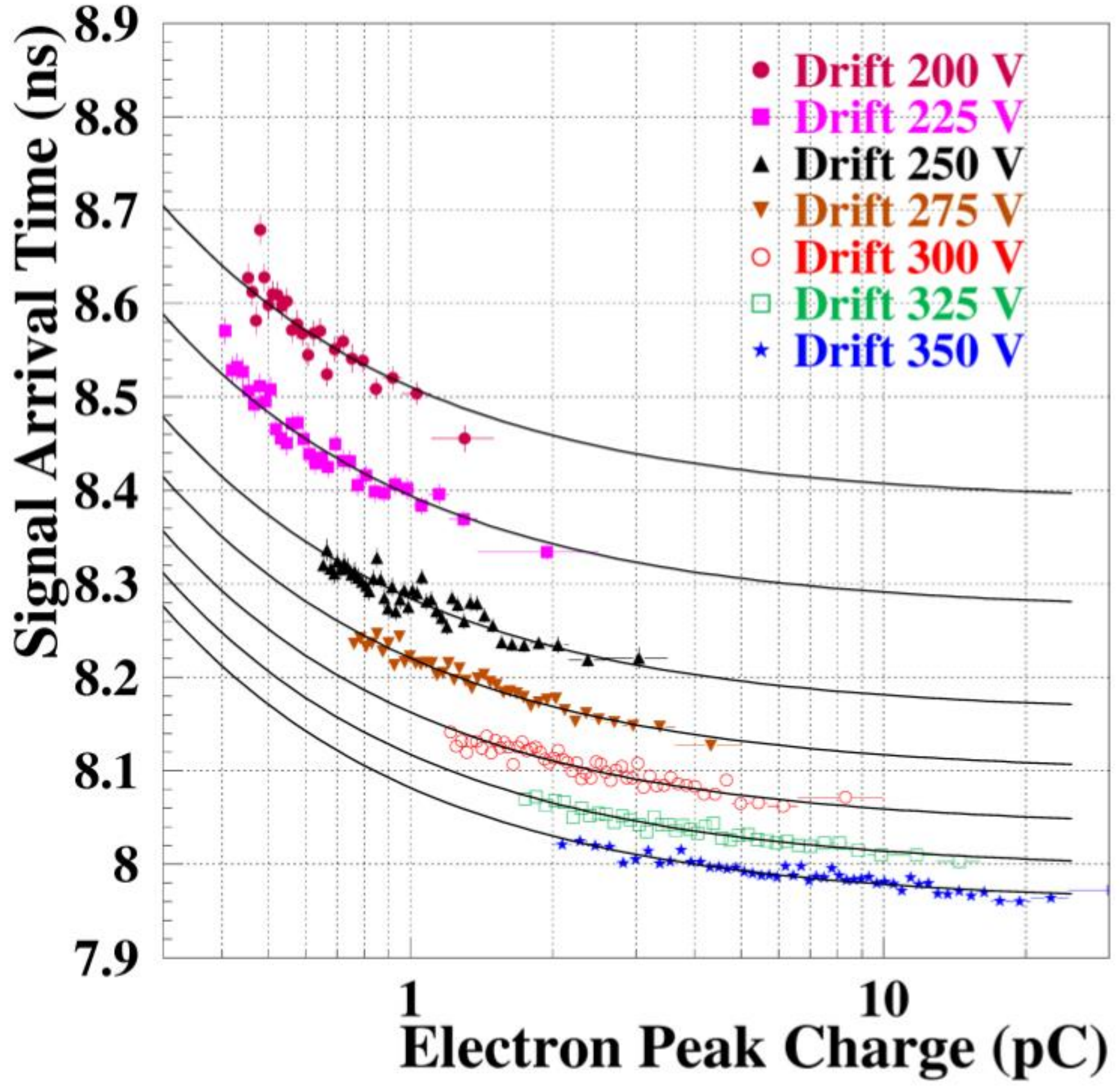
Signal arrival time (SAT) = <$T_{e\text{-peak}}$>

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

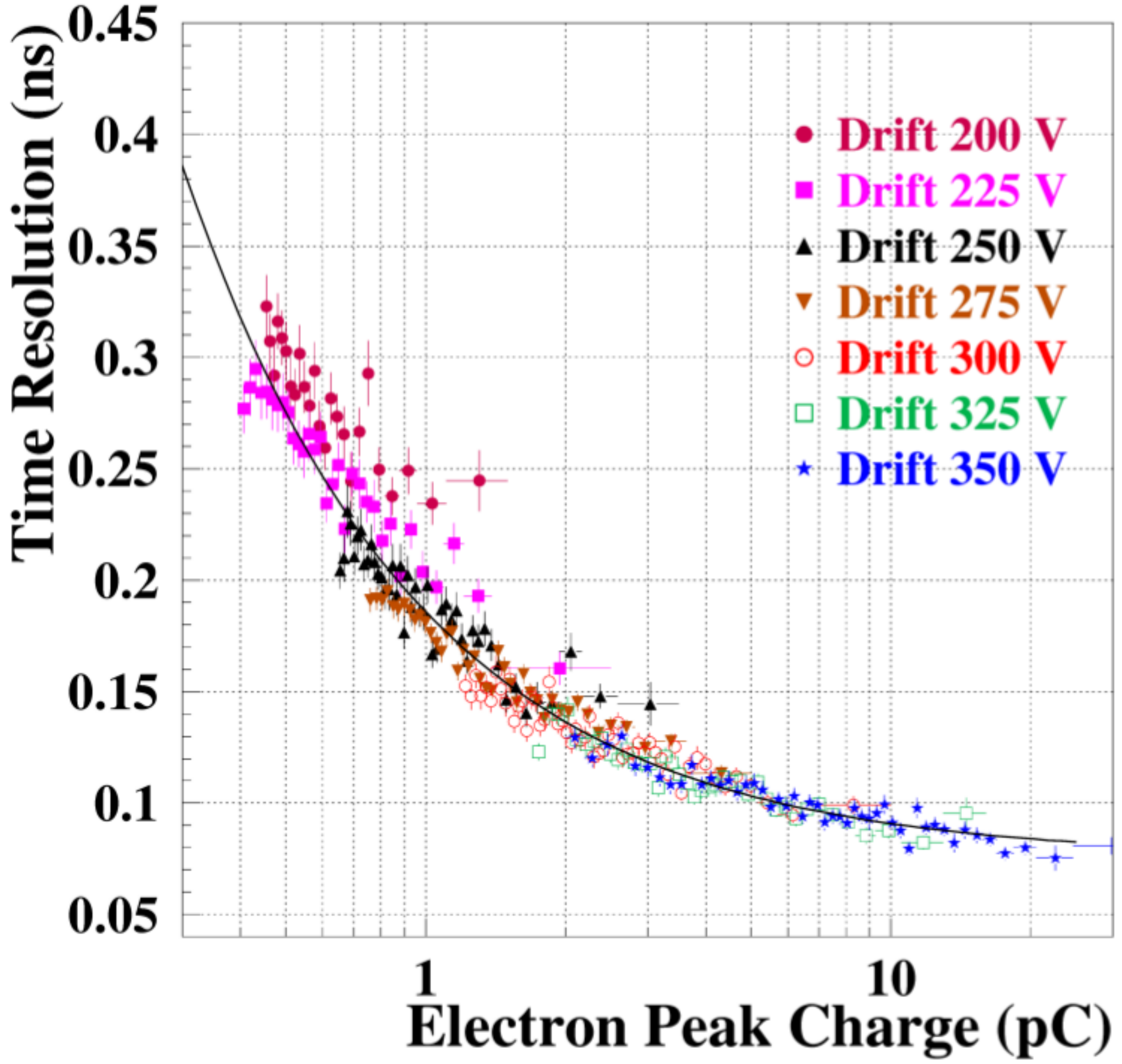
Narrower SAT distribution for higher pre-amplification field



Signal arrival time



Time resolution



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/

Detector response

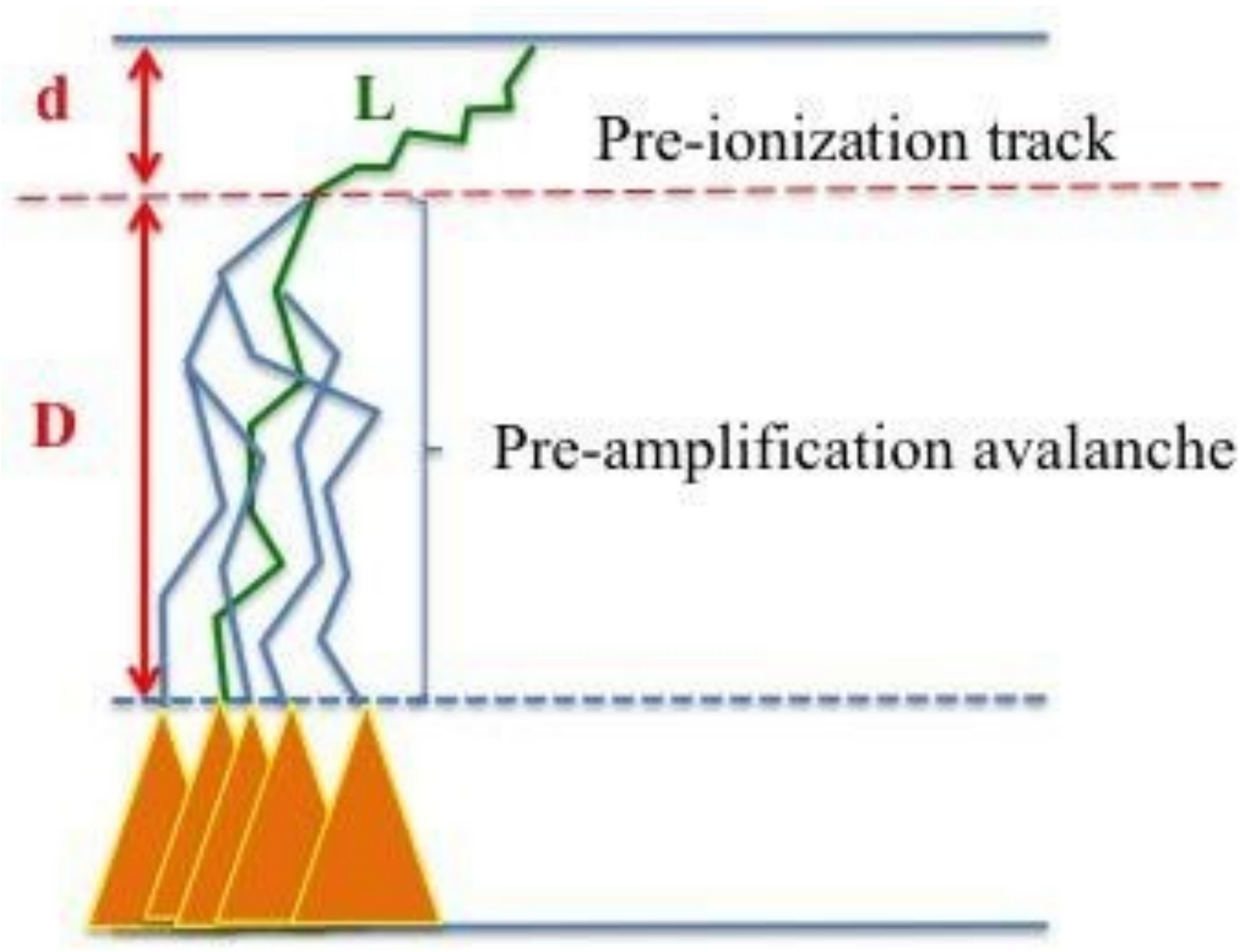
Time resolution depends primarily on e-peak charge

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

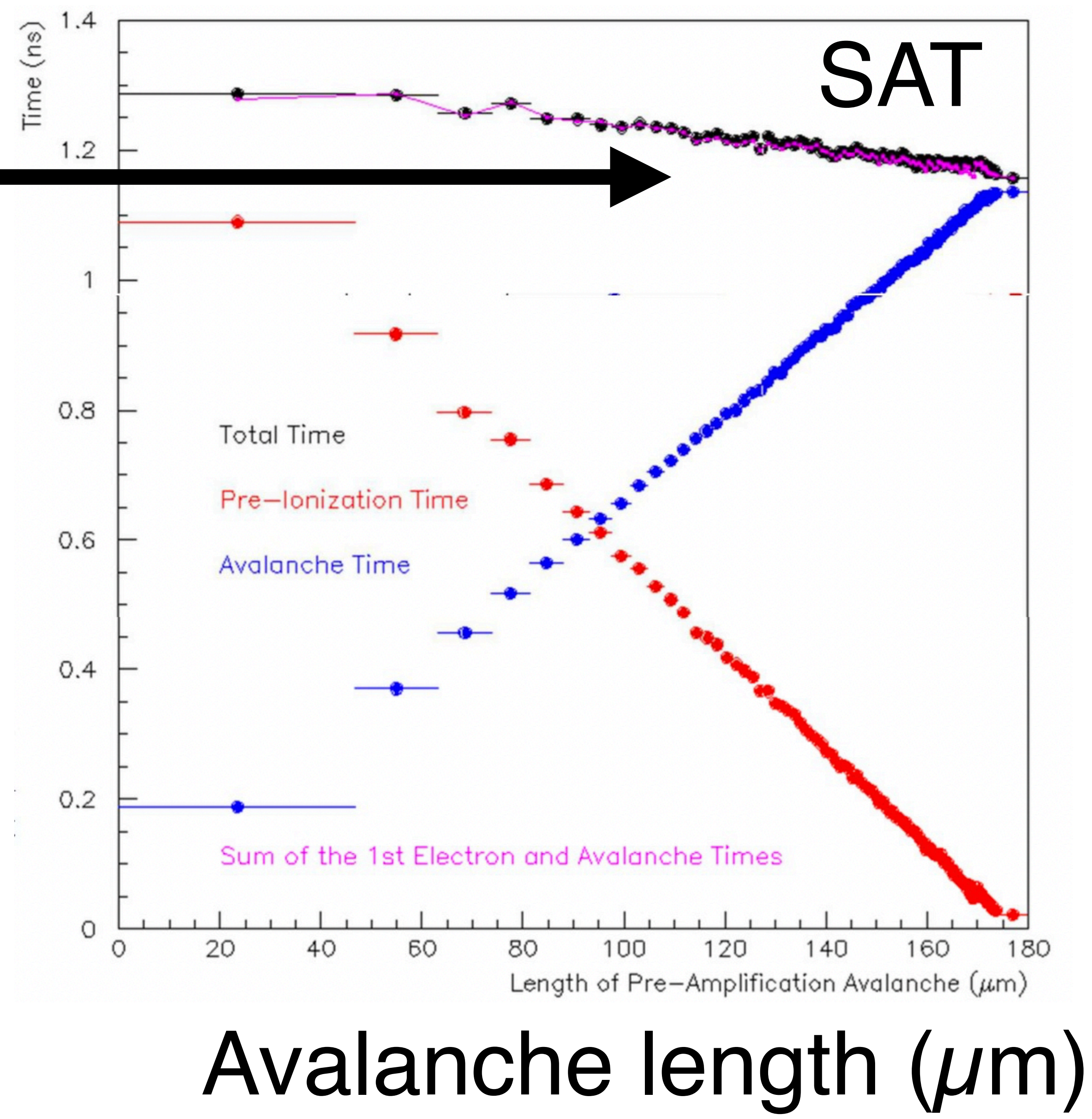
Location of first ionisation determines length of avalanche

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

J.Bortfeldt et al., “Modeling the timing characteristics of the PICOSEC Micromegas detector”, NIM A (993), 2021, https://doi.org/10.1016/j.nima.2021.165049

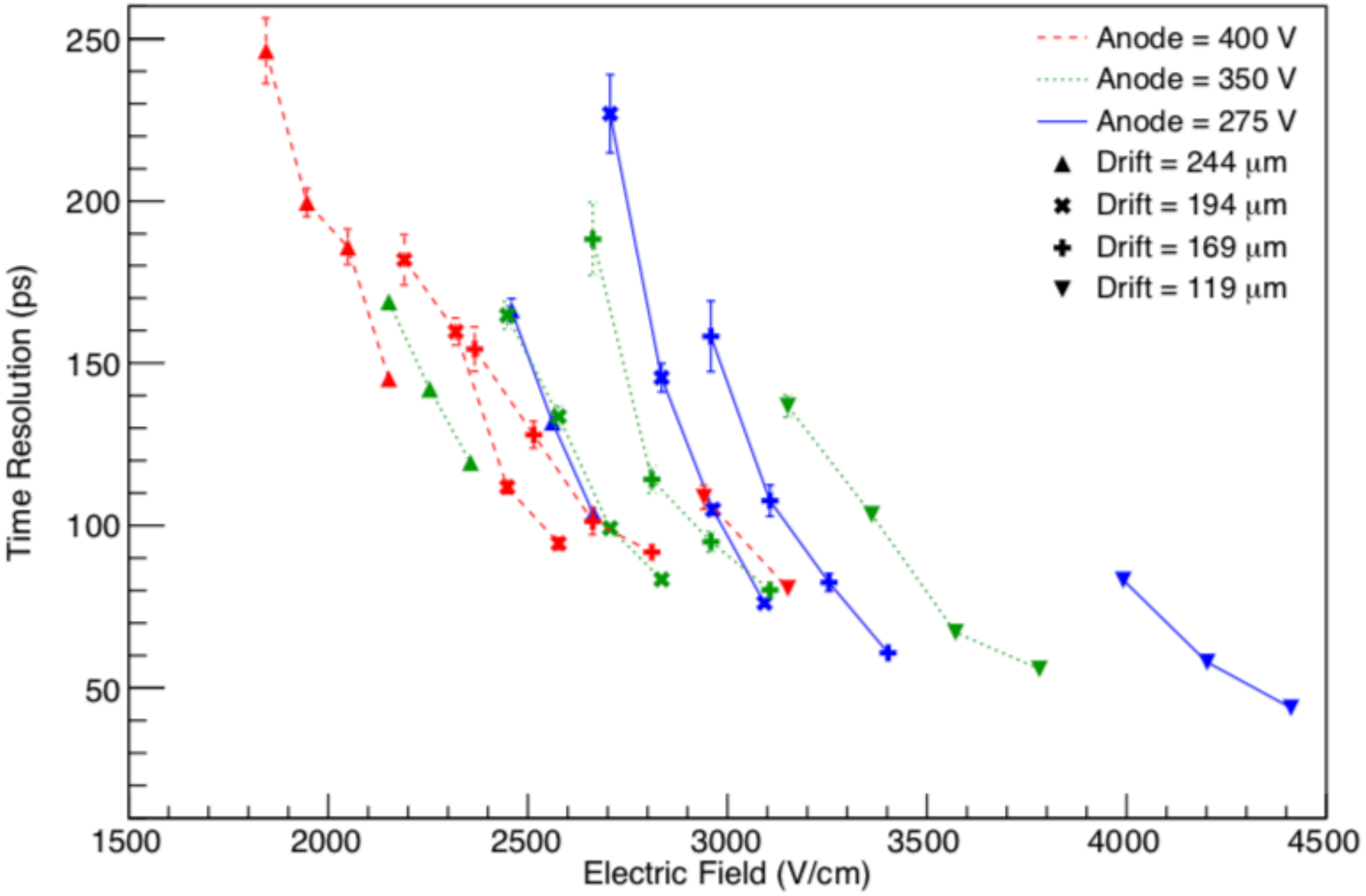


https://indico.cern.ch/event/716539/contributions/3246636/



Thin gap Picosec

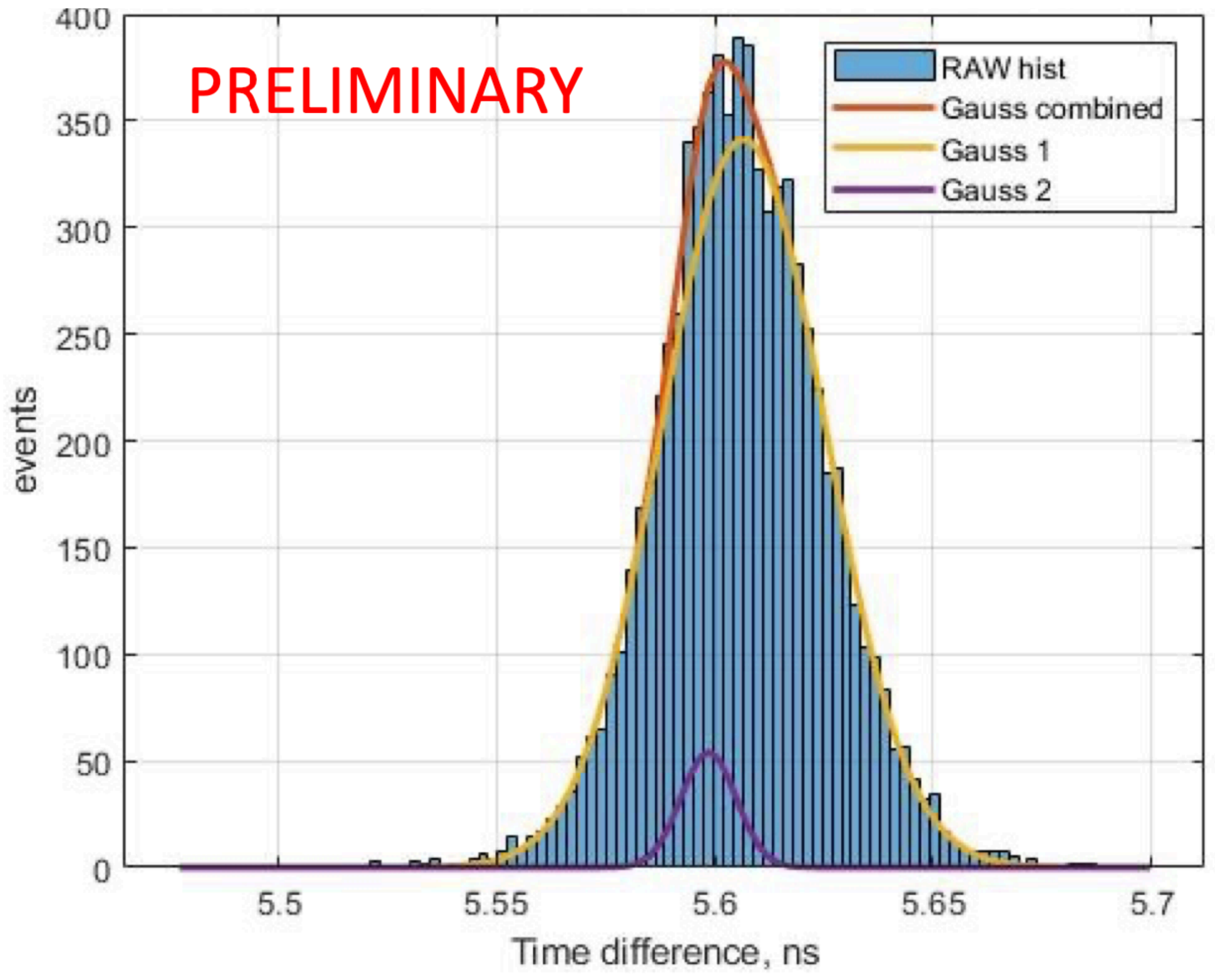
Systematic tests of electric field configurations (drift / amplification fields), drift gaps and gas mixtures performed in laser facility



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)

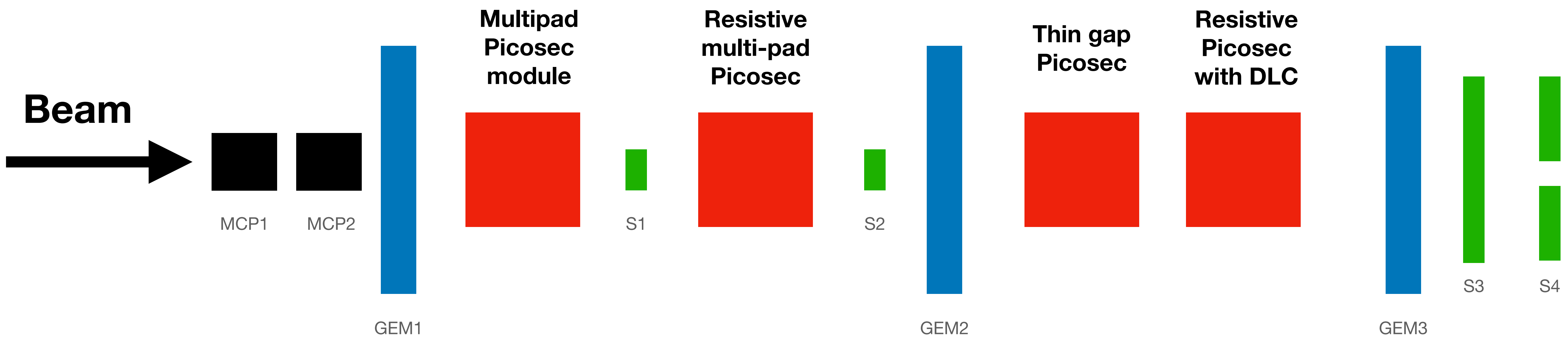
Smaller drift gap has better performance at same gain (Shorter drift time of the first electron)

Excellent timing performance recently confirmed in MIP test beam with **thin gap Picosec** (≈120μm drift gap) - analysis ongoing



T. Papaevangelou, A. Utrobicic, M Lisowska

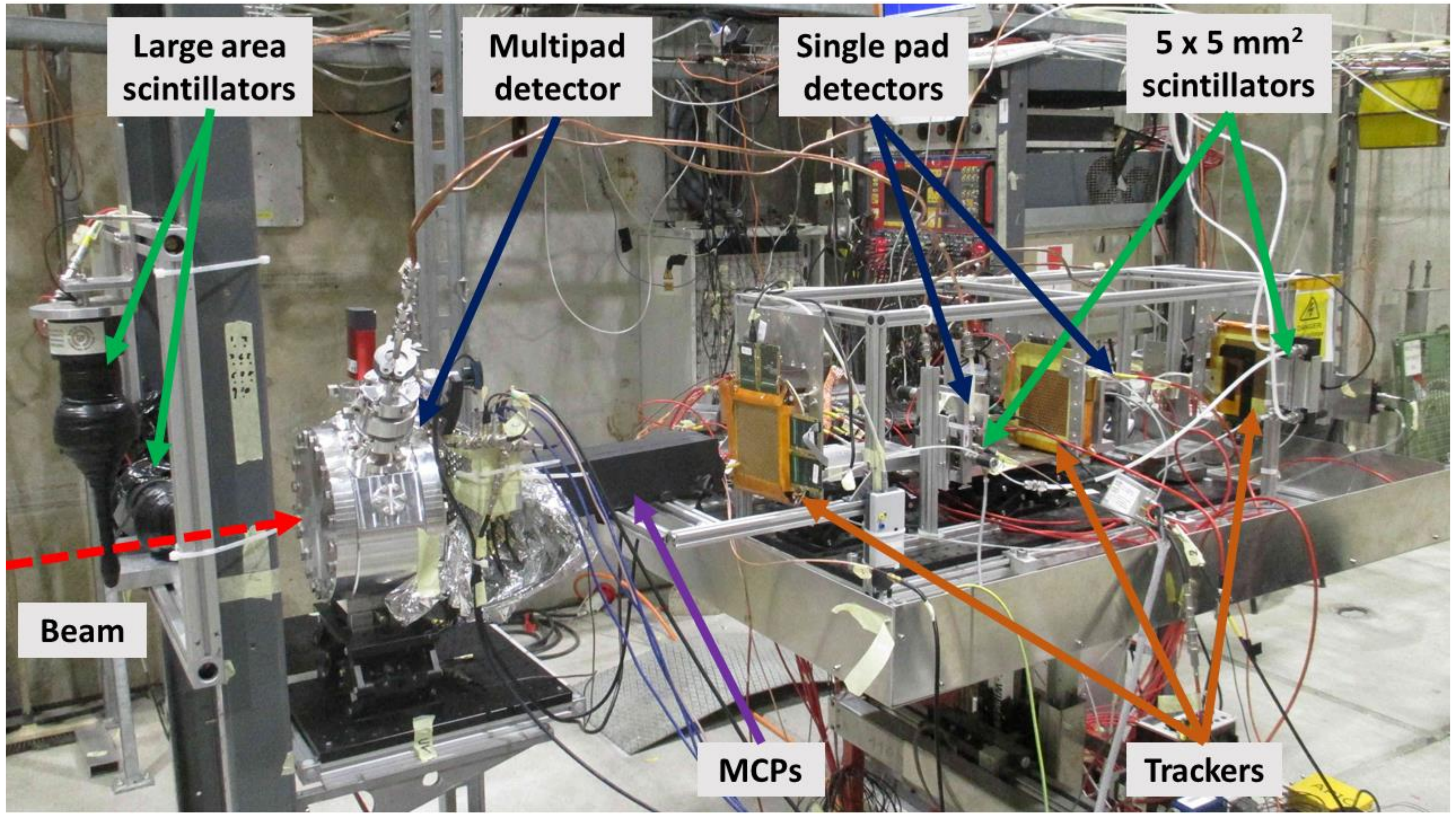
MIP beam tests



Completed several beam test campaigns at CERN SPS H4 beam line
150 GeV muons and pions

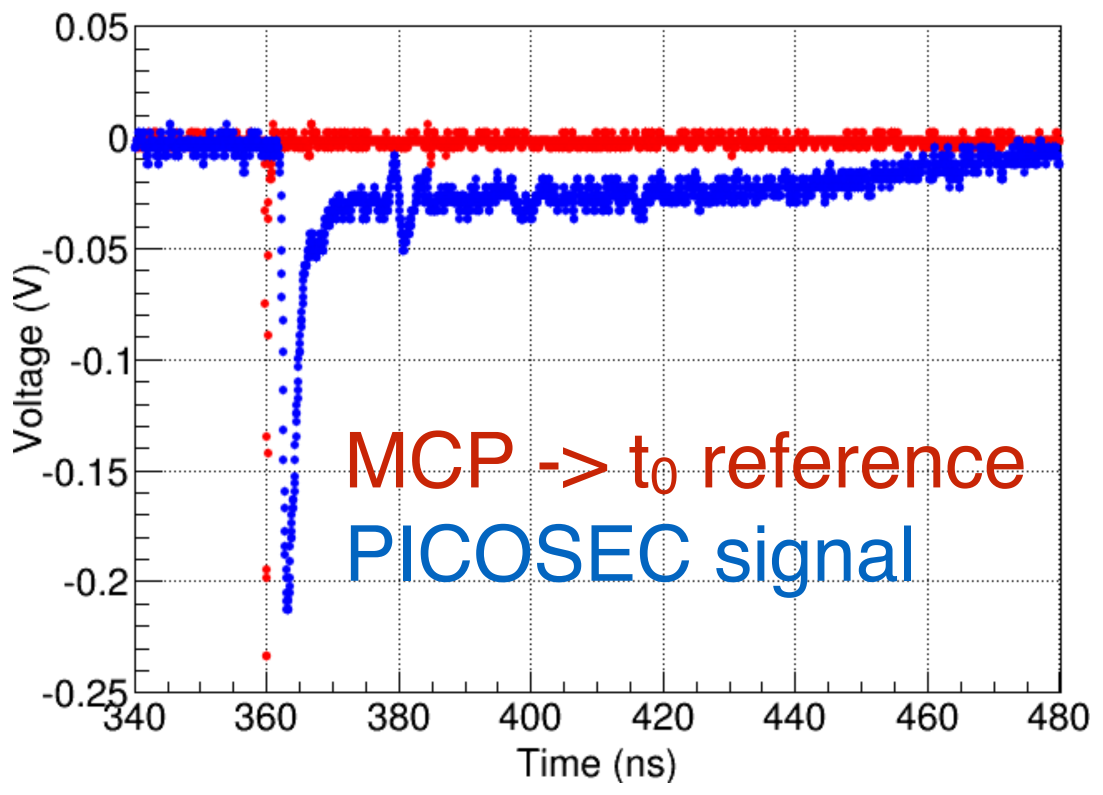
Versatile test beam setup:

- **Tracking** system with triple-GEMs (40 μm precision)
- Two MCP-PMTs used as precise **timing reference** (<5 ps resolution)
- Scintillator as DAQ trigger to select tracking regions



Schematic not drawn to scale

MIP beam tests

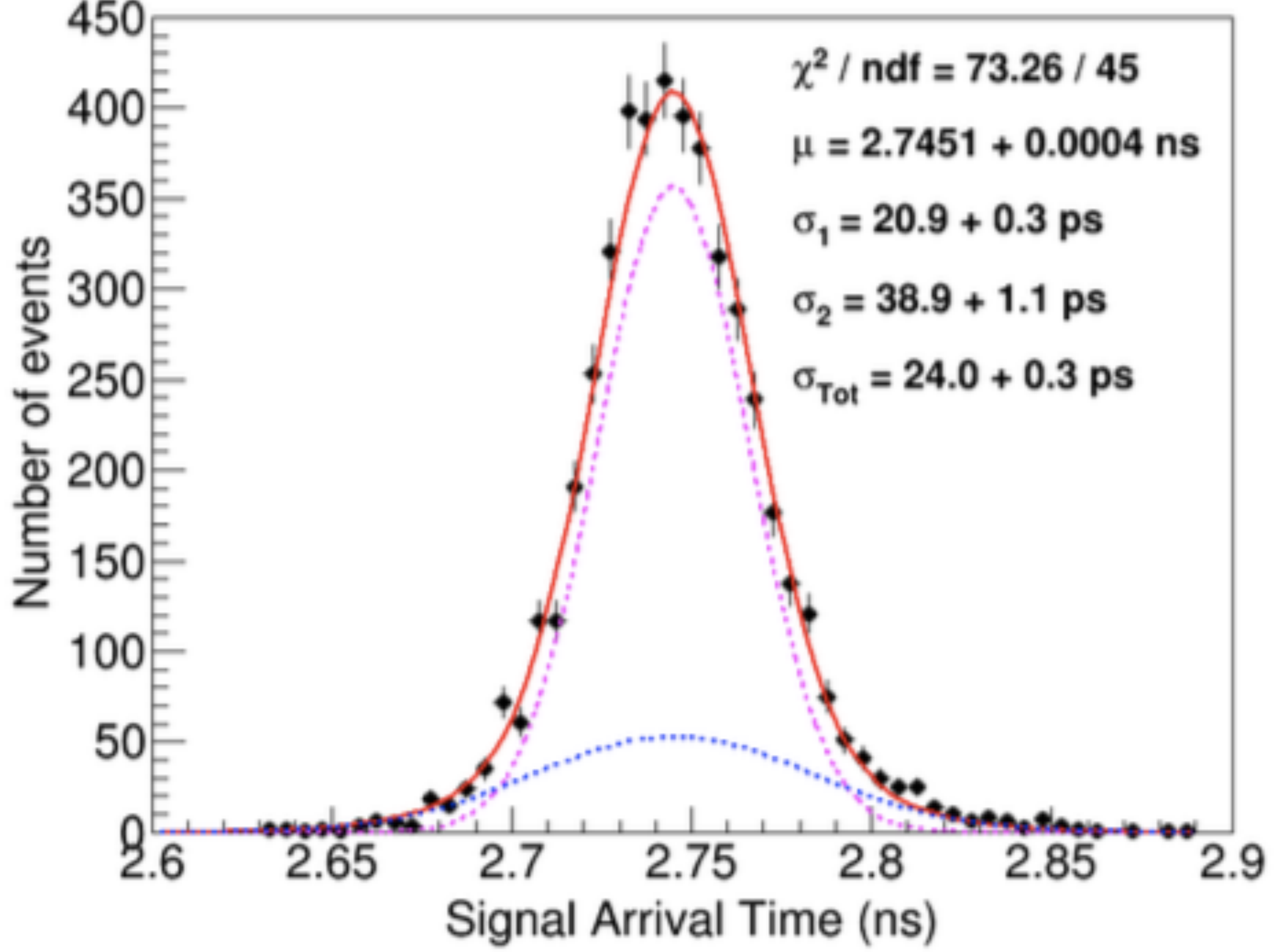


Time resolution for 150 GeV muons: 24 ps

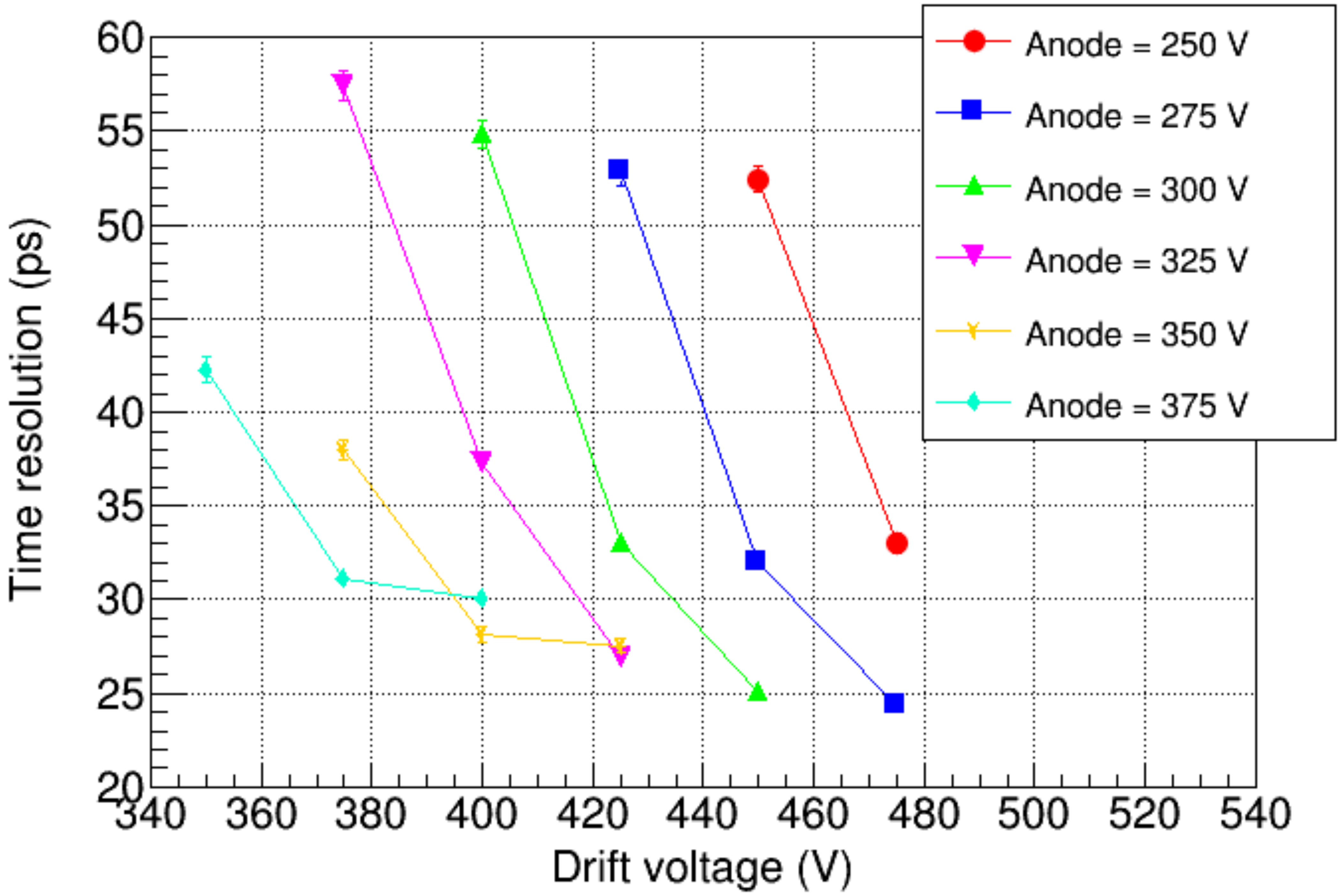
Optimum operation point: Anode +275 V / Drift – 475 V

Mean number of photoelectrons per muon = 10.4 ± 0.4

MIP timing jitter



MIP time resolution

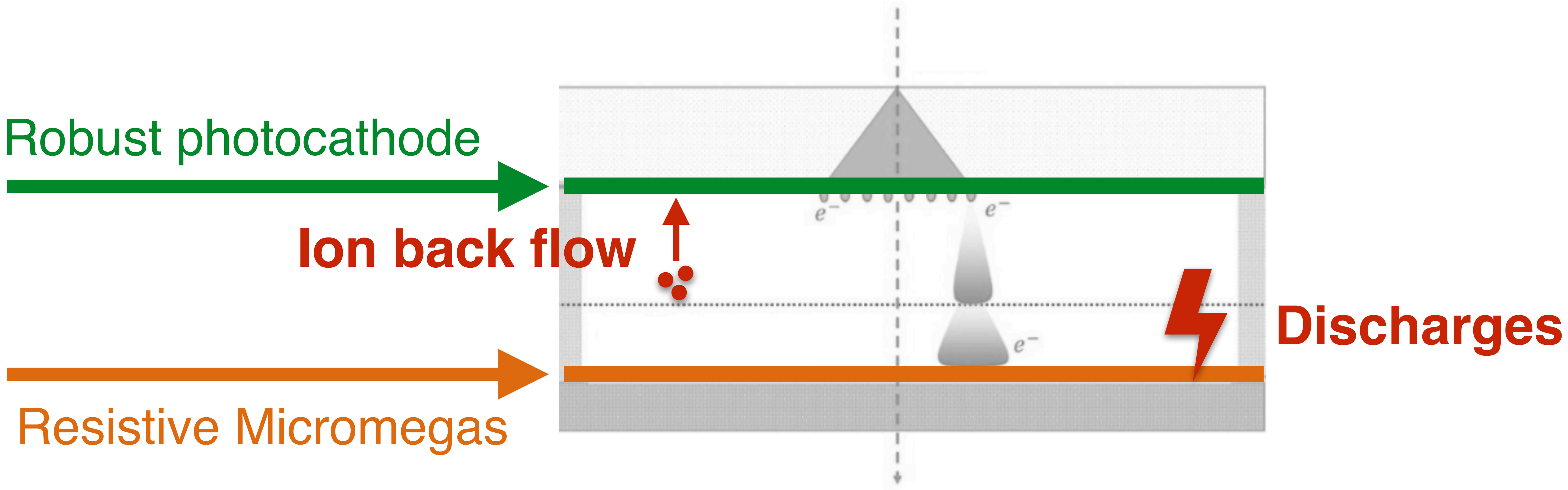


J. Bortfeldt et. al. (RD51-PICOSEC collaboration), NIM A (903), 2018, https://doi.org/10.1016/j.nima.2018.04.033

Towards a robust, large-area detector

Robustness

- Photocathode robustness against ion back flow
- Resistive Micromegas for spark protection


Robust photocathode

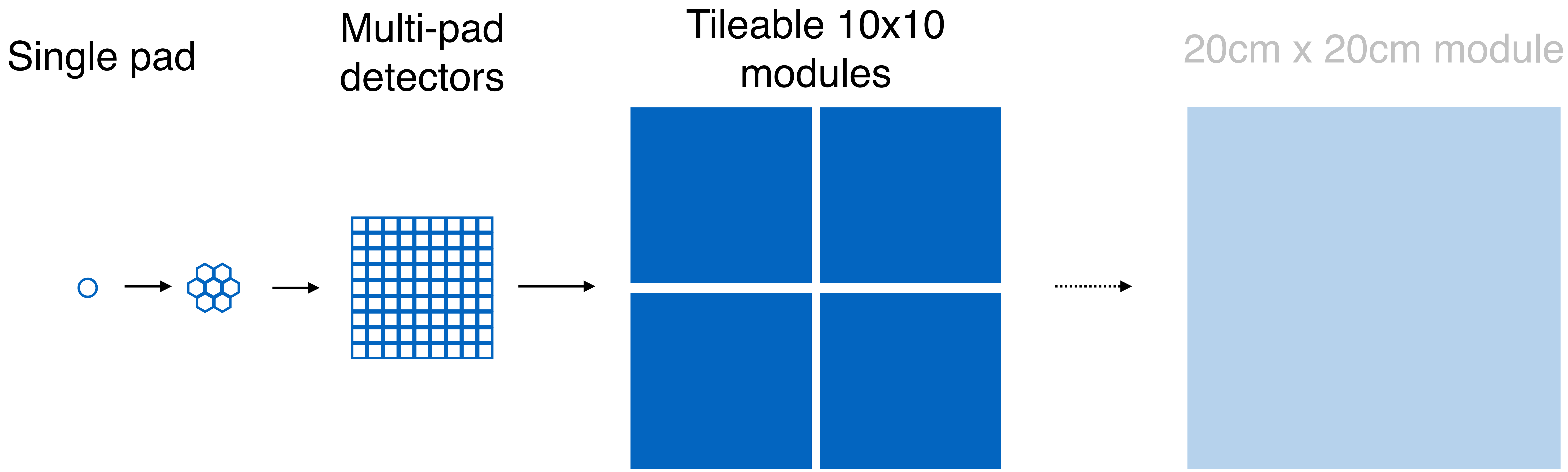
Ion back flow

Discharges

Resistive Micromegas

Area coverage

- Single pad to multi pad
- Detector modules


Single pad

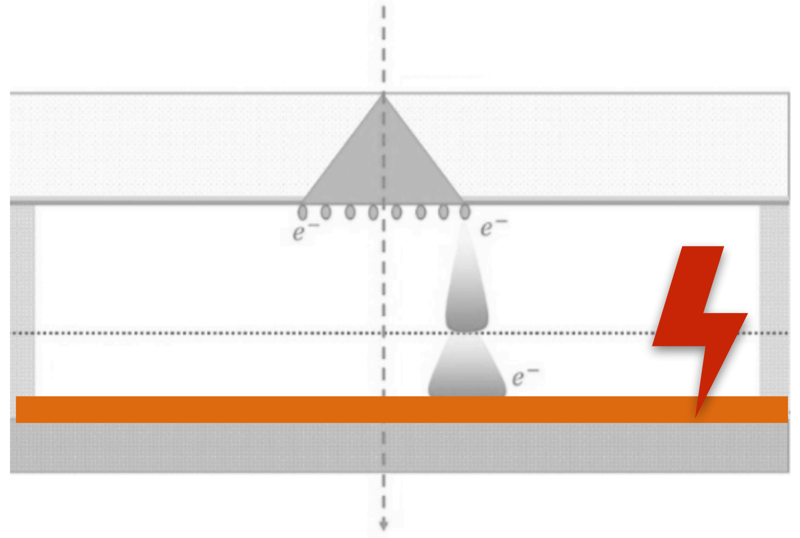
Multi-pad detectors

Tileable 10x10 modules

20cm x 20cm module

Schematic not drawn to scale

Resistive Micromegas

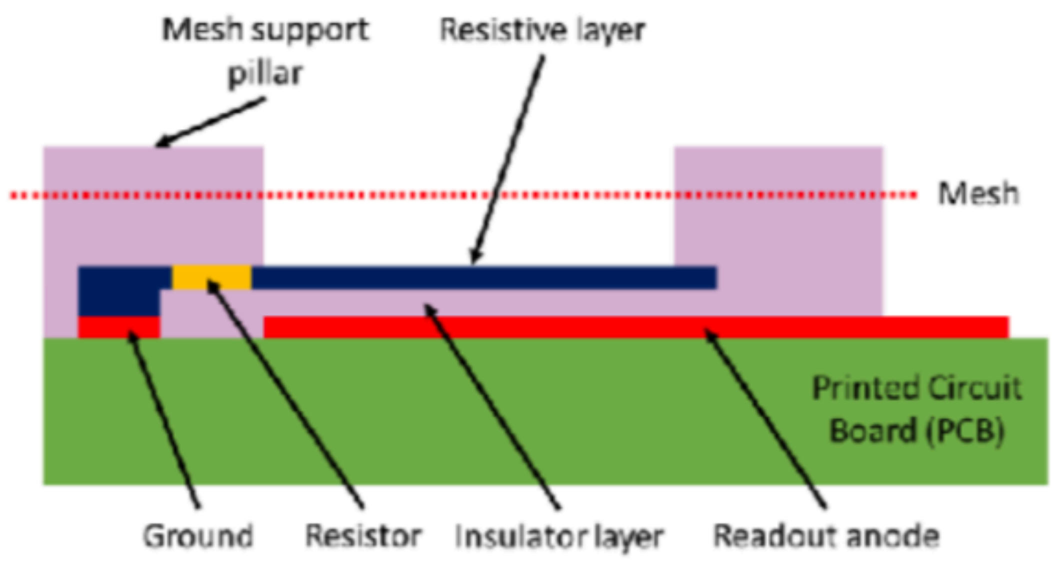


Resistive elements (layer, discrete resistors) for readout anodes to limit destructive effect of discharges by limiting energy released

Two design approaches tested and evaluated in beam test campaigns

Optimise resistivity value for **multi-channel detectors** with systematic tests of **different resistivities** and **simulations**

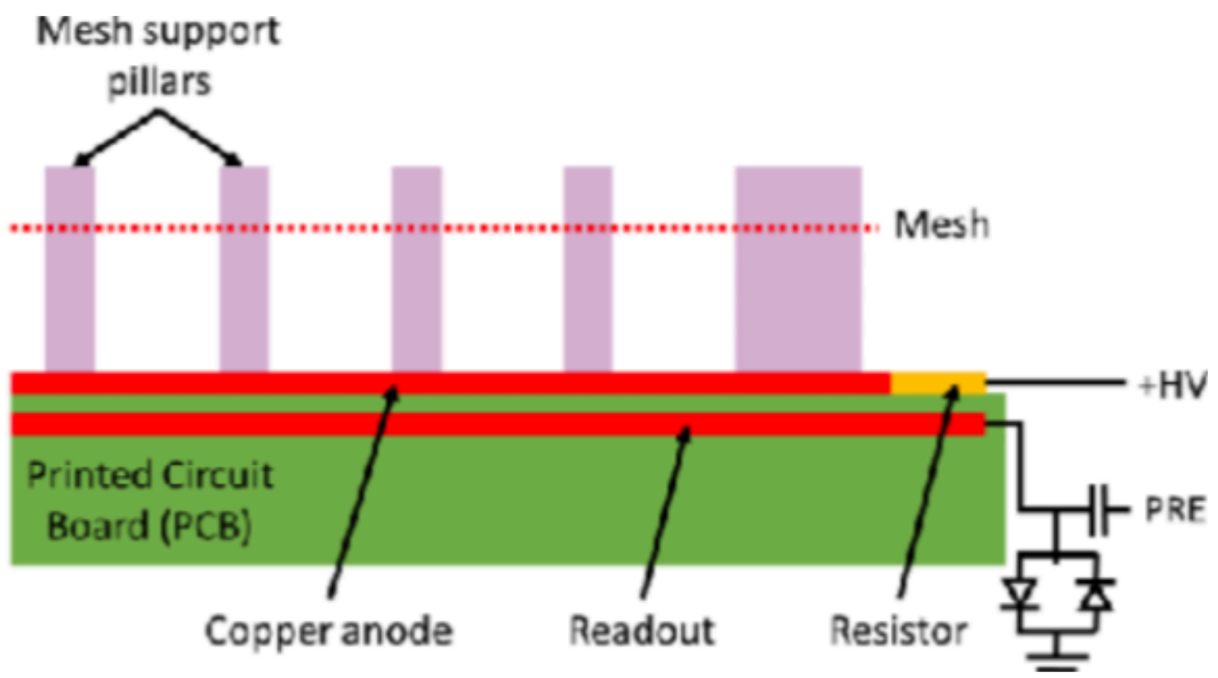
Resistive strips (MAMMA)



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

σ = 41 ps

Floating strips (COMPASS)

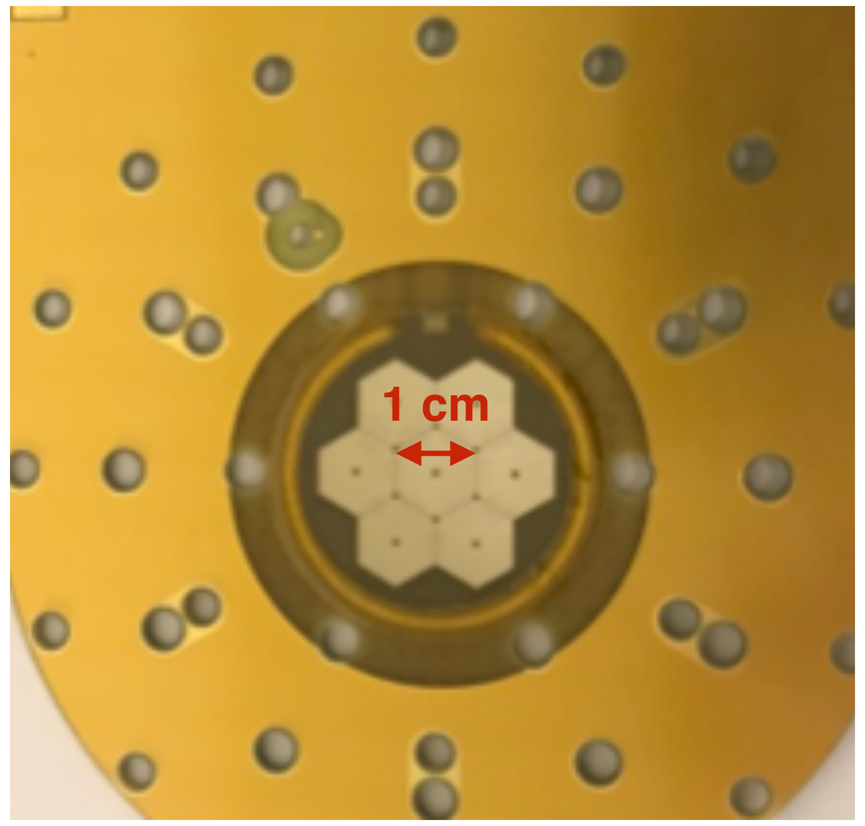


σ = 28 ps

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

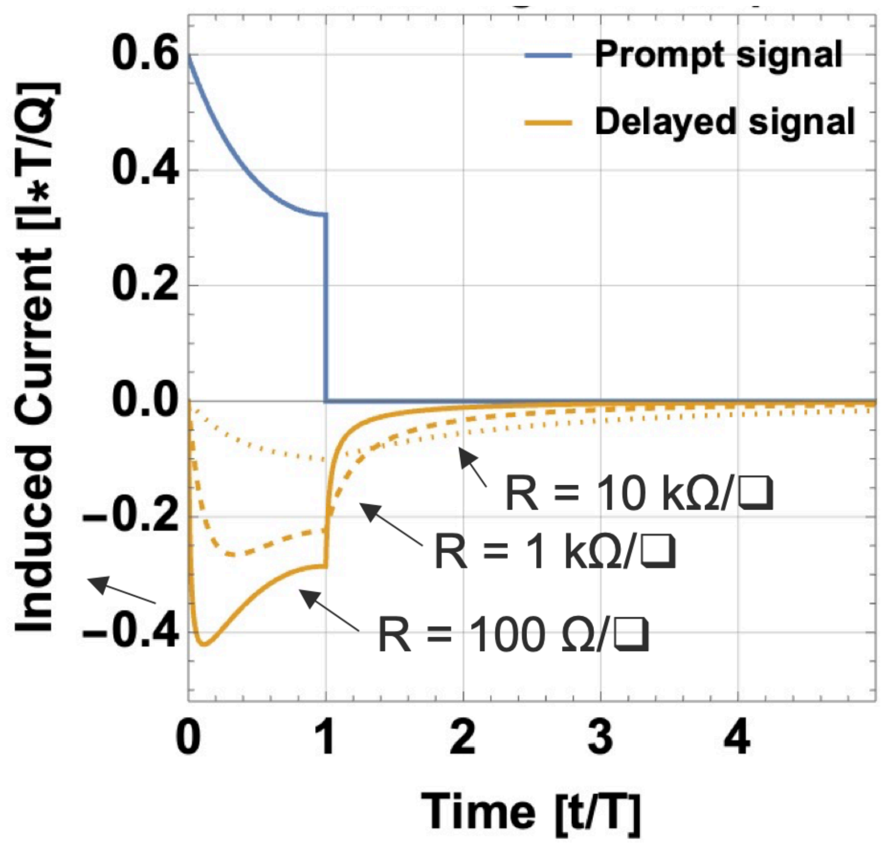
Schematic not drawn to scale

Resistive multi-pad Picosec



T. Papaevangelou,
L. Sohl, CEA Saclay

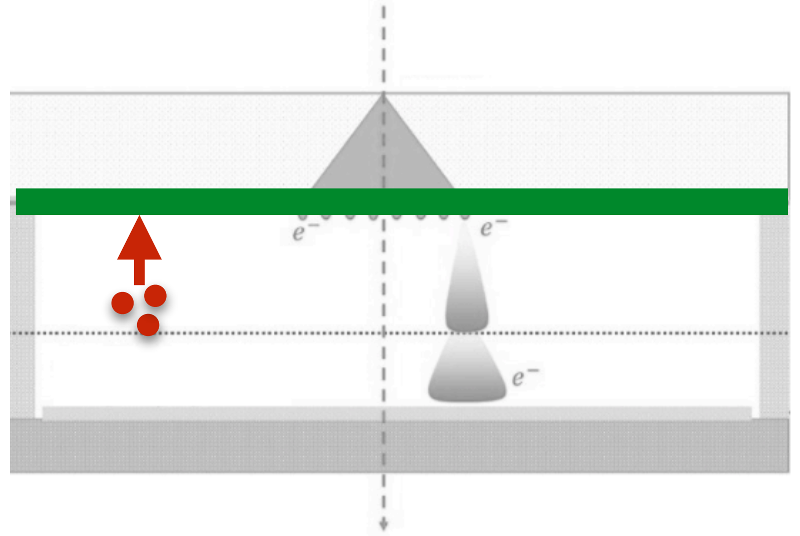
Simulation of signals induced in resistive detectors



D. Janssens, CERN

Photocathode robustness

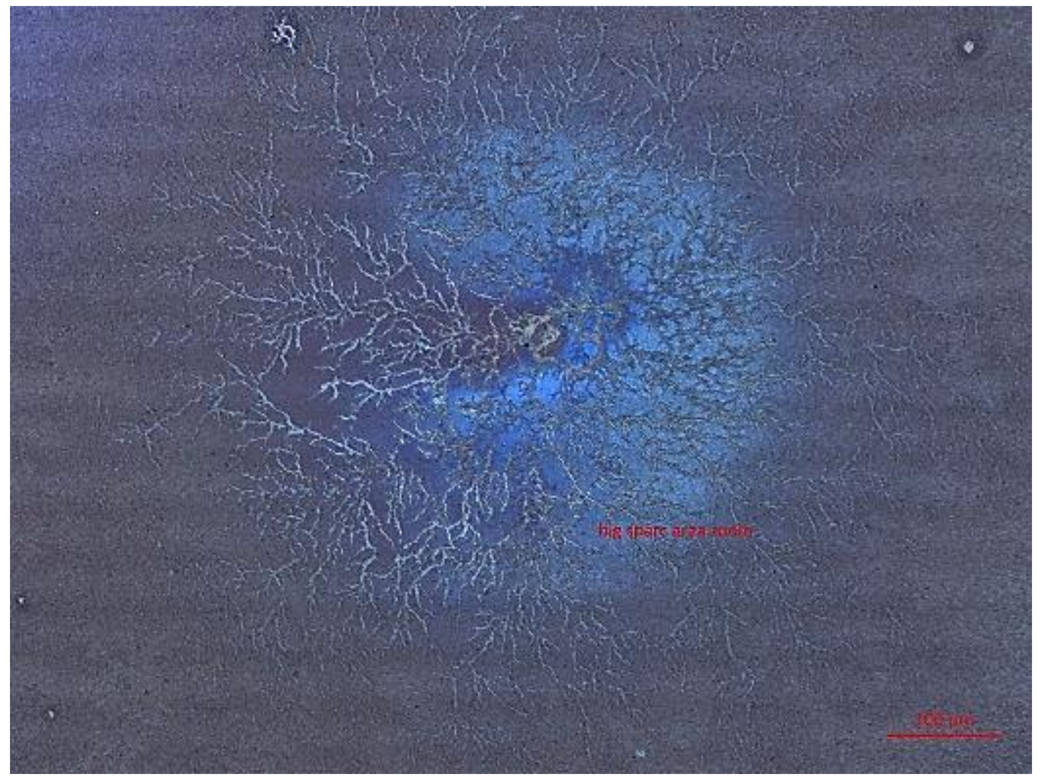
Limitations of CsI



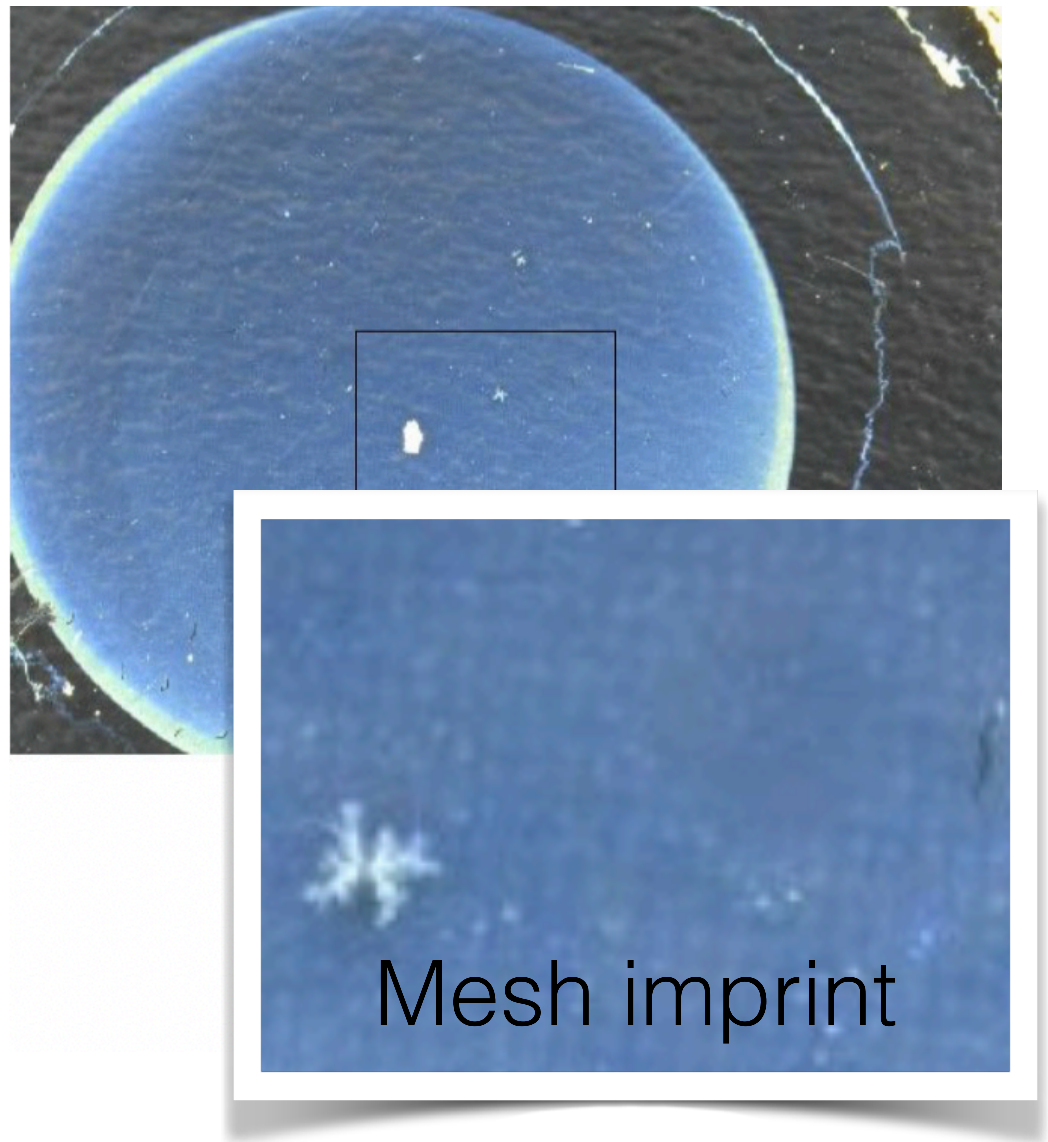
Standard PICOSEC photocathode: 18 nm CsI + 3 nm Cr → ≈10 p.e. / MIP

CsI sensitive to humidity, ion backflow and sparks

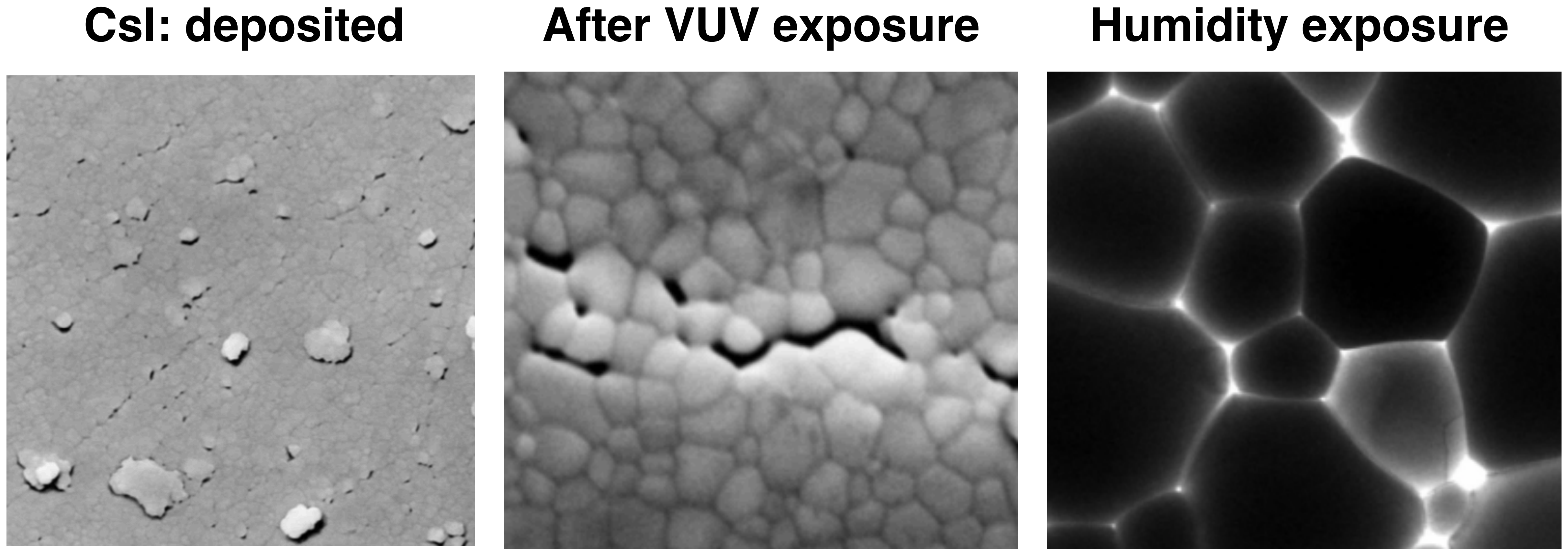
CsI photocathode after spark



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

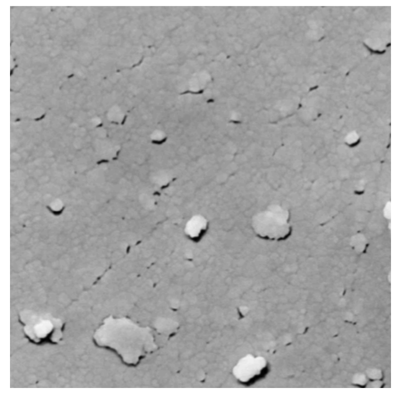
Photocathode robustness

Protection and alternatives

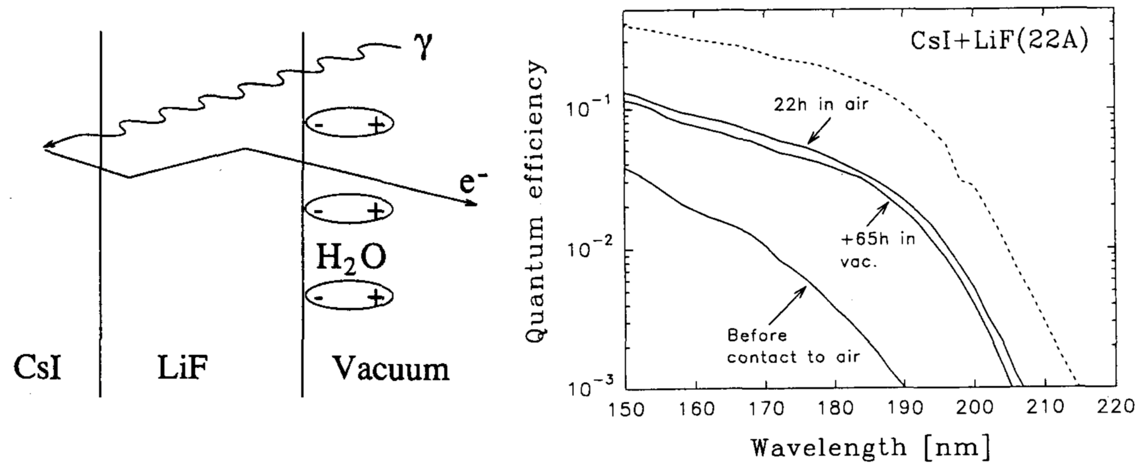
Robustness of photocathode is important to preserve QE and thus detector efficiency and timing resolution during prolonged operation. This may be address in two ways:

Making CsI more robust

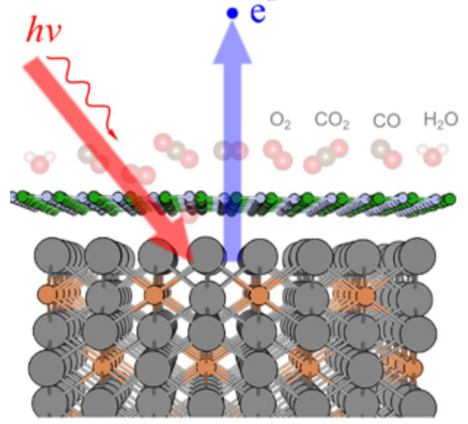
- Minimise effect of ion back flow while preserving QE
- Protection layers (MgF_2, LiF, graphene, …)



10.1016/ j.nima.2009.05.179



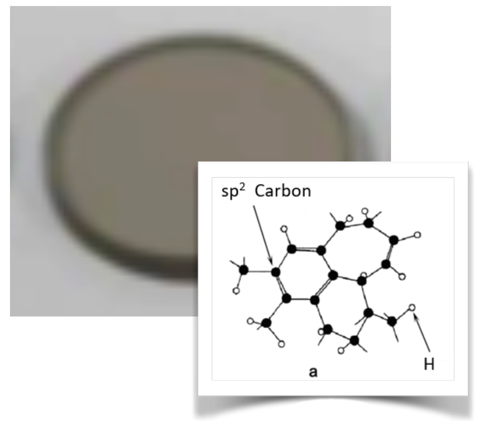
CsI + LiF_2, A. Breskin et al., 10.1109/23.467832



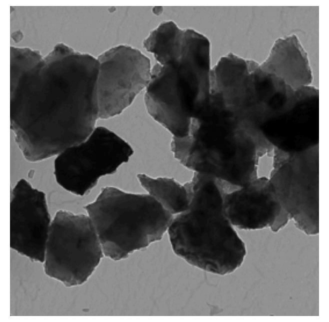
Graphene passivation, G. Wang et al

Alternative photocathodes

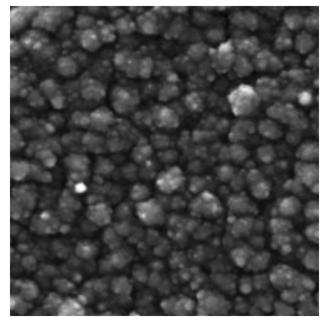
- Inherently robust materials (with possible lower QE)
- Metallic, DLC, B_4C, nano diamonds, CVD diamond, GaN, …



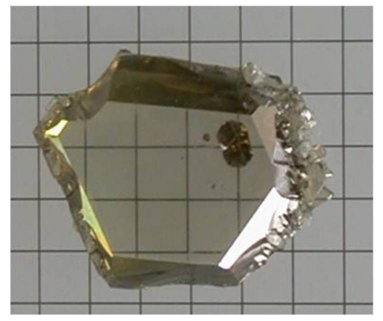
DLC, Y. Zhou et al.



ND, L. Velardi et al.

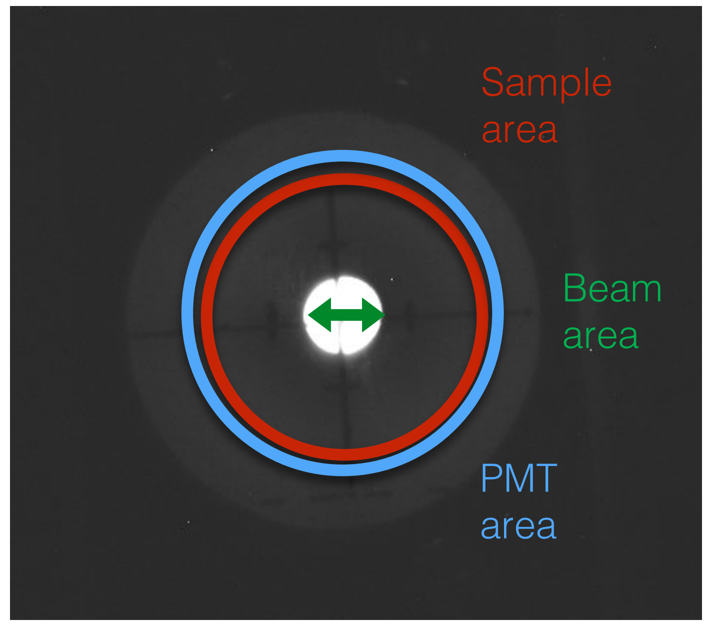


B_4C, 10.1016/ j.jnucmat.2015.01.015



GaN crystal

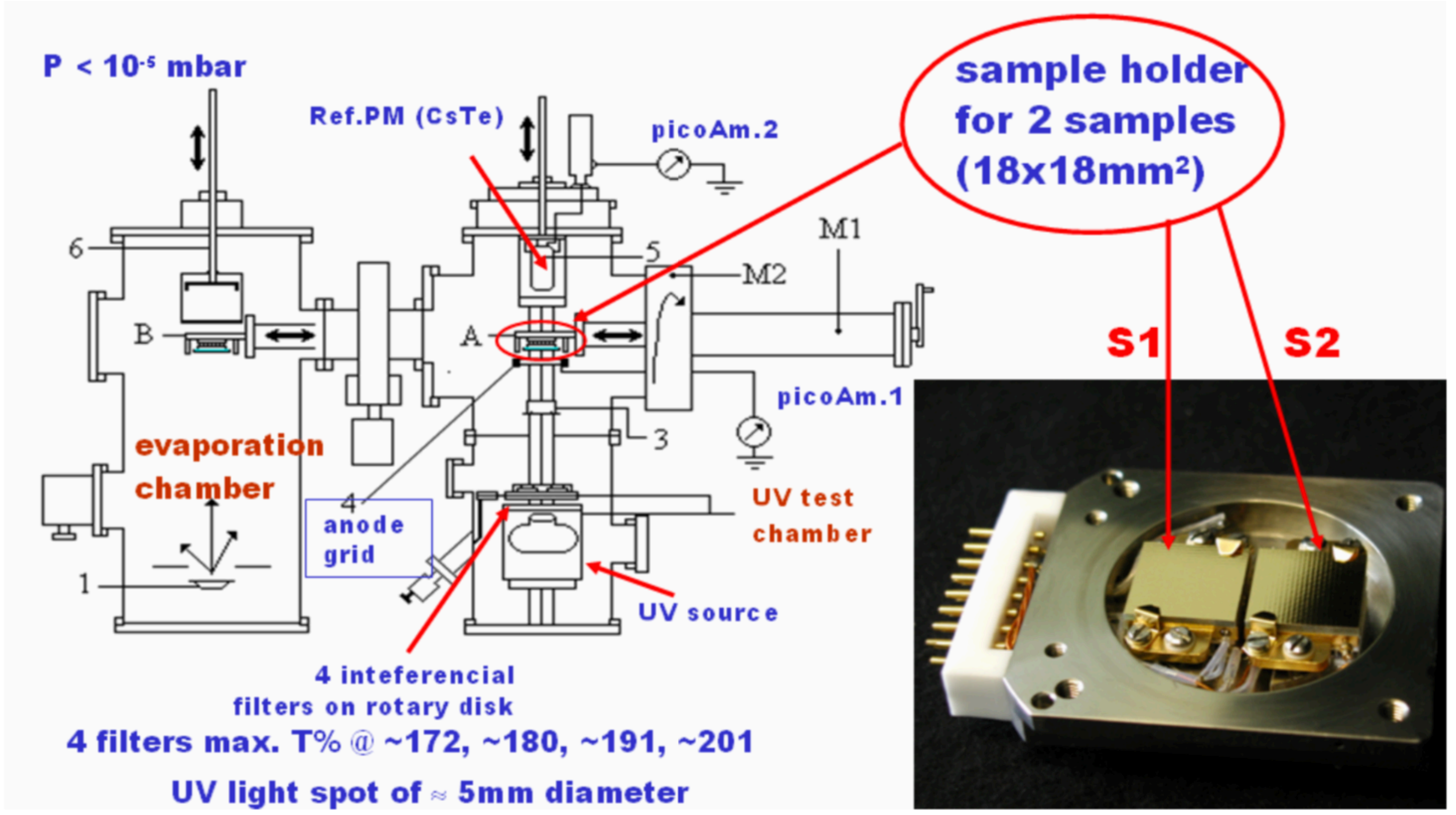
ASSET



Dedicated setup for **photocathode characterisation** in vacuum-UV (125-200nm) of small samples and quantify degradation

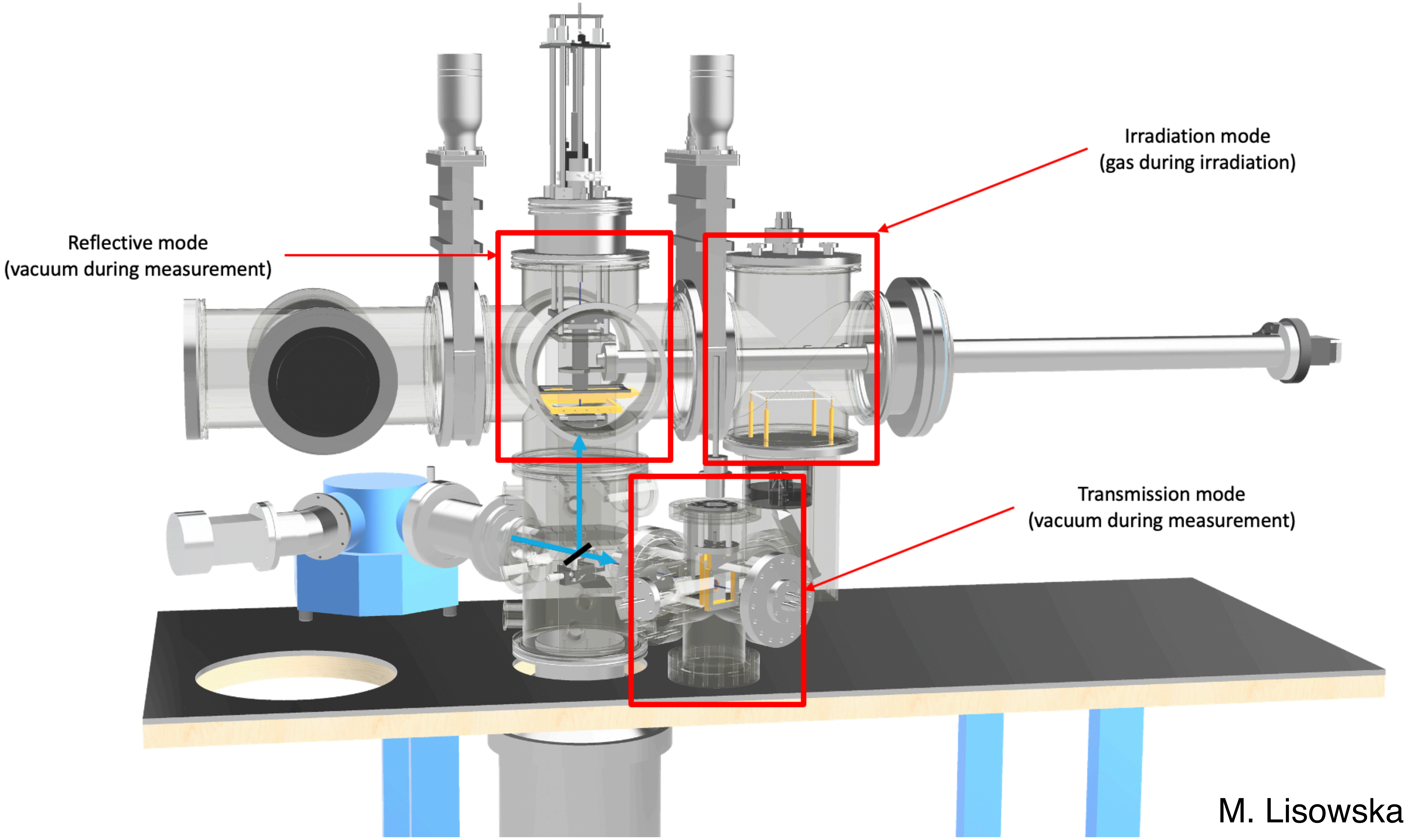
- Reflection / transmission mode QE
- Ion bombardment
- VUV transmission
- Scan across samples

Originally developed for ALICE/HMPID



H. Hödlmoser, PhD thesis

Modified and upgraded in GDD lab



Reflective mode
(vacuum during measurement)

Irradiation mode
(gas during irradiation)

Transmission mode
(vacuum during measurement)

M. Lisowska

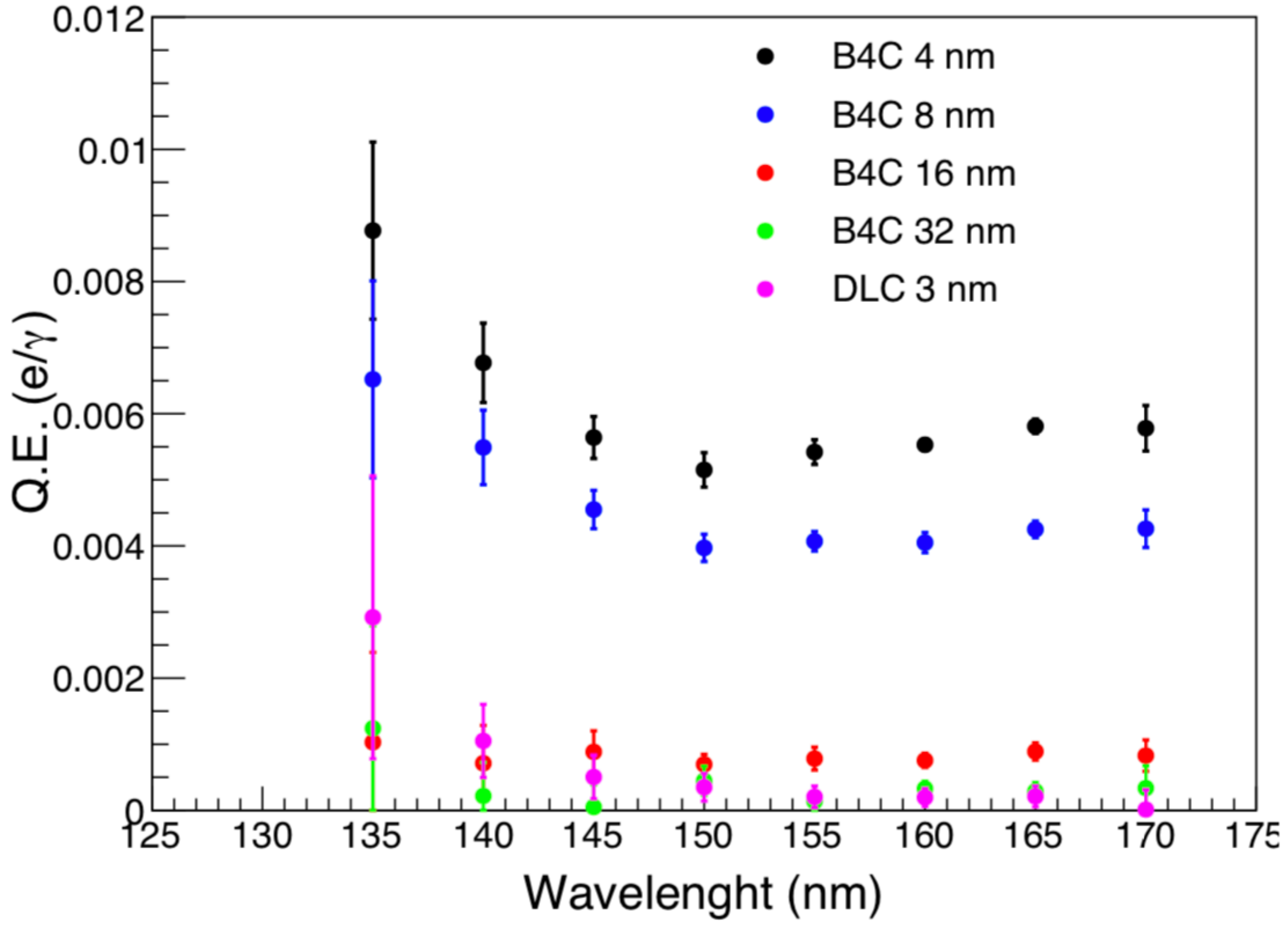
Photocathode studies with ASSET

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

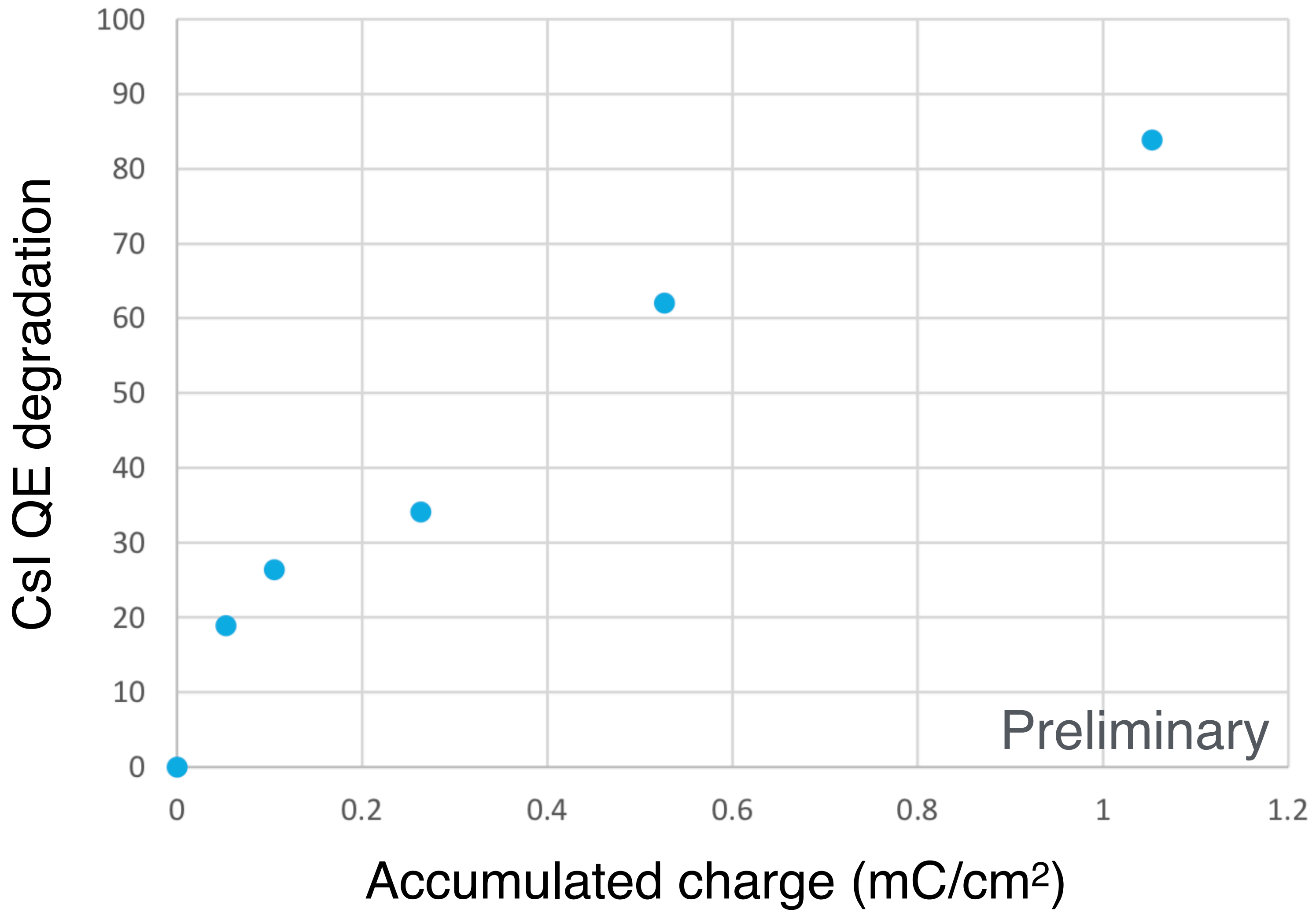
Reflective/transmissive QE, ion bombardment degradation and VUV transparency measurements

B_4C / DLC transmission QE

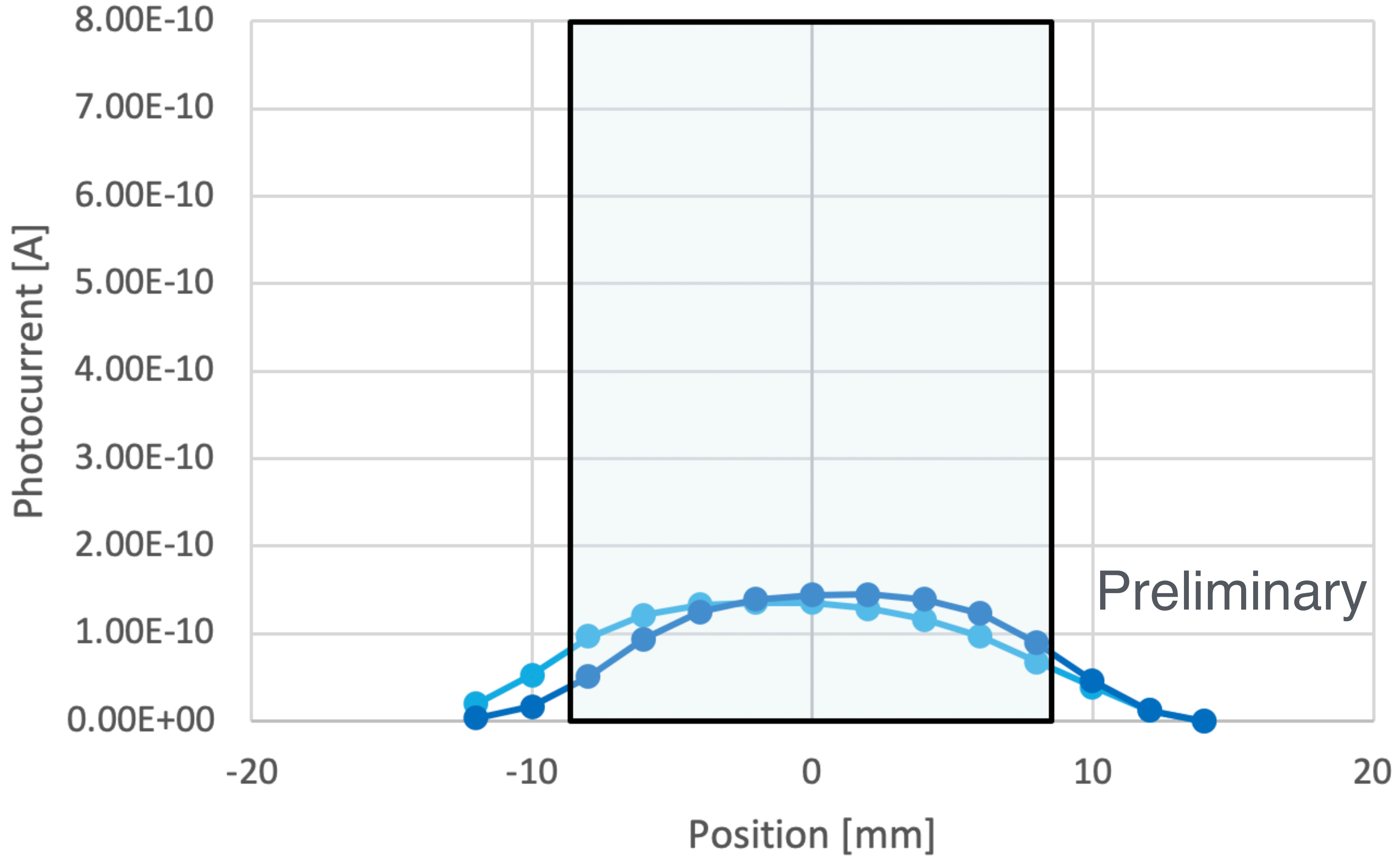


L. Sohl, Overview on recent PICOSEC-Micromegas developments and performance tests, RD51 Mini-Week February 2020, https://indico.cern.ch/event/872501/contributions/3726013/

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

Photocathode materials

Alternatives tested during test beam campaigns

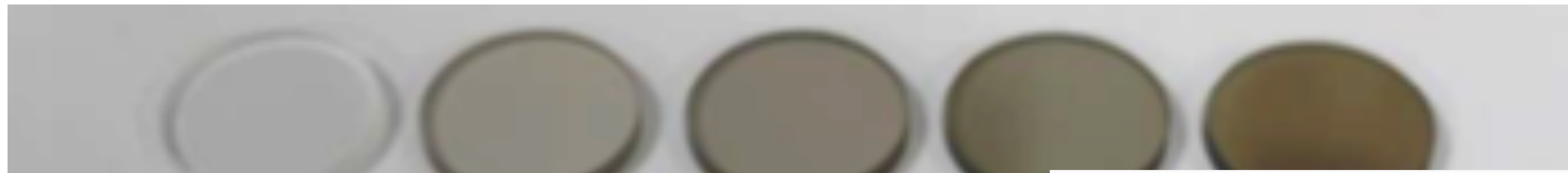
Photocathode	$N_{ph.e.}$ / muon
Cr +18 nm CsI	10.4 ± 0.4
20 nm Cr	0.66 ± 0.13
6 nm Al	1.69 ± 0.01
10 nm Al	2.20 ± 0.05
Cr + 5nm diamond	1.85

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

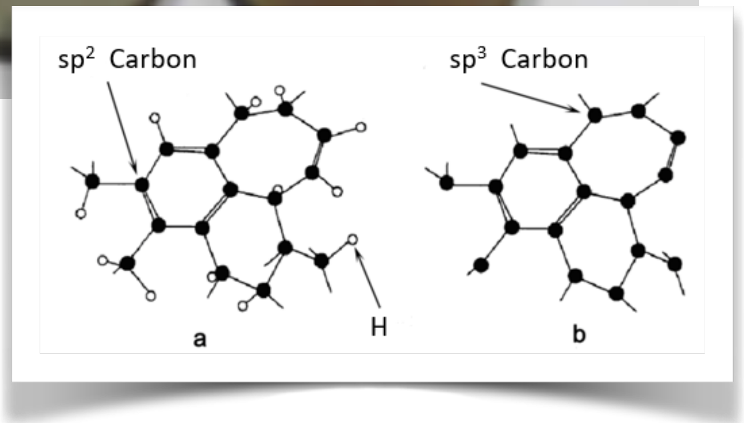
DLC thickness	$N_{ph.e.}$ / muon
2.5nm	3.7
5nm	3.4
7.5nm	2.2
10nm	1.7

Diamond-like carbon (DLC)

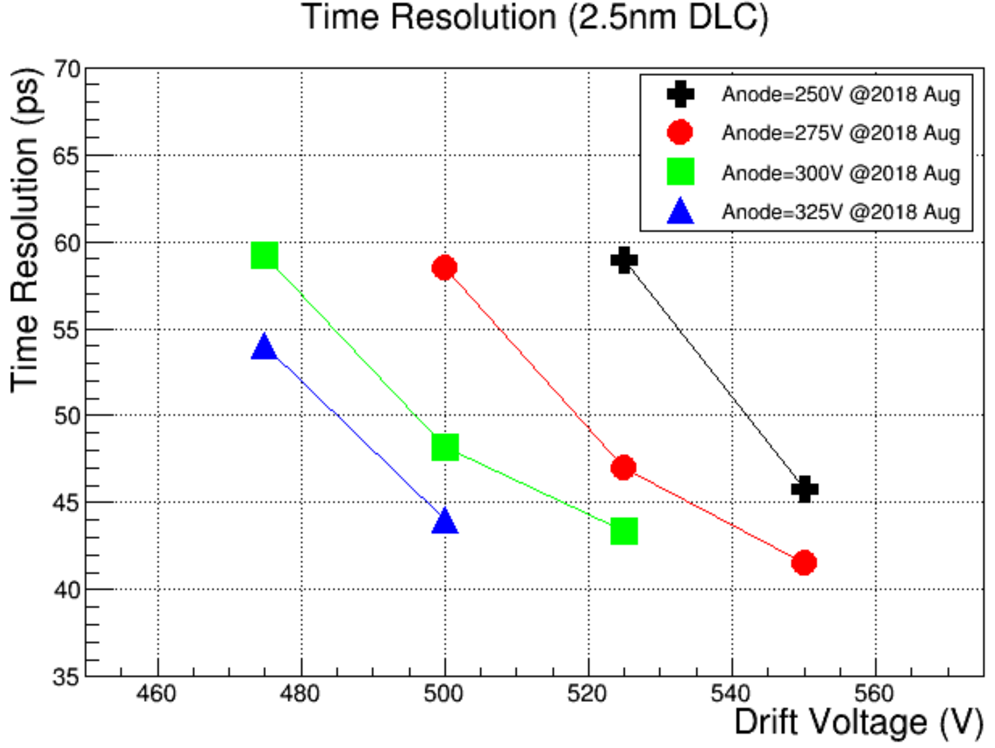
Robust material used for resistive electrodes and with promising properties as photocathode.

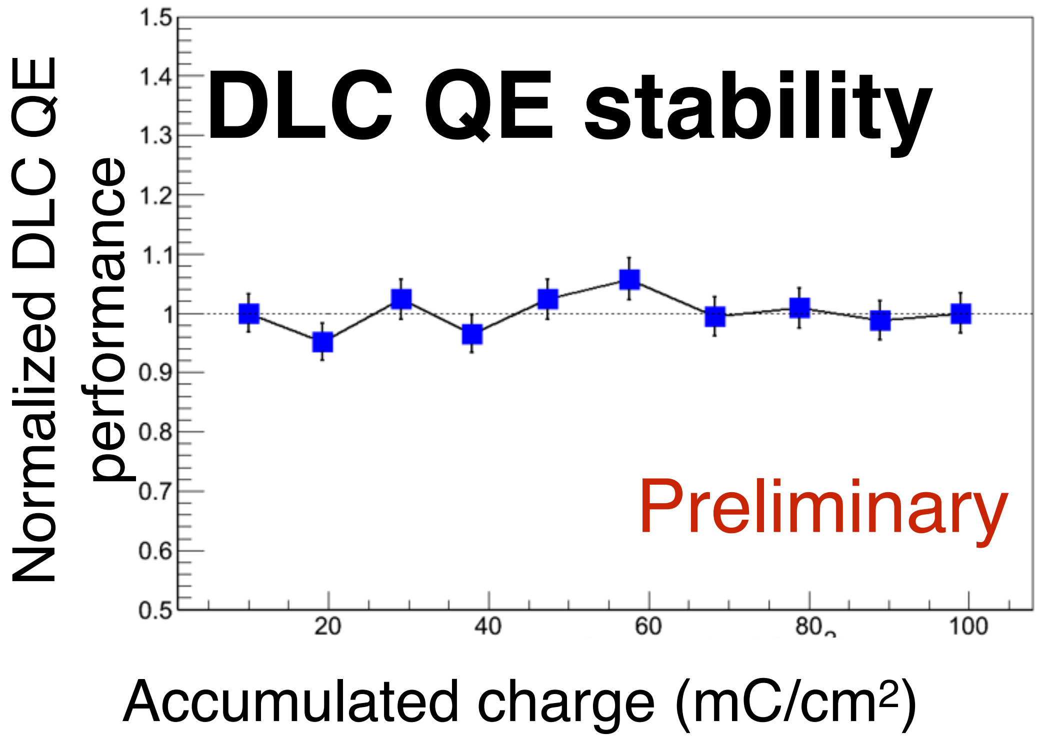


https://indico.cern.ch/event/709670/contributions/3012912/attachments/1671364/2681277/DLC-photo-cathode.pdf



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

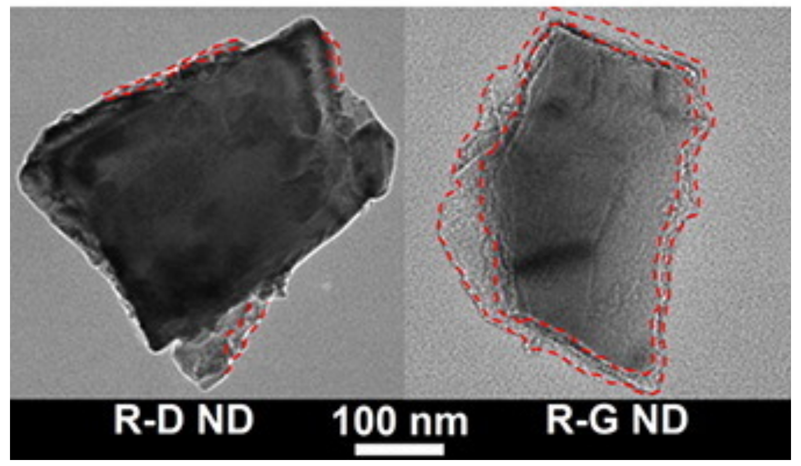


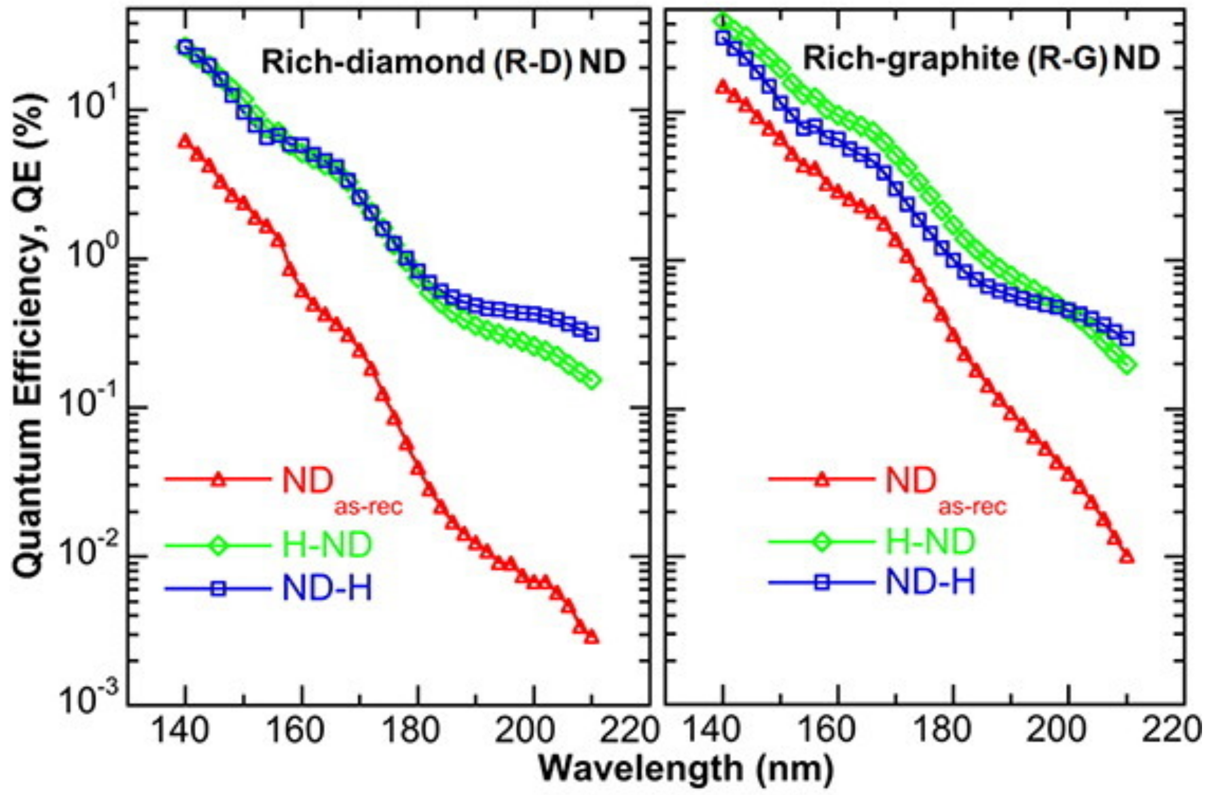


X. Wang, Recent photocathode and sensor developments for the PICOSEC Micromegas detector, MPGD 2019 https://indico.cern.ch/event/757322/contributions/3387110

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

Picosec detector modules

Scaling up to tileable modules for larger area coverage

Detector

Preamplifier

Digitisation

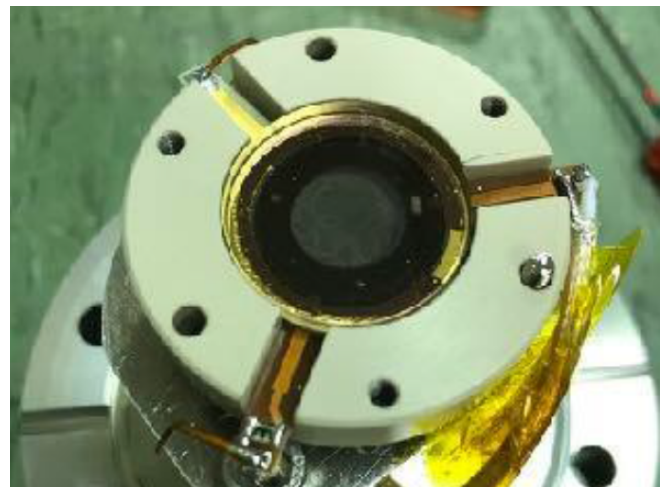
Several variants of multi-channel PICOSEC prototypes in development / under test to address challenges associated with scaling to larger areas:

Integration

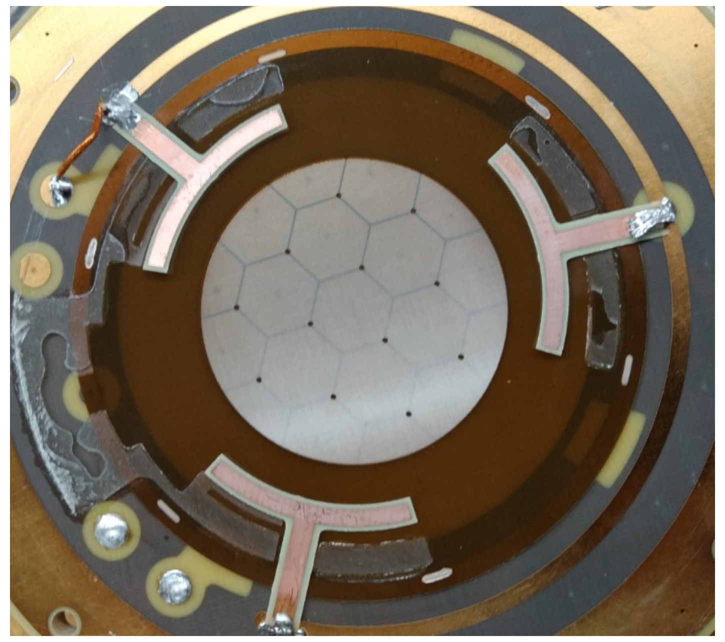
- Mechanics to preserve precise gaps
- Large Cherenkov radiators and photocathodes
- Tileing & compact detector vessel
- Sealed detector
- Resistive multi pad

Electronics

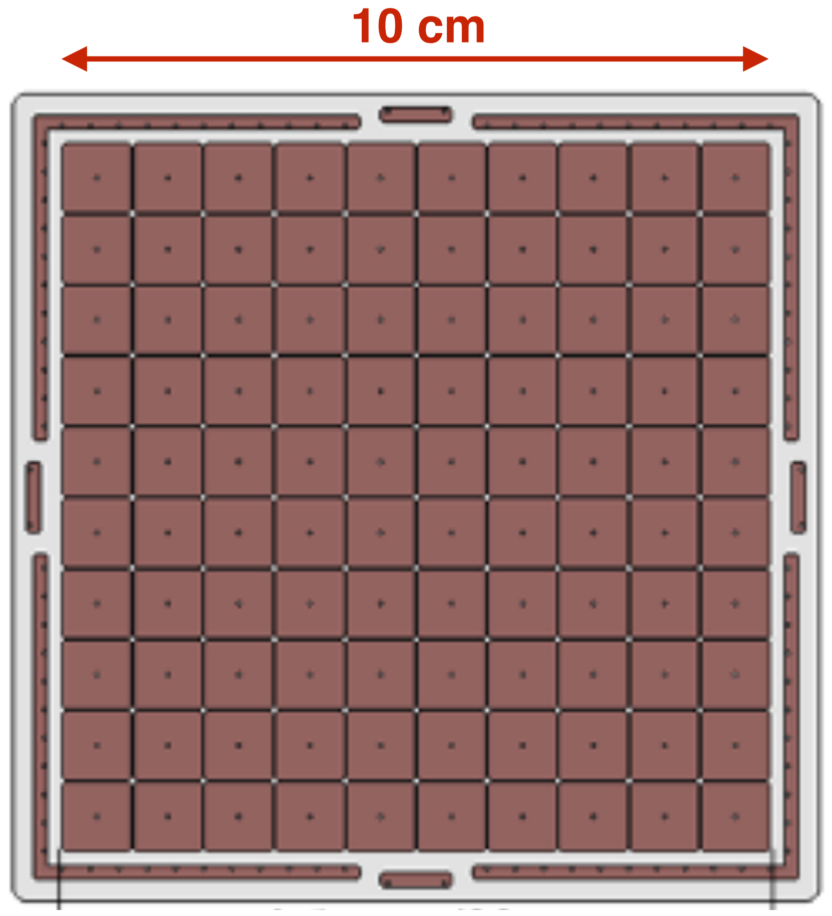
- Signal sharing between pads
- Premplifiers
- Multi-channel digitisers



Single pad (2016)
⌀1 cm



Multi pad (2017)
⬡ 1 cm

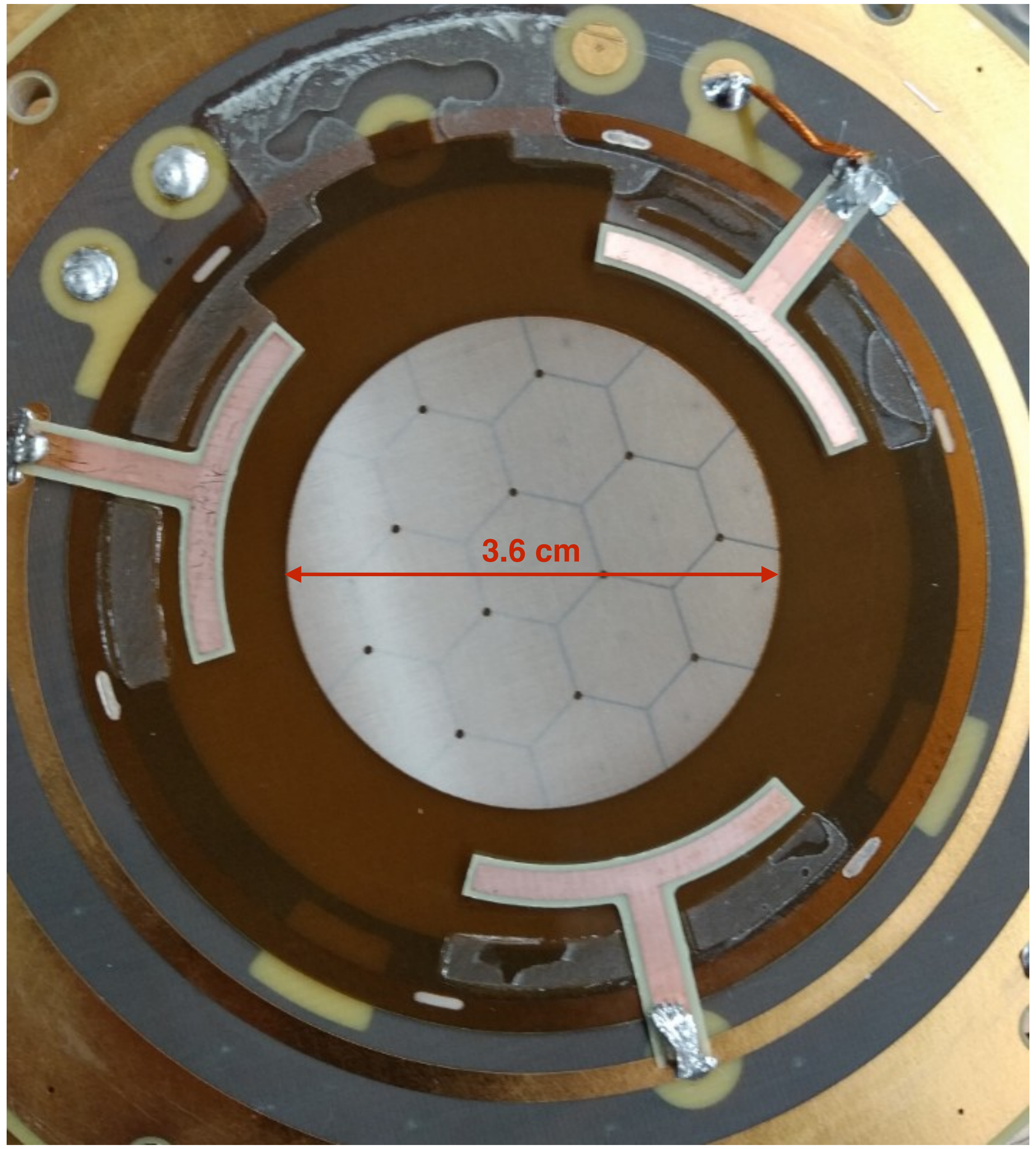


10x10 module
◻ 1 cm

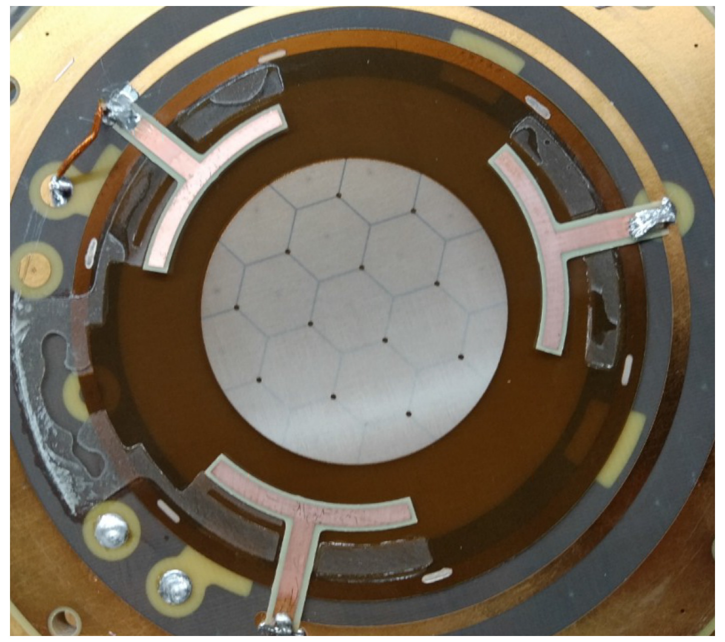
Large-area coverage

Scaling up multi-channel PICOSEC

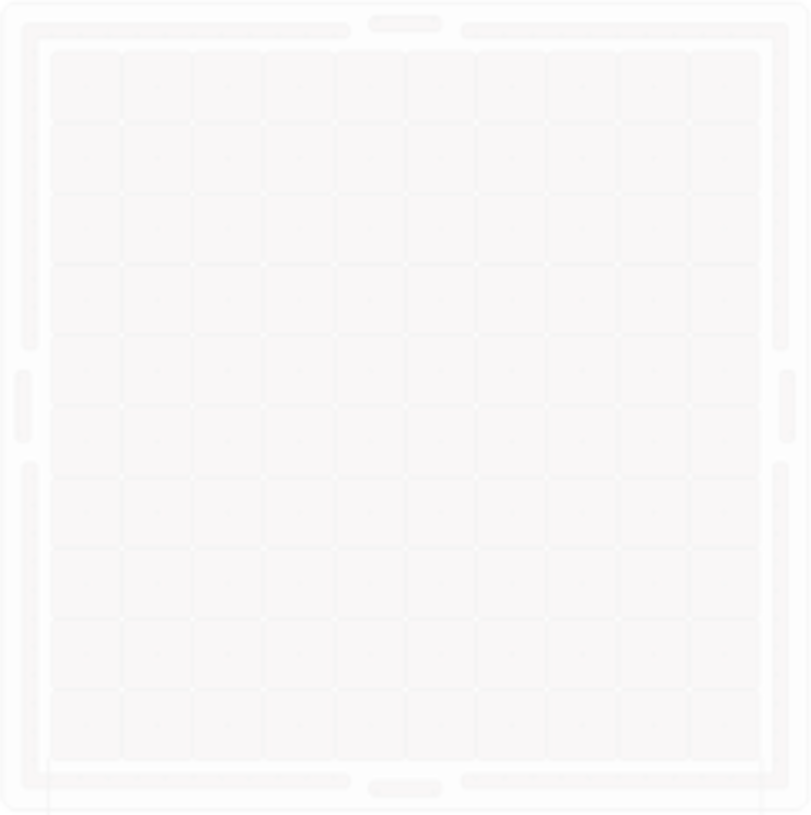
Multi-pad prototype was evaluated in test beam campaigns to study achievable time resolution for **signal shared across multiple pads**



Single pad (2016)
⌀1 cm



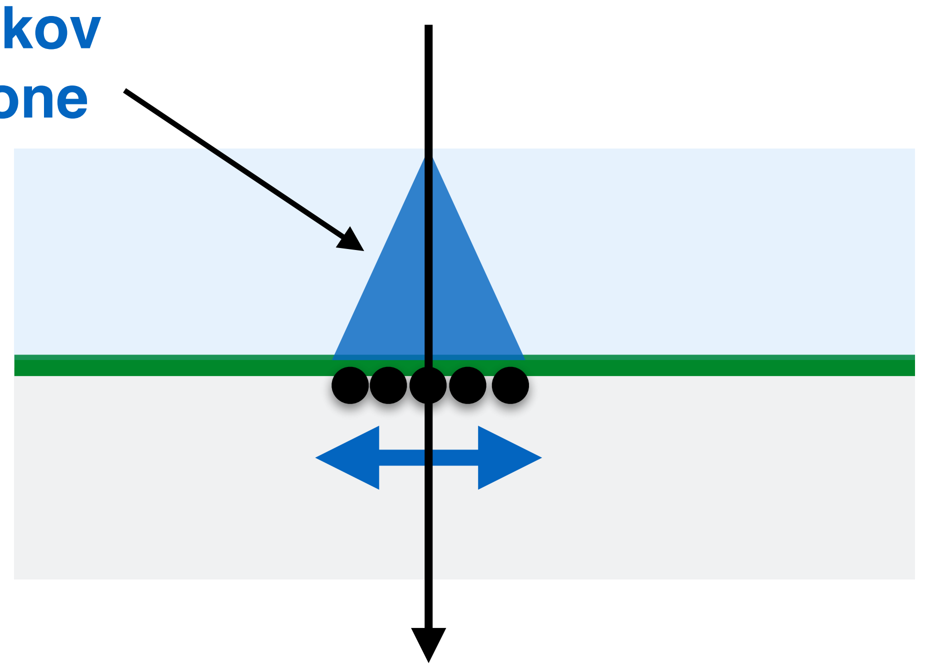
Multi pad (2017)
⬡ 1 cm

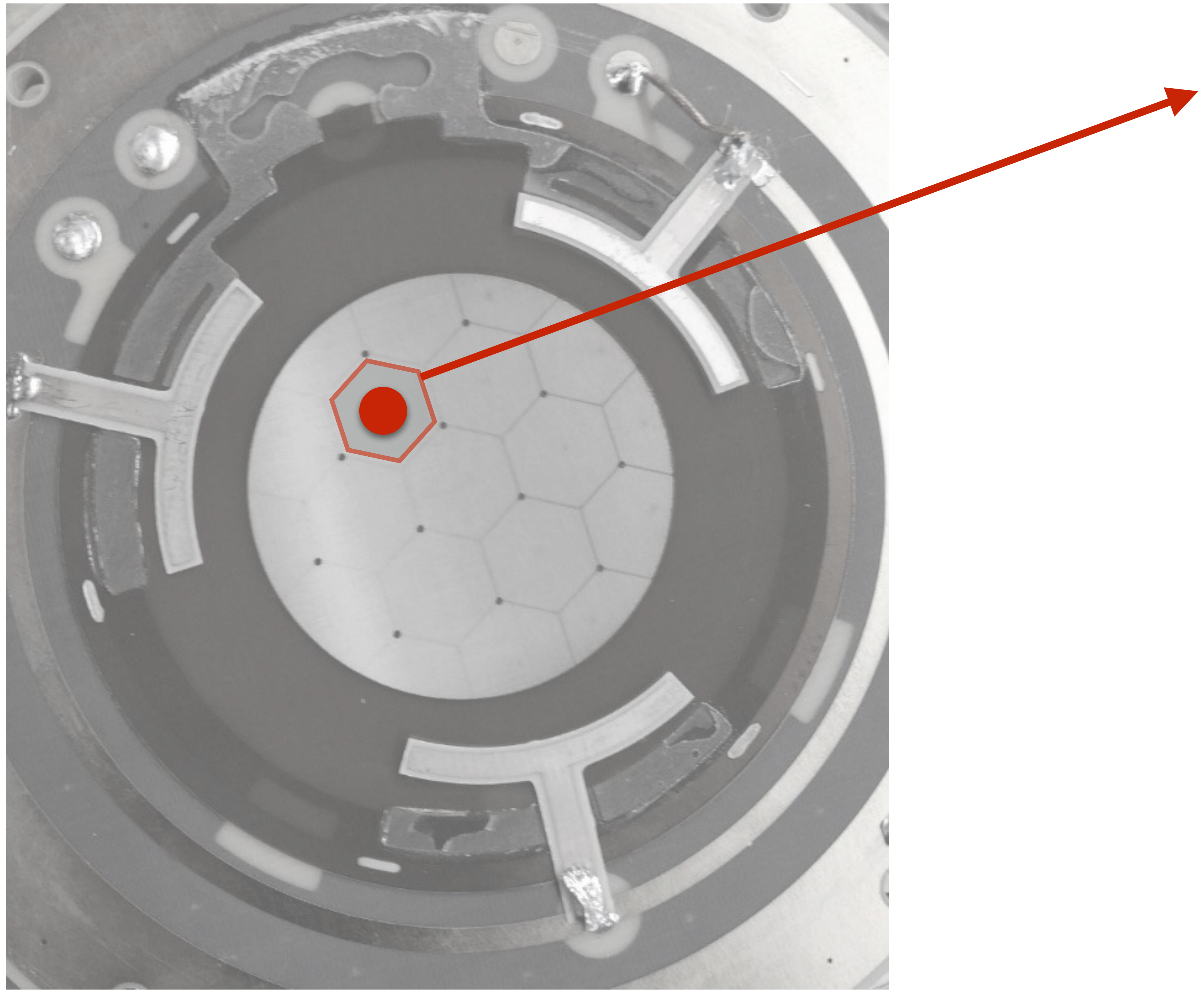


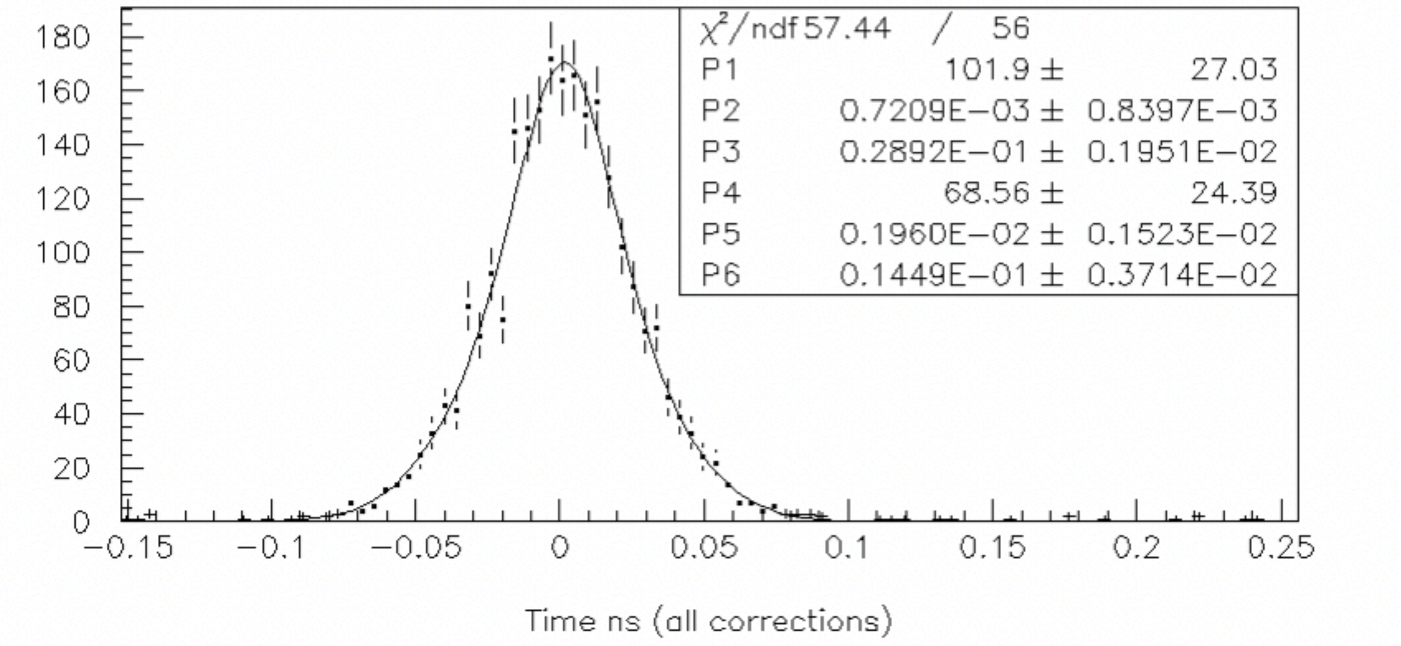
10x10 module
□ 1 cm

Large-area coverage

Scaling up multi-channel PICOSEC





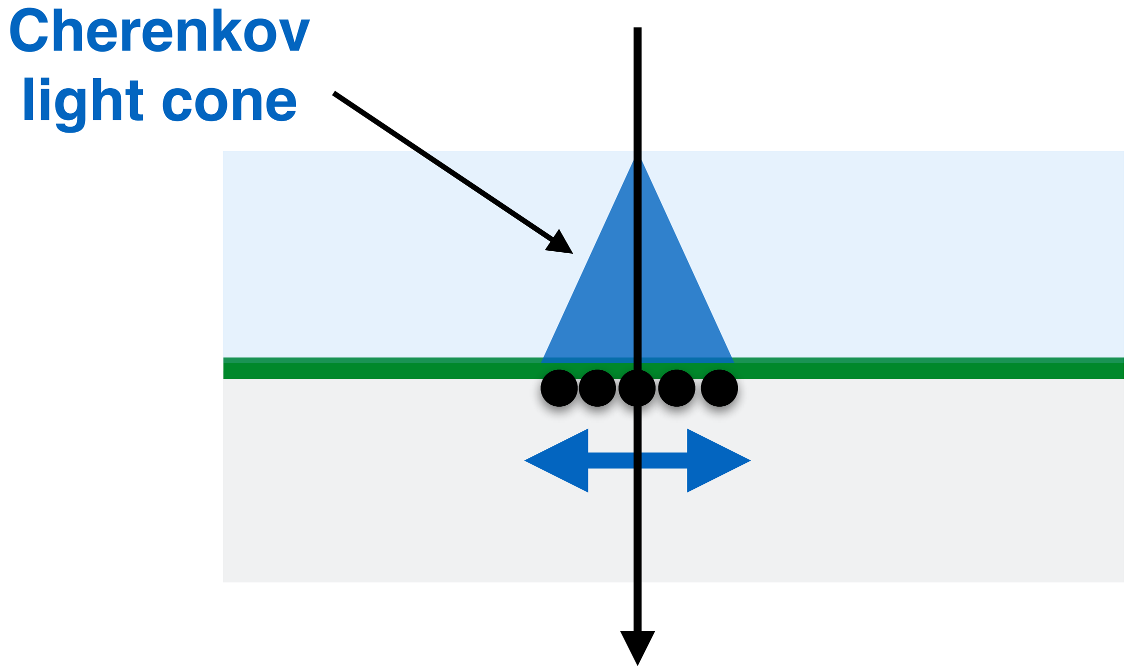


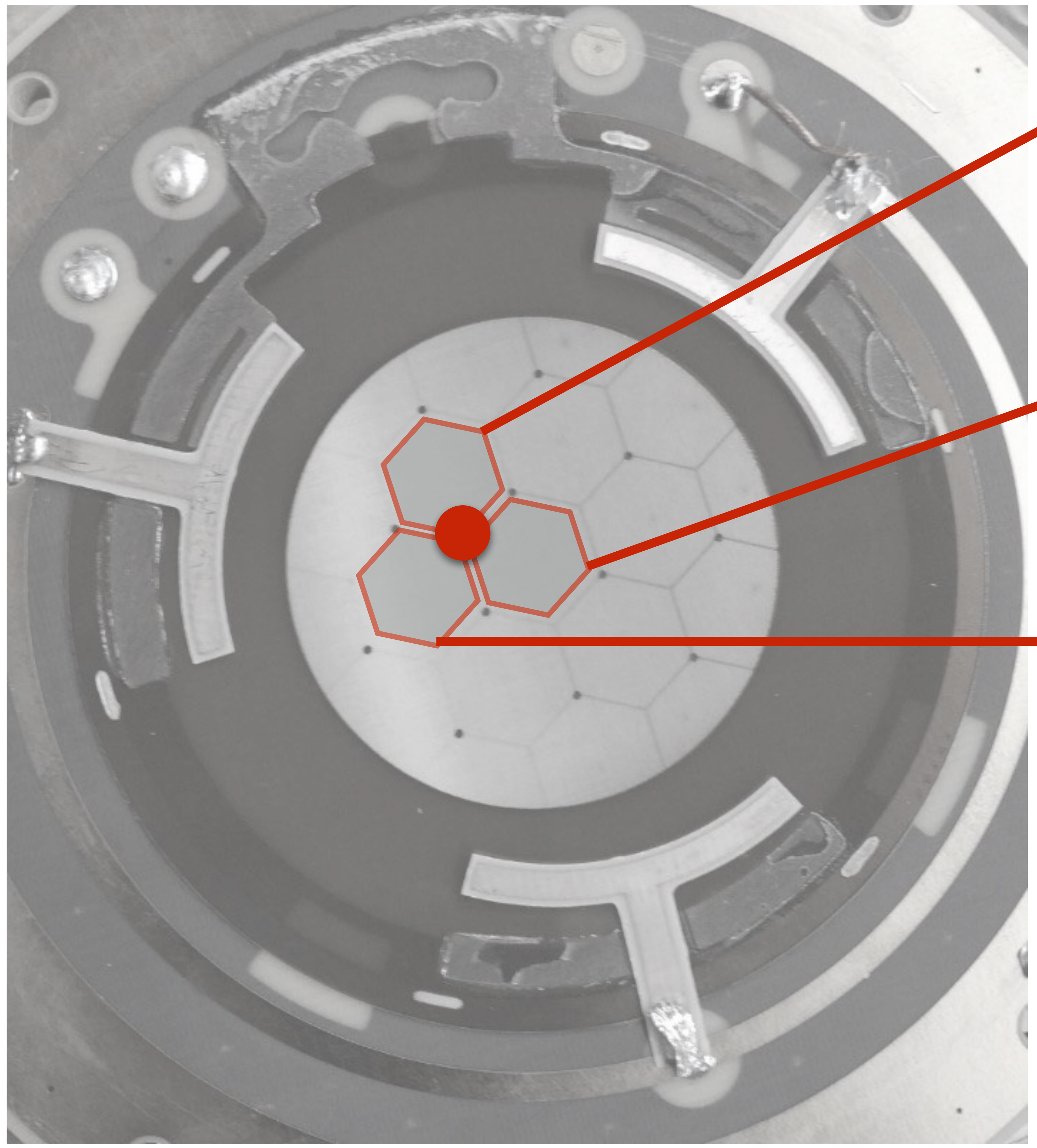
Single pad hit:
25 ps timing resolution for all pads

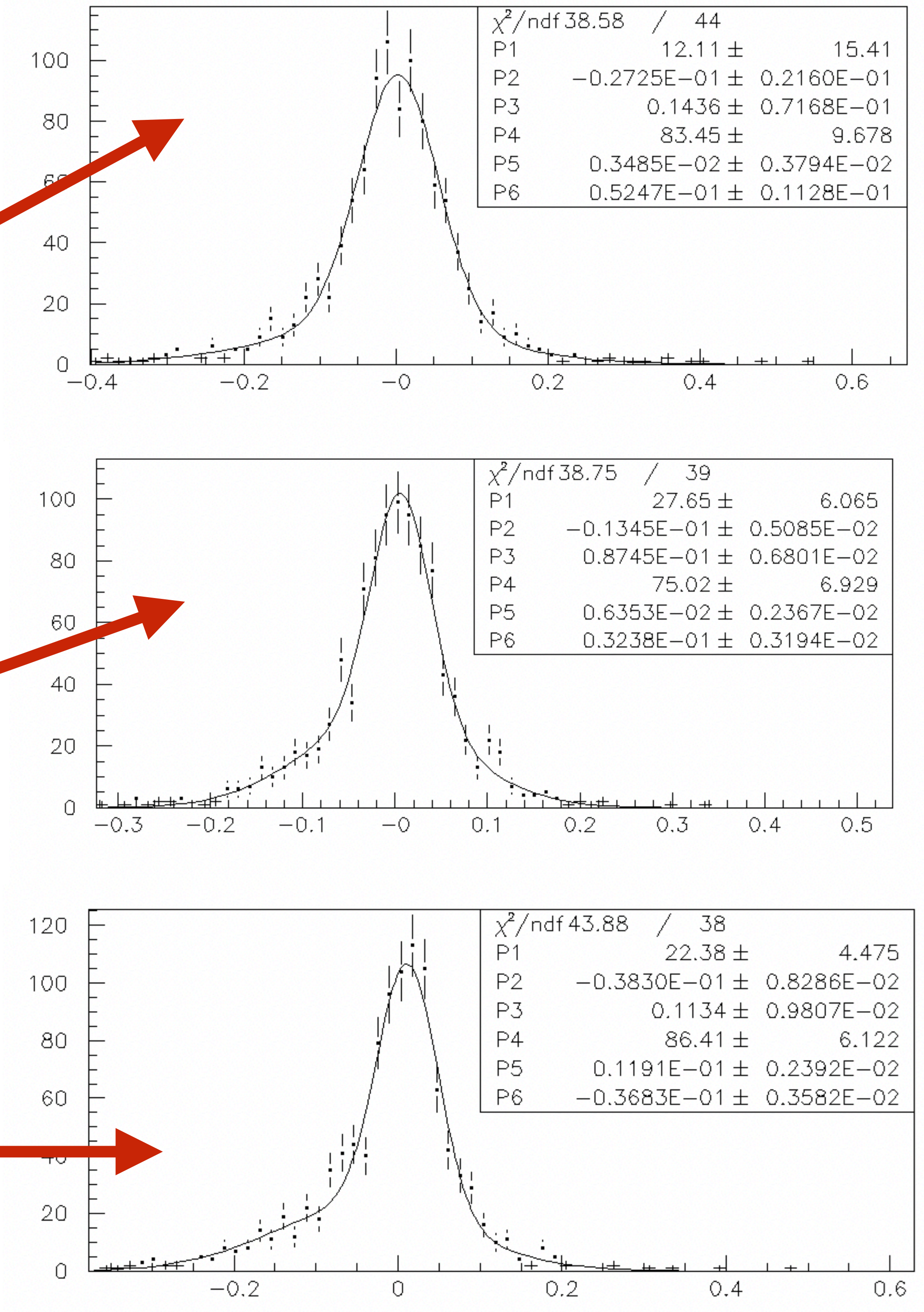
S. Aune et al., “Timing performance of a multi-pad PICOSEC-Micromegas detector prototype”, NIM A (993), 2021, https://doi.org/10.1016/j.nima.2021.165076

Large-area coverage

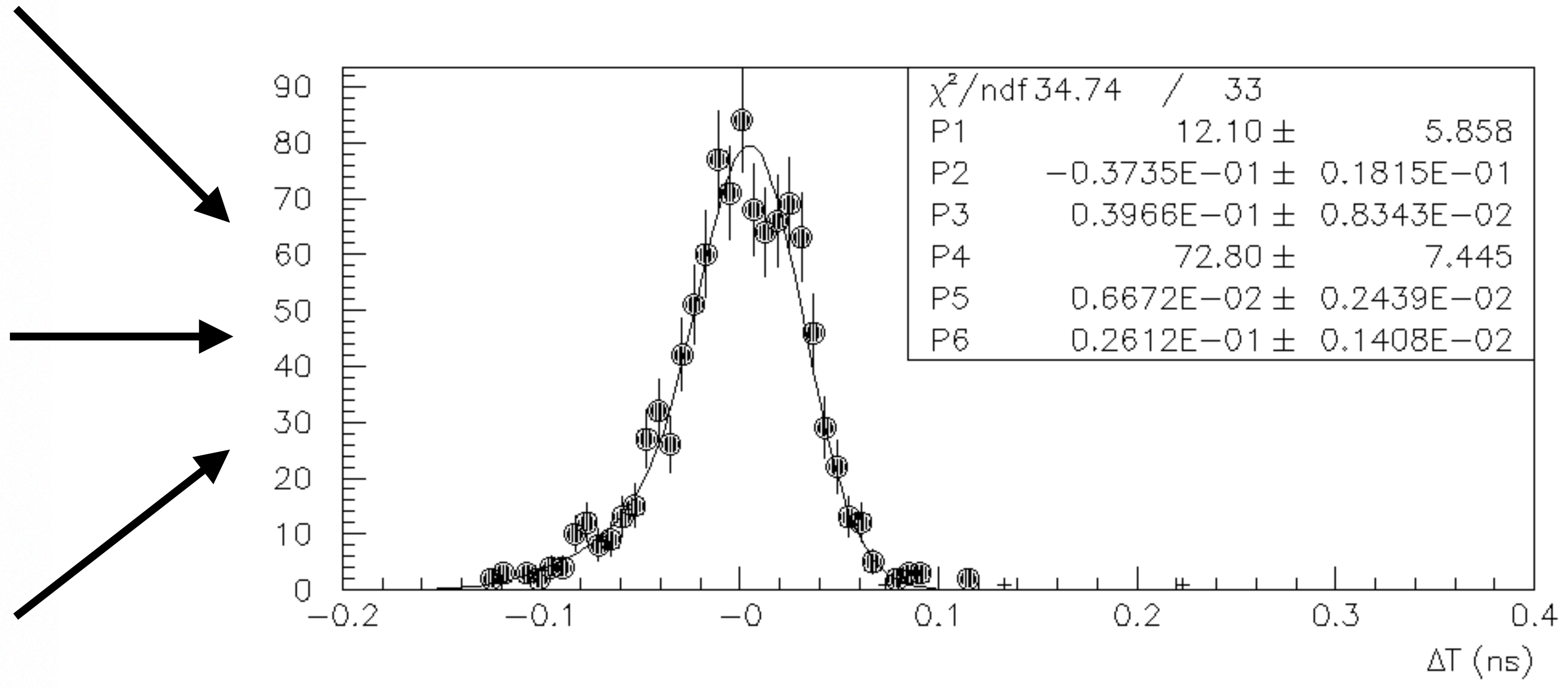
Scaling up multi-channel PICOSEC







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



Combined:
31 ps timing resolution

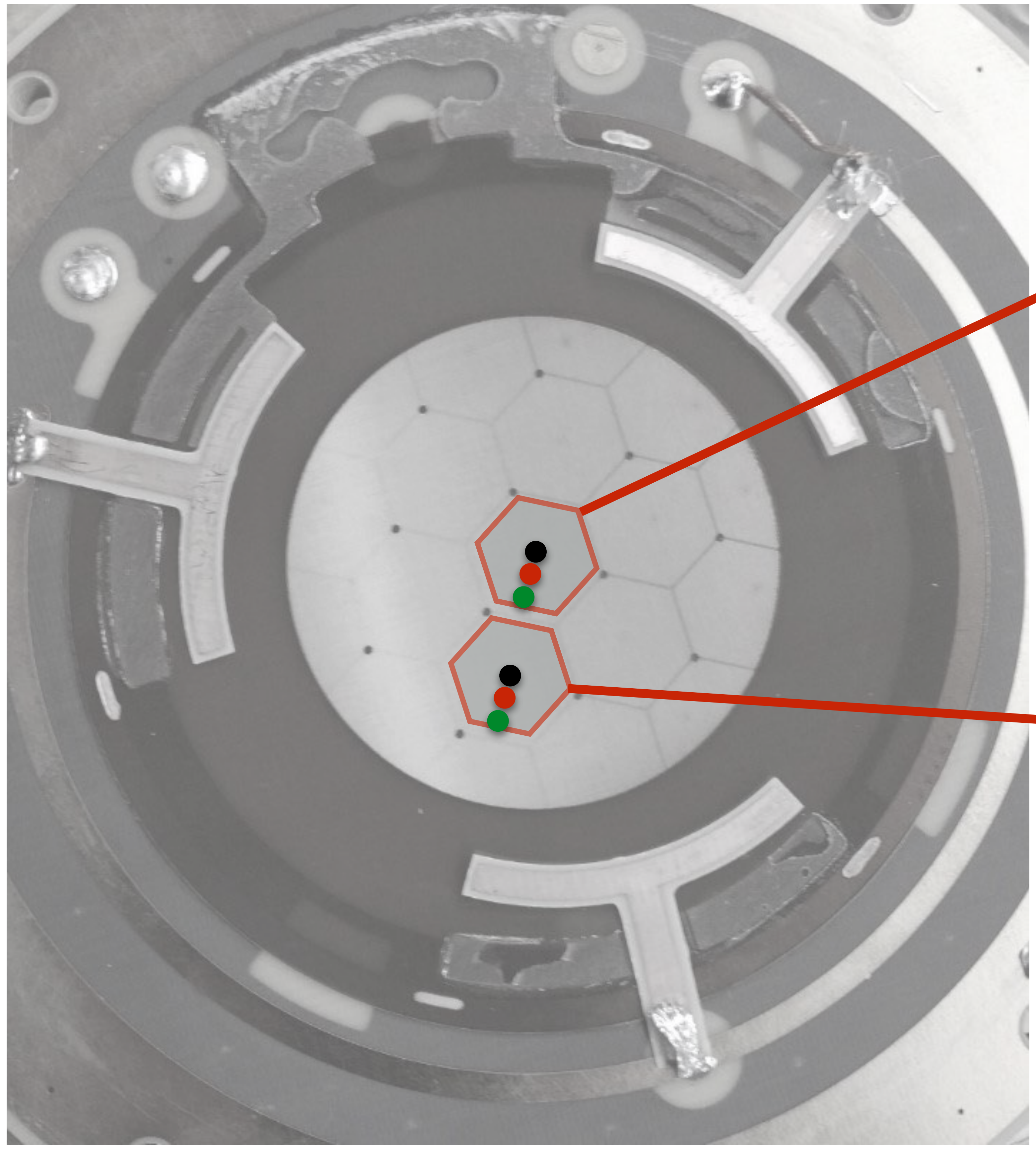
$$\chi^2 = \sum_{i=1,4} \frac{\left(\left[t_i - \left\{\langle SAT\rangle(R_i,\theta_i) - \langle SAT\rangle(R_i,90^\circ)\right\} - \left\{SL(Q)\right\} - \hat{t}\right]\right)^2}{\left(\mathrm{Res}(Q_i)\right)^2}$$

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

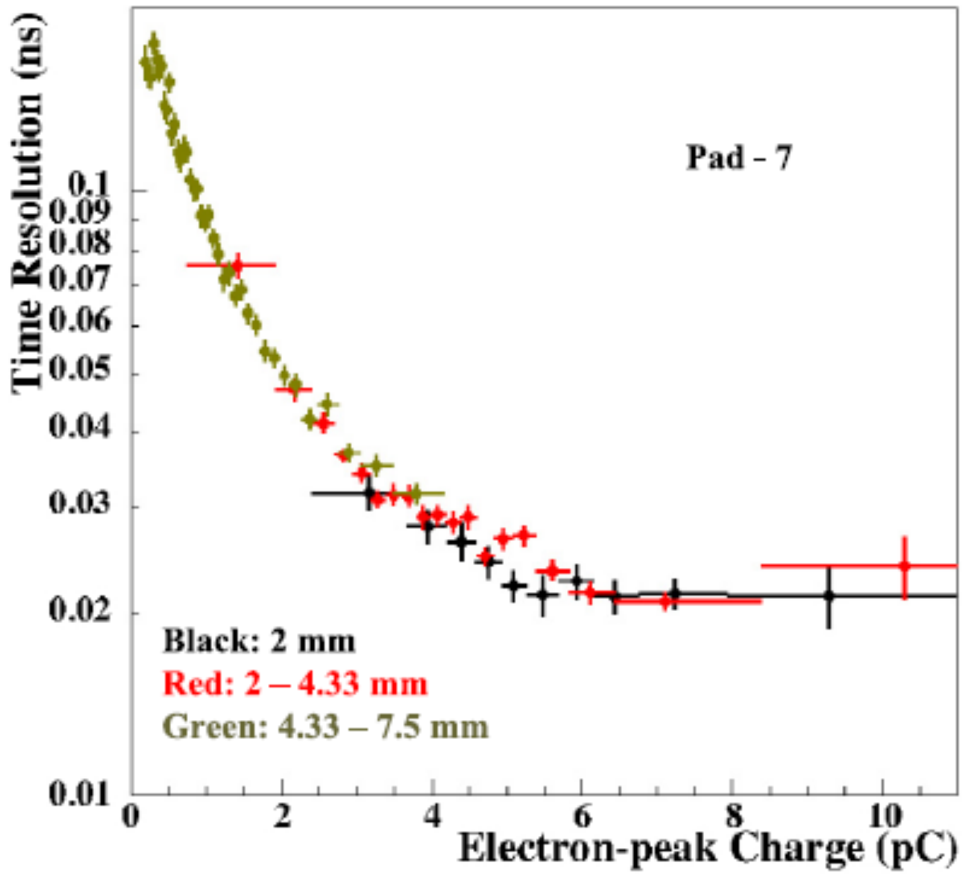
Large-area coverage

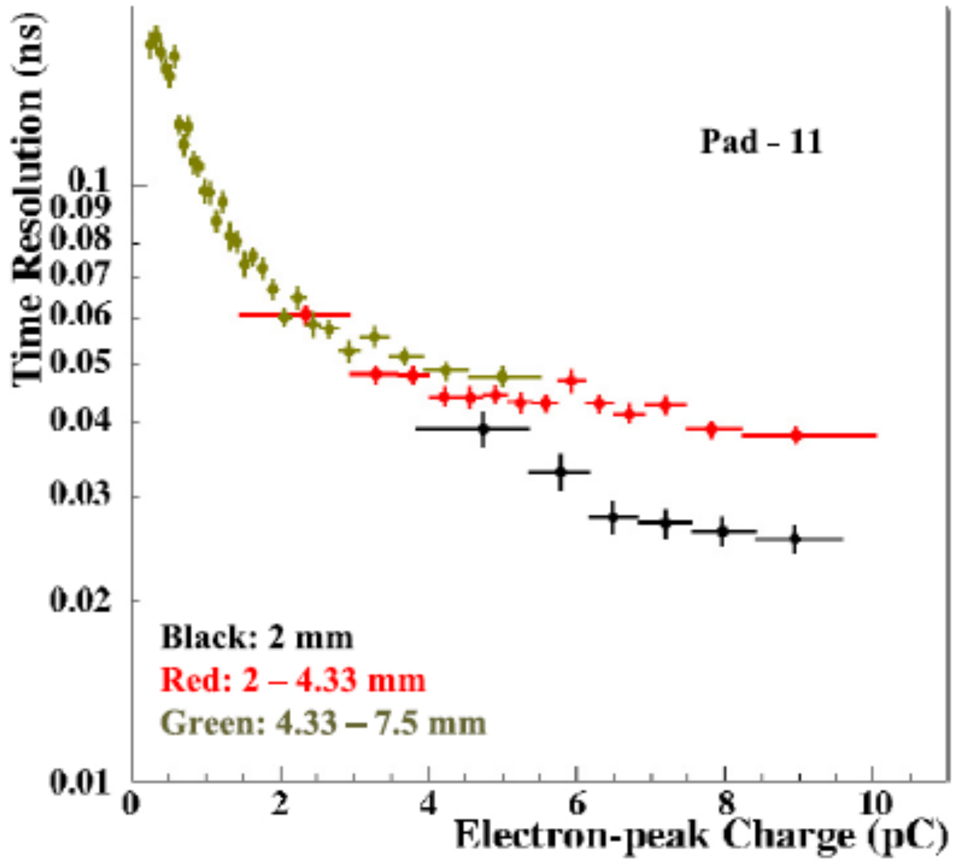
Scaling up multi-channel PICOSEC

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

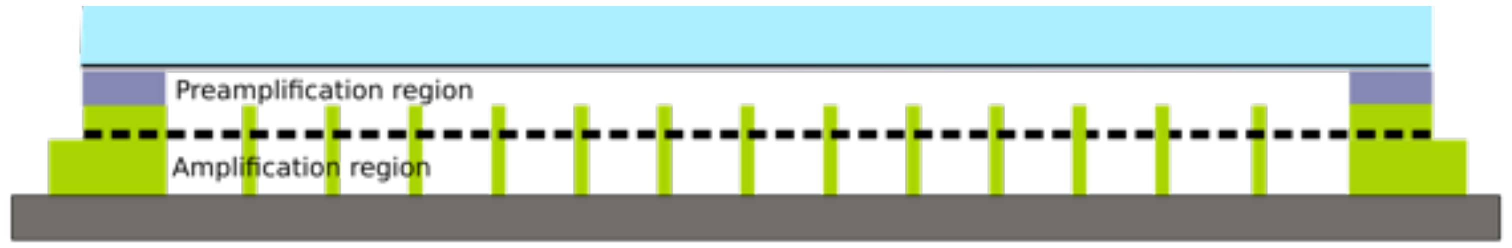


Schematic hit locations not drawn to scale

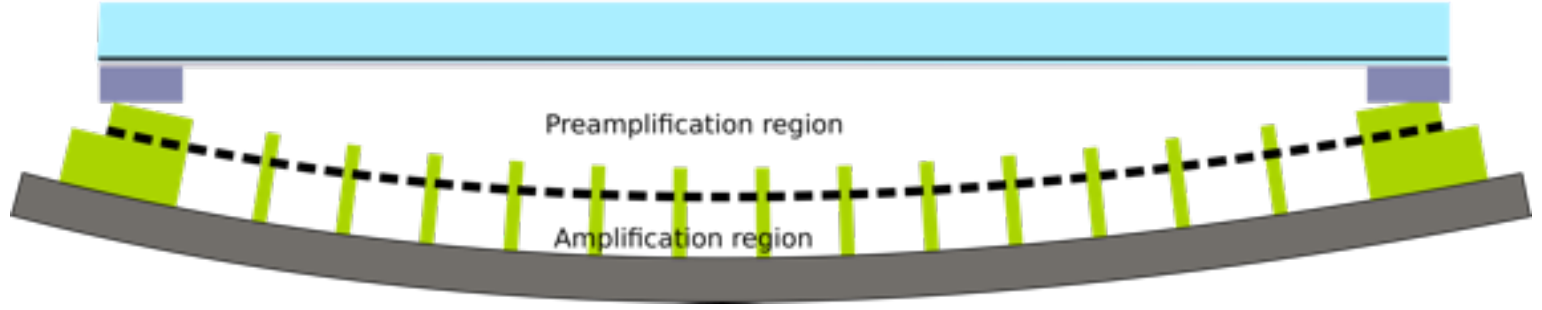




Ideal, uniform preampfification gap

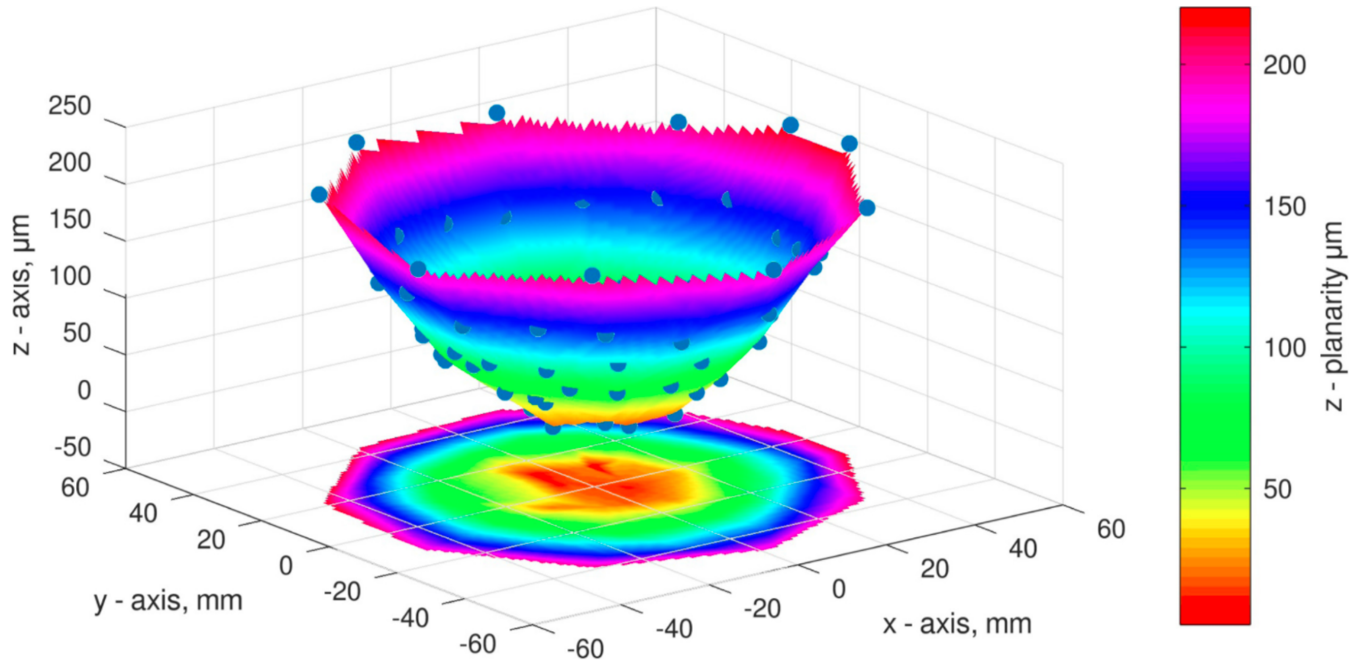


Observed, deformed preamplification gap



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

Detector module mechanics

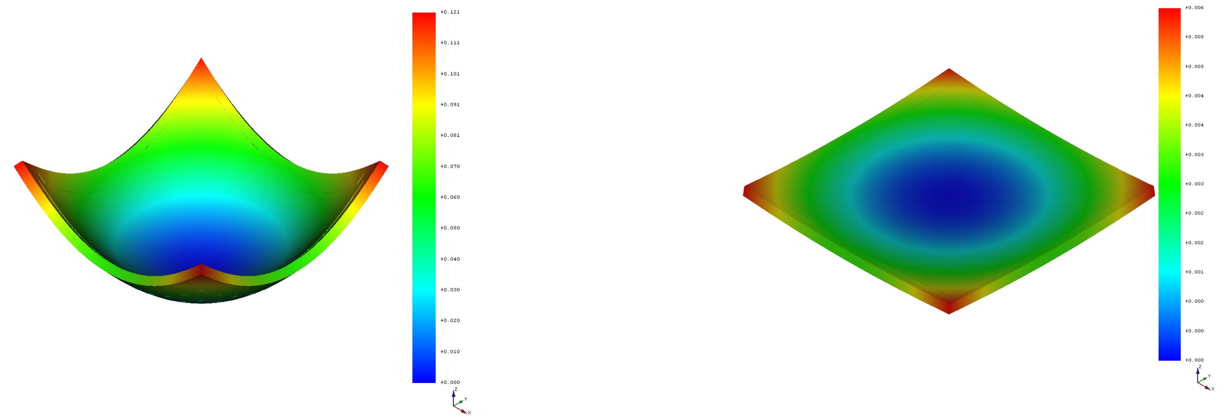
Experience from first multi-pad prototype:
uniform pre-amplification gap thickness crucial for timing performance

Increasingly challenging with larger detectors to maintain high gap uniformity (<10μm across tens of cm)

Challenges on gap uniformity:

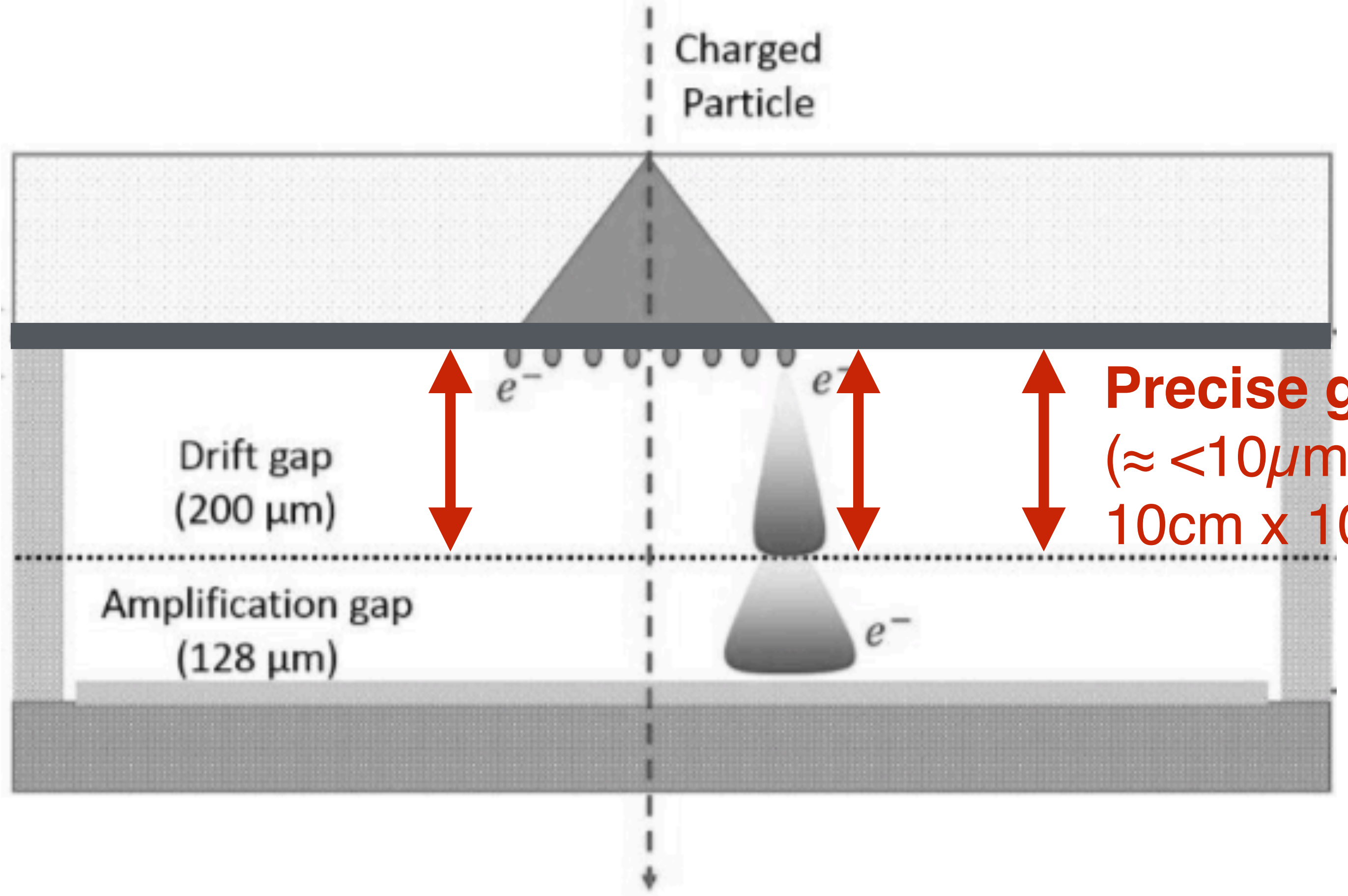
- Stress from stretched micro mesh (14 N/cm) tension
  → **rigid ceramic PCB**
- Mechanic force when fixed directly to housing
  → **decoupled Micromegas** from housing
- Force from spring-loaded contact pins
  → low spring force contacts

Simulation of PCB deformation under mechanical stress



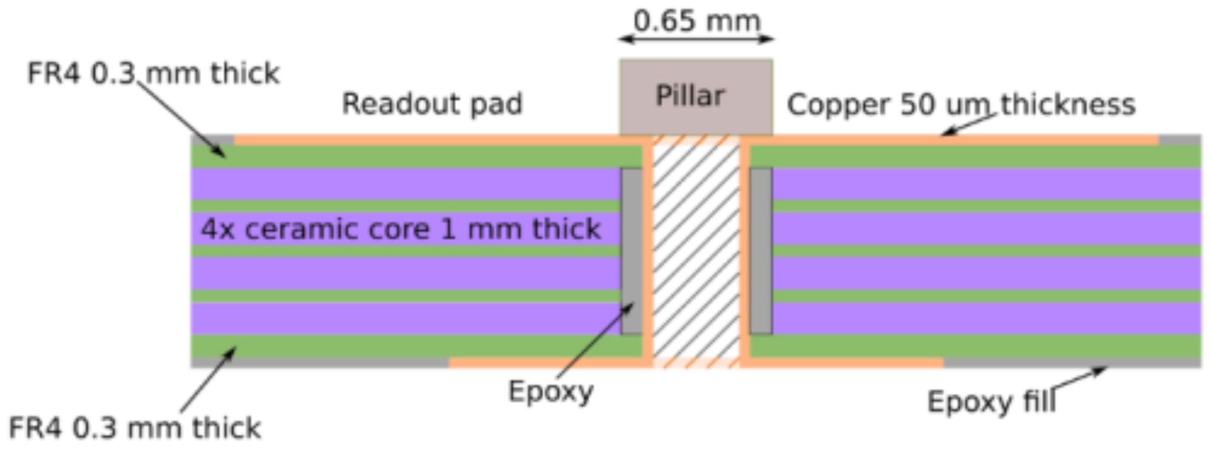
Deformation of **FR4** PCB: ≈100μm

Deformation of **ceramic core** PCB: ≈4μm



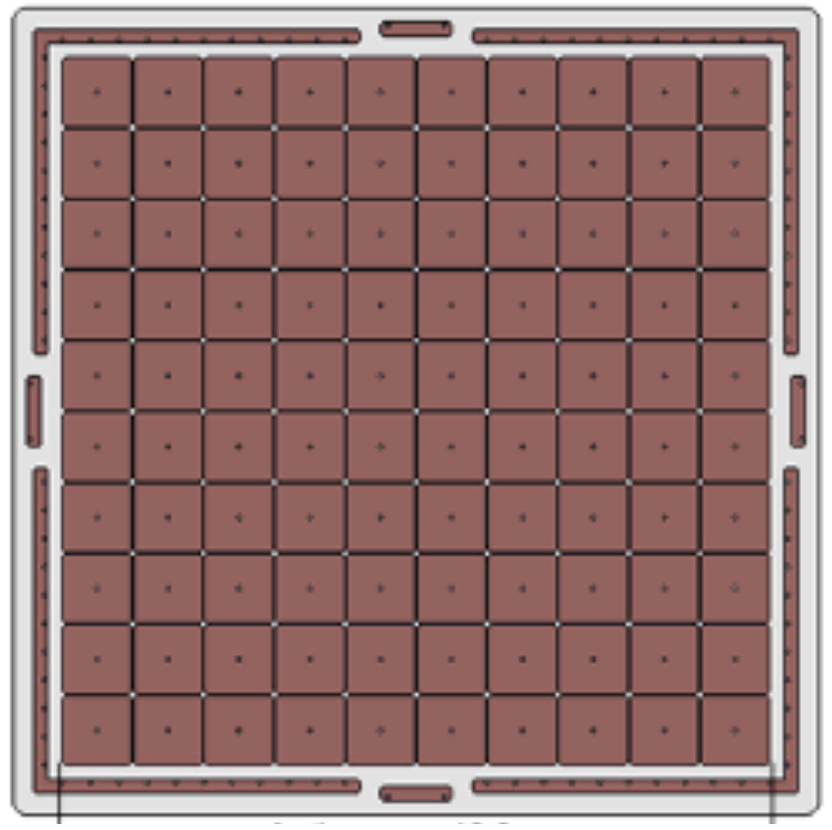
Precise gap required (≈ <10μm across 10cm x 10cm)

4x 1mm ceramic core PCB chosen for rigidity



Single pad (2016)
⌀1 cm

Multi pad (2017)
⬡ 1 cm



10x10 module
□ 1 cm

Schematic not drawn to scale

Detector module mechanics

Compact Aluminium vessel with fully decoupled Micromegas PCB

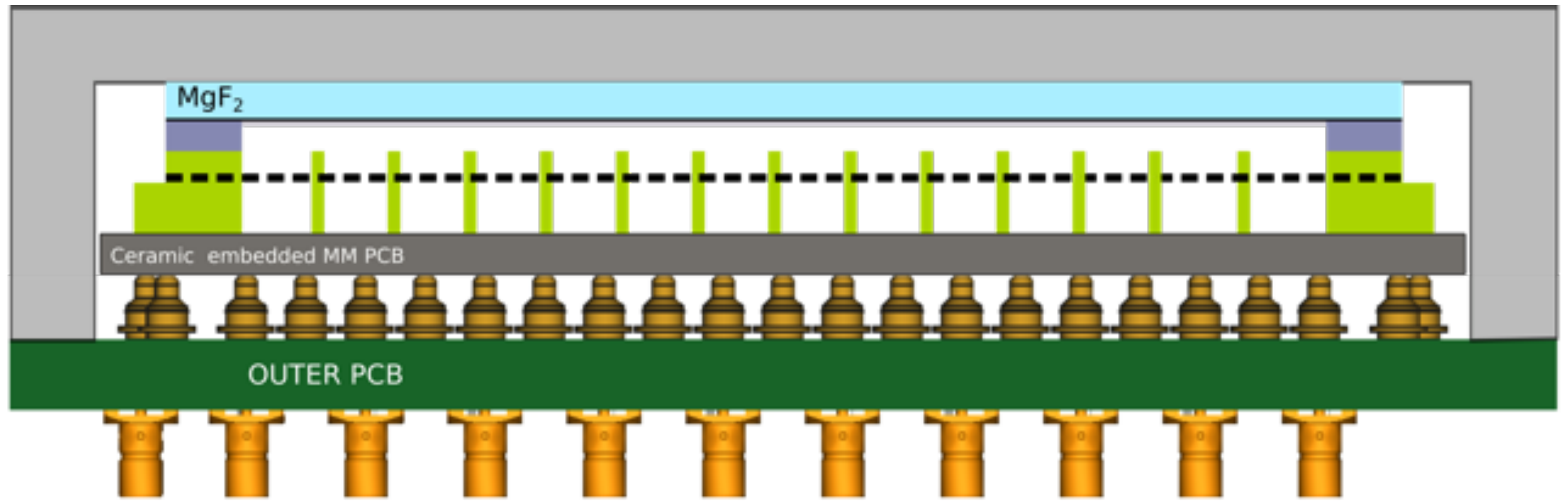
10.4cm x 10.4cm MgF_2 crystal as radiator

Spacers to define pre-amplification gap thickness

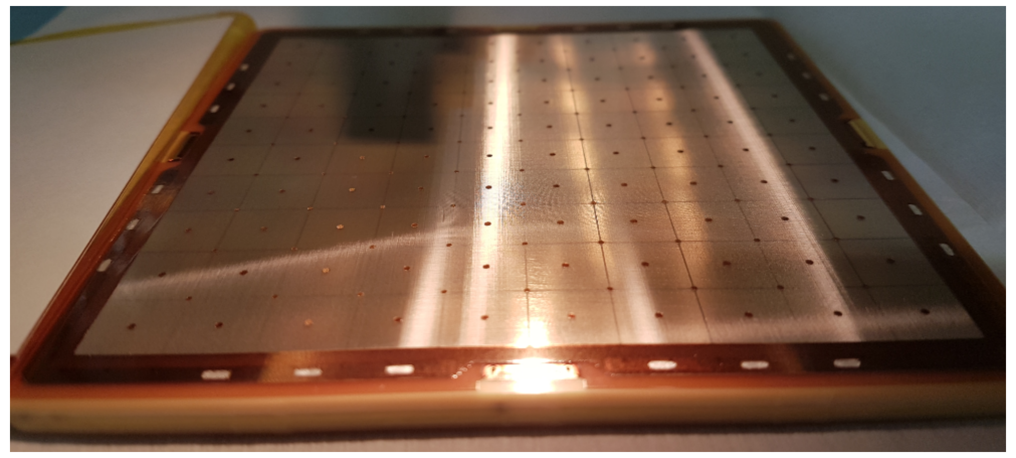
Bulk Micromegas with minimised dead area on ceramic-core PCB
- 10x10 pads with 10cm x 10cm active area
- Iterative **polishing** steps to improve substrate and final board planarity
- **<10 μm deformation** across active area

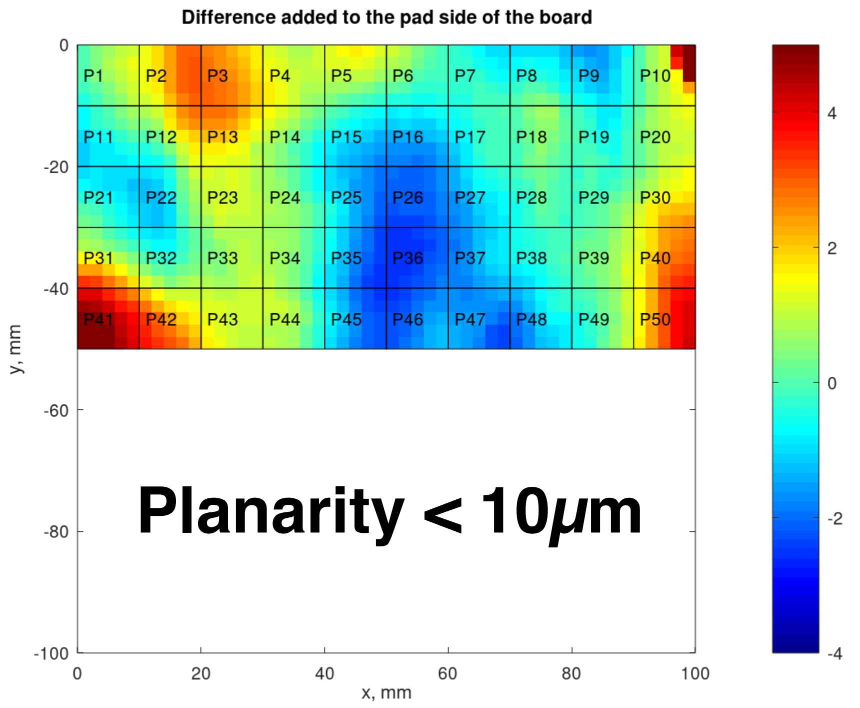
Gain map shows small variation of gain across active area compatible with residual (<10μm) non-planarity of Micromegas PCB

Cross-section



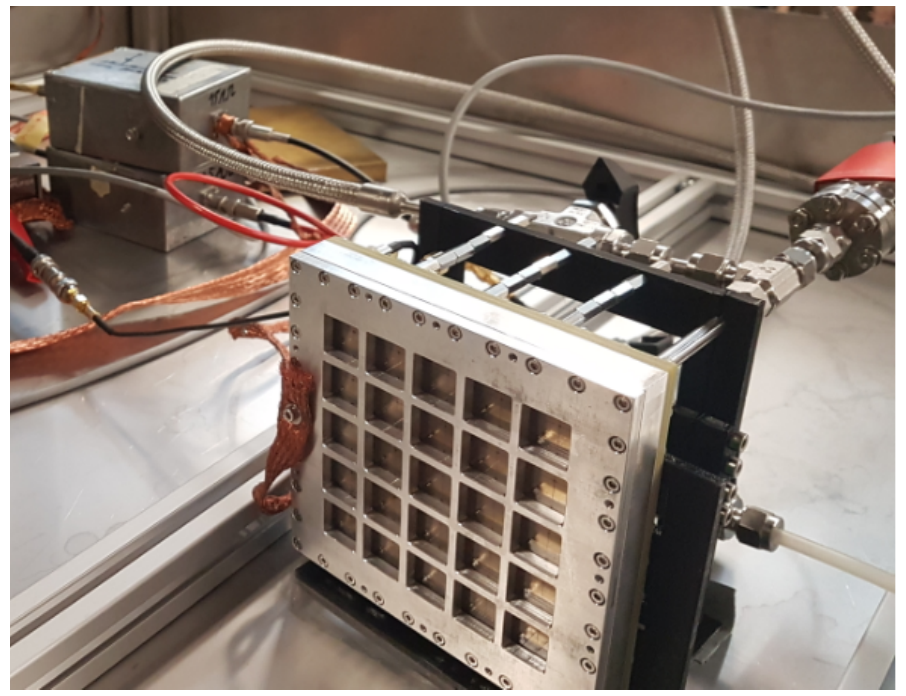
Bulk Micromegas on ceramic PCB



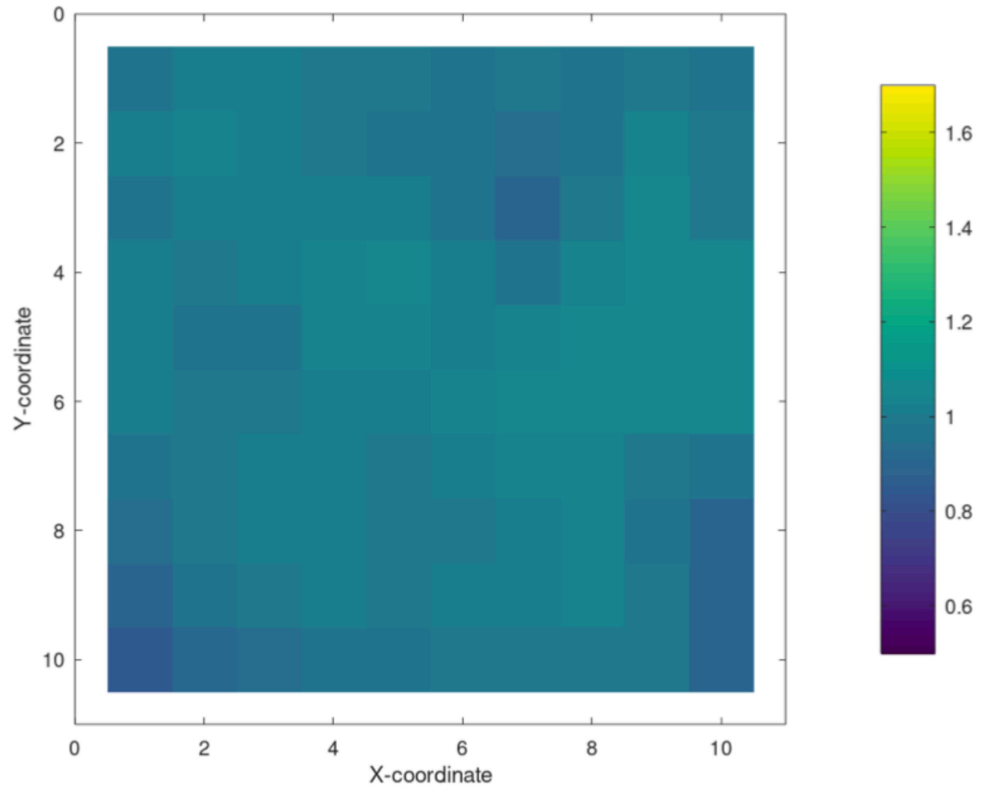


Planarity < 10μm

Lab test



Gain uniformy σ = 3.9 %



A. Utrobičić

Picosec detector module

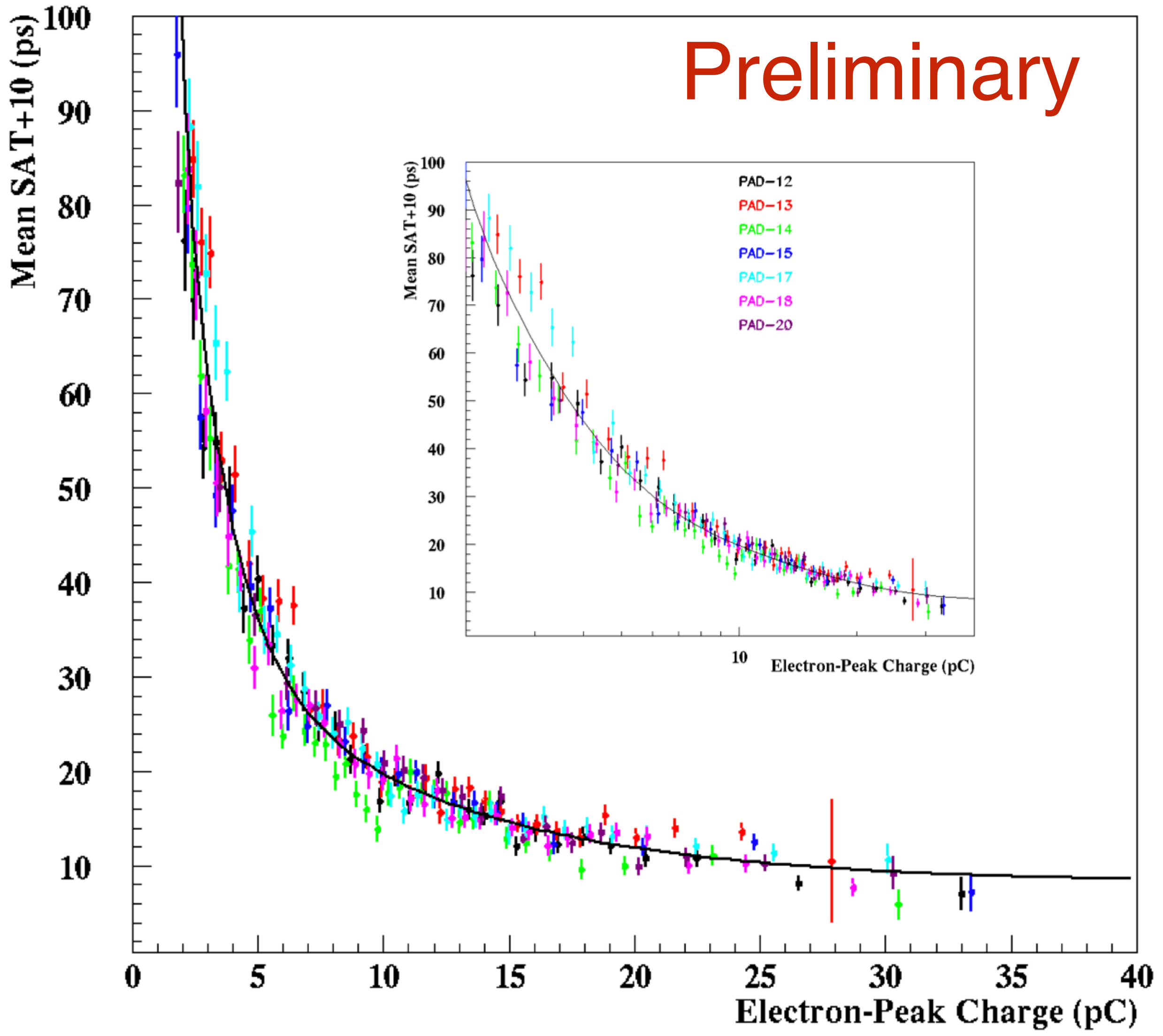
Characterisation of 100-channel module

Measurements of signal-arrival-time and time resolution on different anode pads in MIP beams

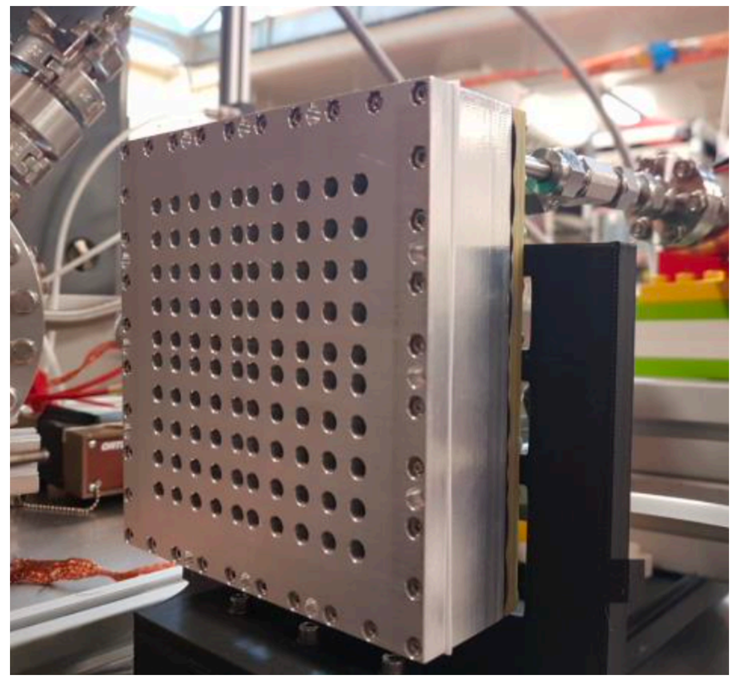
Confirm planarity and global time walk behaviour

Test **CsI** photocathode (>10 p.e.) and **DLC** photocathode (≈3 p.e.)

Global parametrisation of timewalk across measured pads



G. Maniatis, A. Kallitsopoulou, S. Tzamarias



		24.6 ps			24.1 ps				
	24.6 ps	23.9 ps		22.1 ps	22.9 ps	24.7 ps	23.0 ps		23.0 ps
					23.9 ps				
					23.9 ps				
24 ps									

Achieved significantly improved planarity and uniformity of response across 10cm x 10cm active area

Timing performance with CsI photocathode compatible with single channel prototypes

Achieved good timing performance with robust DLC photocathode

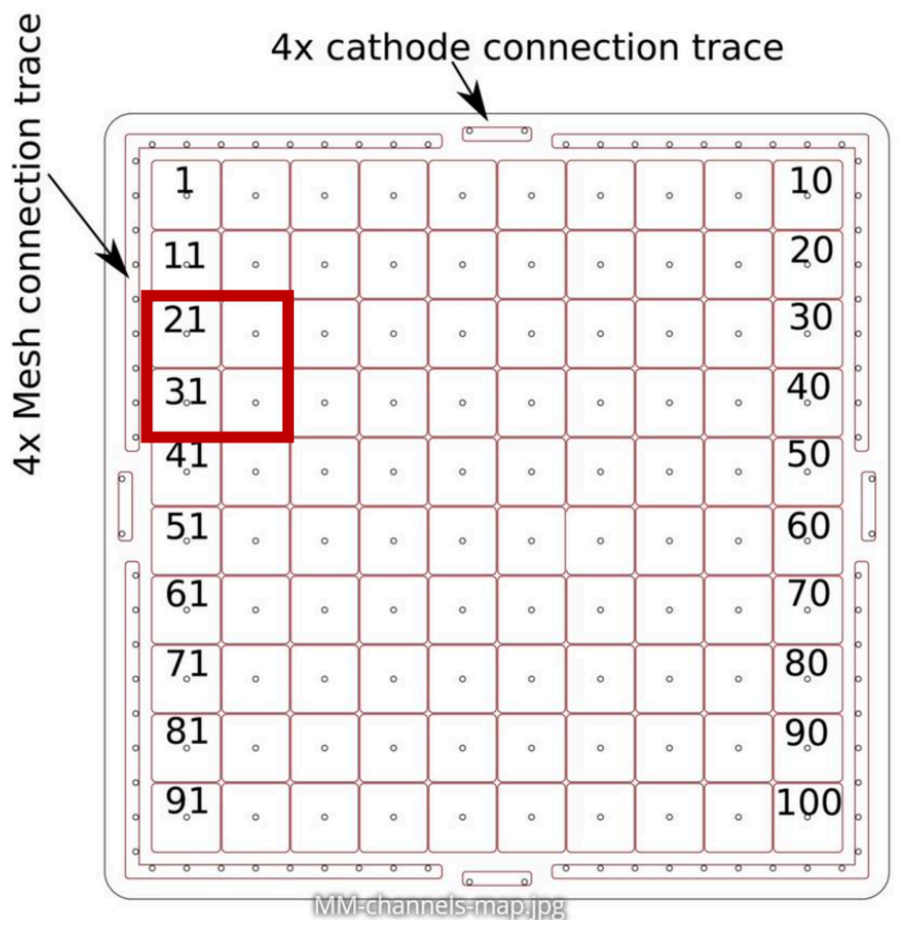
A. Utrobicic, Picosec precise timing detectors : recent results, status and plans, RD51 Collaboration Meeting Nov 2021, https://indico.cern.ch/event/1071632/contributions/4612229/

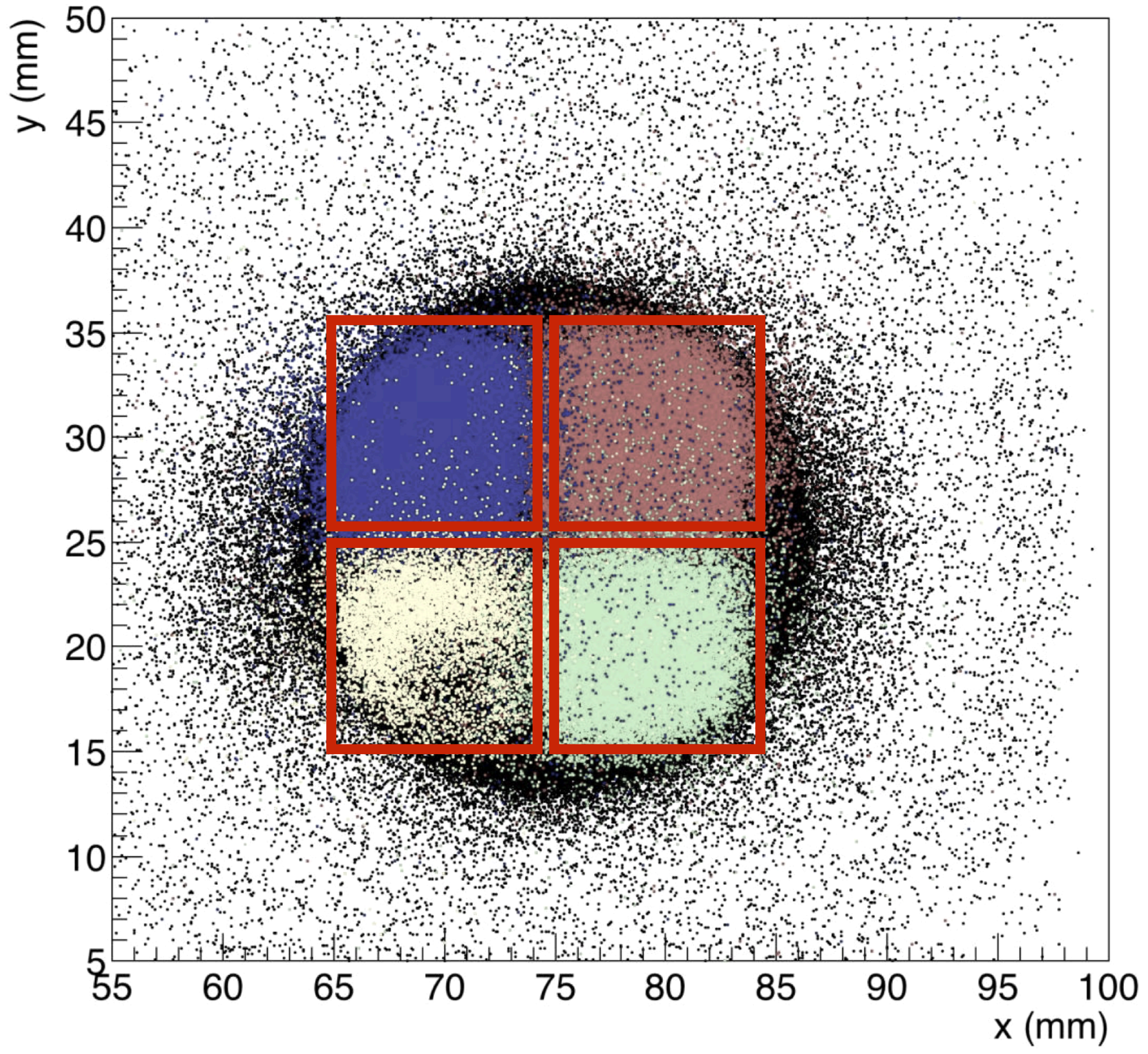
Schematic not drawn to scale

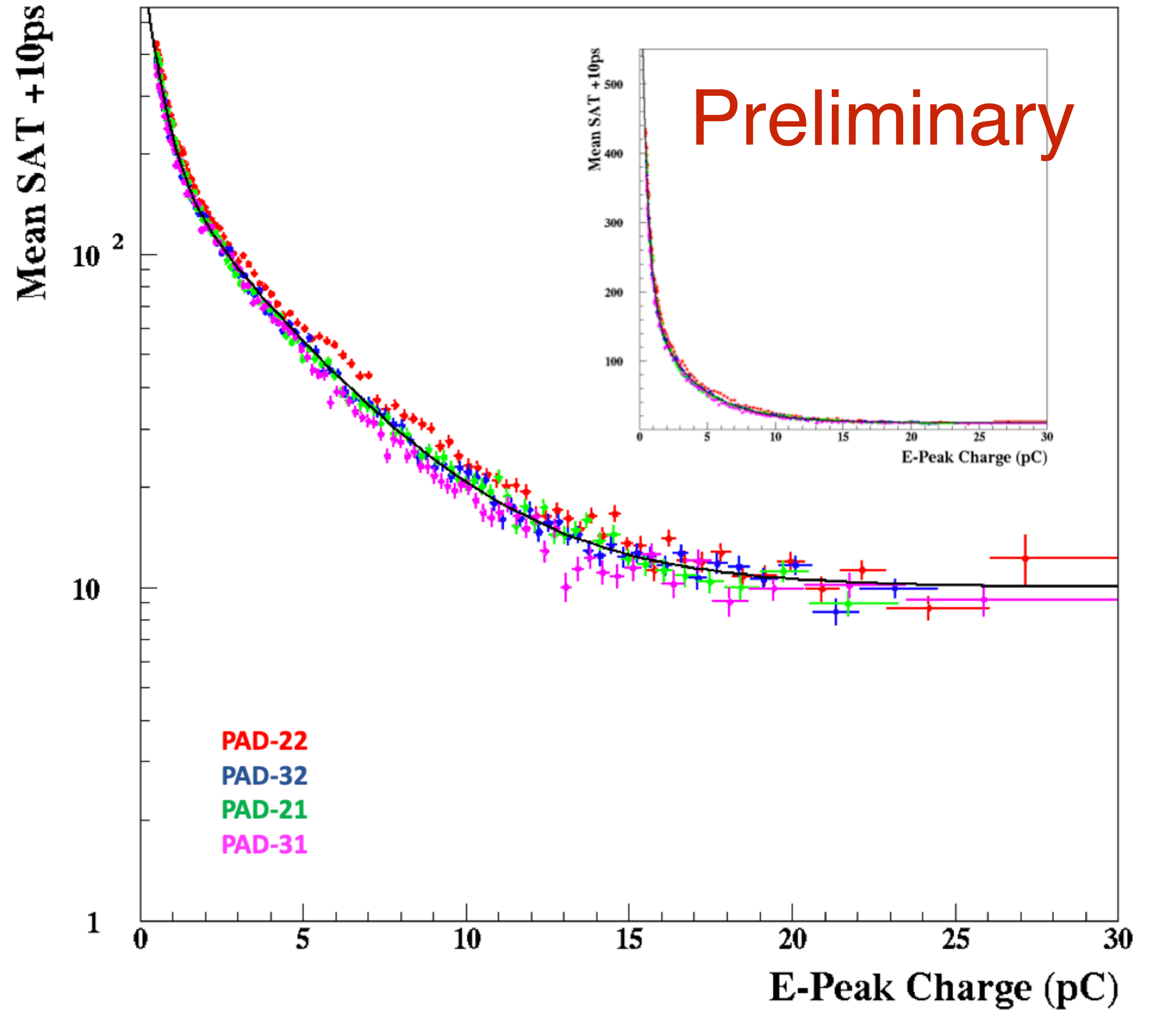
Signal sharing

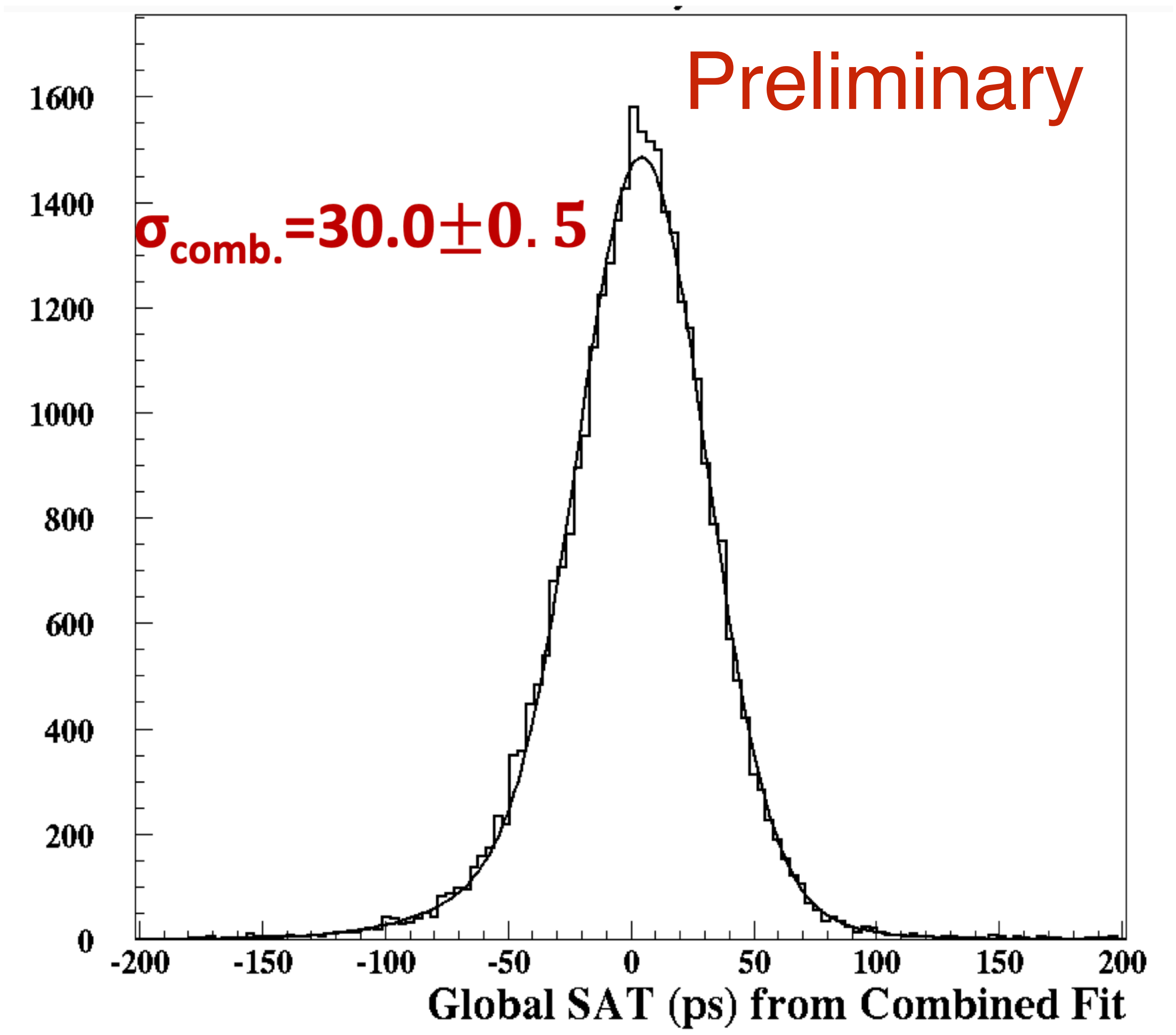
Detector shows uniform response and different anode pads exhibit the same trend of signal-arrival-time as function of electron peak charge → **universal time walk correction**

Signals shared across multiple pads can be combined to achieve a combined time resolution of σ **= 30.0±0.5 ps**









$$\hat{t}_{comb.} = \frac{1}{\sum_{i=1}^{N} \frac{1}{(\mathrm{R}(q_i))^2}} \cdot \sum_{i=1}^{N} \frac{t_{SAT}^{i} - W(q_i)}{(\mathrm{R}(q_i))^2}$$

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

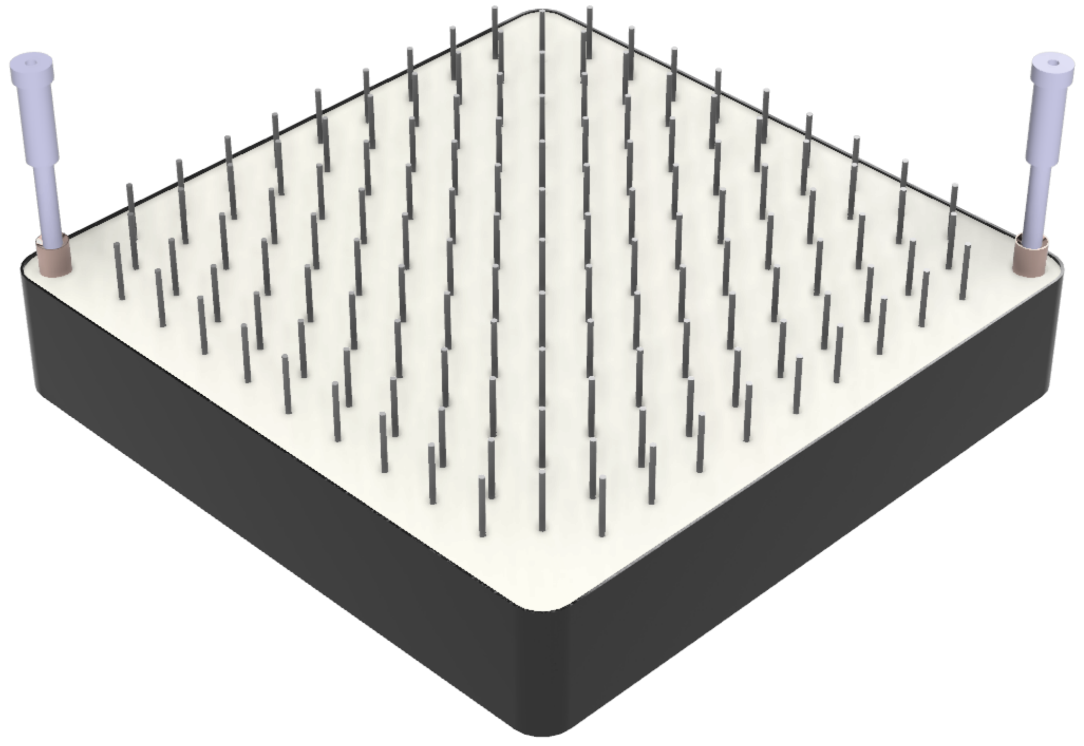
Sealed detector

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

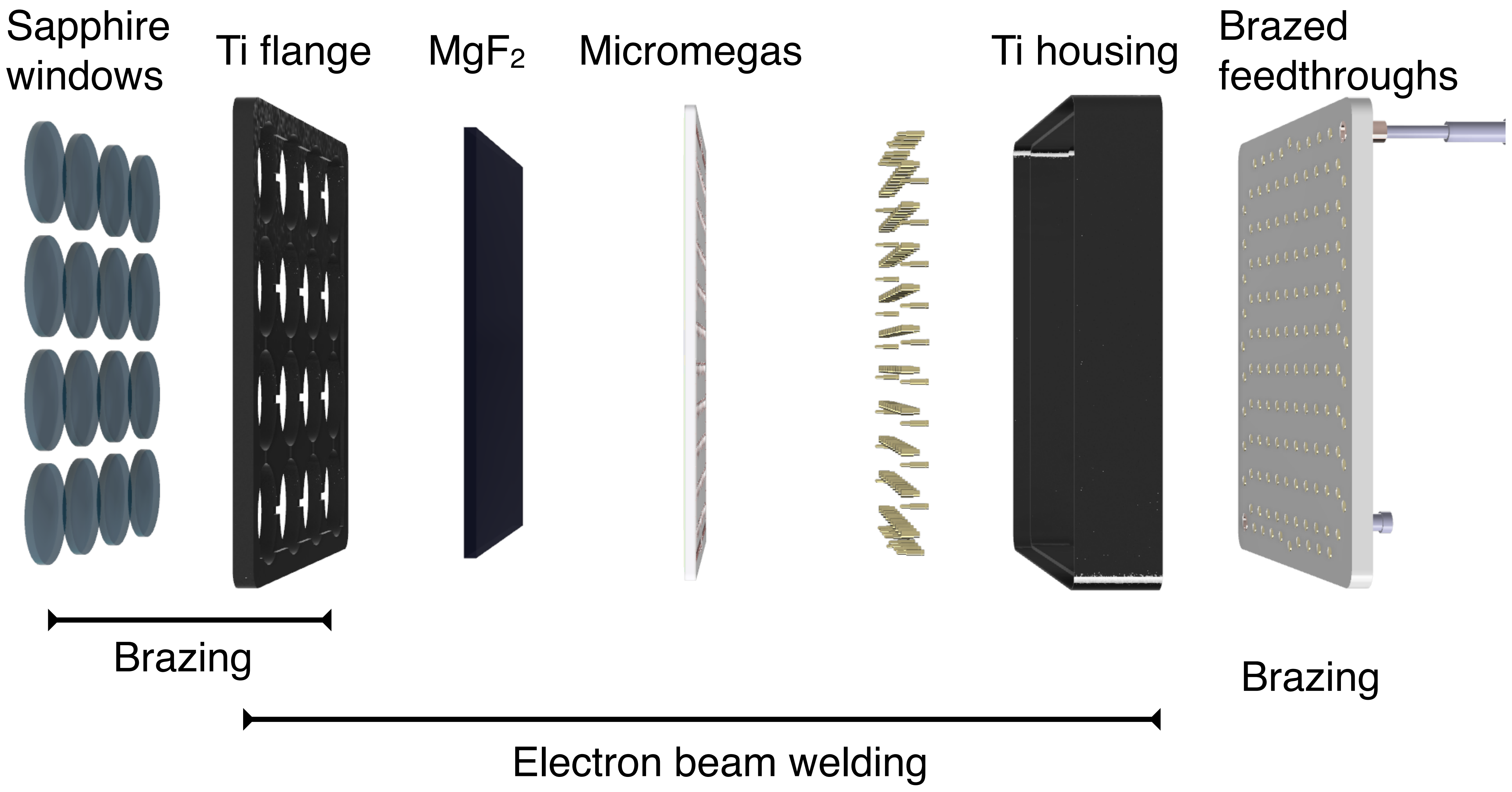
Use of **low outgassing** components in detector (ceramic PCBs) and **sealing** techniques (brazing, electron beam welding) for minimal contamination and hermetic sealing.

- **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



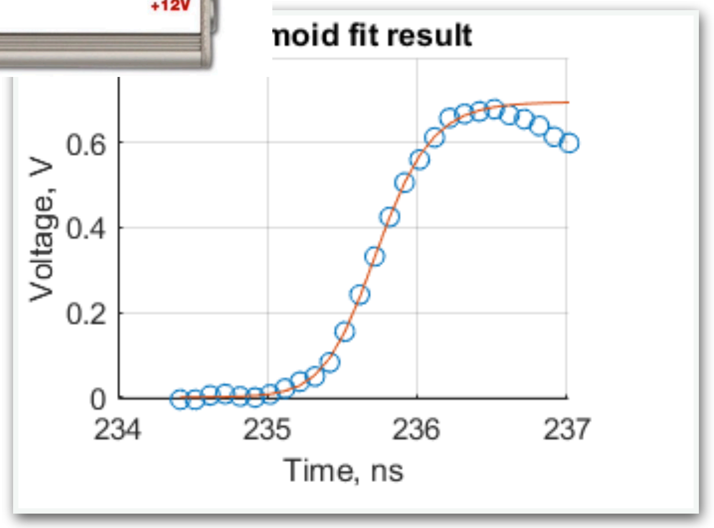
M. Lisowska

Readout electronics

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

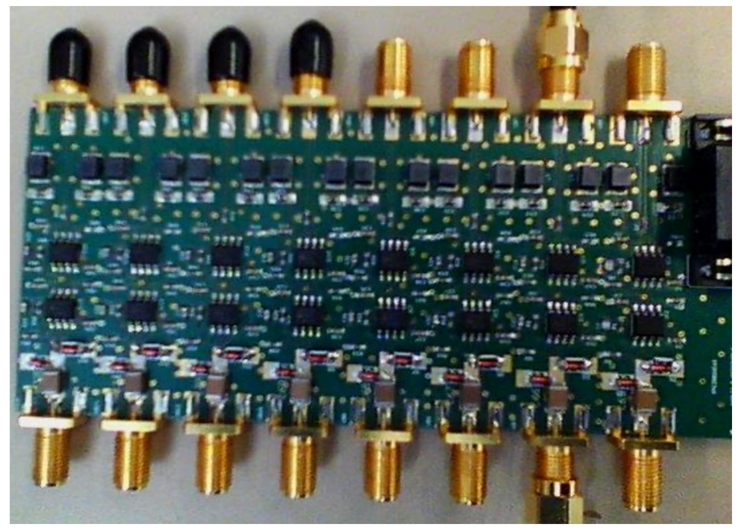
Detector → **Preamplifier** → Digitisation

Proprietary Cividec preamp
- Single channel
- High-bandwidth, 40db gain

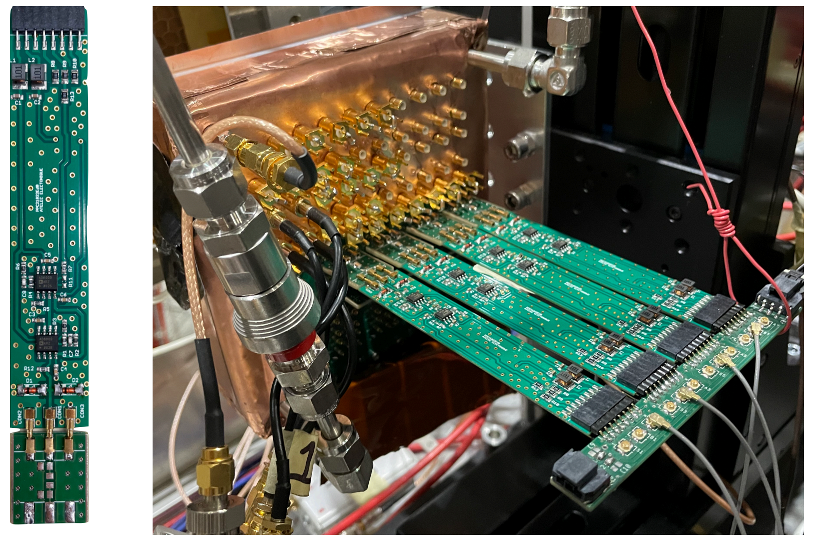


https://
cividec.at/

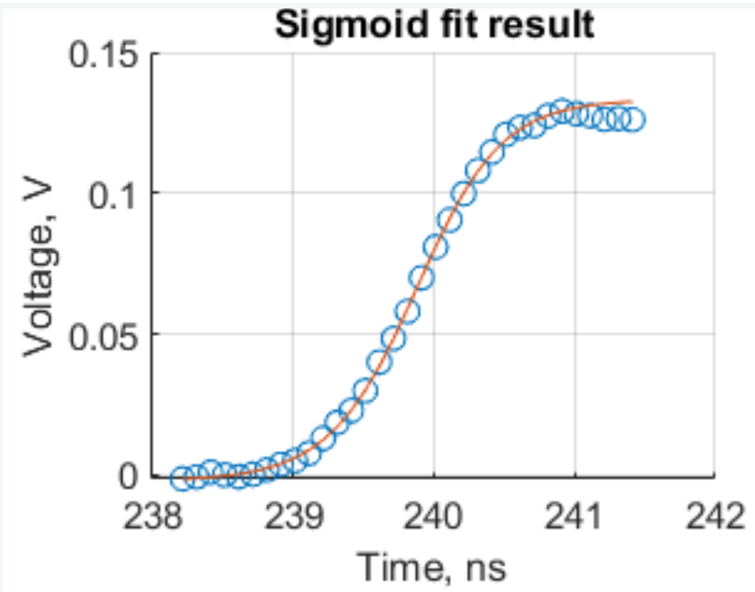
Custom preamplifiers (P. Legou, CEA Saclay)
- Fast risetime, low noise, moderate gain
- Good timing resolution
- Different circuits being tested and optimised
- Scalability by plugging preamp cards into detector modules or integrating directly on detector PCB



8ch preamp

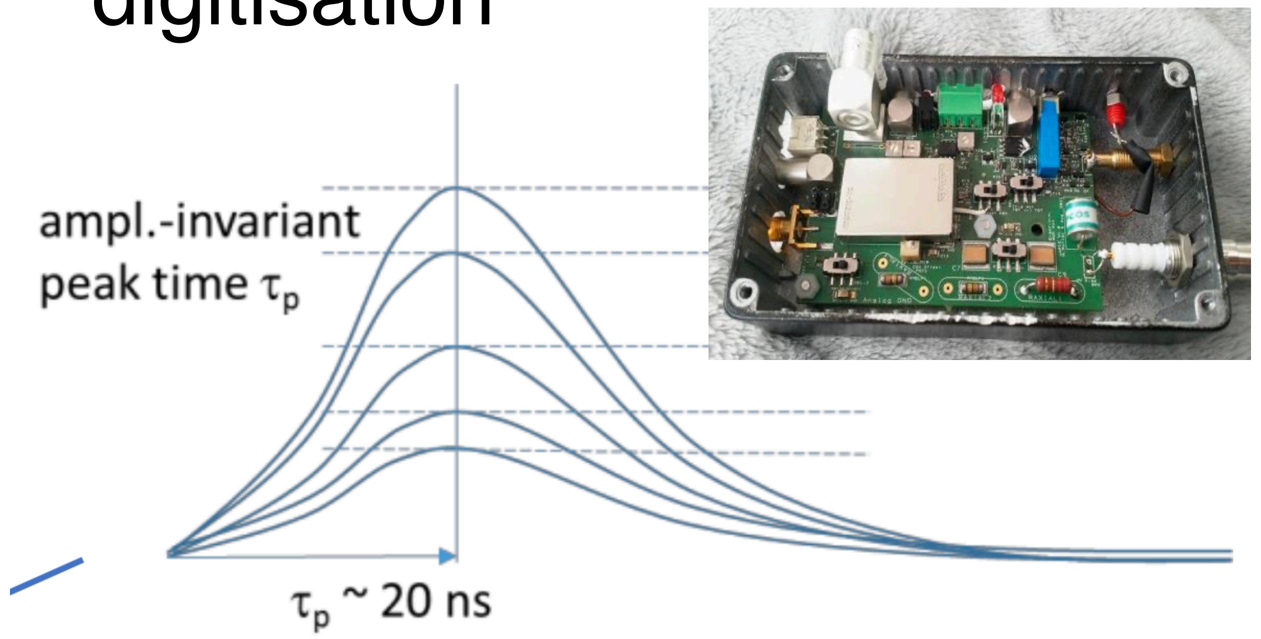


Preamp card, 10x10 module



Rising edge of electron peak

Alternative approach: CSA-shaper macro uAPIC
- O(10ns) shaper without time walk
- Release requirements on digitisation



CSA-shaper, H. Muller, CERN

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

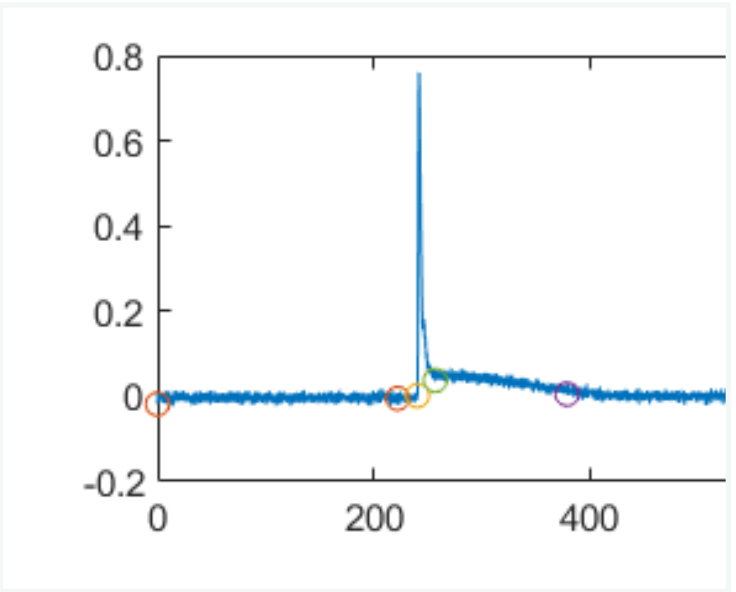
Readout electronics

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

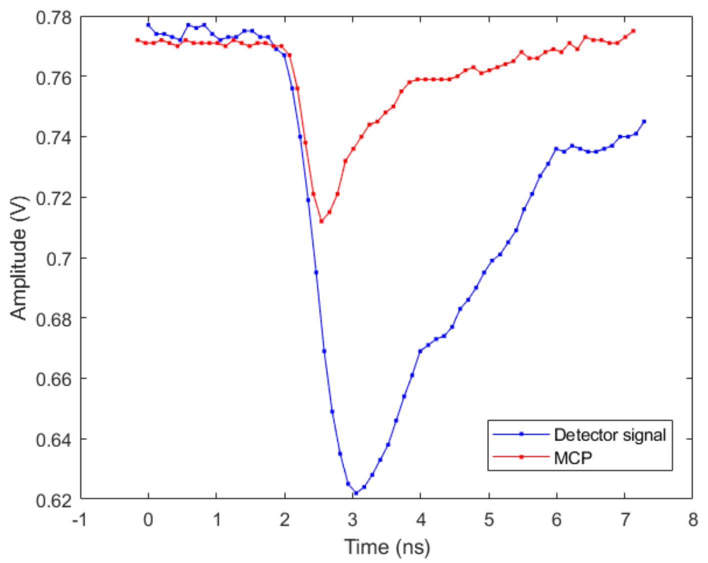
- Record full waveform (electron + ion)



SAMPIC Waveform TDC

- Waveform sampling of rising edge of electron peak and time extraction with sigmoid fit and 20% CFD
- Tested 6.4 / 8.5 GS/s sampling frequency

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

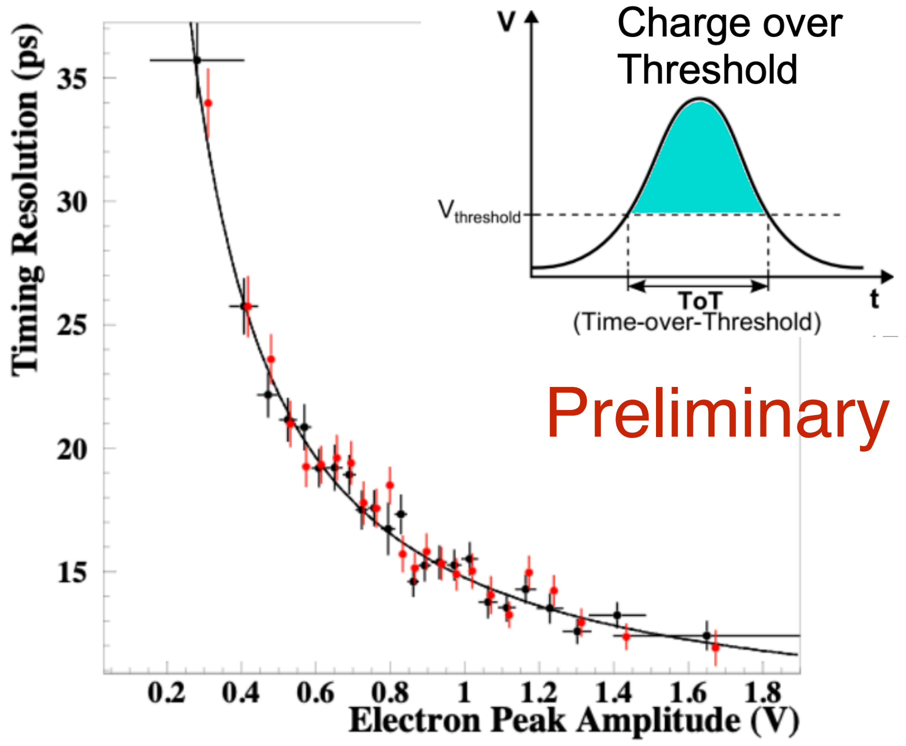


Waveforms recorded at 8.5 GS/s

Alternative approaches:

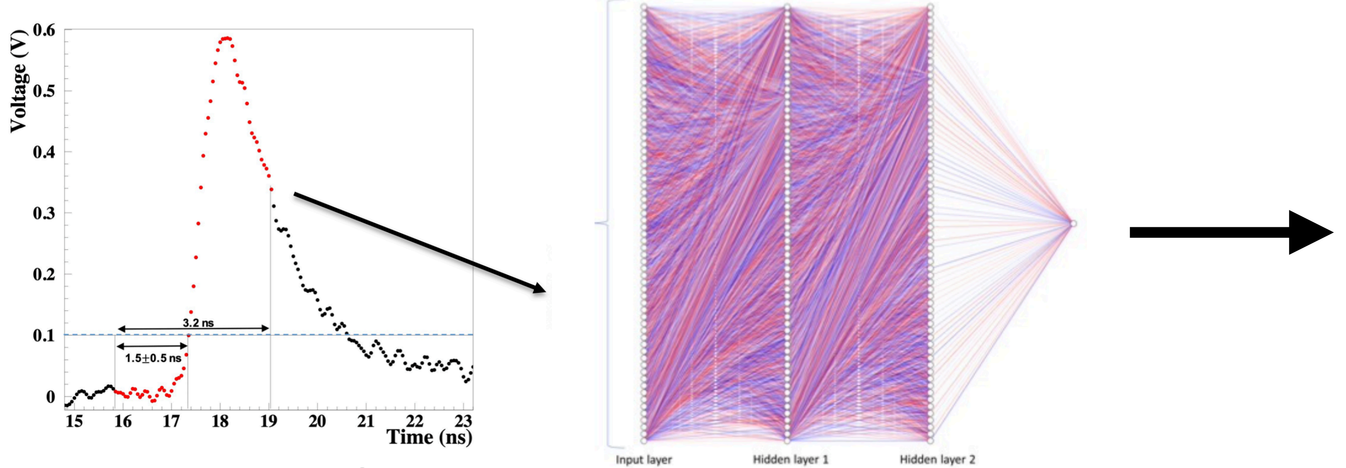
Single threshold timing with time walk correction from multi-threshold ToT

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**

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

Summary

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

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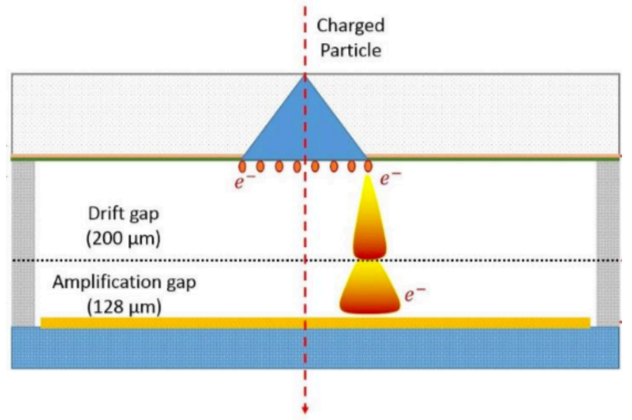
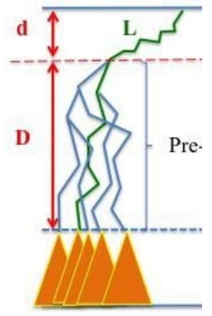
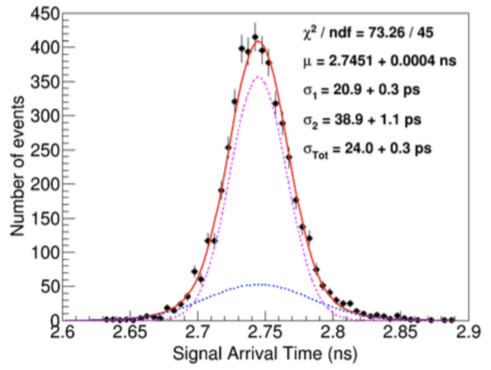
Tileable 10x10 pad detector modules have been tested in MIP test beams and provide good timing resolution also for signals shared across pads.

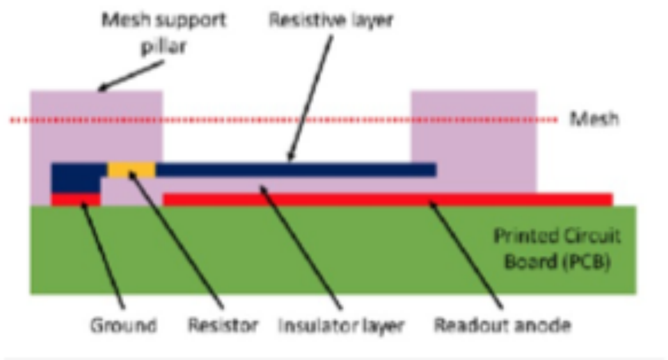
Robust photocathodes (**DLC**), **resistive multi-pad** Micromegas and scaling to **larger area coverage** are implemented in new prototypes.

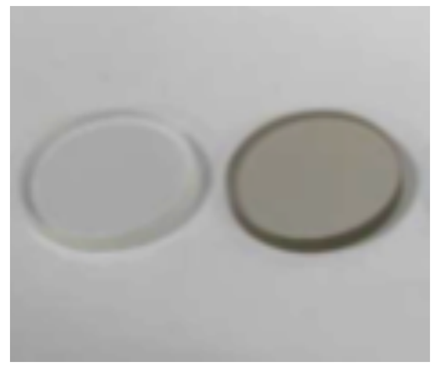
Scalable readout electronics (custom preamplifiers + SAMPIC WTDC) are developed and tested.

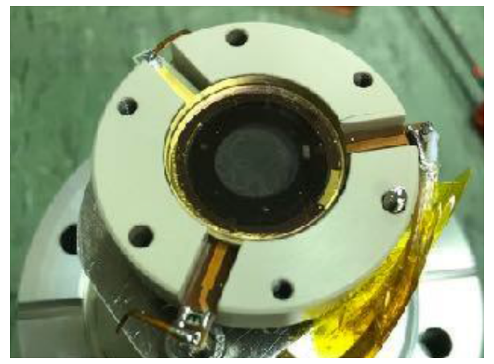


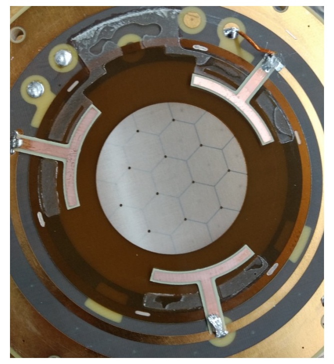


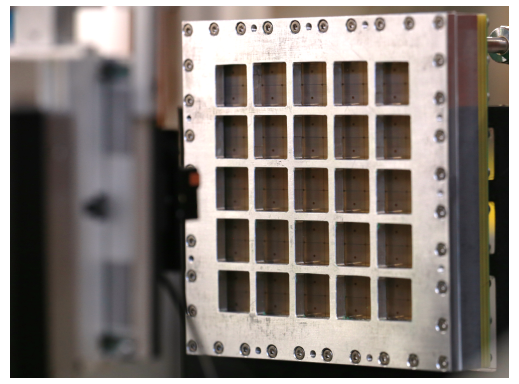


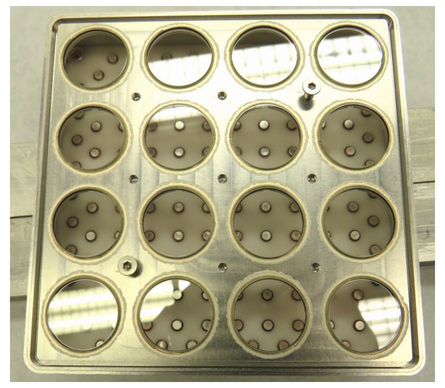


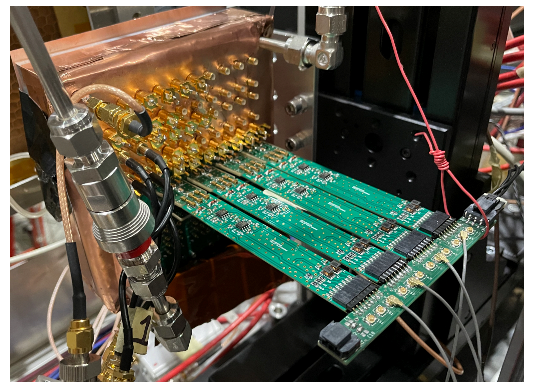












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Future perspectives

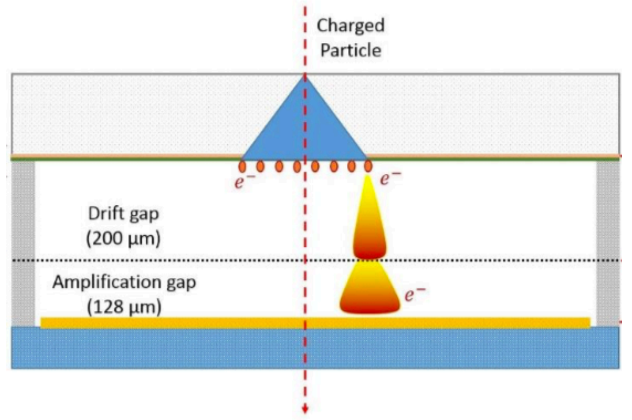
Secondary emitters: minimise material budget

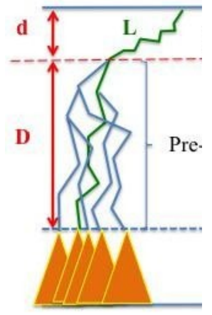
Spatial resolution: adjusting pad size, charge sharing

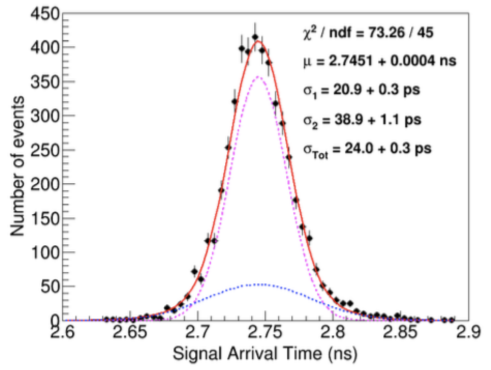
Optical readout with SiPMs

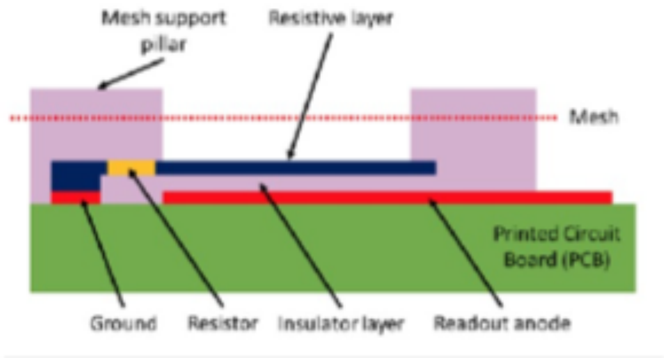
Amplification structure: optimised double/single gaps, mesh geometries/technologies, resistive multi-pad

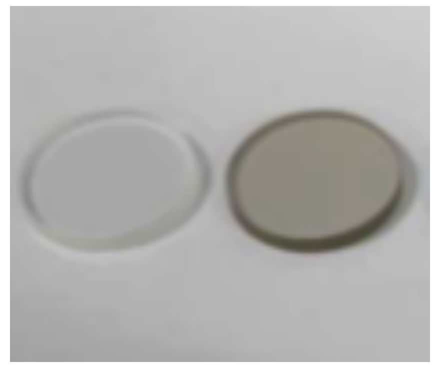
Electronics: waveform digitisation vs. threshold based timing

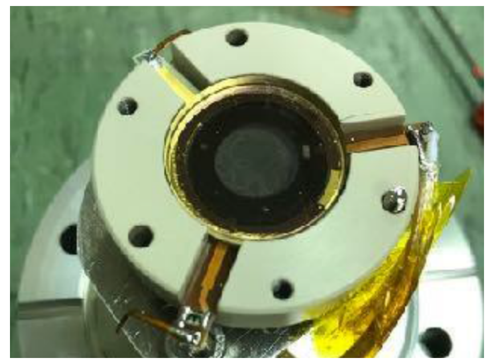


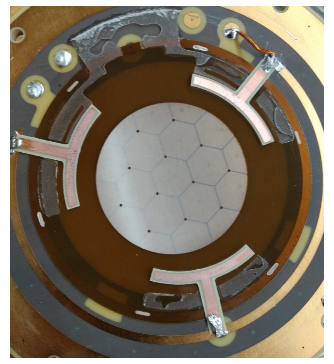


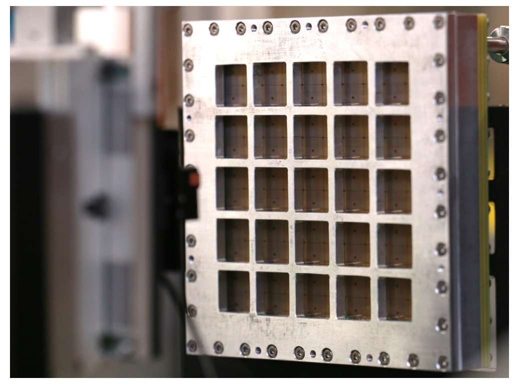


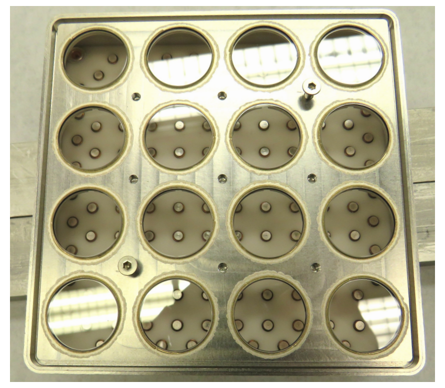


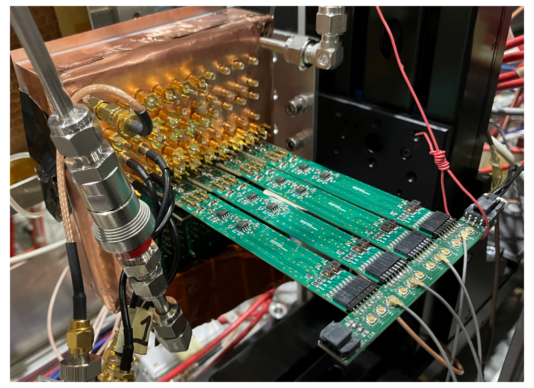












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RD51 PICOSEC-Micromegas Collaboration

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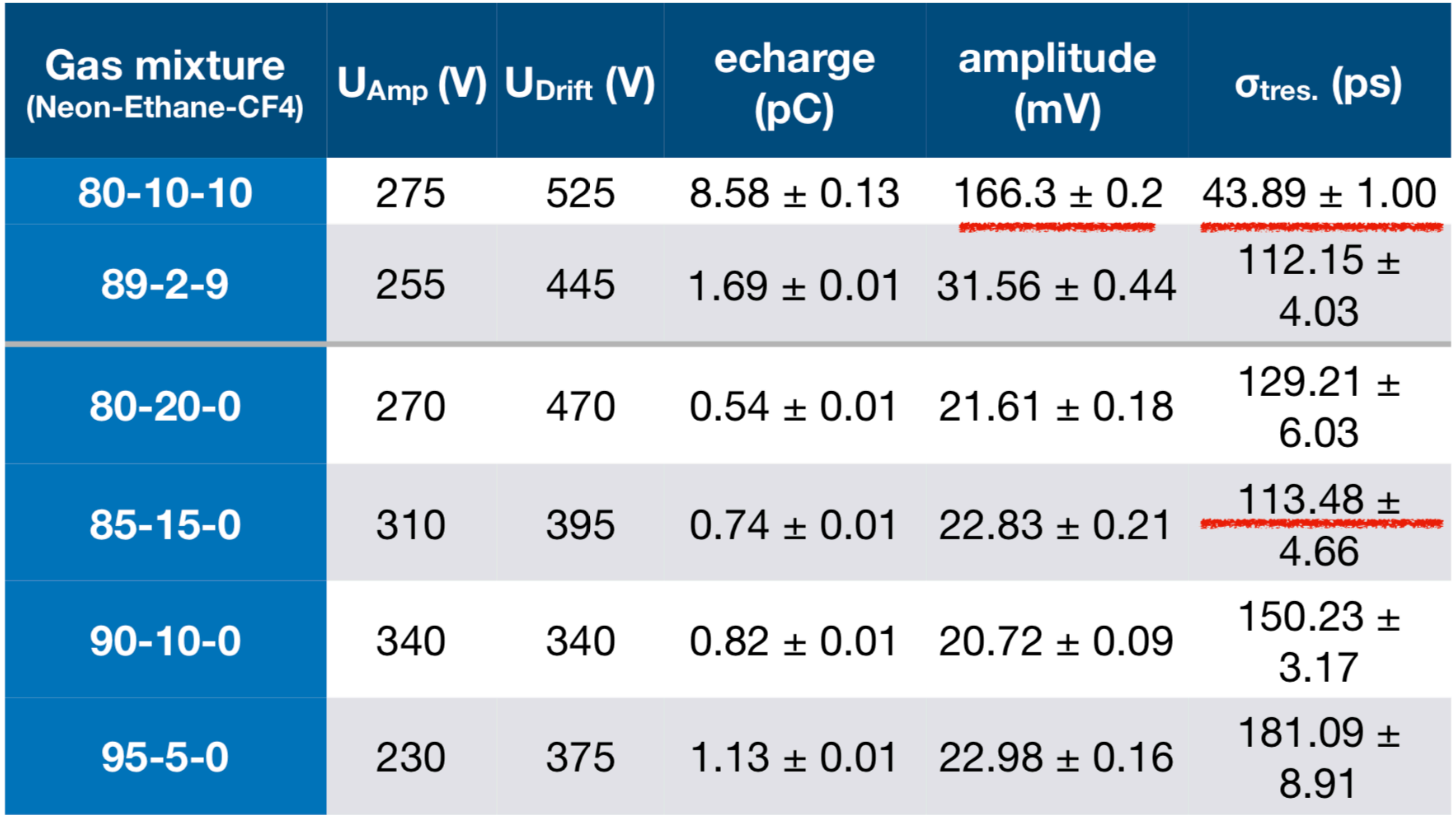
3) Also University of Virginia.

4) Now at University of Birmingham

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/

Multi-pad prototype