PICOSEC
Micromegas

Precise timing with PICOSEC Micromegas: Status and Developments

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on behalf of the PICOSEC Micromegas collaboration

Joint FCC-France & Italy workshop, November 22, 2022

Outline

PICOSEC detection concept: precise timing with Micromegas

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

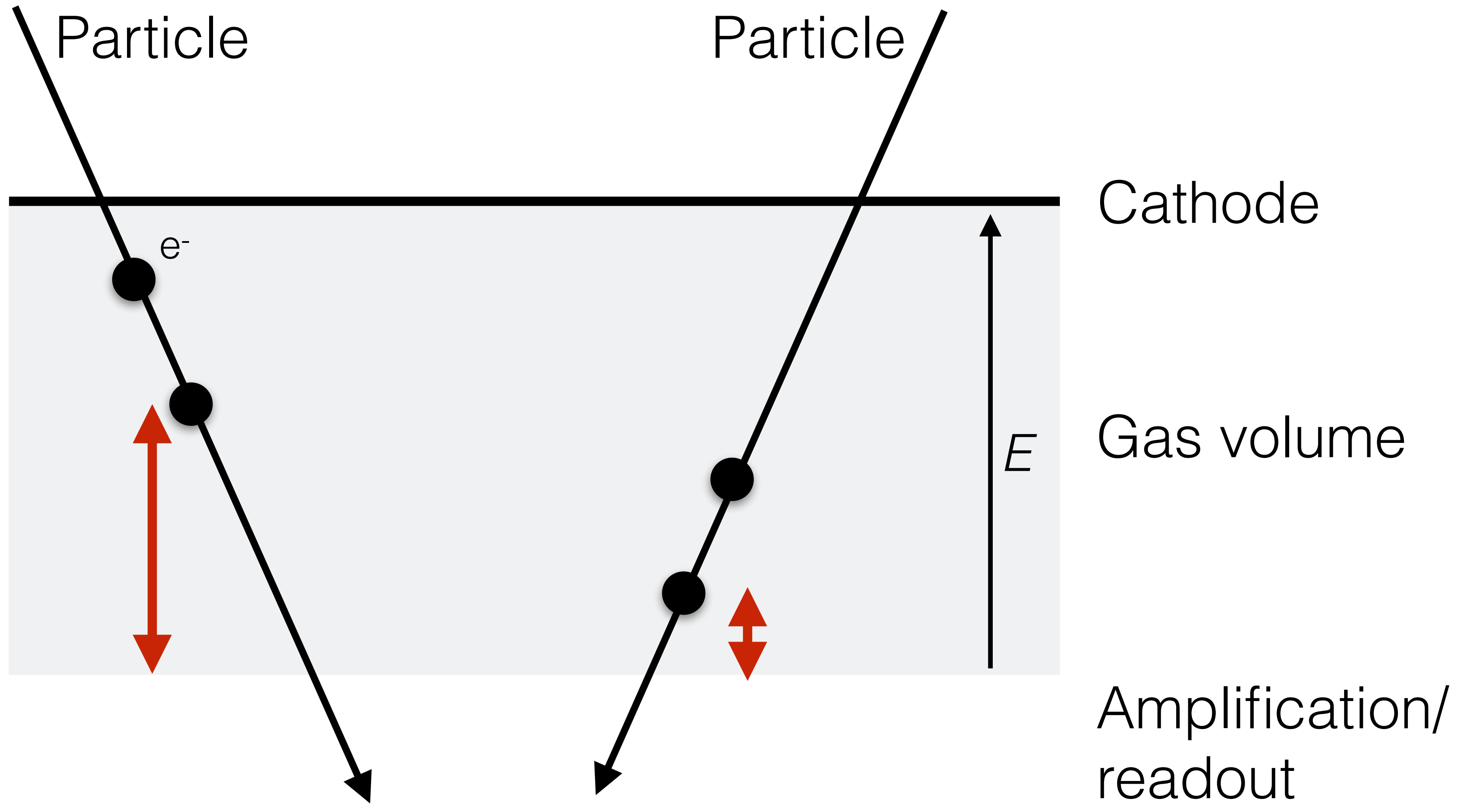
Towards a robust large-area detector:
- Resistive Micromegas
- Robust photocathodes
- Tileable modules
- Scalable readout electronics

Timing limitations of gaseous detectors

Ionisation of gas in active volume

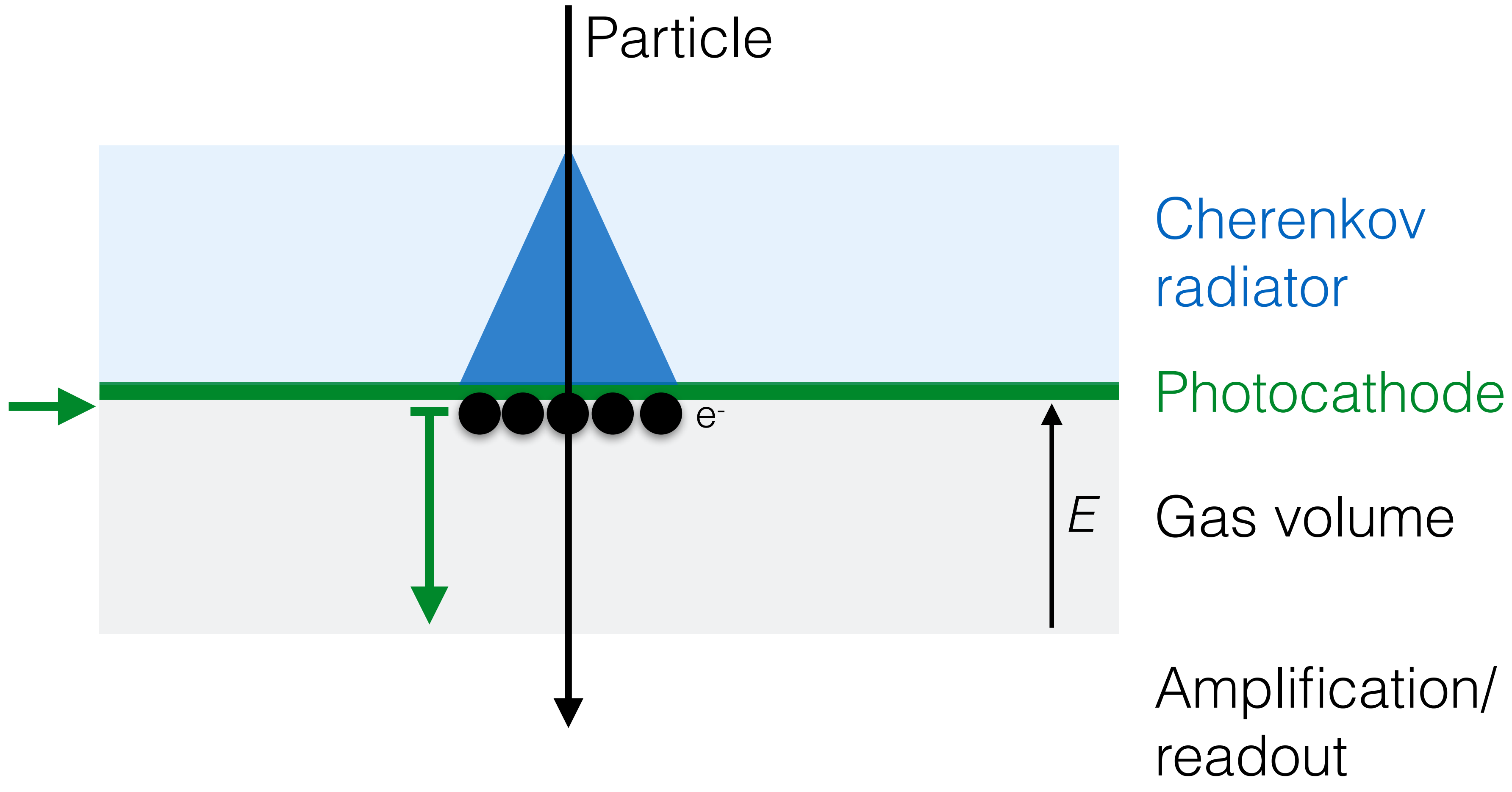
Primary electrons produced by ionisation along particle trajectory in drift region

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

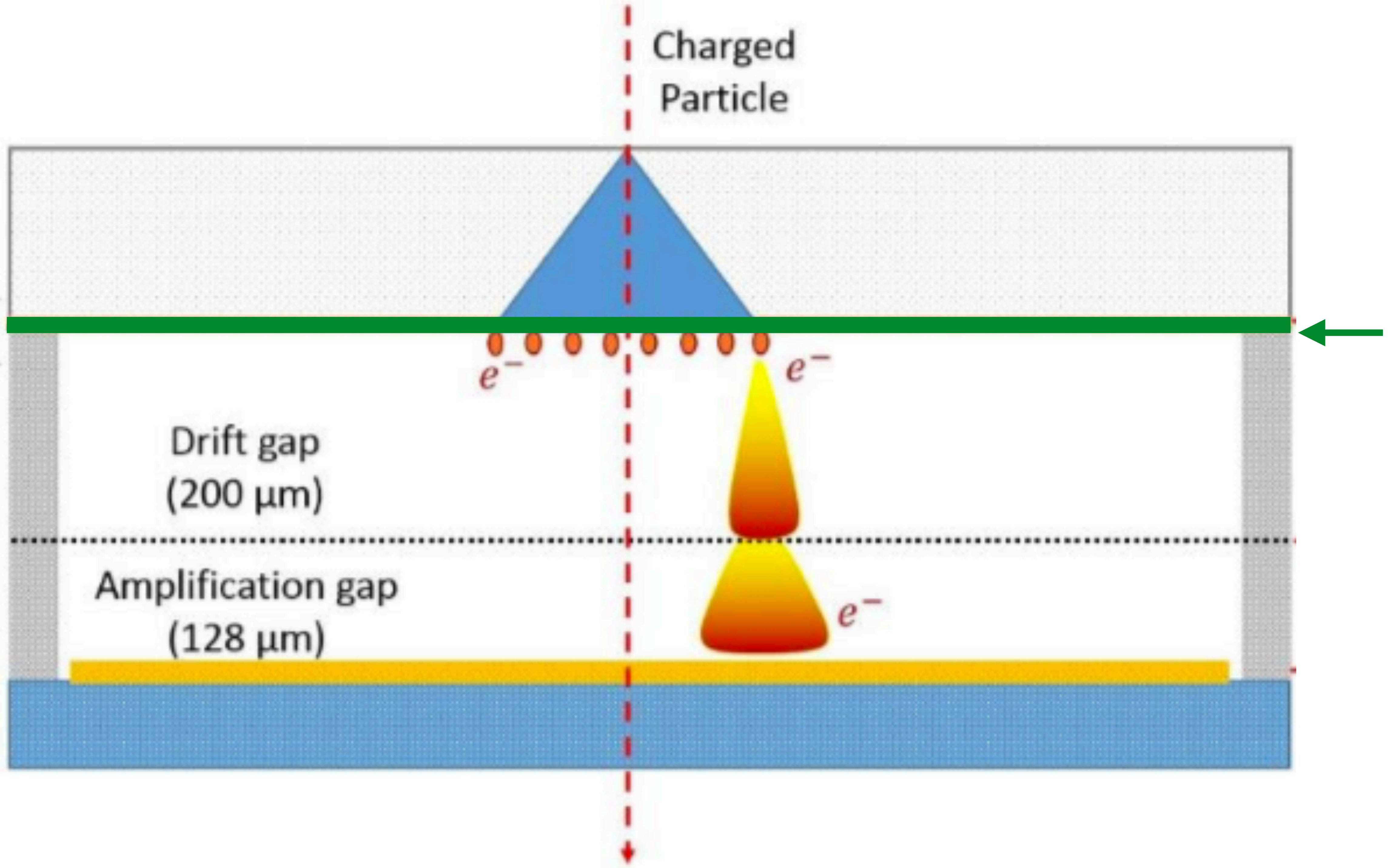
PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector
J. Bortfeldt et. al. (RD51-PICOSEC collaboration), NIM A (903), 2018, https://doi.org/10.1016/j.nima.2018.04.033

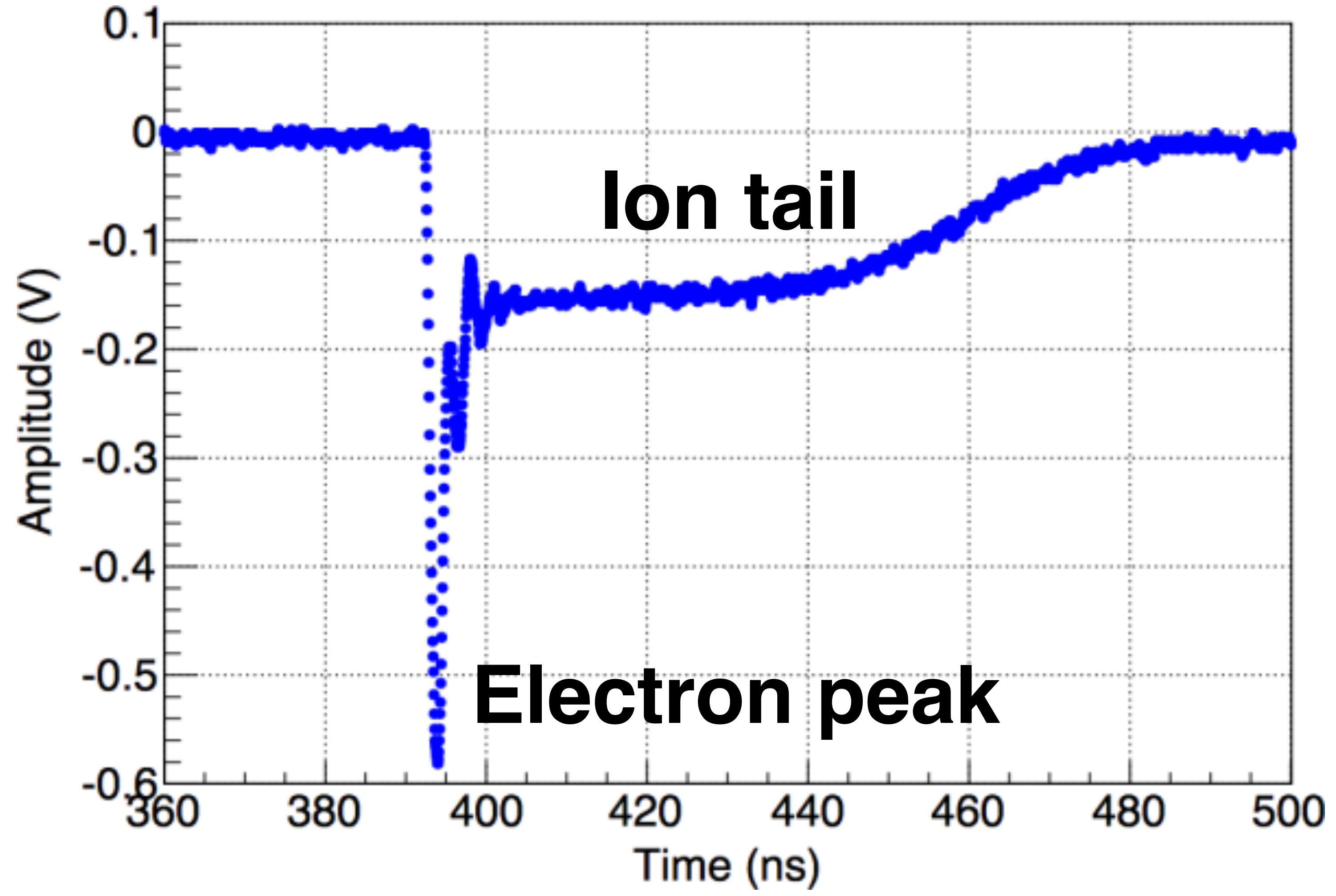
Cherenkov radiator
(3 mm MgF_2)

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

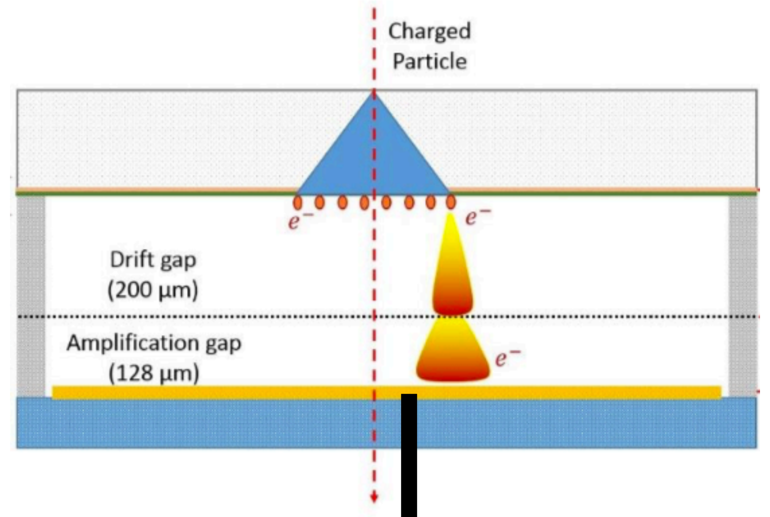
X. Wang et al., Study of DLC photocathode for PICOSEC detector, RD51 collaboration meeting, October 2018

PICOSEC detection concept

Precise timing with Micromegas

Signals are recorded from anode pads, amplified and digitised

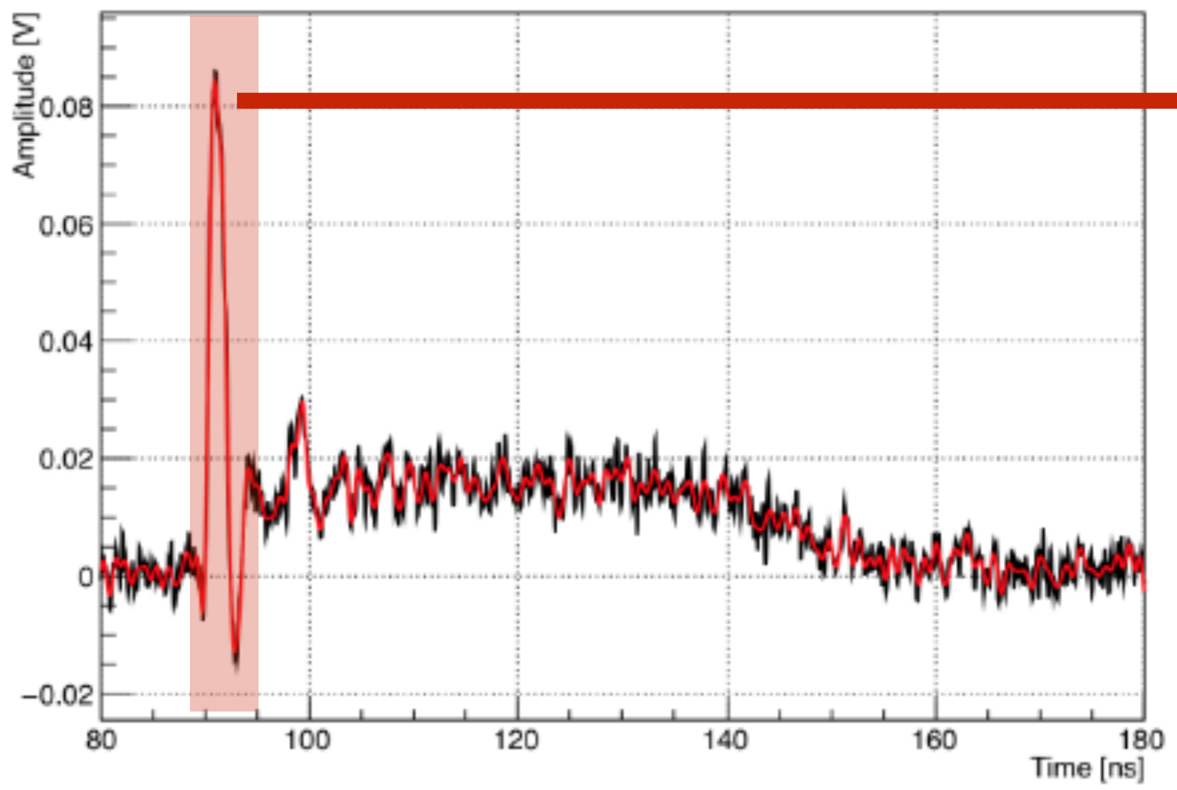
Rising edge of fast electron peak is used for timing measurements with Constant Fraction Discrimination to account for time walk



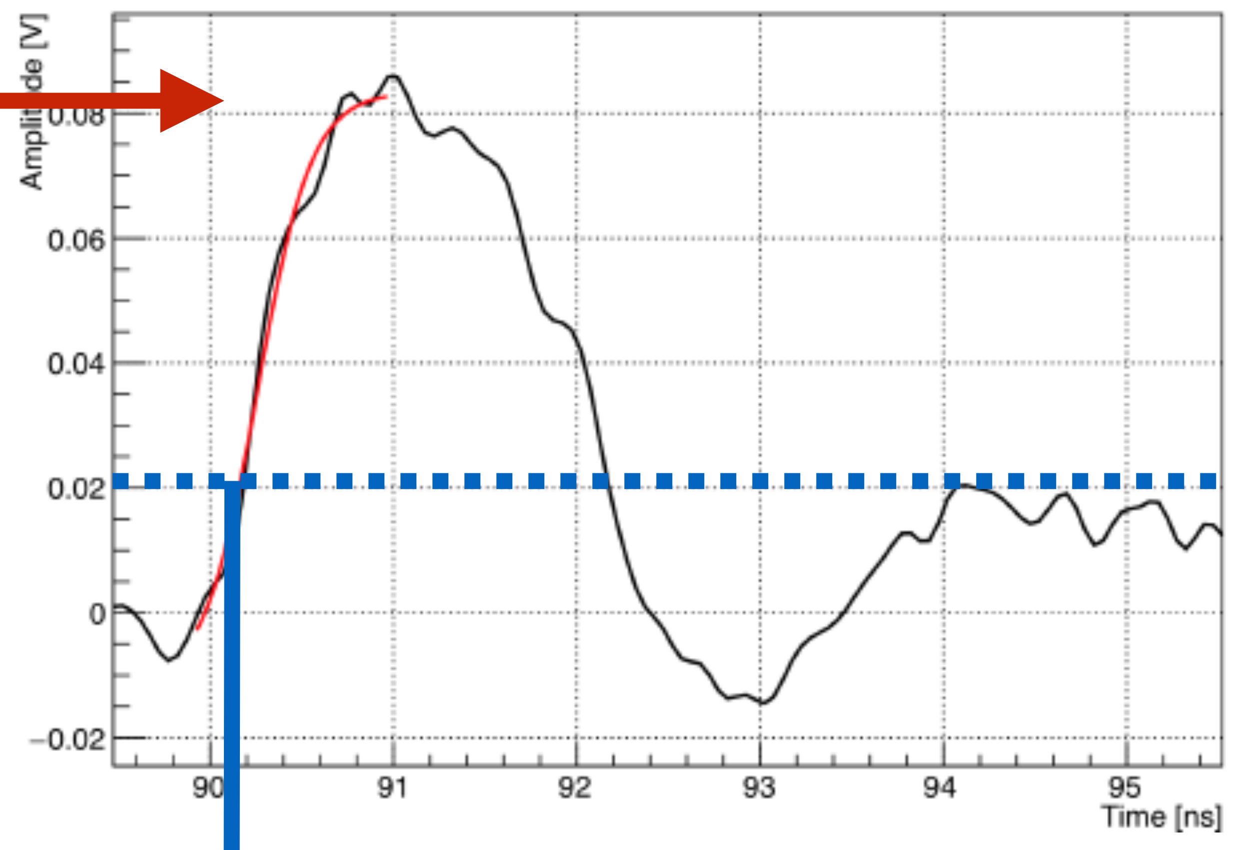
Preamplification of induced signal

Digitized by high-bandwidth oscilloscope @ 20GSamples/s

Recorded waveform

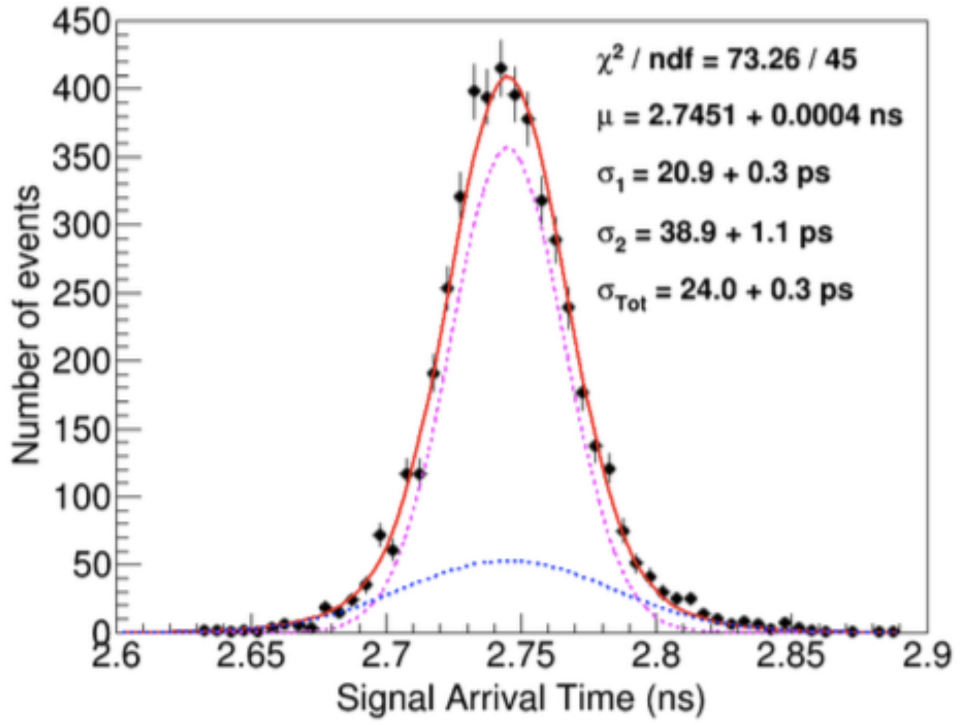


Zoom: electron peak



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

24 ps timing resolution (for MIPs)



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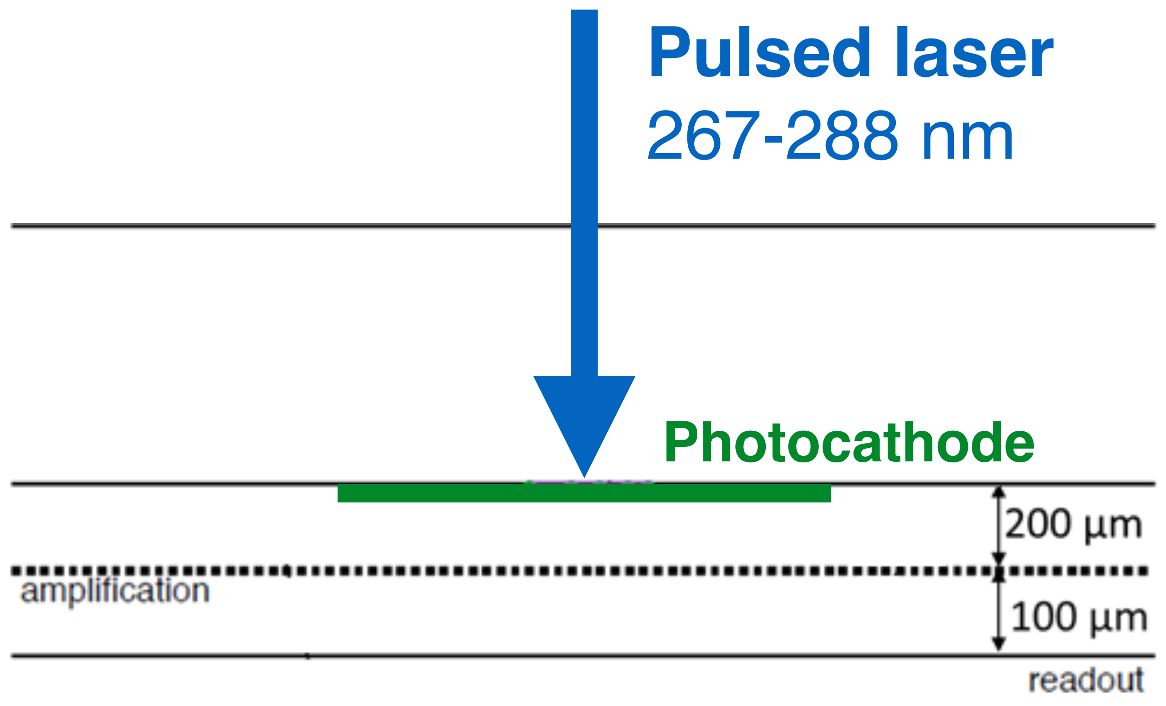
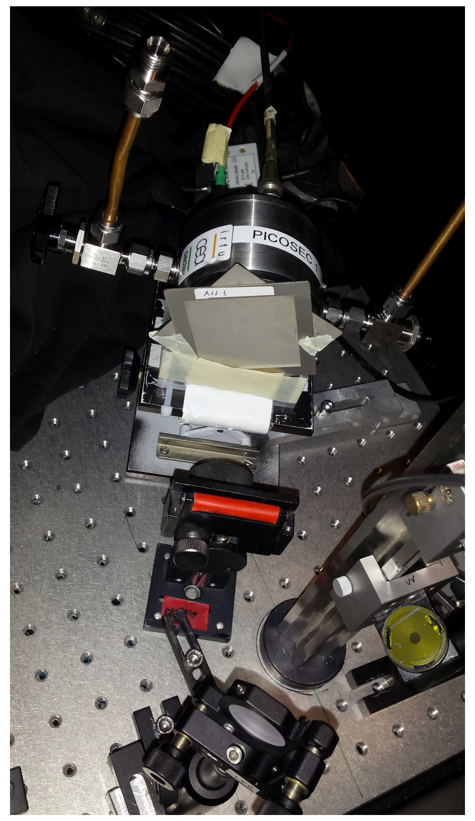
Measurements of timing performance

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.

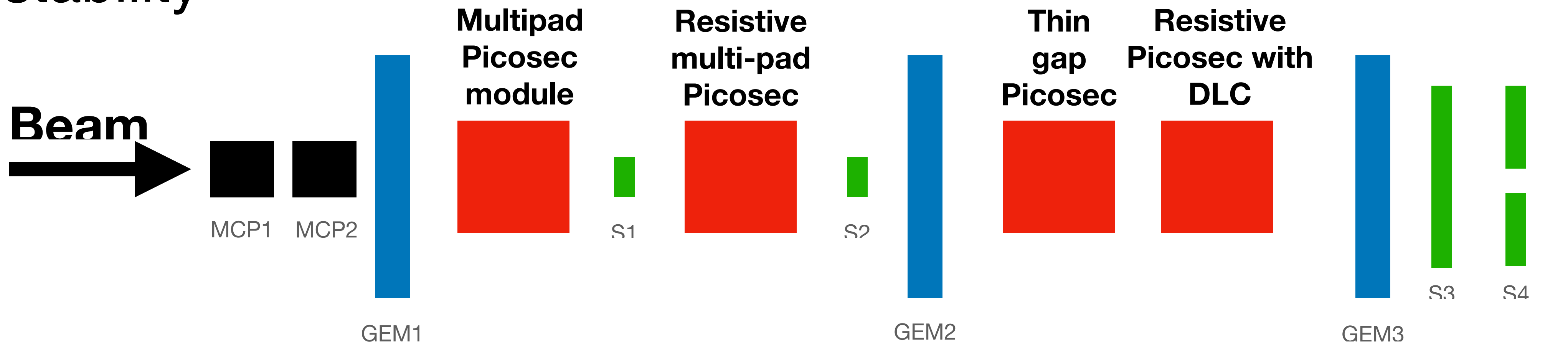
L. Sohl, Overview on recent PICOSEC-Micromegas developments and performance tests, RD51 Mini-Week February 2020, https://indico.cern.ch/event/872501/contributions/3726013/

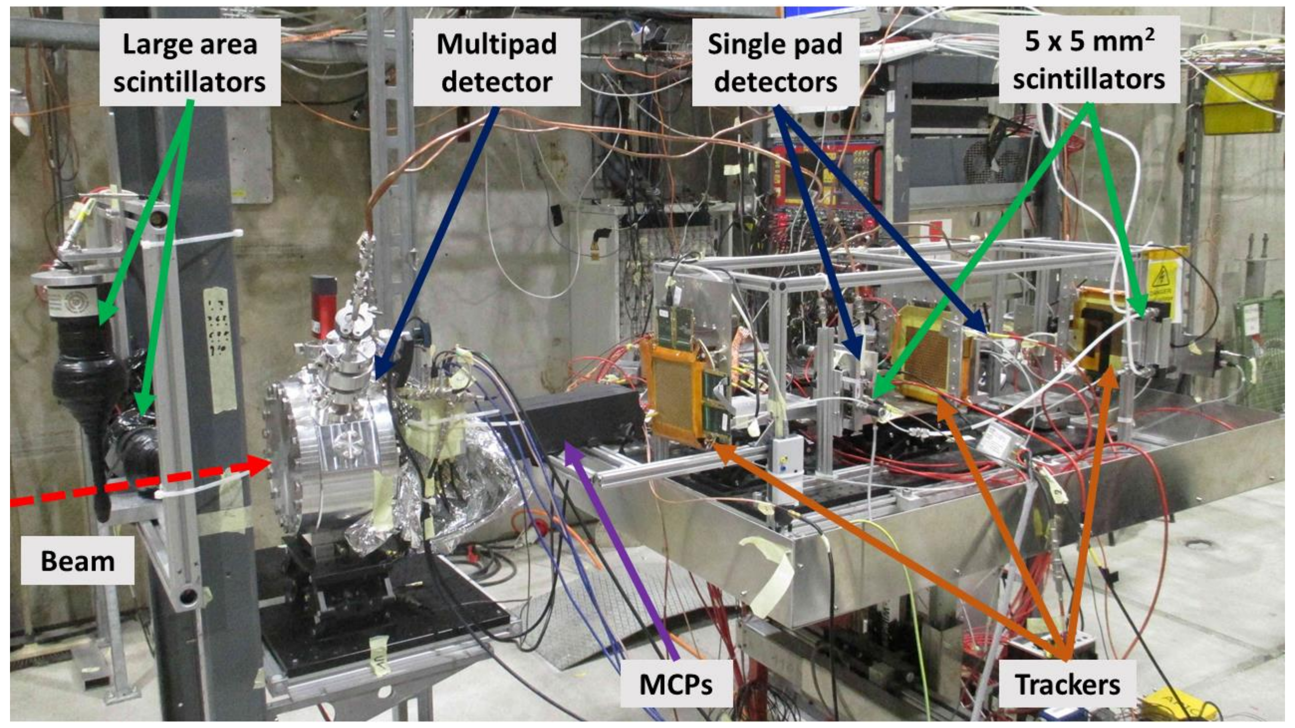
MIP test beam campaigns

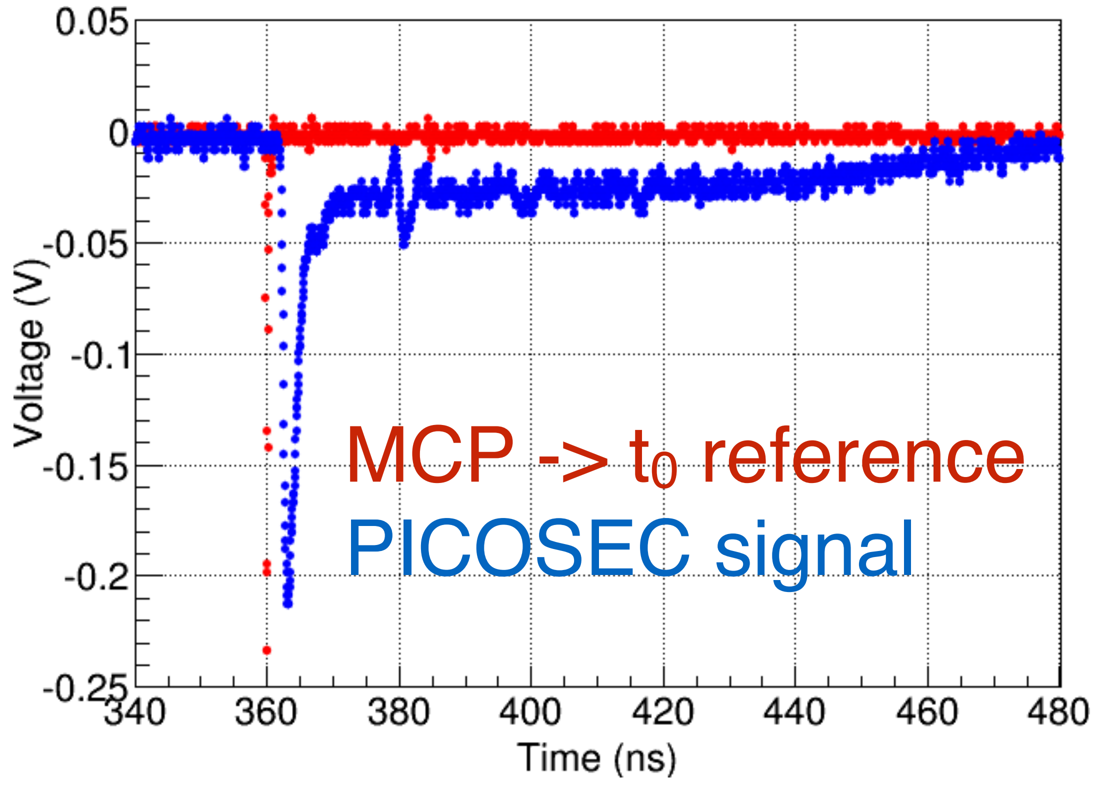
150 GeV muons and pions from SPS

Two **MCP-PMTs** used as timing reference (<5 ps resolution)
Tracking system with triple-GEMs (40 μm precision)

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







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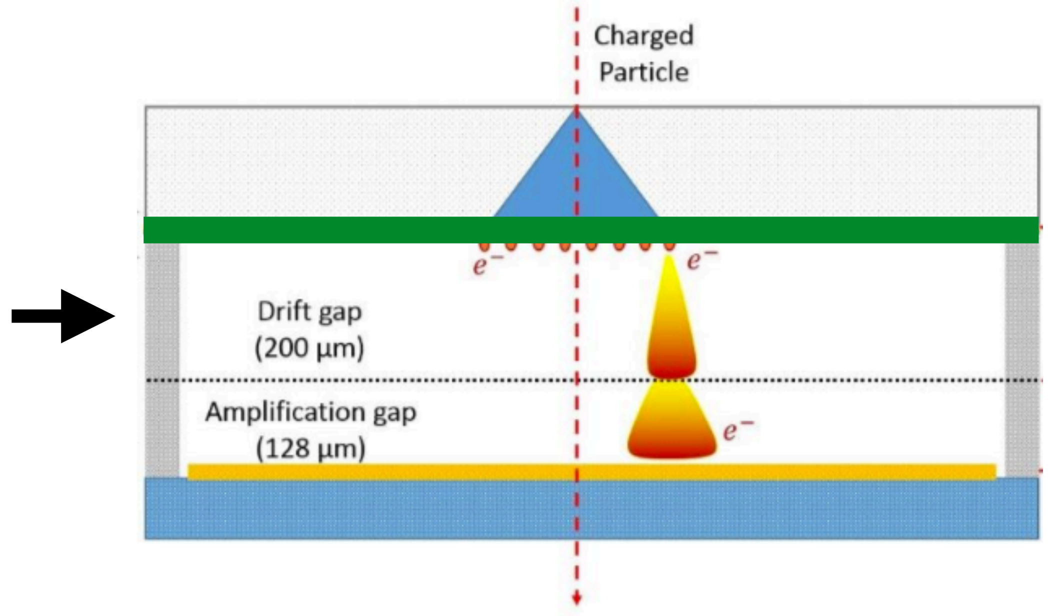
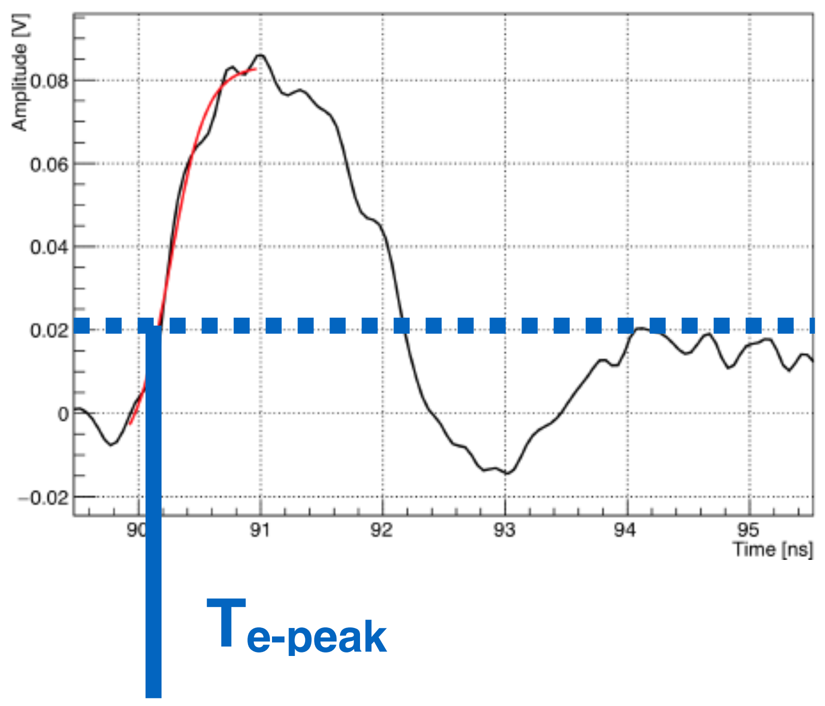
Detector response

Correlation of signal arrival time and pulse amplitude



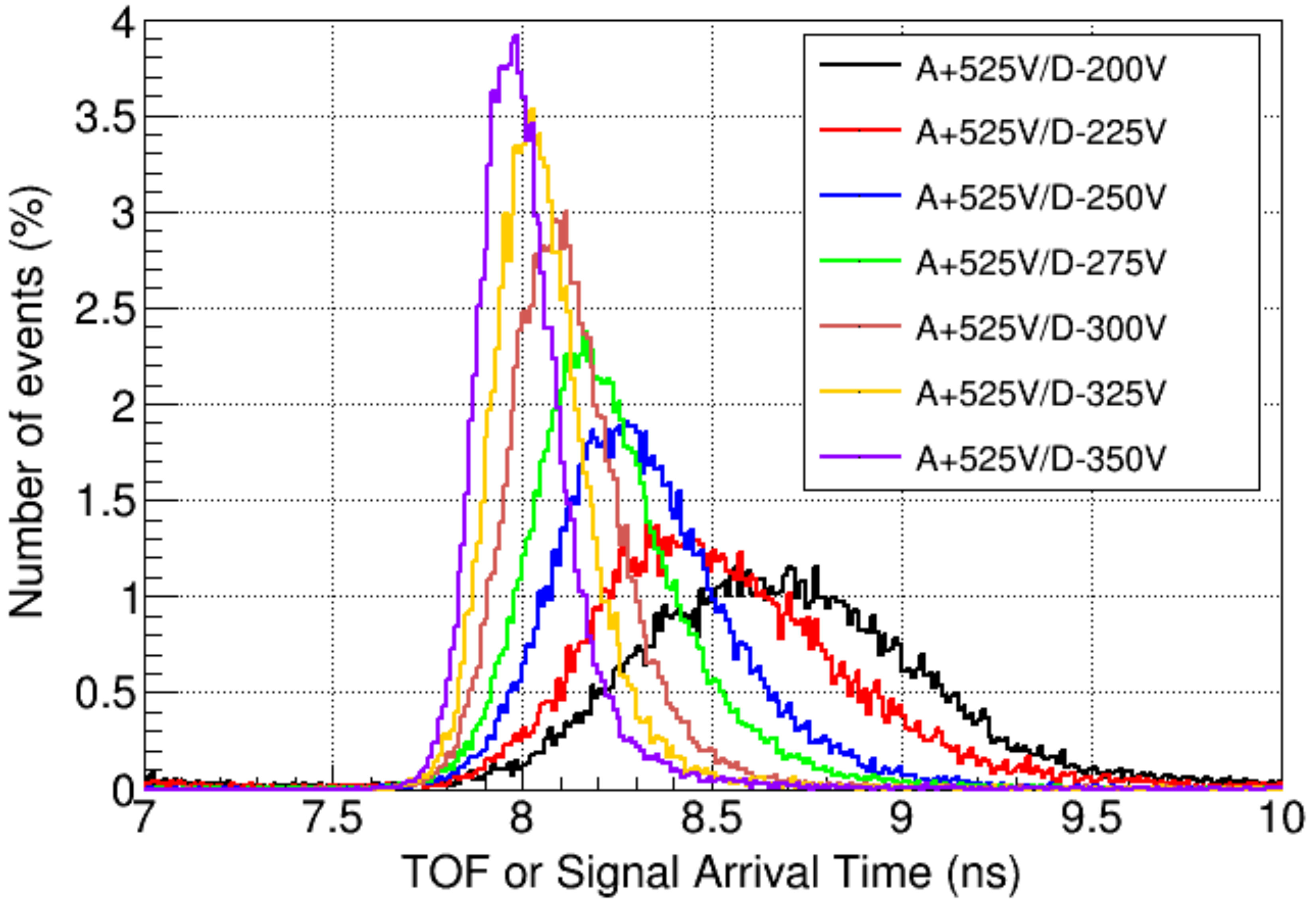


Time resolution depends primarily on e-peak charge

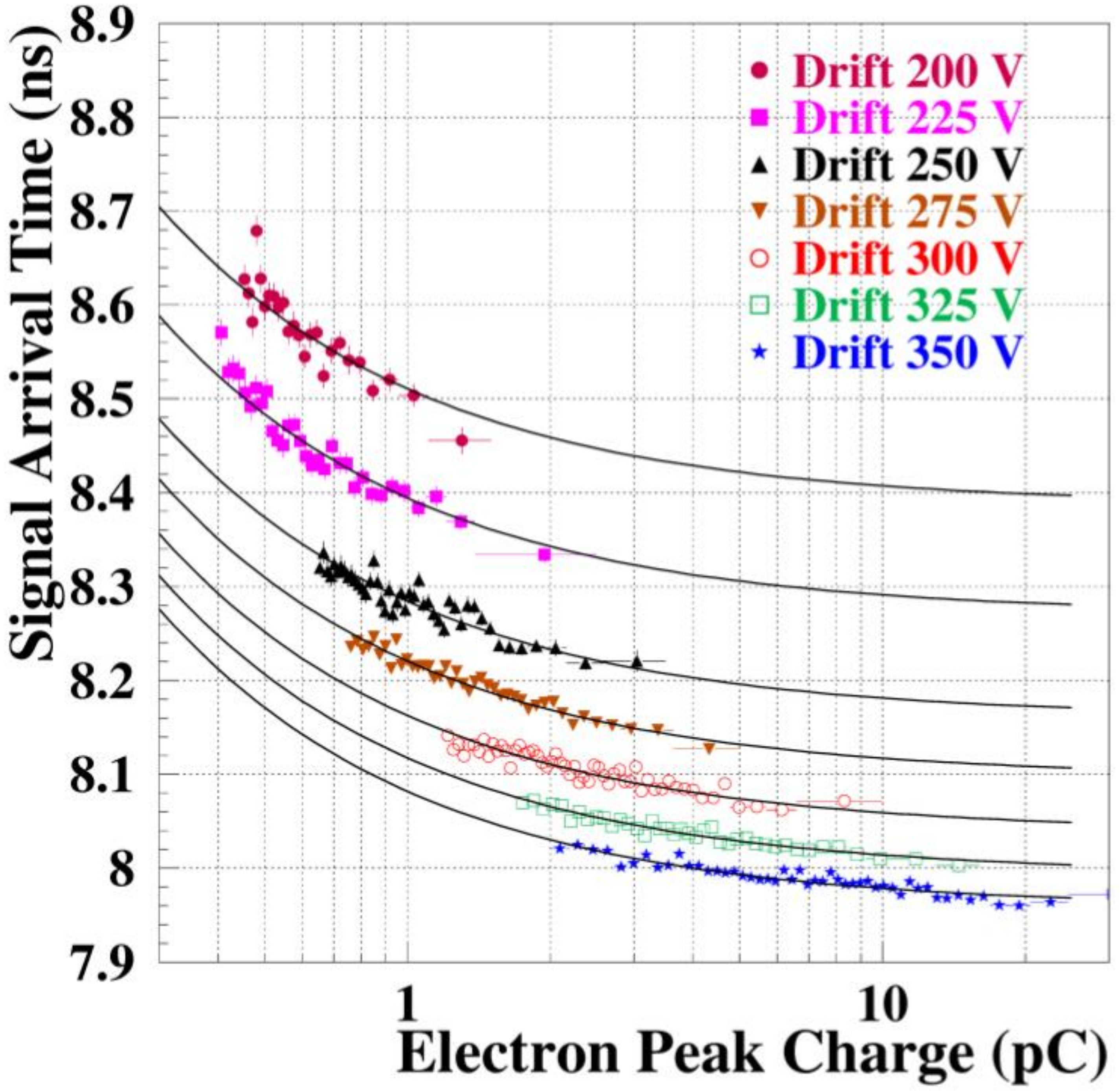
Signal arrival time (SAT) = $\langle T_{e\text{-peak}} \rangle$

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

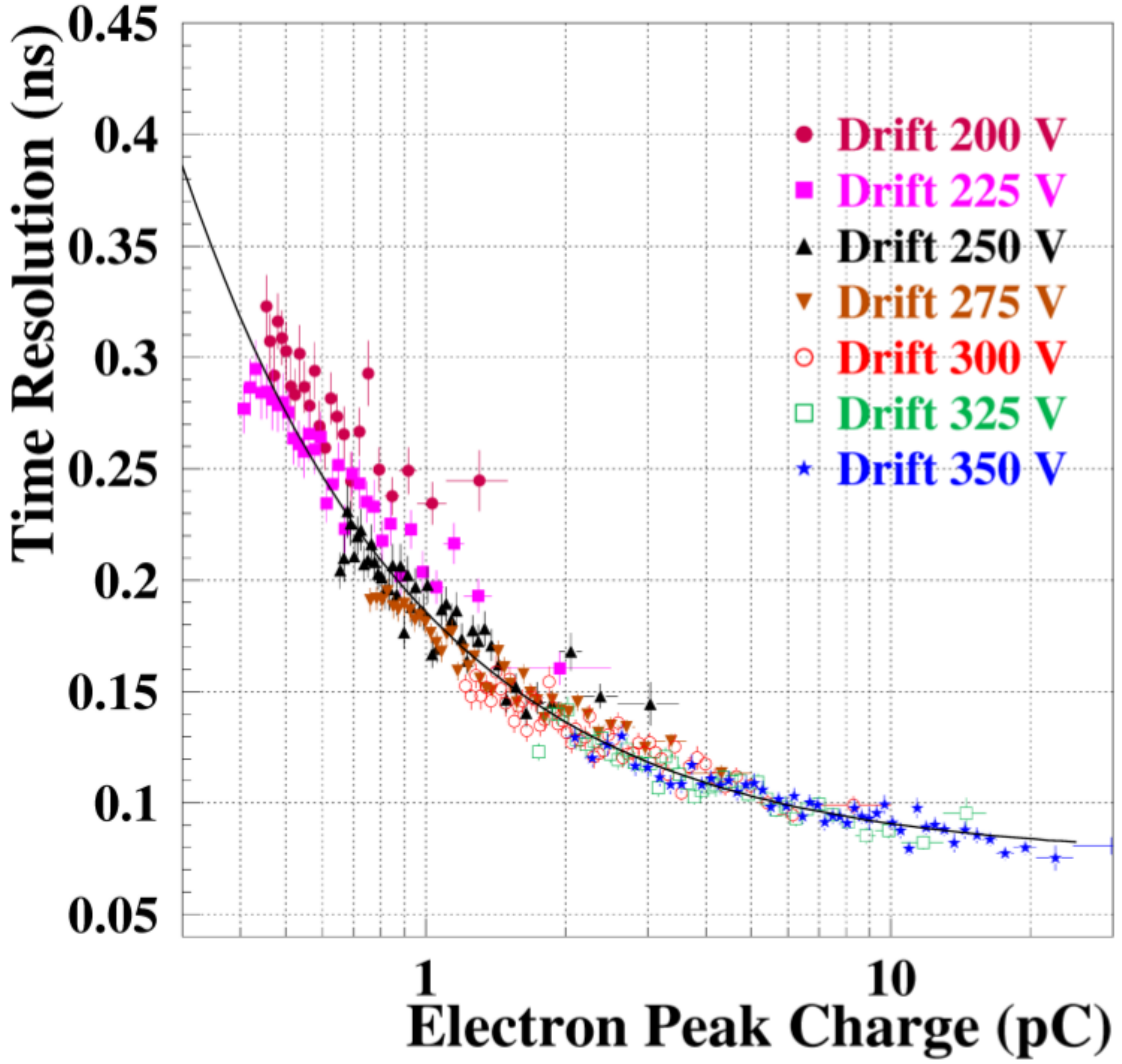
Narrower SAT distribution for higher pre-amplification field



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

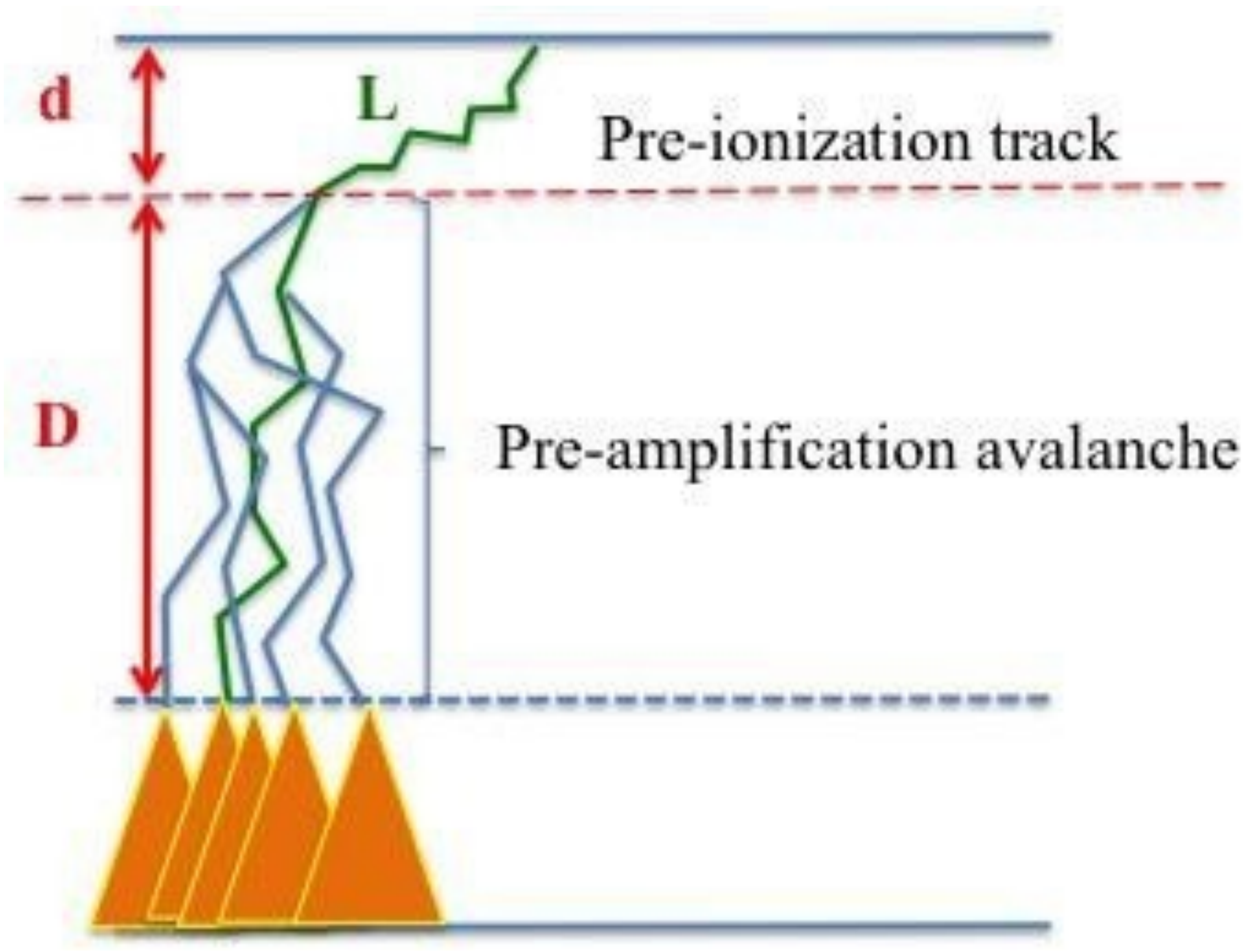
Time resolution depends primarily on e-peak charge

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



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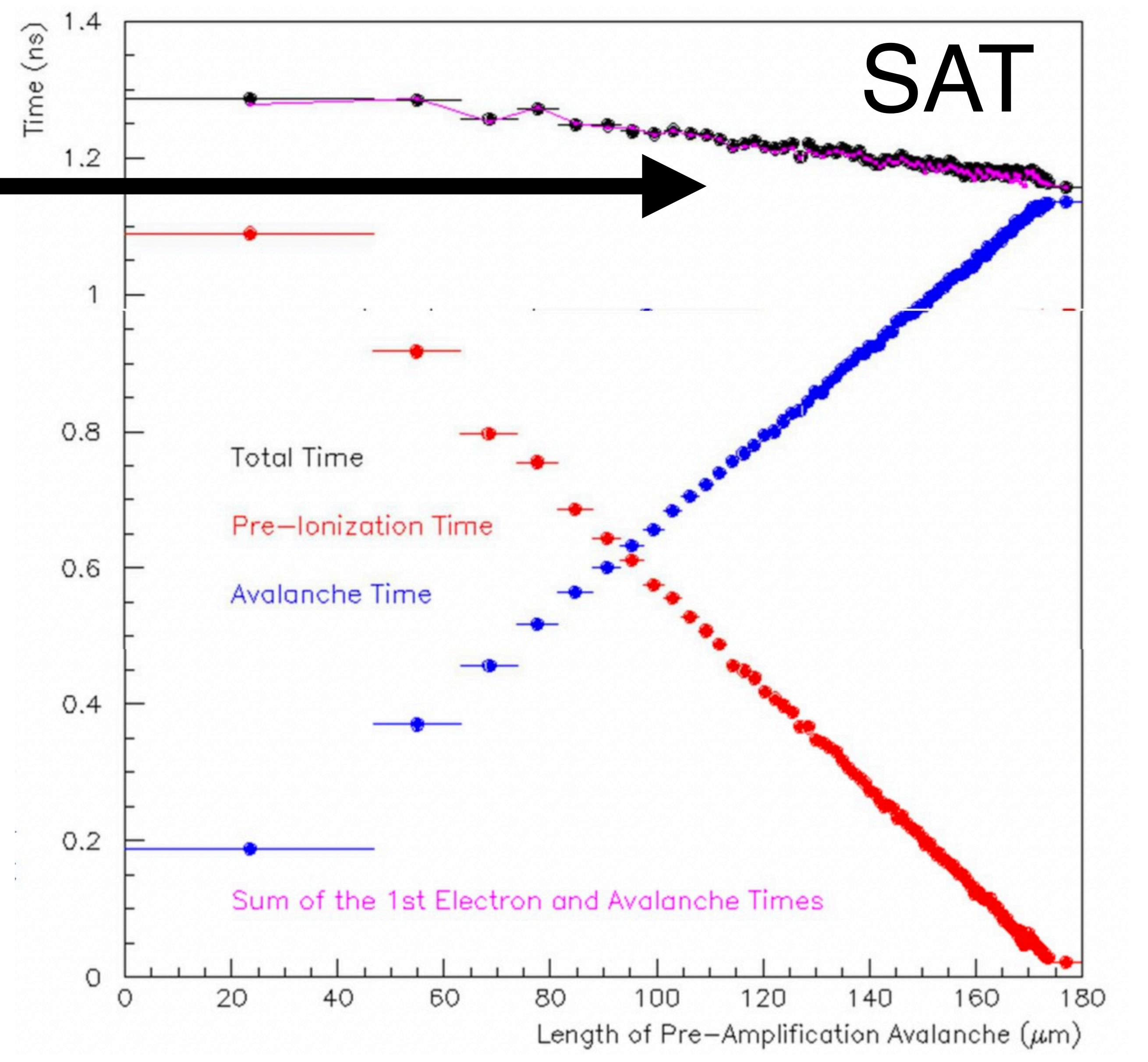
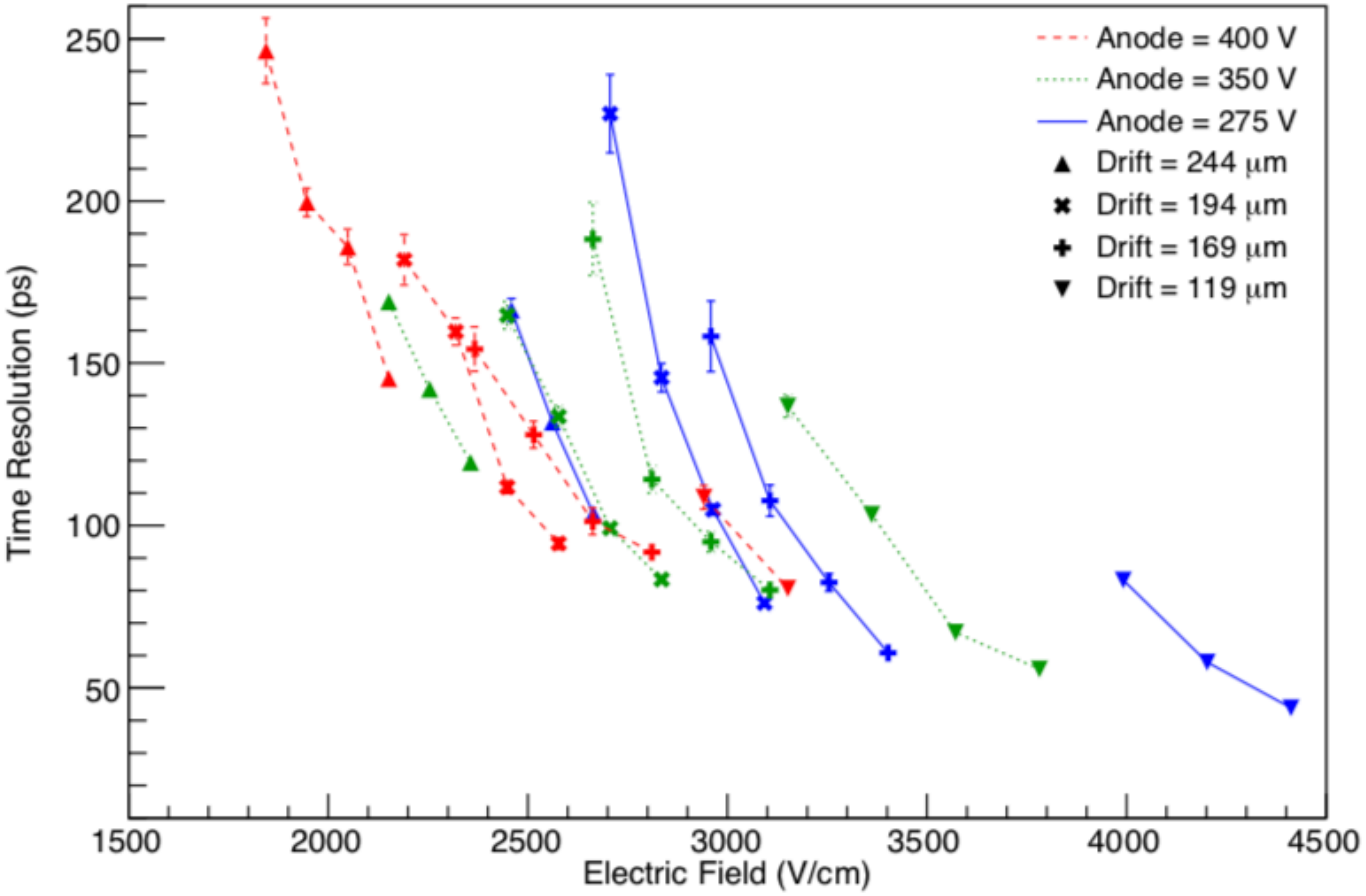


Avalanche length (μm)

Thin gap Picosec

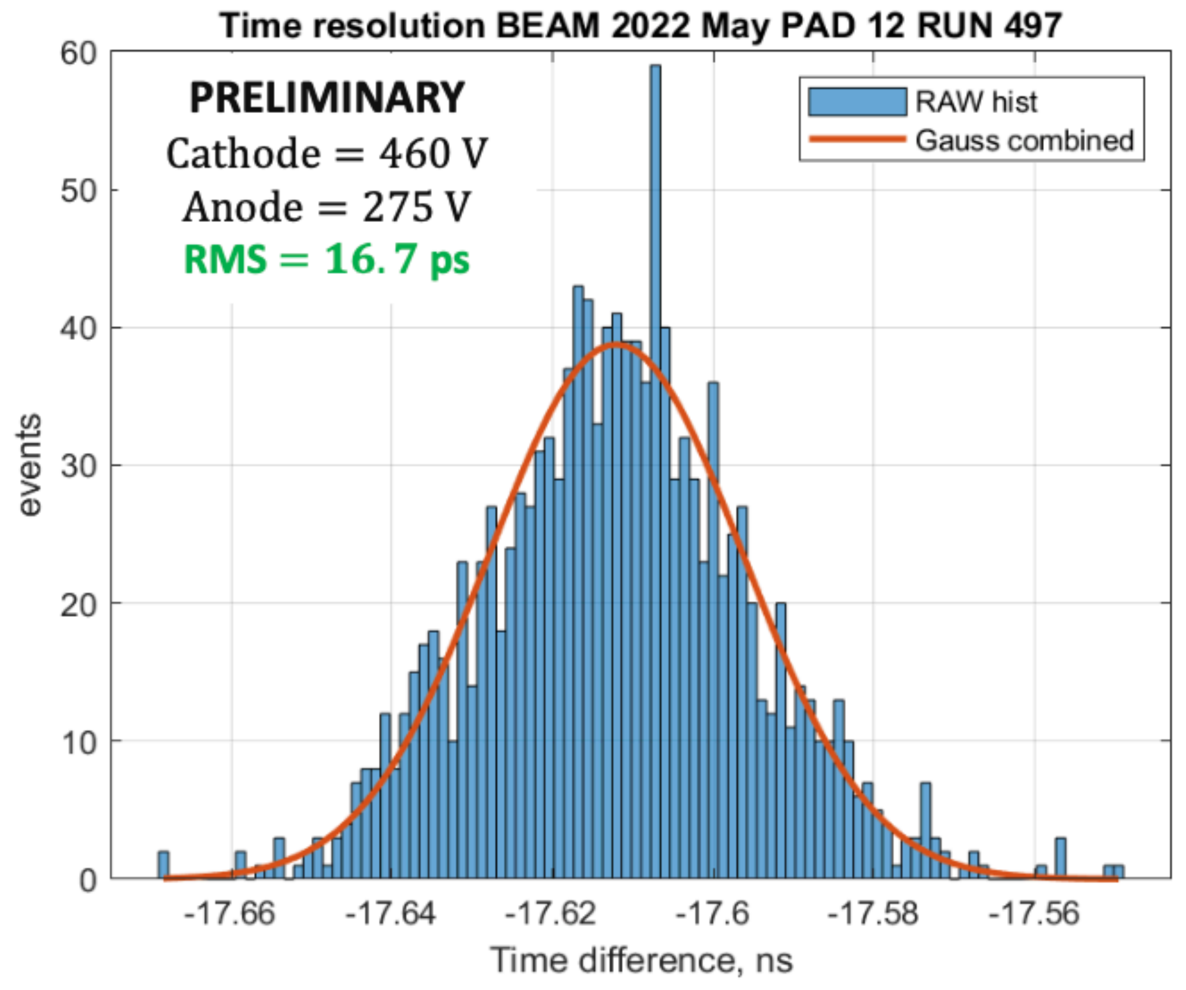
Systematic tests of electric field configurations (drift / amplification fields), drift gaps and gas mixtures performed in laser facility



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)

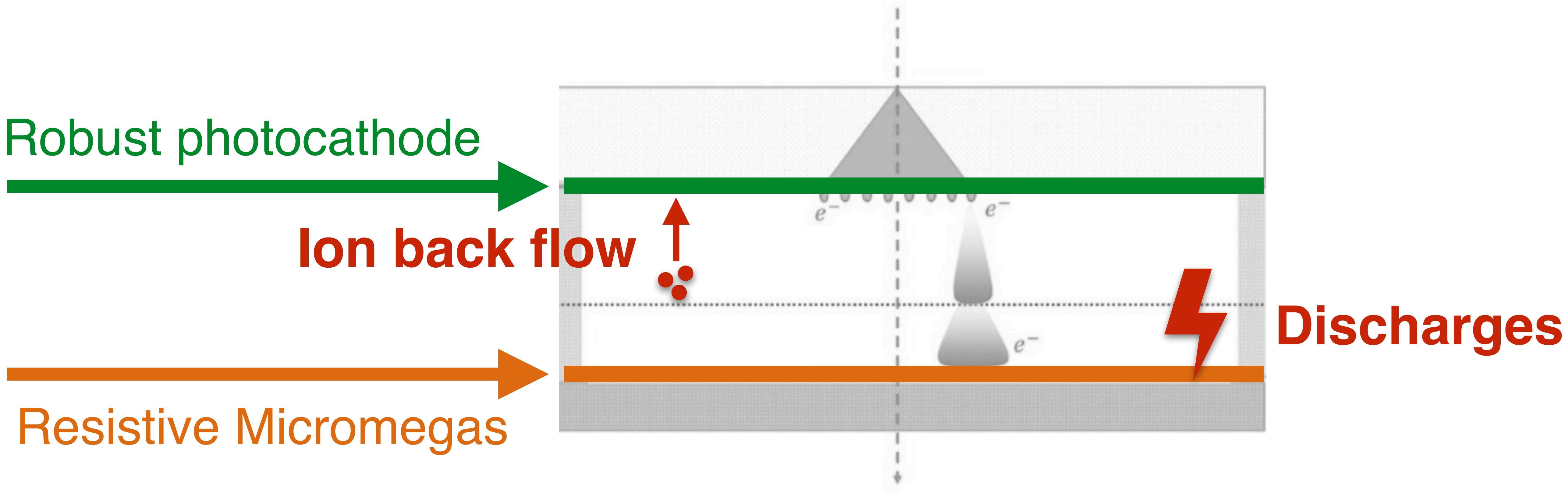
Excellent timing performance recently confirmed in MIP test beam with **thin gap Picosec**



Towards a robust, large-area detector

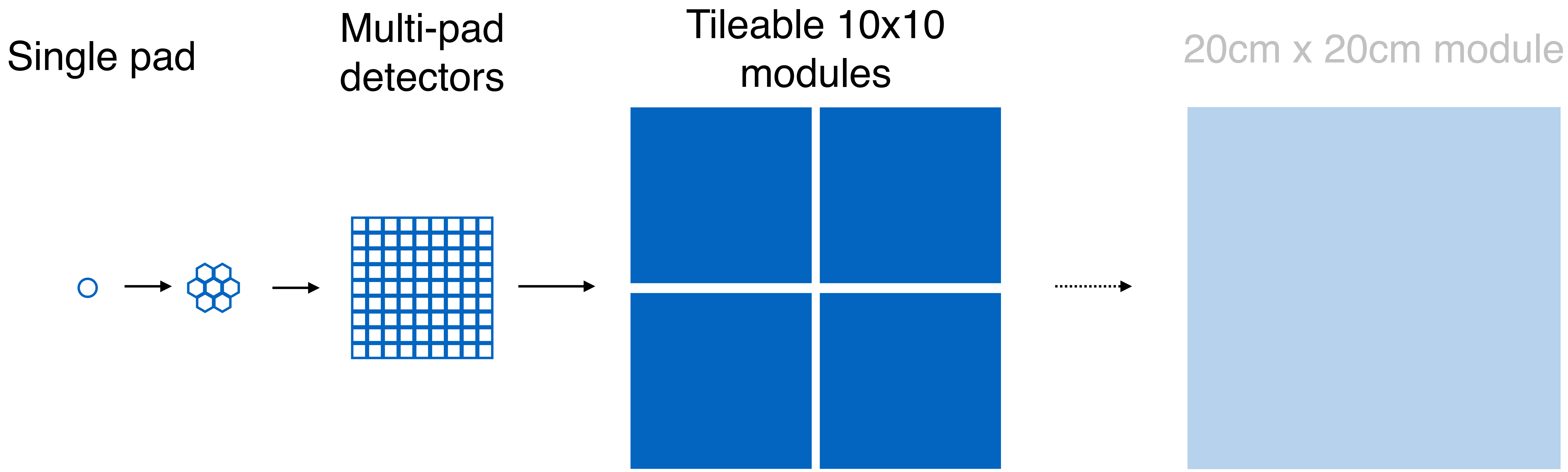
Robustness

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



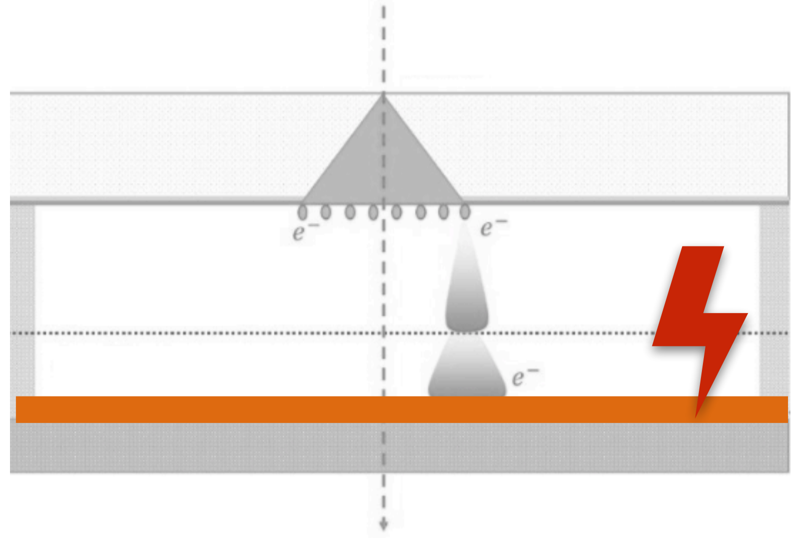
Area coverage

- Single pad to multi pad
- Detector modules



Schematic not drawn to scale

Resistive Micromegas

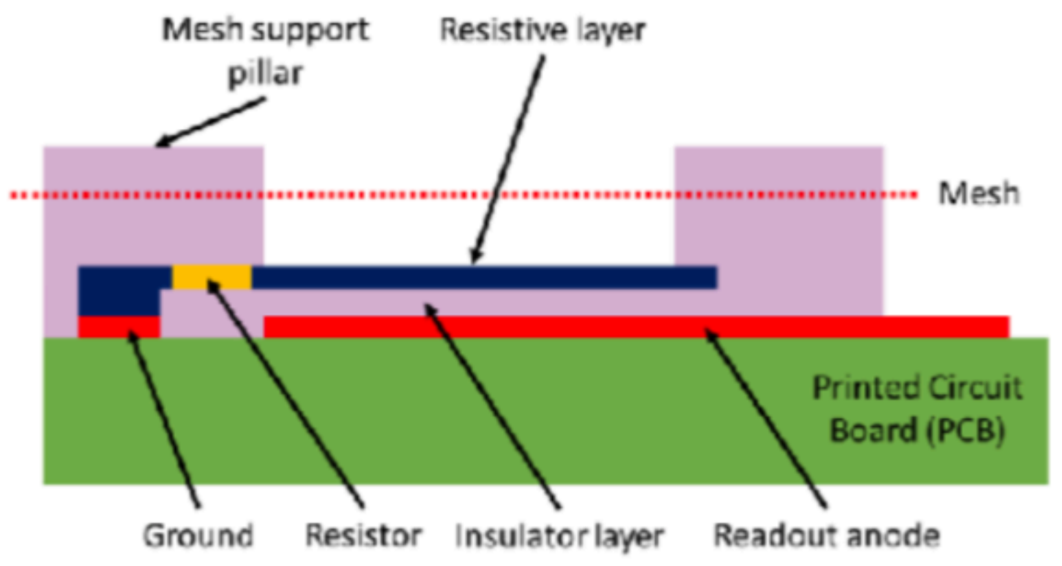


Resistive elements (layer, discrete resistors) for readout anodes to limit destructive effect of discharges by limiting energy released

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**

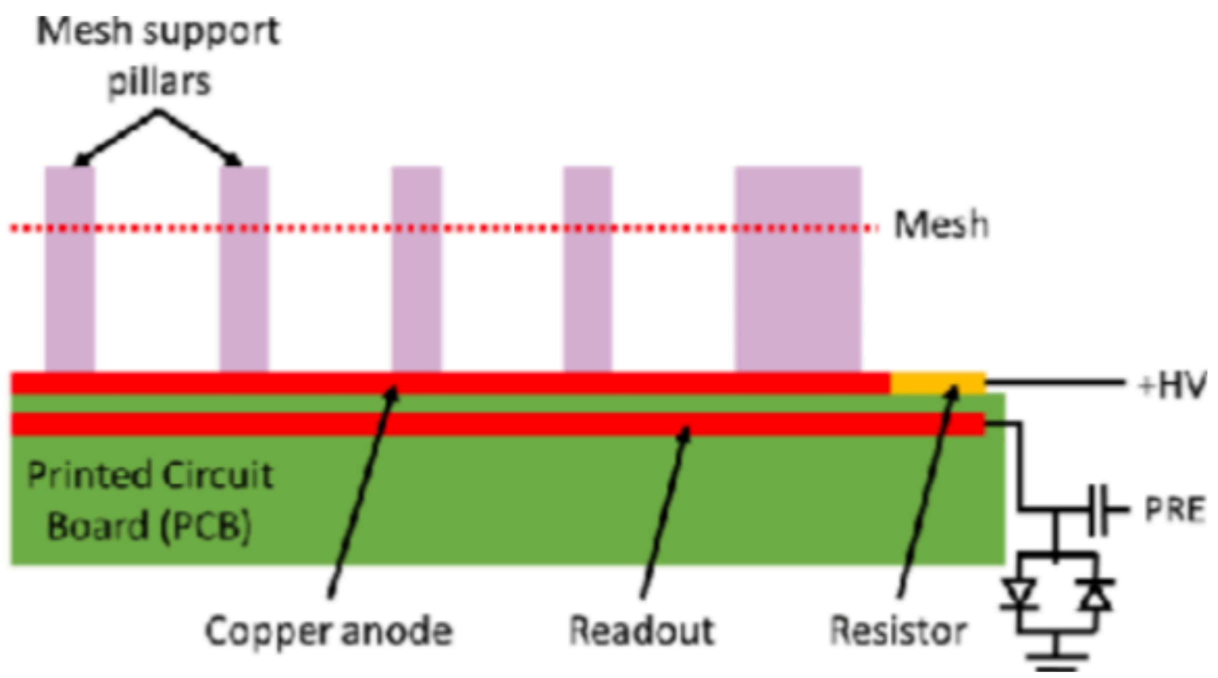
Resistive strips (MAMMA)



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

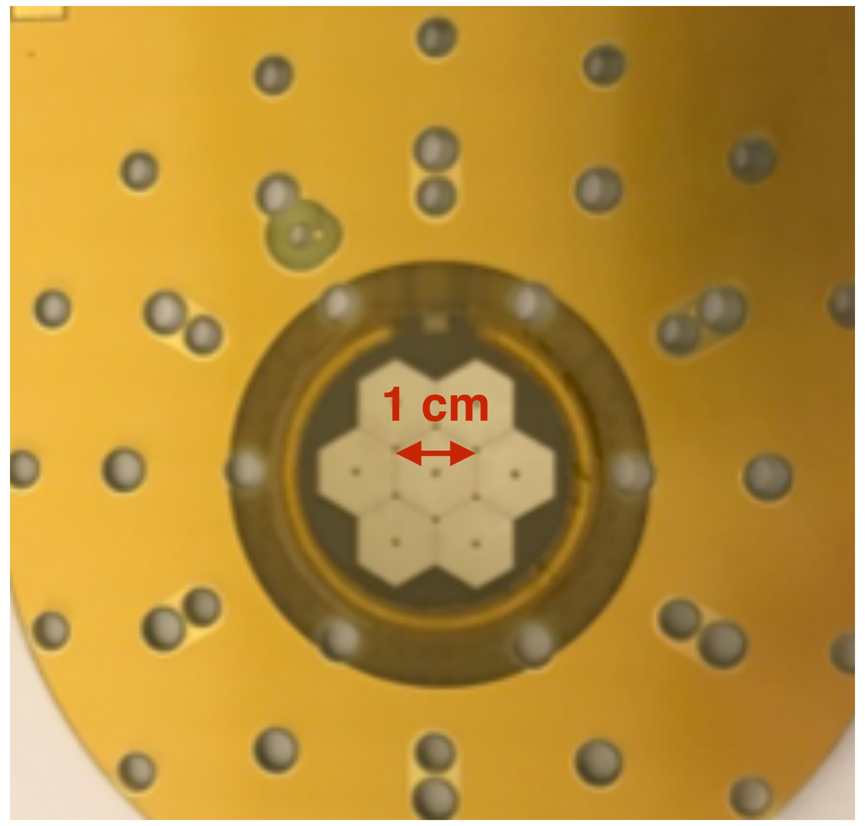
σ = 41 ps

Floating strips (COMPASS)



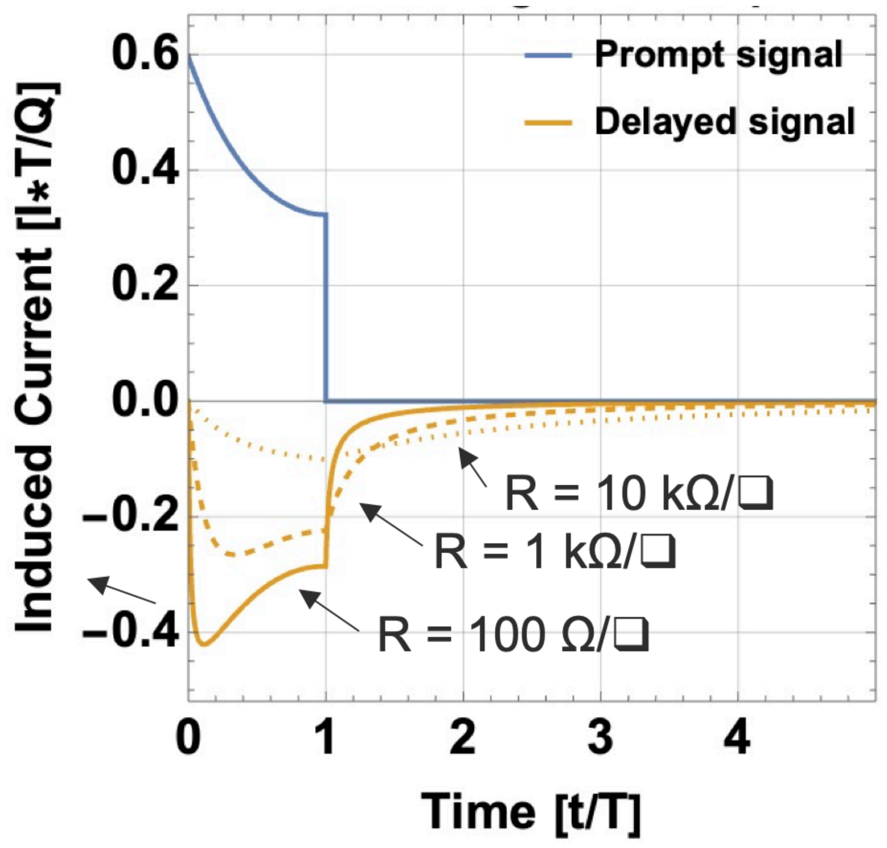
σ = 28 ps

Resistive multi-pad Picosec



T. Papaevangelou,
L. Sohl, CEA Saclay

Simulation of signals induced in resistive detectors



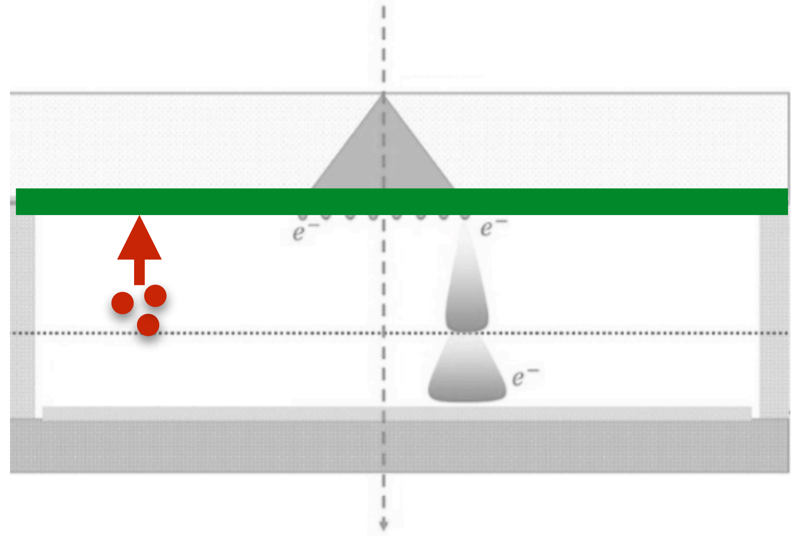
D. Janssens, CERN

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

Photocathode robustness

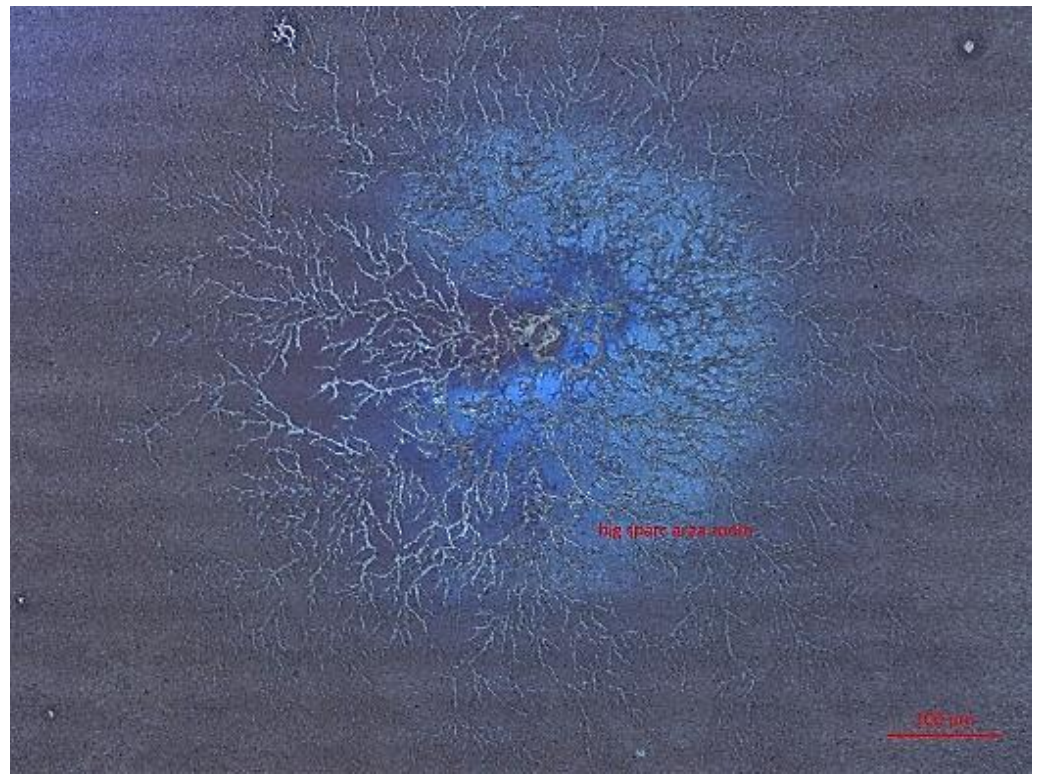
Limitations of CsI



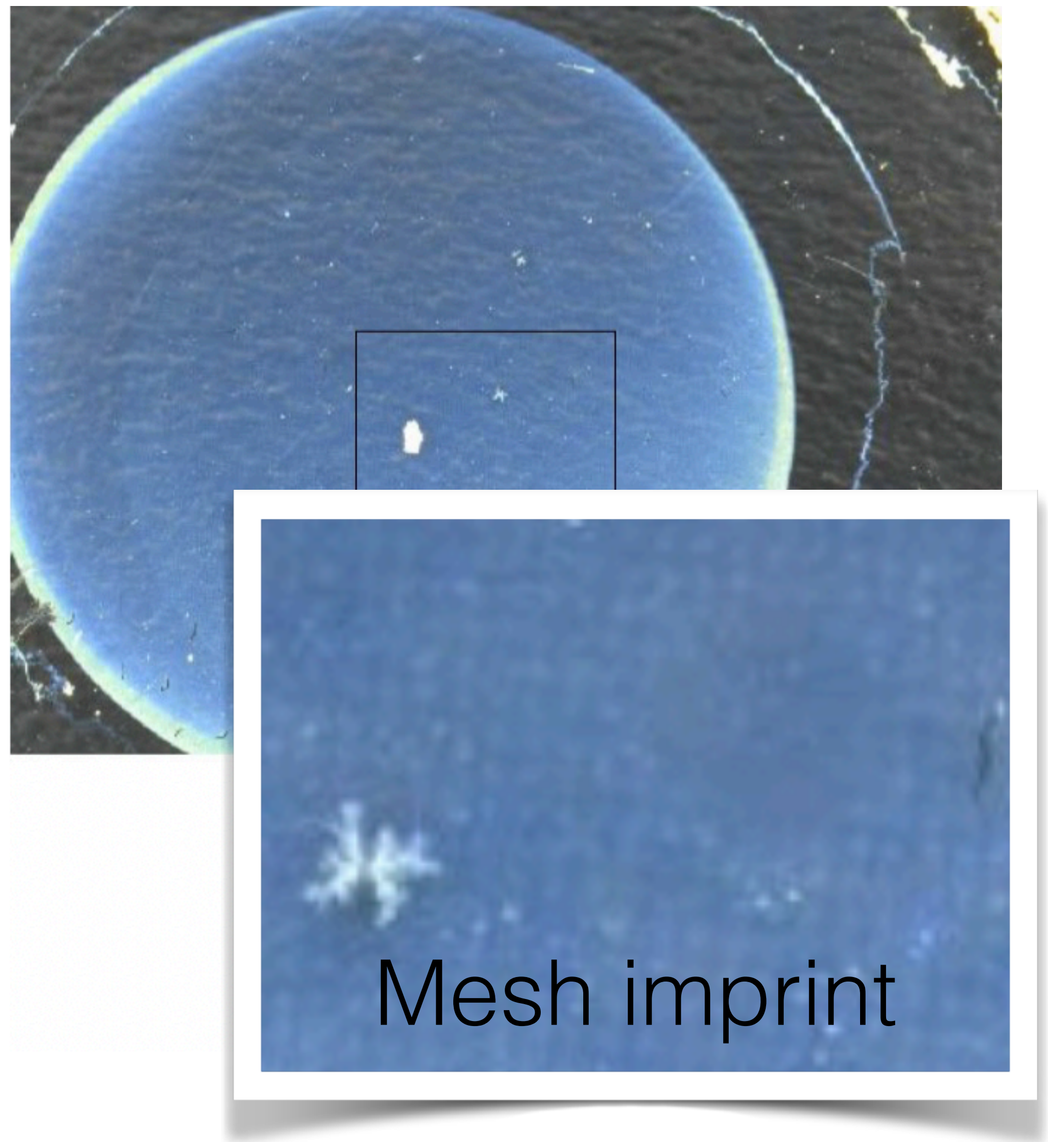
Standard PICOSEC photocathode: 18 nm CsI + 3 nm Cr → ≈10 p.e. / MIP

CsI sensitive to humidity, ion backflow and sparks

CsI photocathode after spark

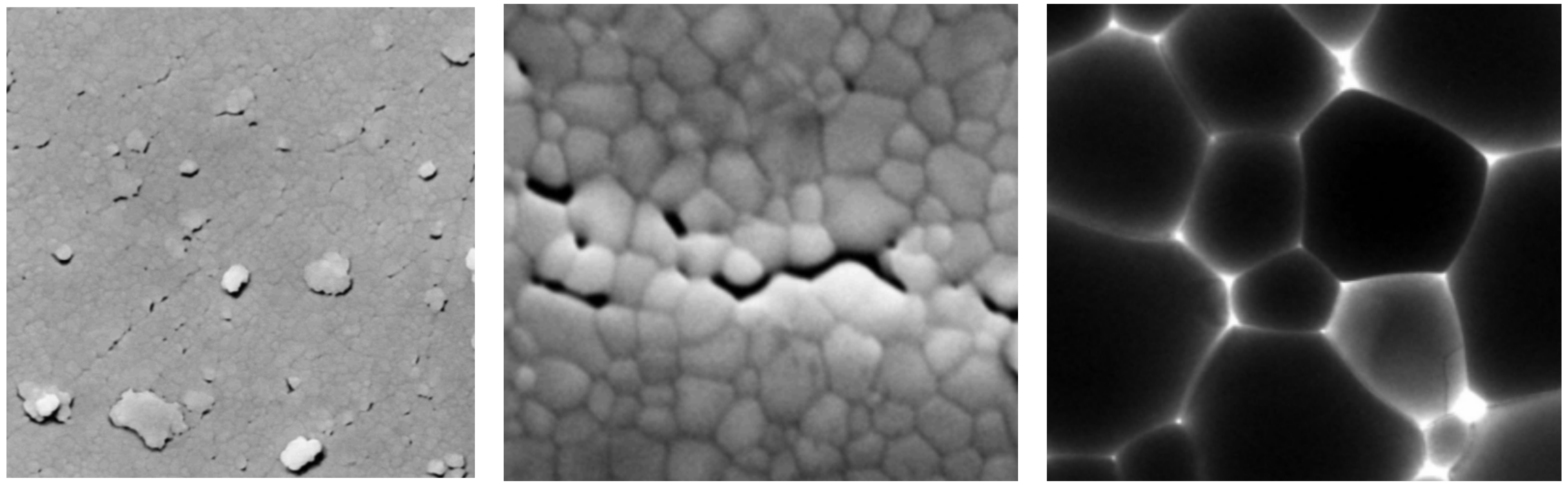


Ion backflow on CsI



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

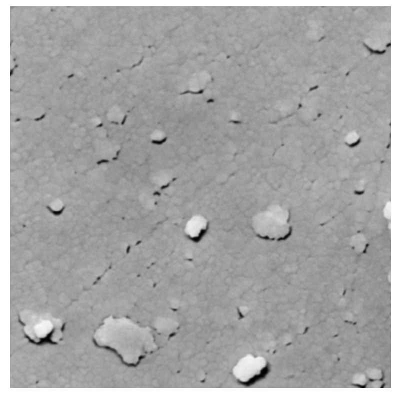
Photocathode robustness

Protection and alternatives

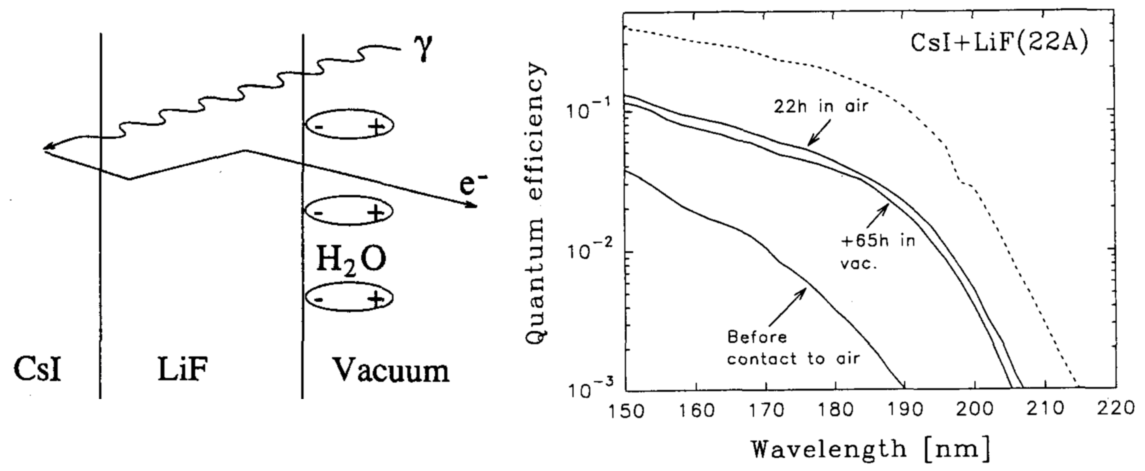
Robustness of photocathode is important to preserve QE and thus detector efficiency and timing resolution during prolonged operation. This may be address in two ways:

Making CsI more robust

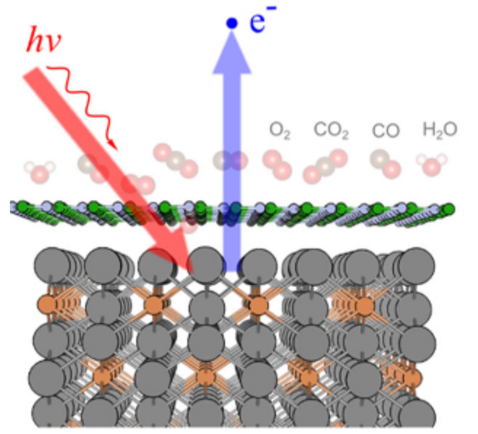
- Minimise effect of ion back flow while preserving QE
- Protection layers (MgF_2, LiF, graphene, …)



10.1016/ j.nima.2009.05.179



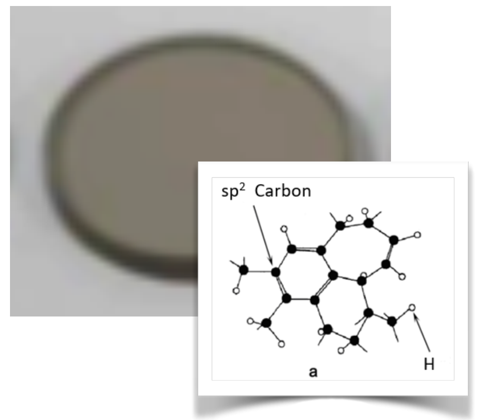
CsI + LiF_2, A. Breskin et al., 10.1109/23.467832



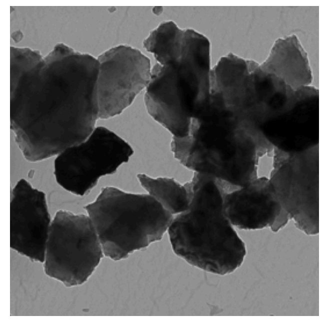
Graphene passivation, G. Wang et al

Alternative photocathodes

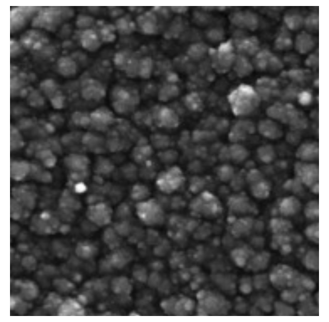
- Inherently robust materials (with possible lower QE)
- Metallic, DLC, B_4C, nano diamonds, CVD diamond, GaN, …



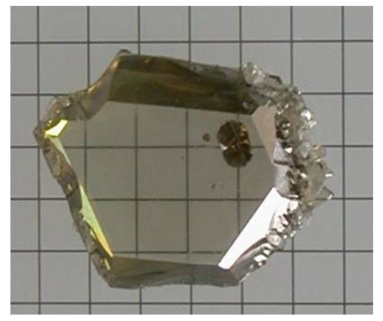
DLC, Y. Zhou et al.



ND, L. Velardi et al.



B_4C, 10.1016/ j.jnucmat.2015.01.015



GaN crystal

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

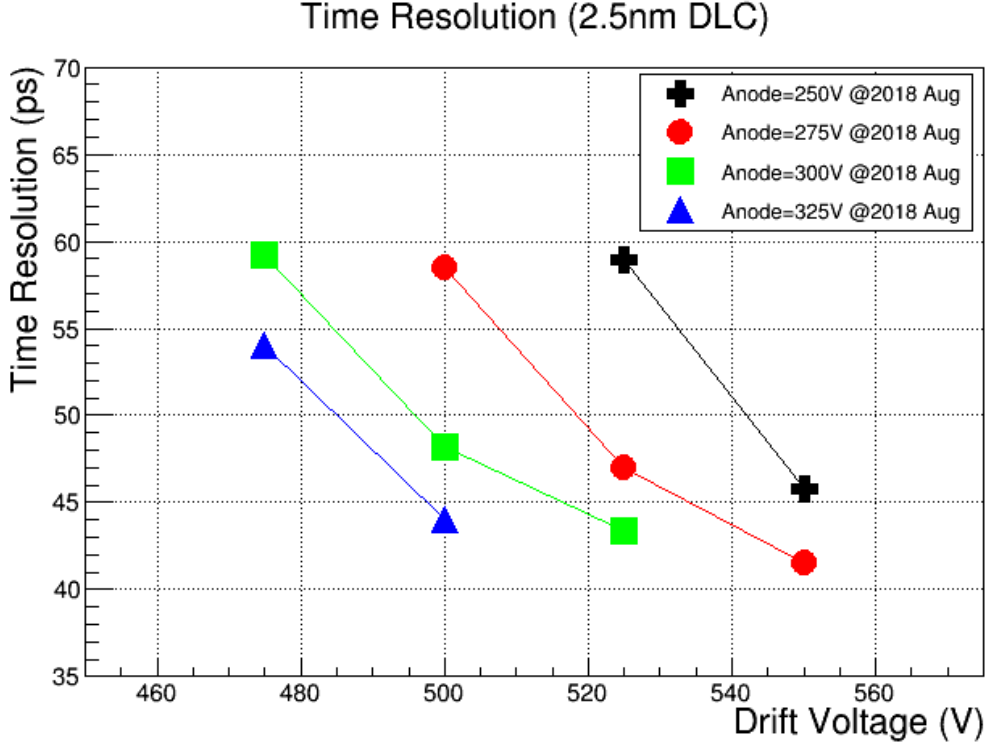
DLC thickness	$N_{ph.e.}$ / muon
2.5nm	3.7
5nm	3.4
7.5nm	2.2
10nm	1.7

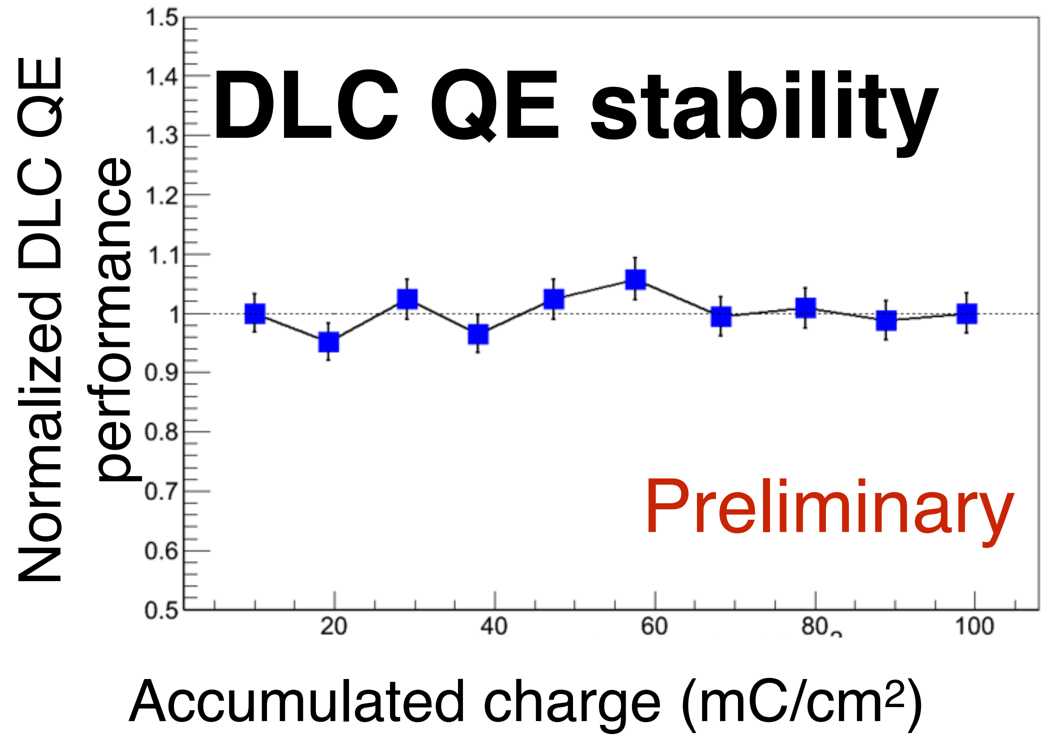
Diamond-like carbon (DLC)

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

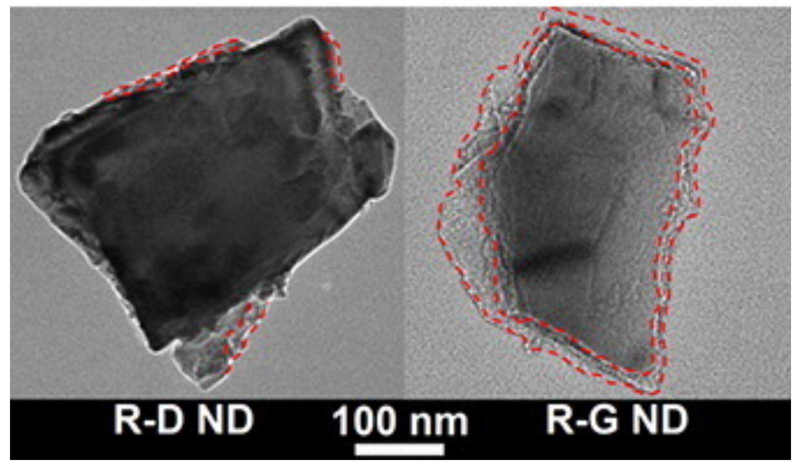


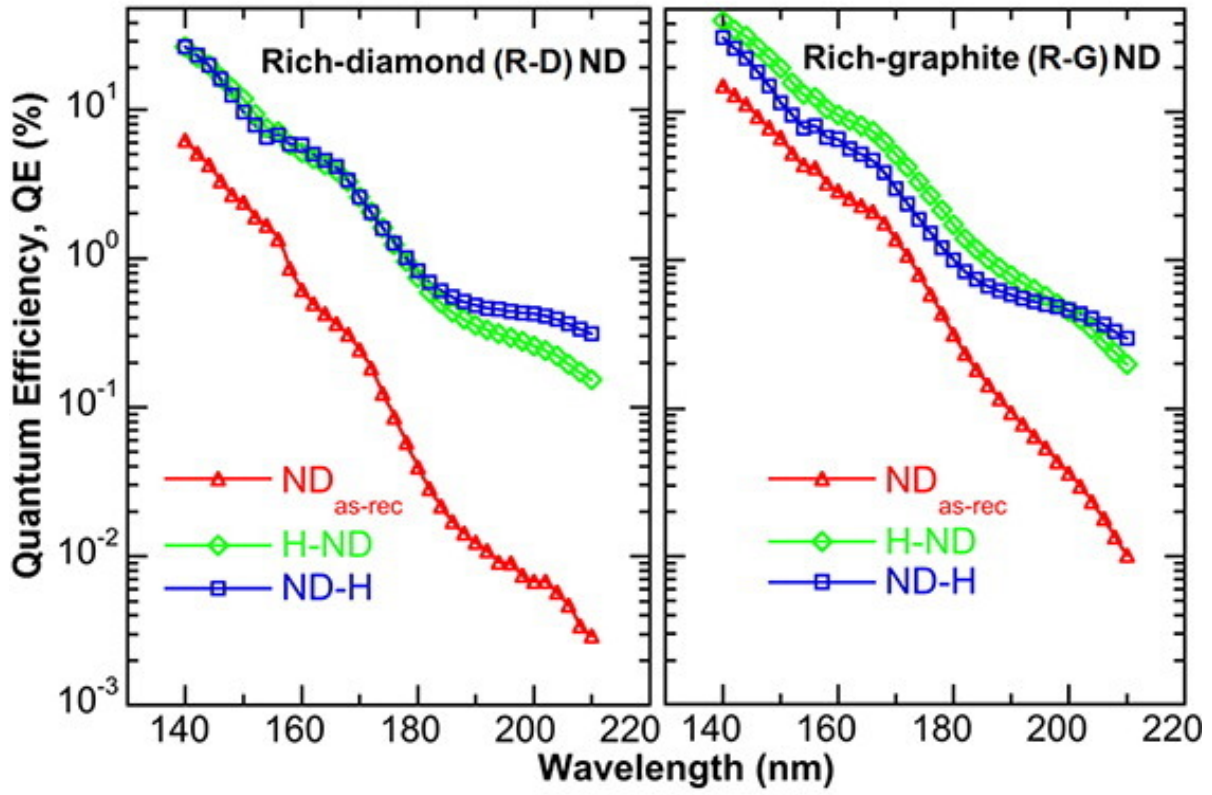


X. Wang, Recent photocathode and sensor developments for the PICOSEC Micromegas detector, MPGD 2019 https://indico.cern.ch/event/757322/contributions/3387110

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

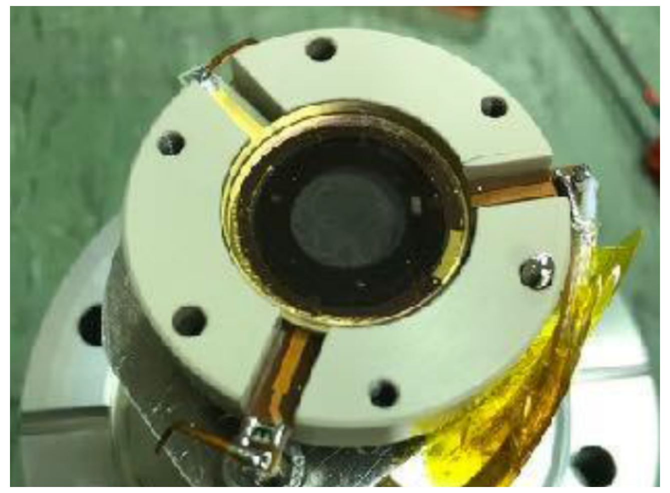
Several variants of multi-channel PICOSEC prototypes in development / under test to address challenges associated with scaling to larger areas:

Integration

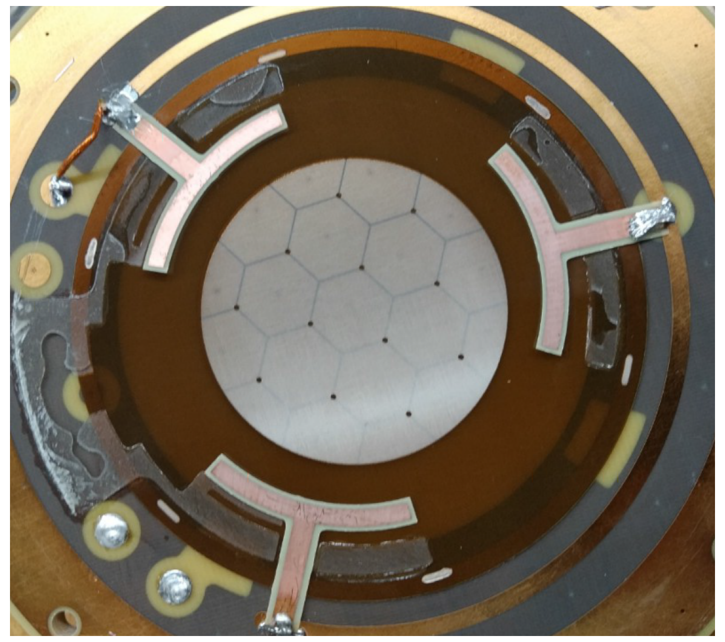
- Mechanics to preserve precise gaps
- Large Cherenkov radiators and photocathodes
- Tileing & compact detector vessel
- Sealed detector
- Resistive multi pad

Electronics

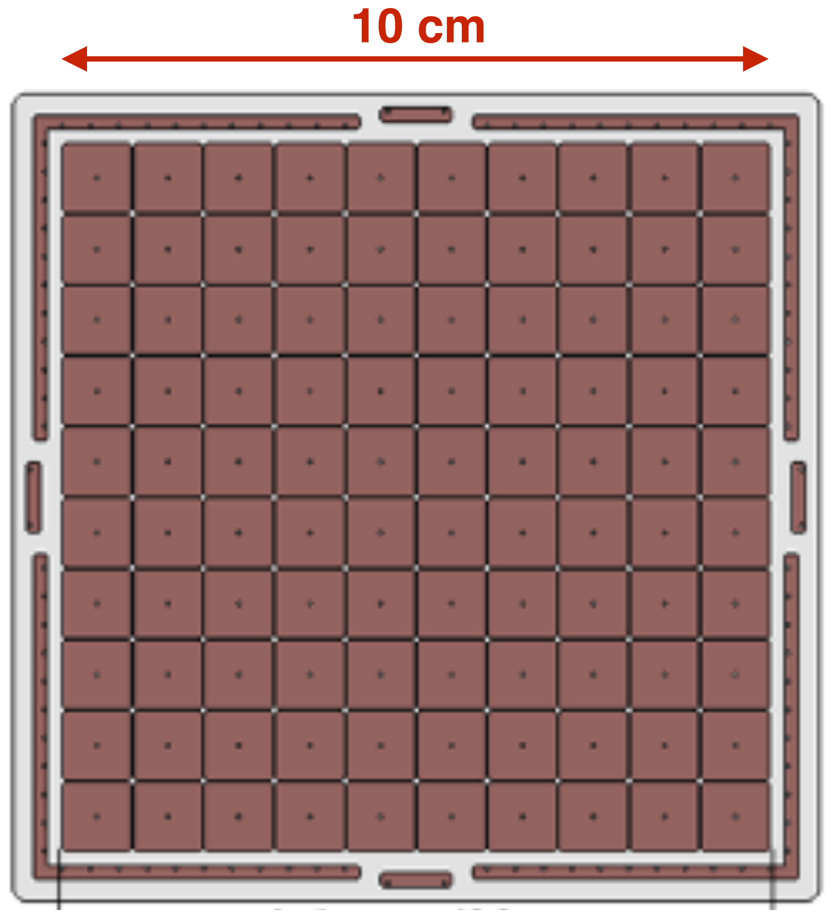
- Signal sharing between pads
- Premplifiers
- Multi-channel digitisers



Single pad (2016)
ø1 cm



Multi pad (2017)
⬡ 1 cm

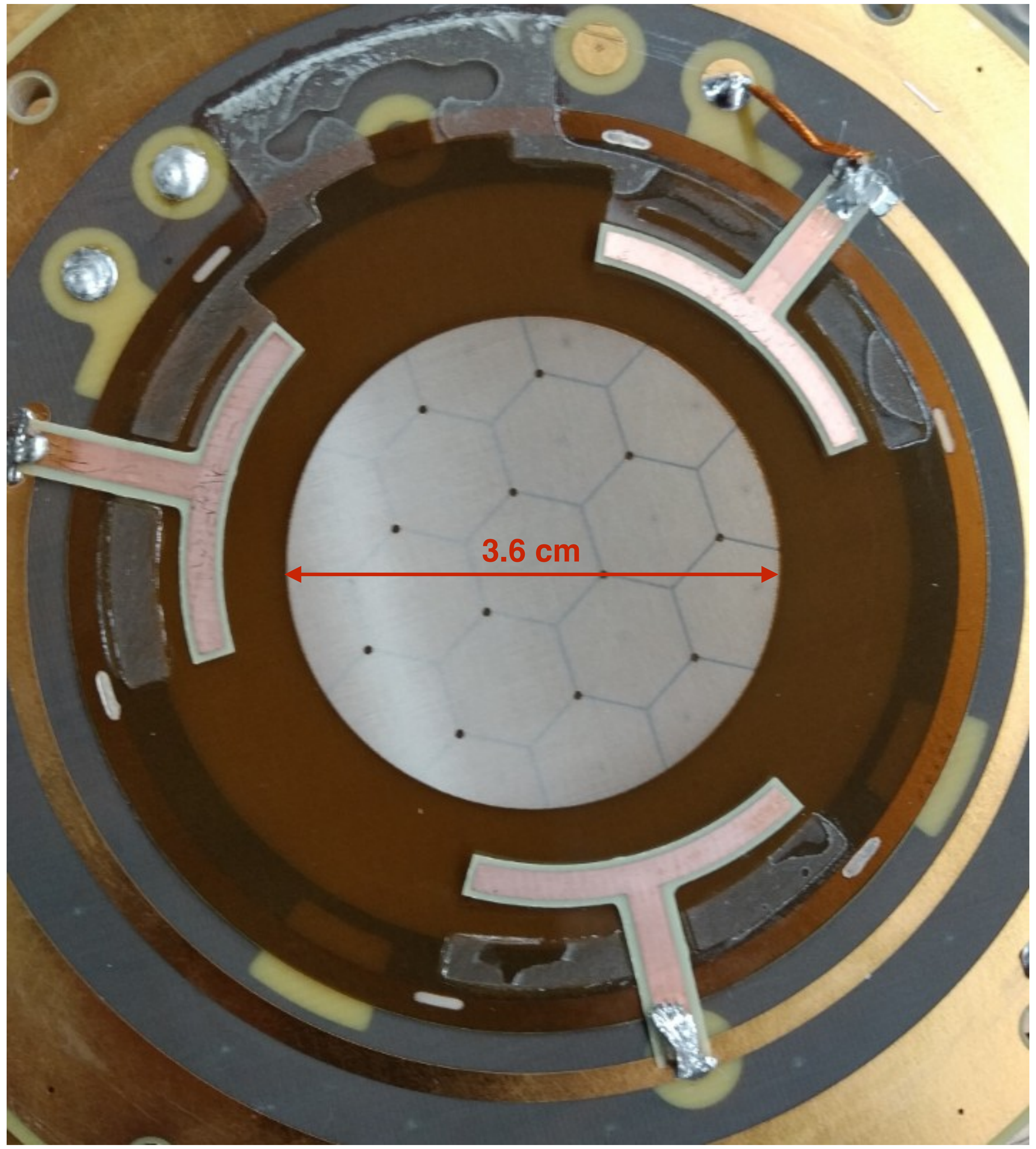


10x10 module
□ 1 cm

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)
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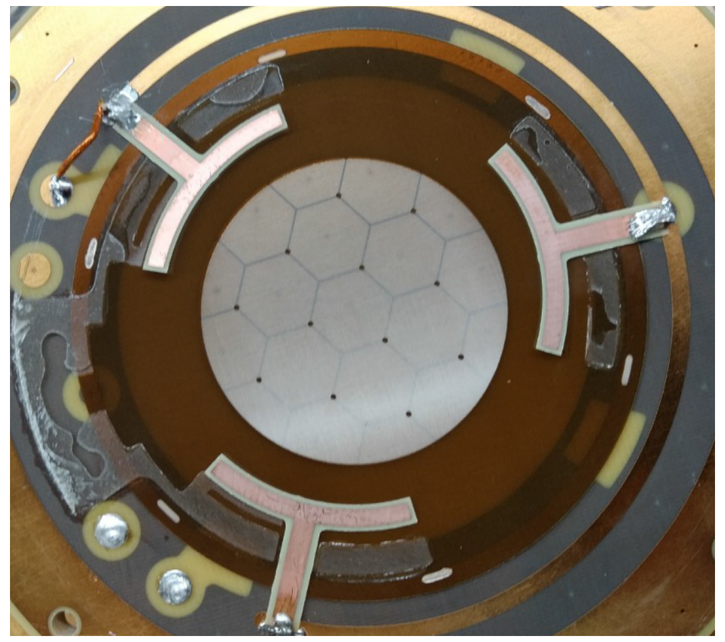
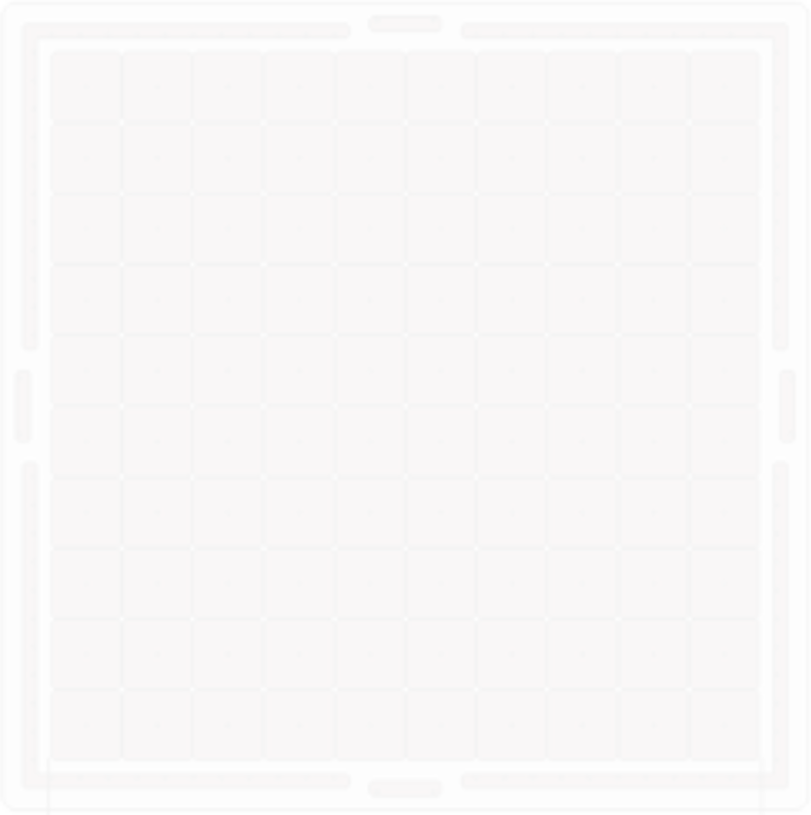


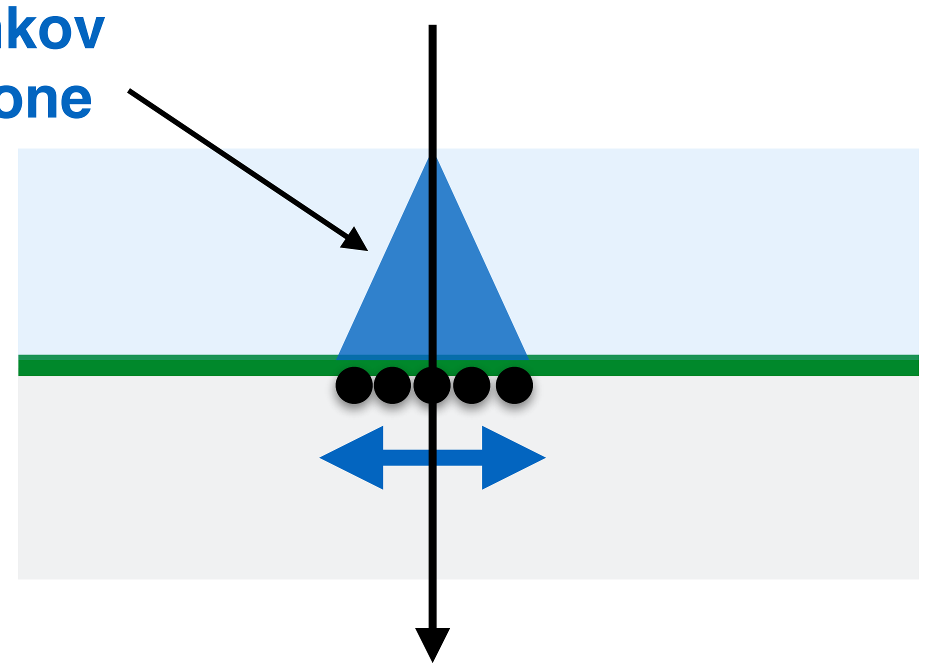
Multi pad (2017)
⬡ 1 cm

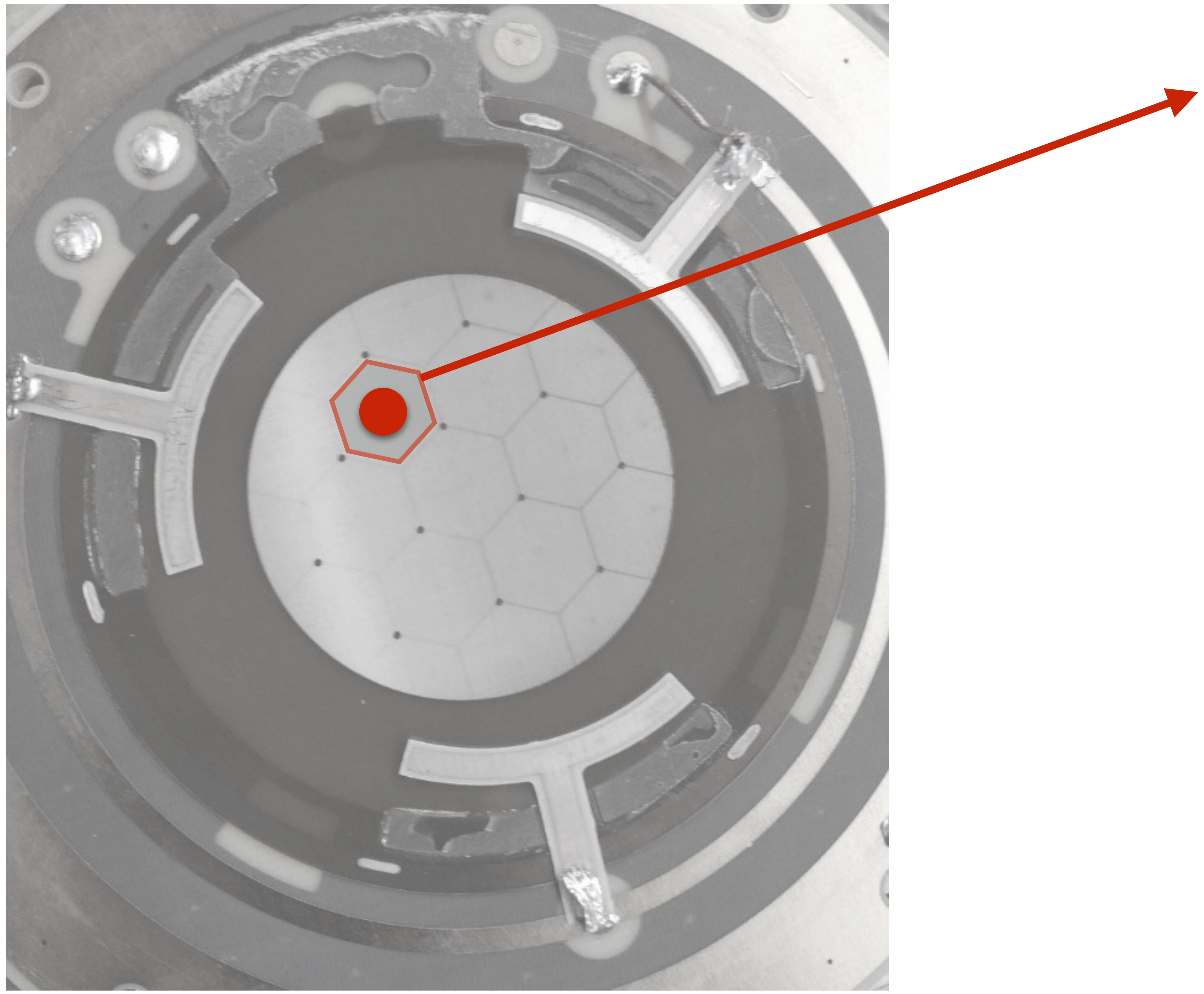


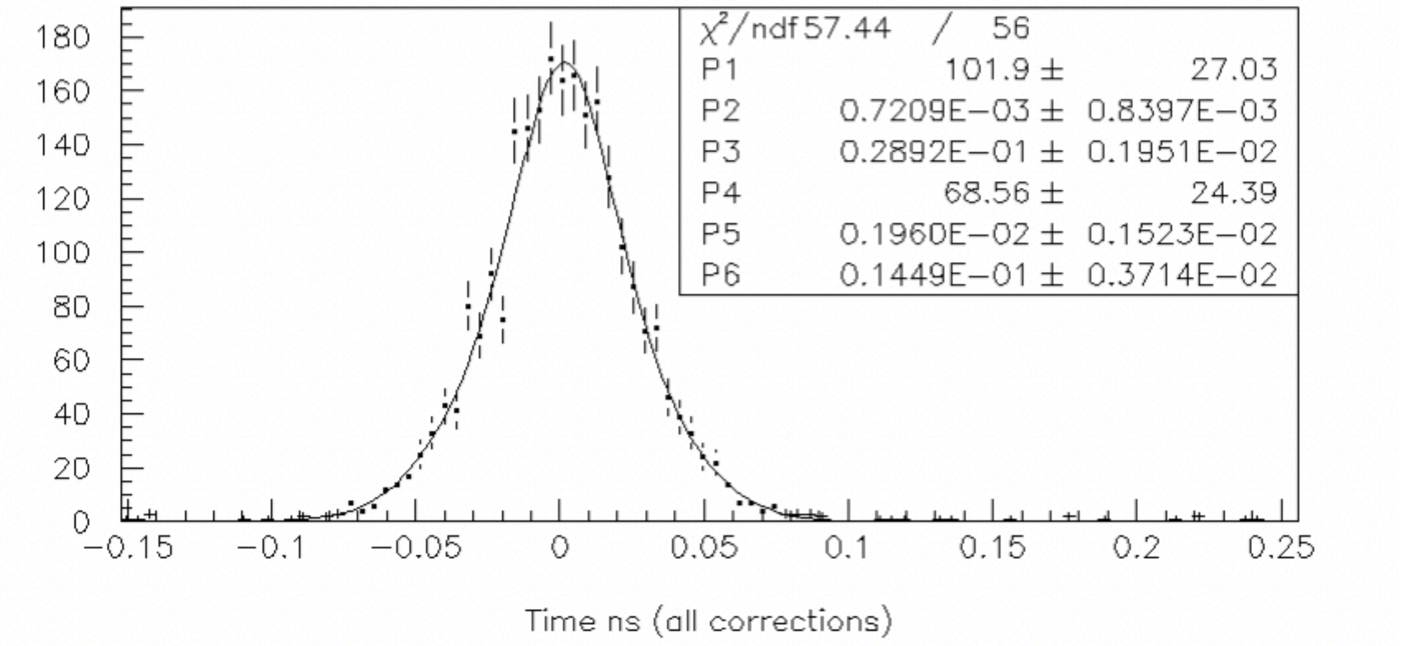
10x10 module
□ 1 cm

Large-area coverage

Scaling up multi-channel PICOSEC





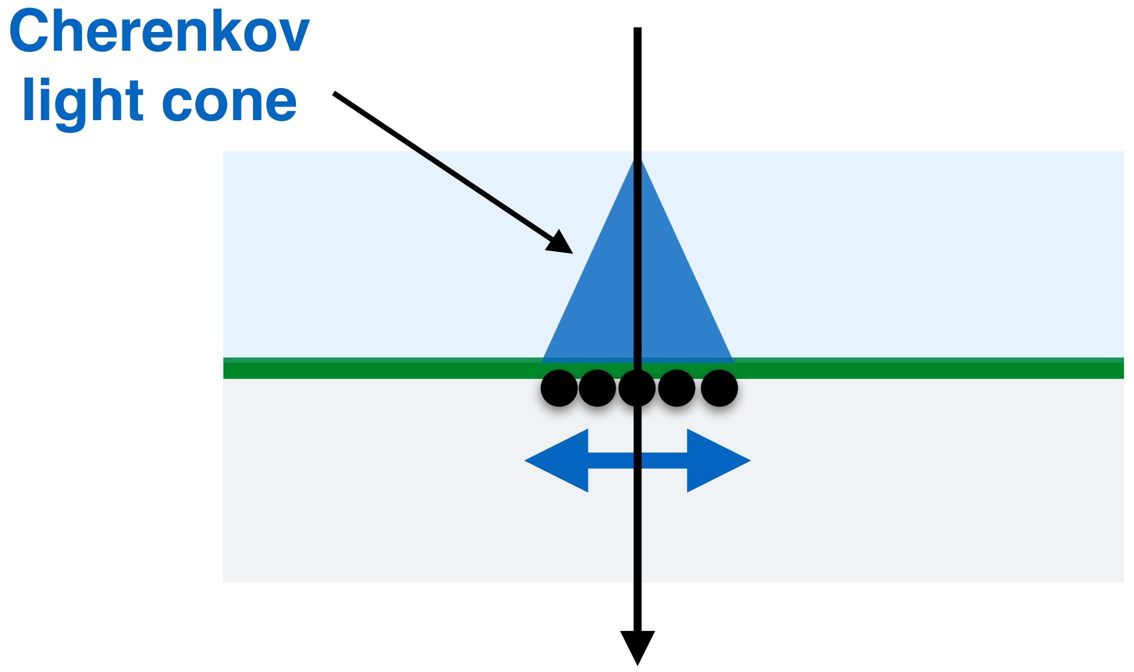


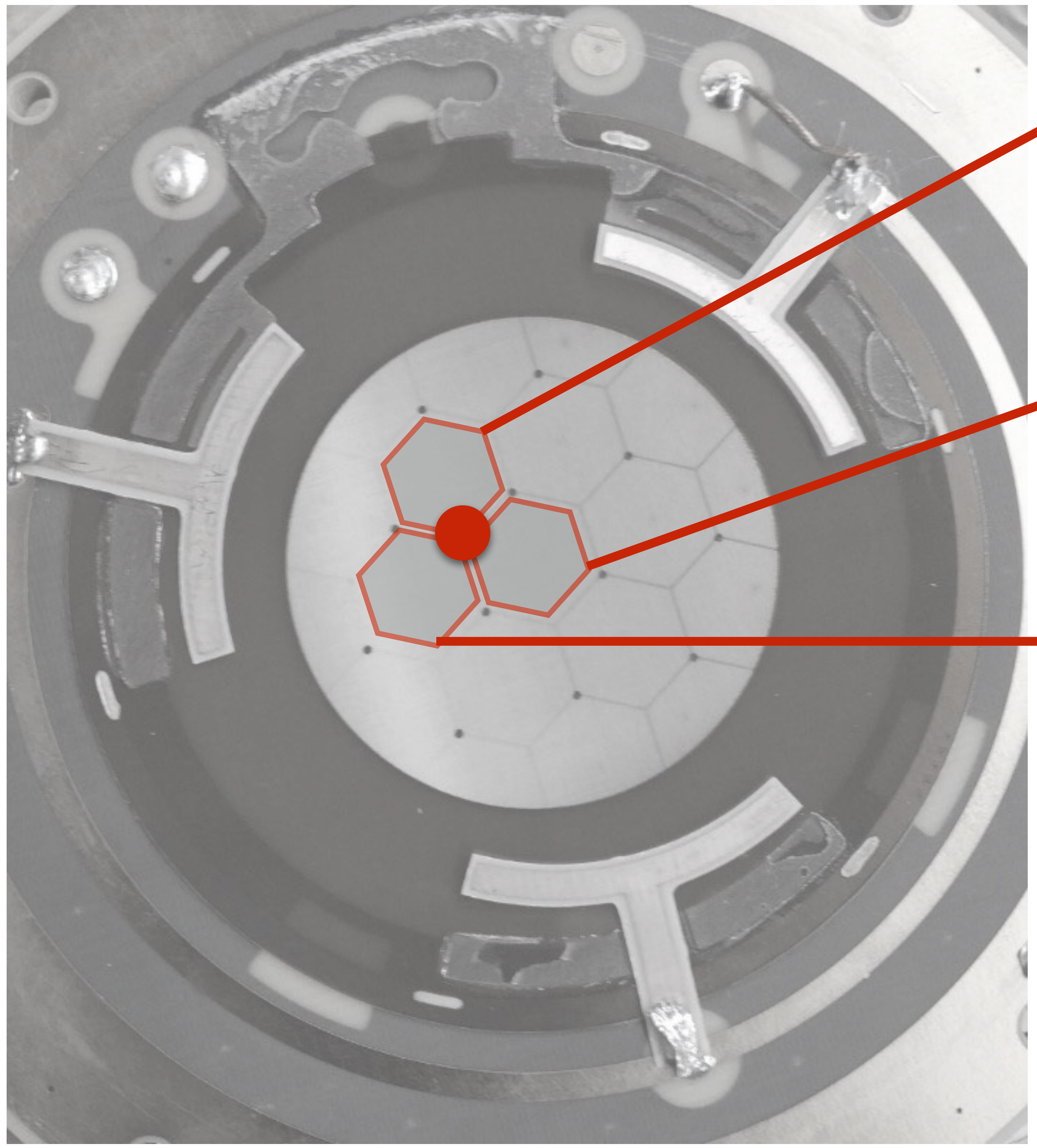
Single pad hit:
25 ps timing resolution for all pads

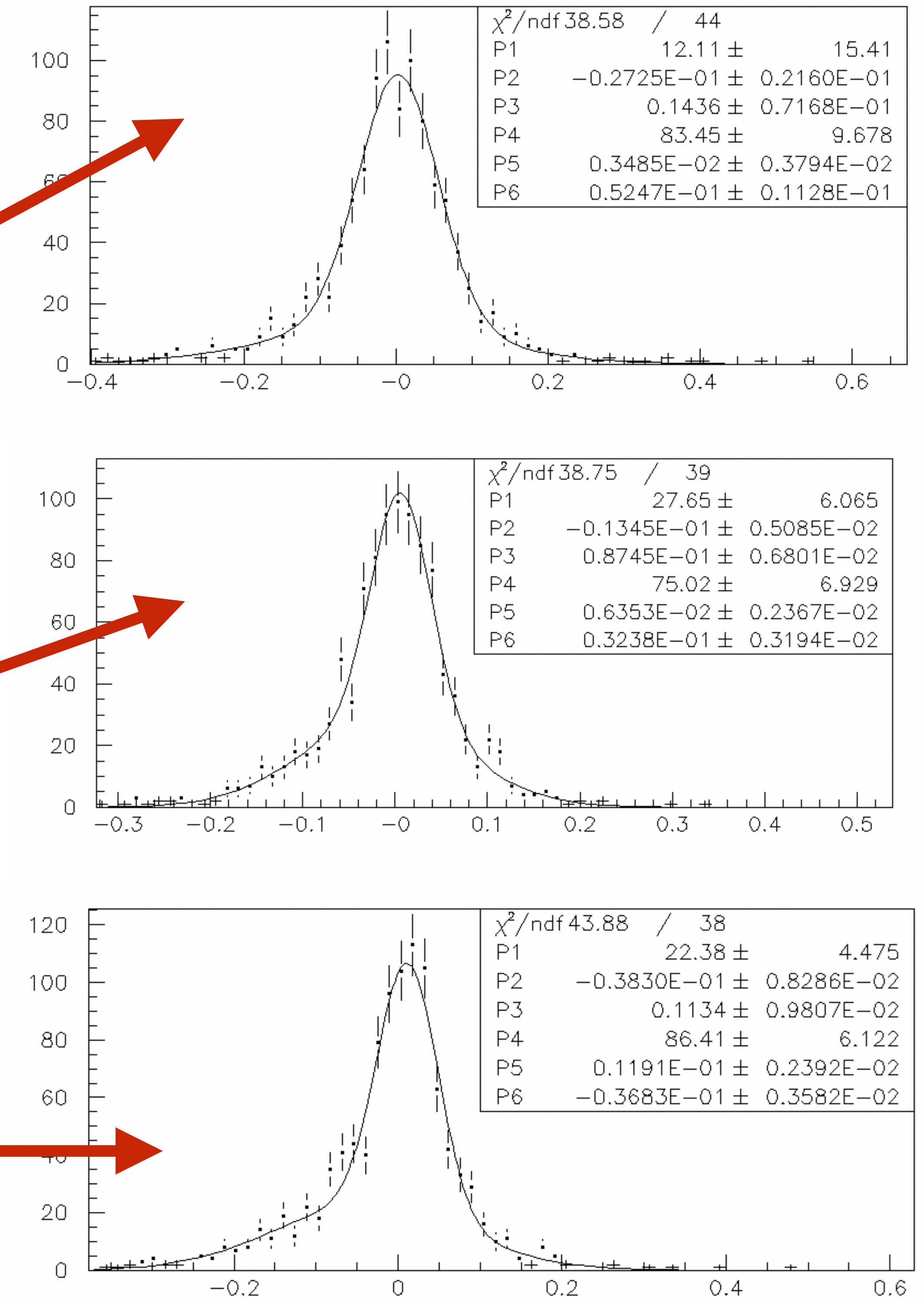
S. Aune et al., "Timing performance of a multi-pad PICOSEC-Micromegas detector prototype", NIM A (993), 2021, https://doi.org/10.1016/j.nima.2021.165076

Large-area coverage

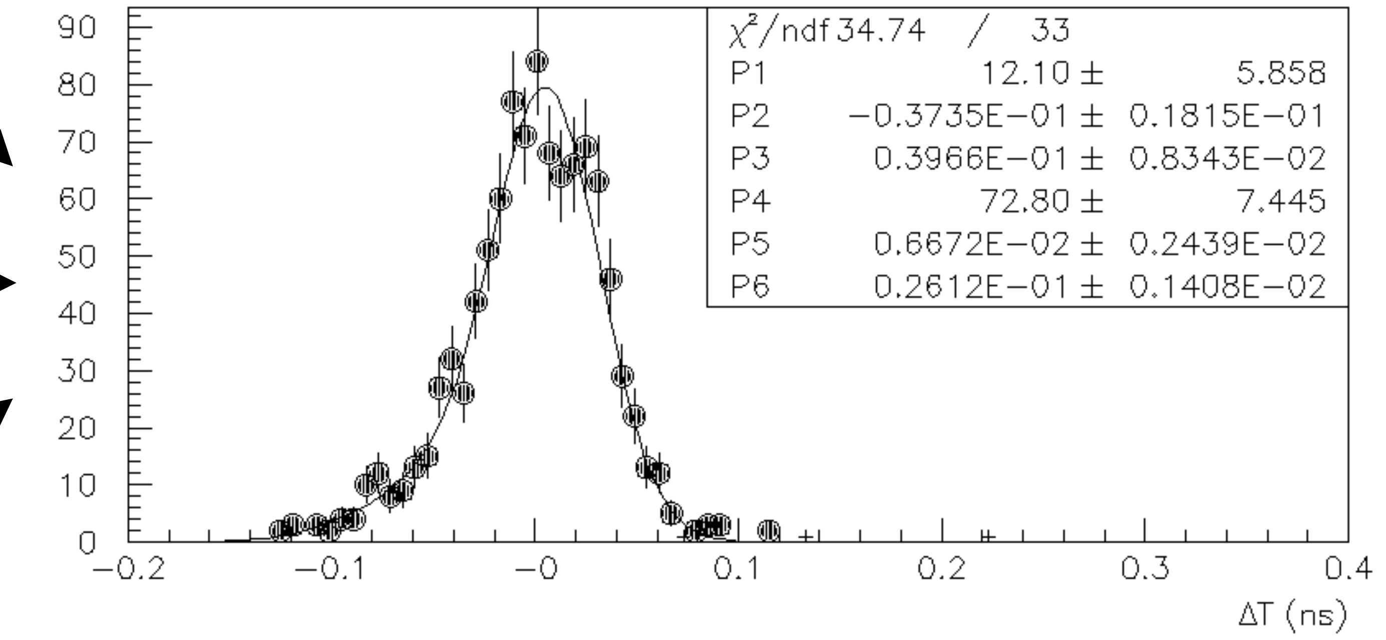
Scaling up multi-channel PICOSEC







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

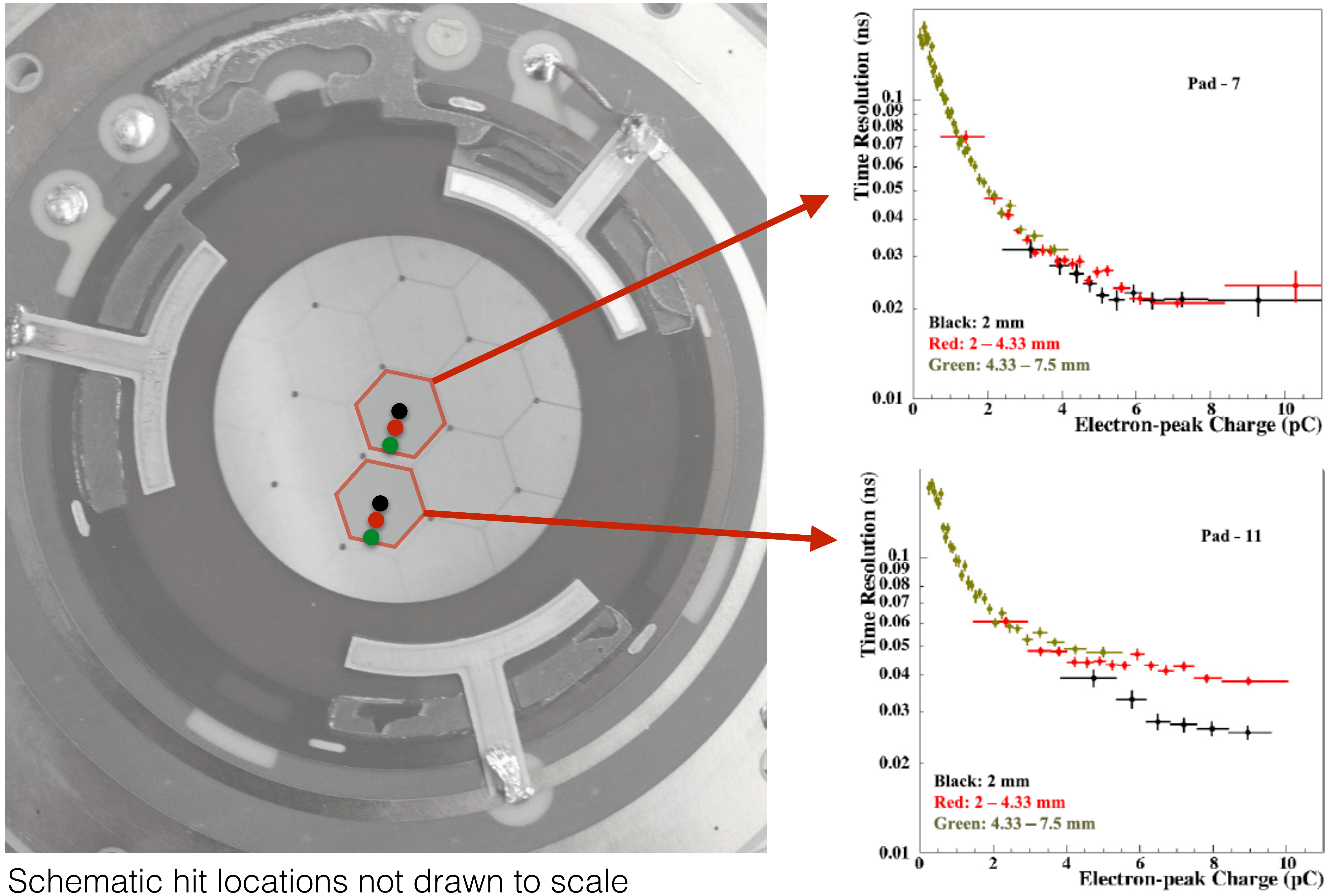
Large-area coverage

Scaling up multi-channel PICOSEC

Using tracking information, dependence of time resolution on hit location within pads (center vs. periphery) was observed:

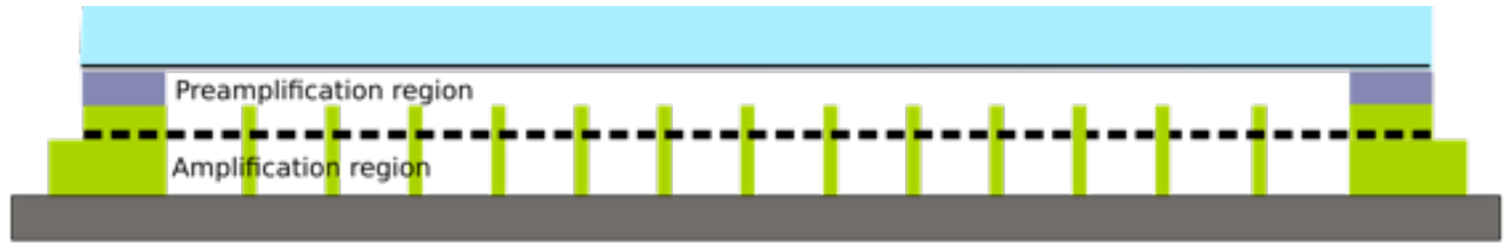
→ **non-uniform pre-amplification gap** from mechanical deformation

→ lower pre-amplification field → lower SAT, wider distribution

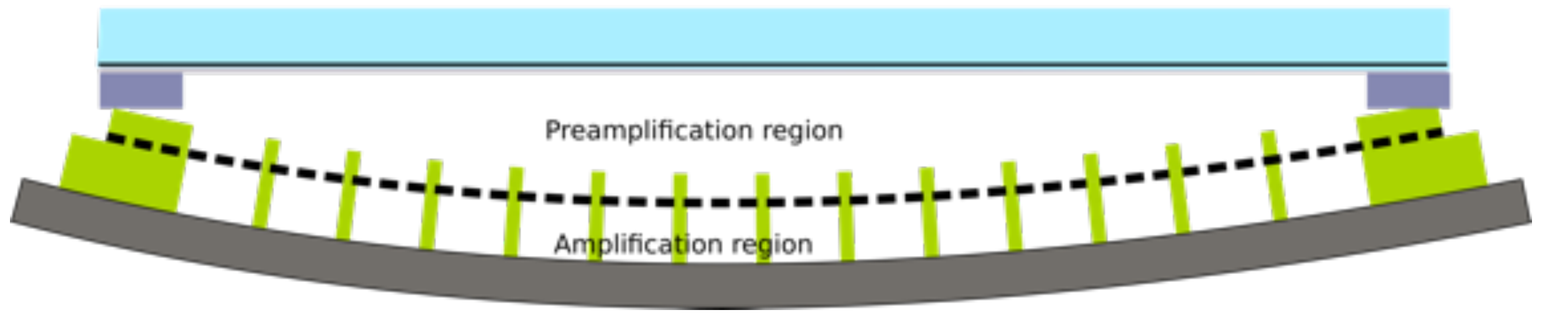


Schematic hit locations not drawn to scale

Ideal, uniform preampfification gap

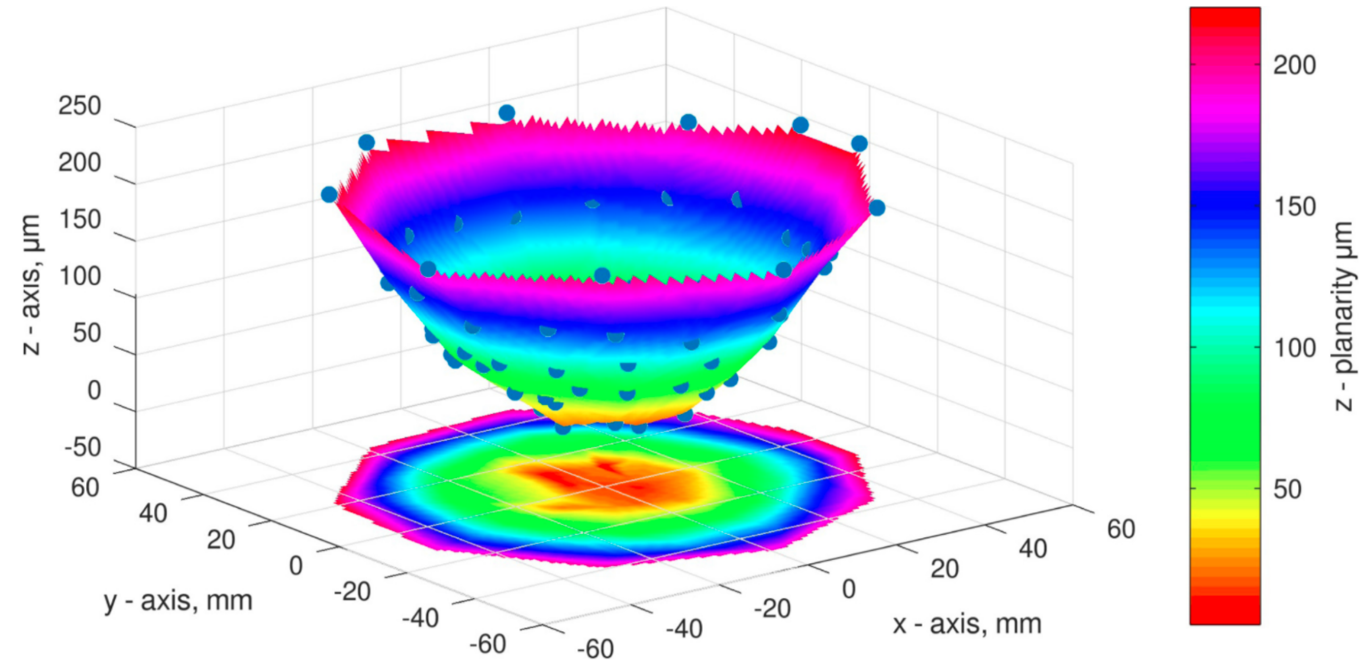


Observed, deformed preamplification gap



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?

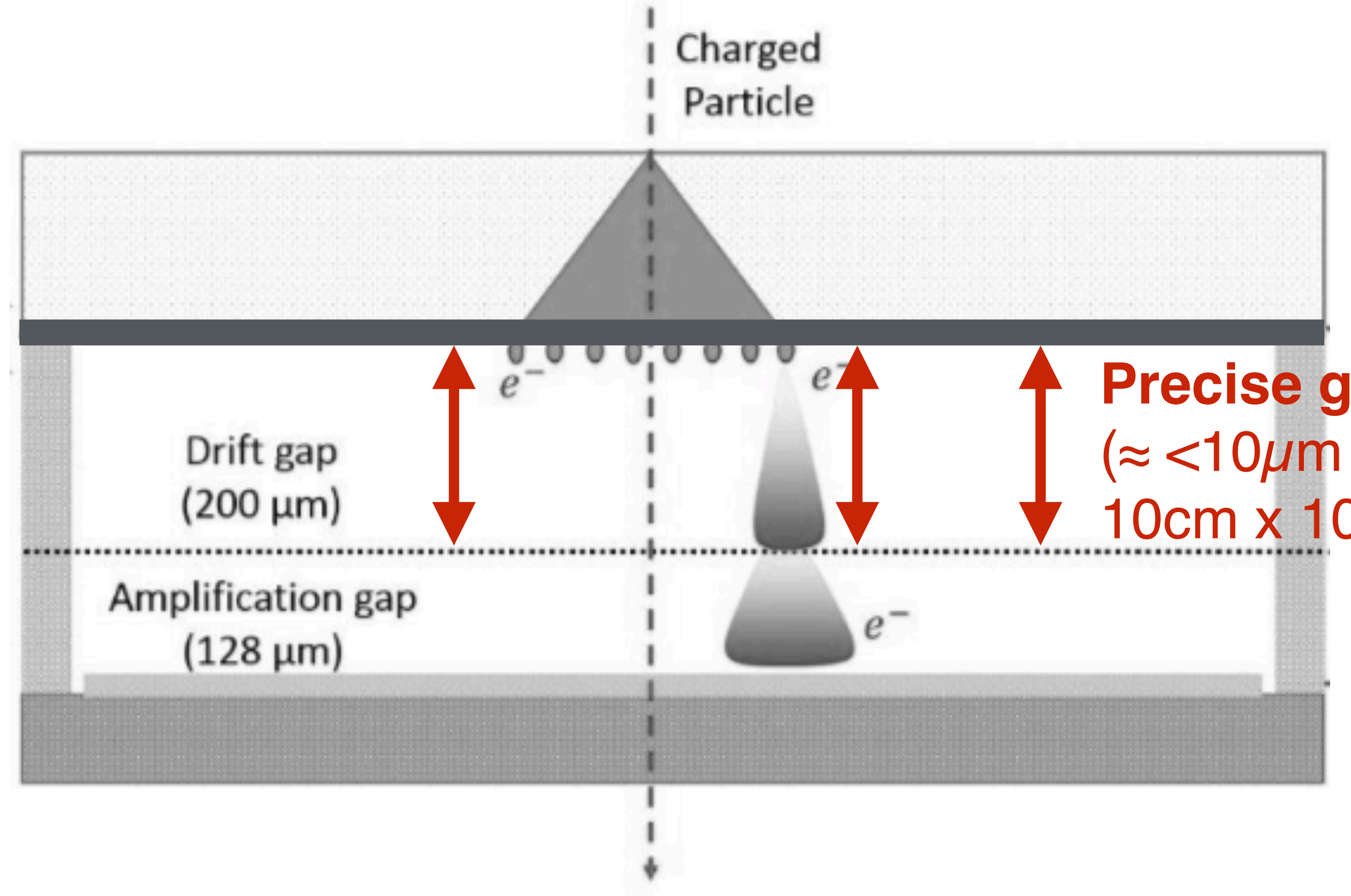
S. Aune et al., NIM A (993), 2021, https://doi.org/10.1016/j.nima.2021.165076

Detector module mechanics

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

Bulk Micromegas with minimised dead area on ceramic-core PCB

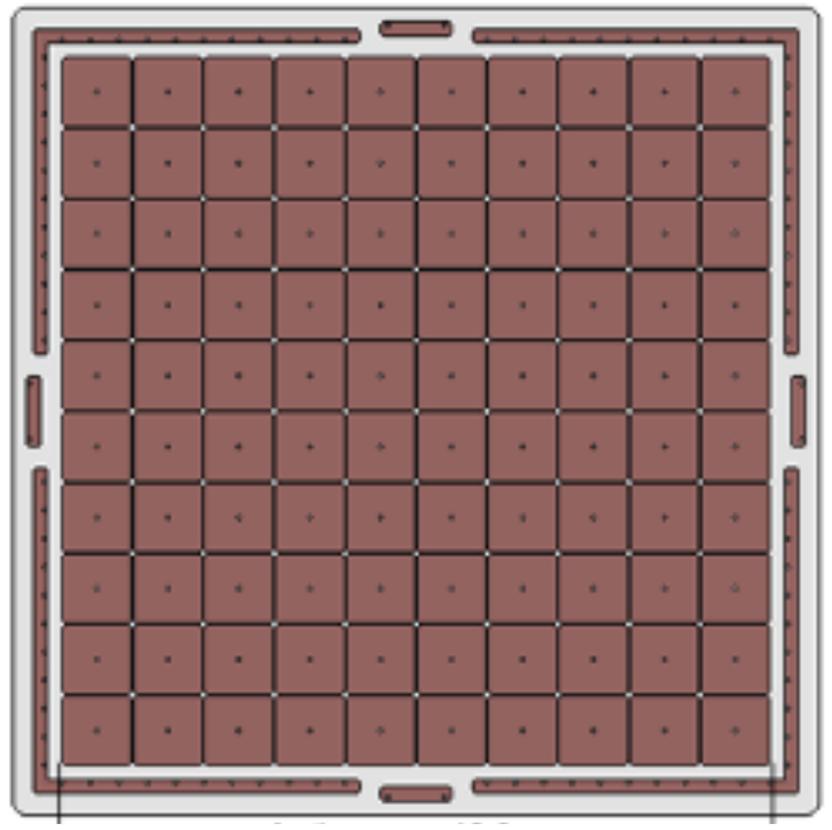
- 10x10 pads with 10cm x 10cm active area
- Iterative **polishing** steps to improve substrate and final board planarity
- **<10 μm deformation** across active area



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

Single pad (2016)
⌀1 cm

Multi pad (2017)
⬡ 1 cm



10x10 module
□ 1 cm

Schematic not drawn to scale

Detector module mechanics

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

Bulk Micromegas with minimised dead area on ceramic-core PCB

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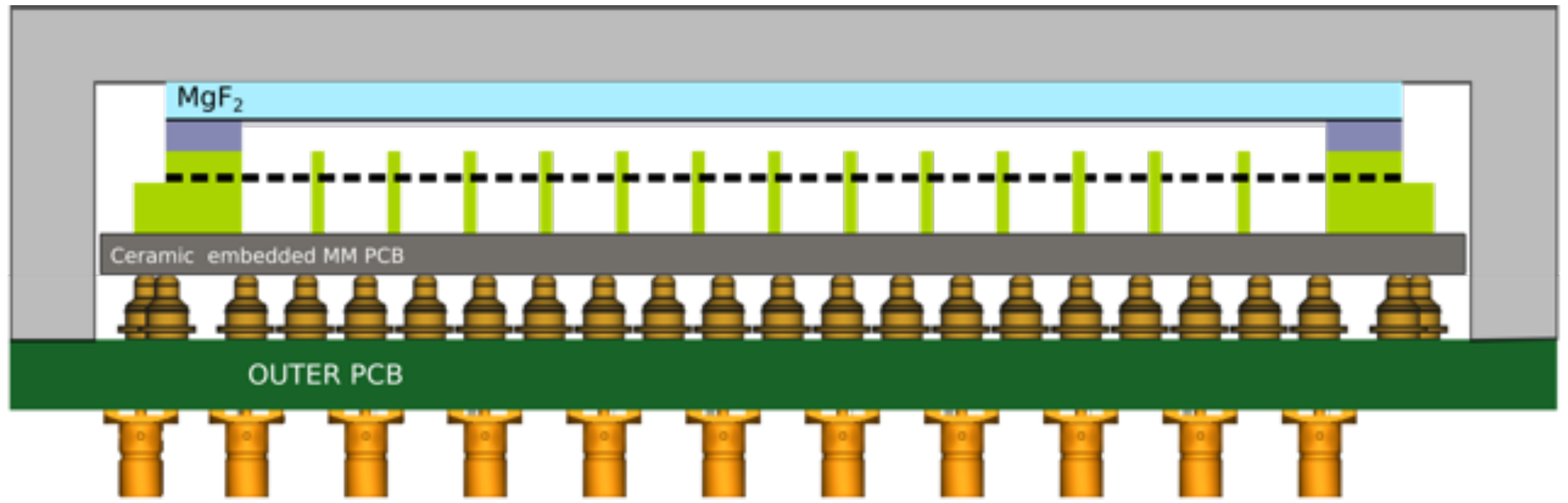
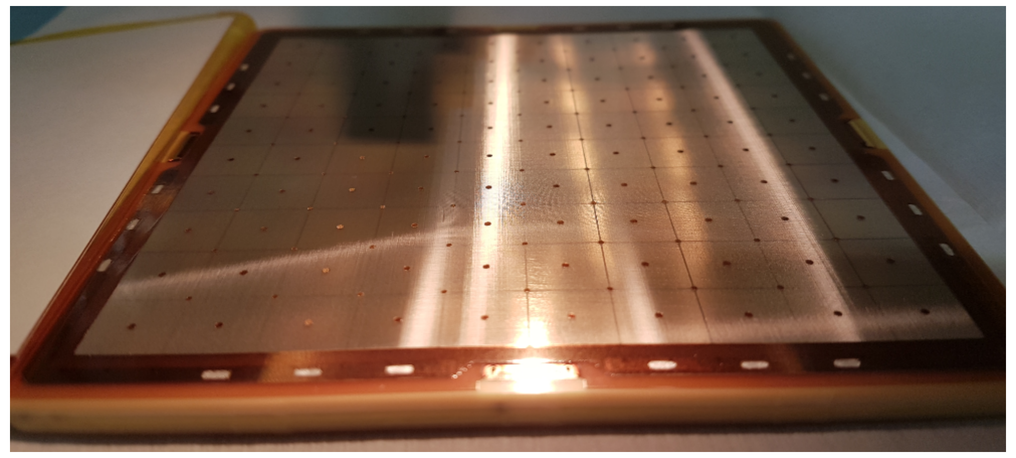
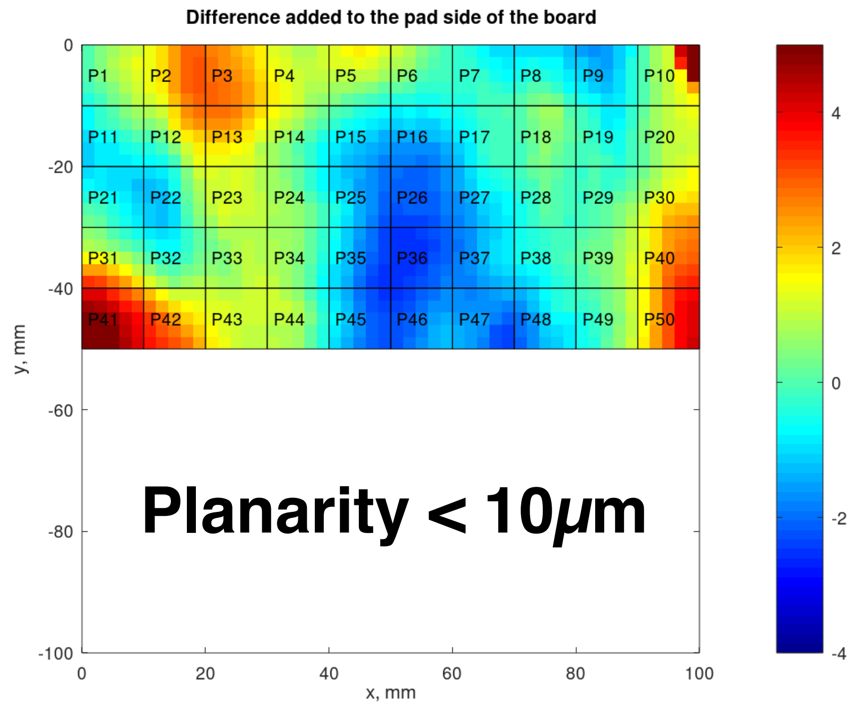
Cross-section

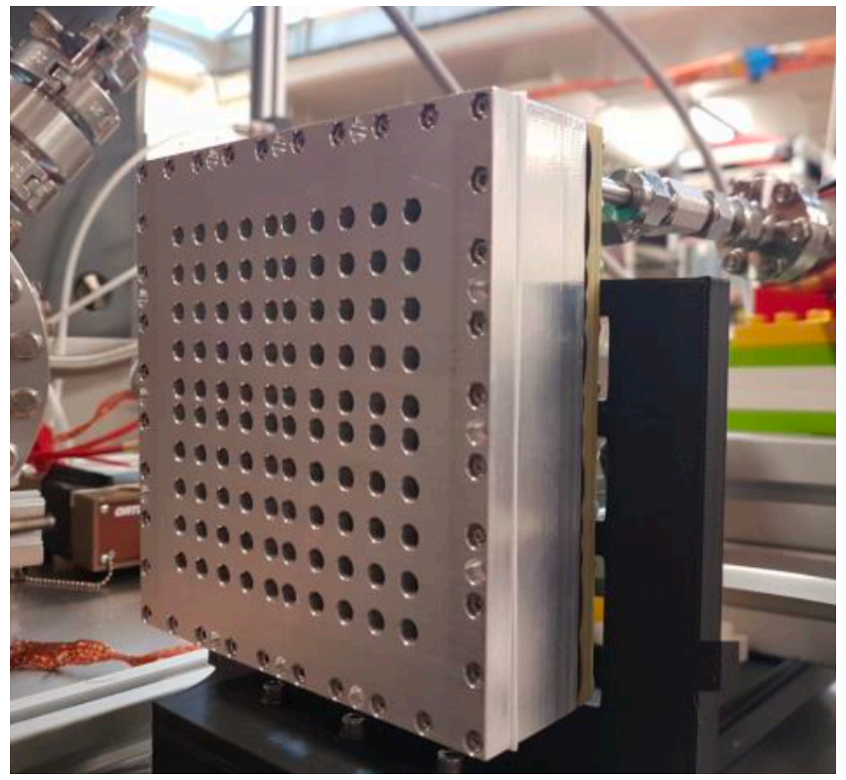


Bulk Micromegas on ceramic PCB



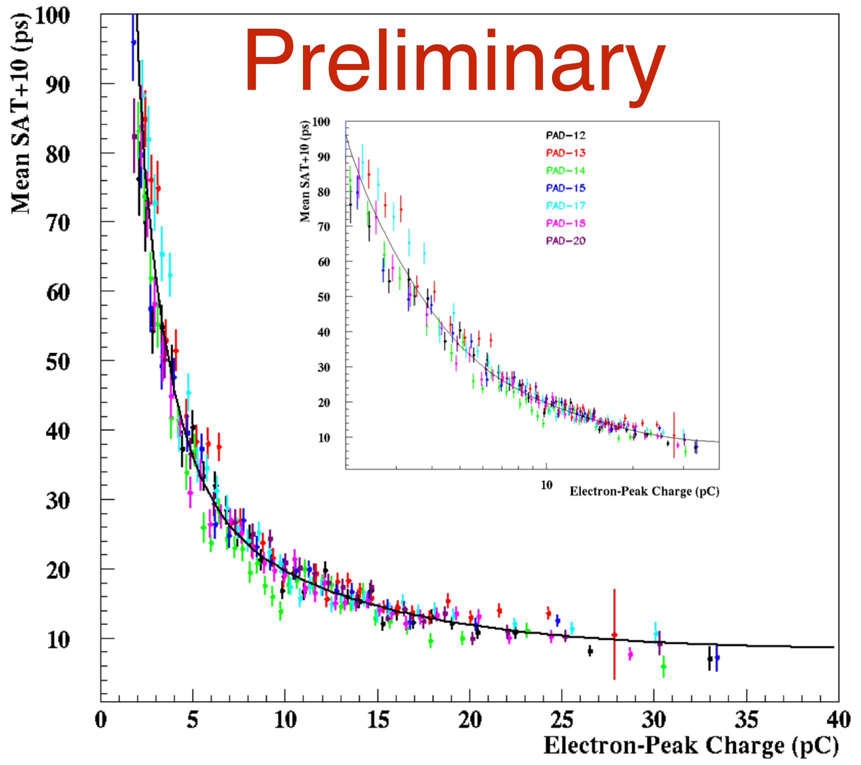


Planarity < 10μm



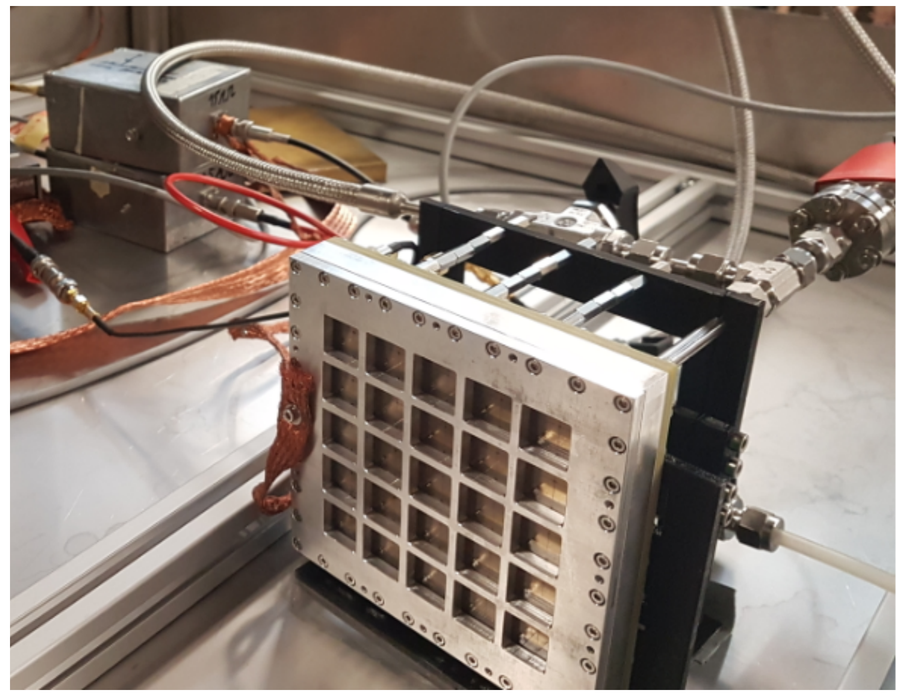
A. Utrobicic, Picosec precise timing detectors : recent results, status and plans, RD51 Collaboration Meeting Nov 2021, https://indico.cern.ch/event/1071632/contributions/4612229/

Global parametrisation of timewalk across measured pads

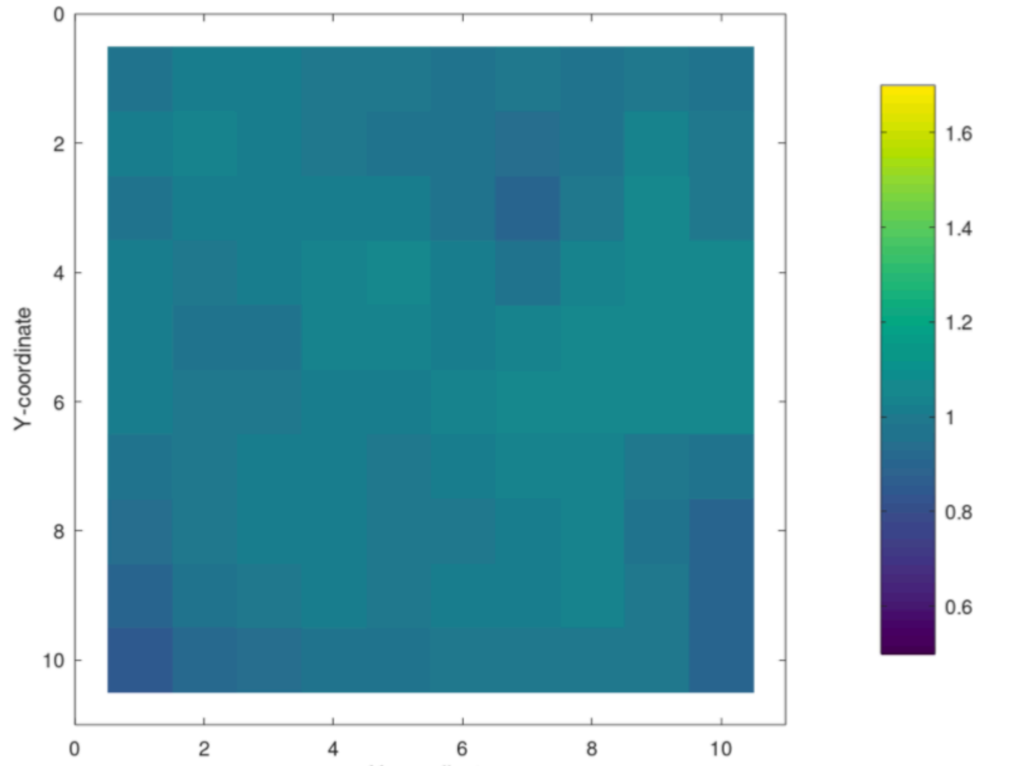


G. Maniatis, A. Kallitsopoulou, S. Tzamarias

Lab test



Gain uniformy σ = 3.9 %



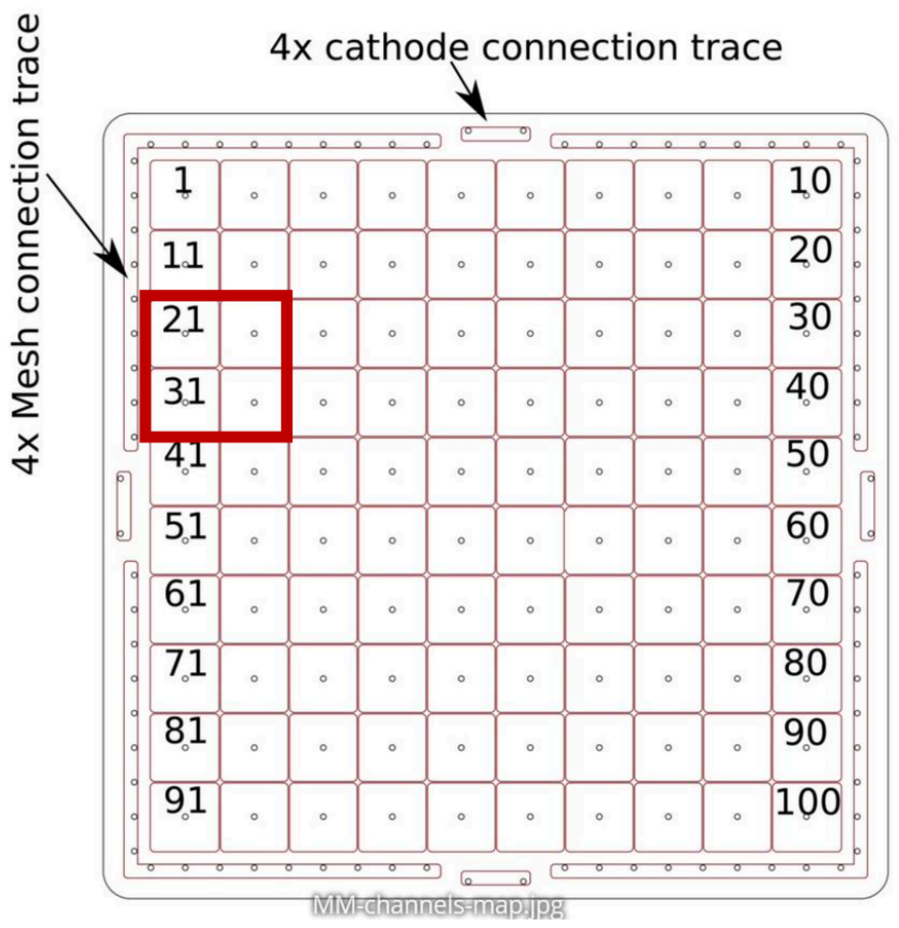
Gain map shows small variation of gain across active area compatible with residual (<10μm) non-planarity of Micromegas PCB

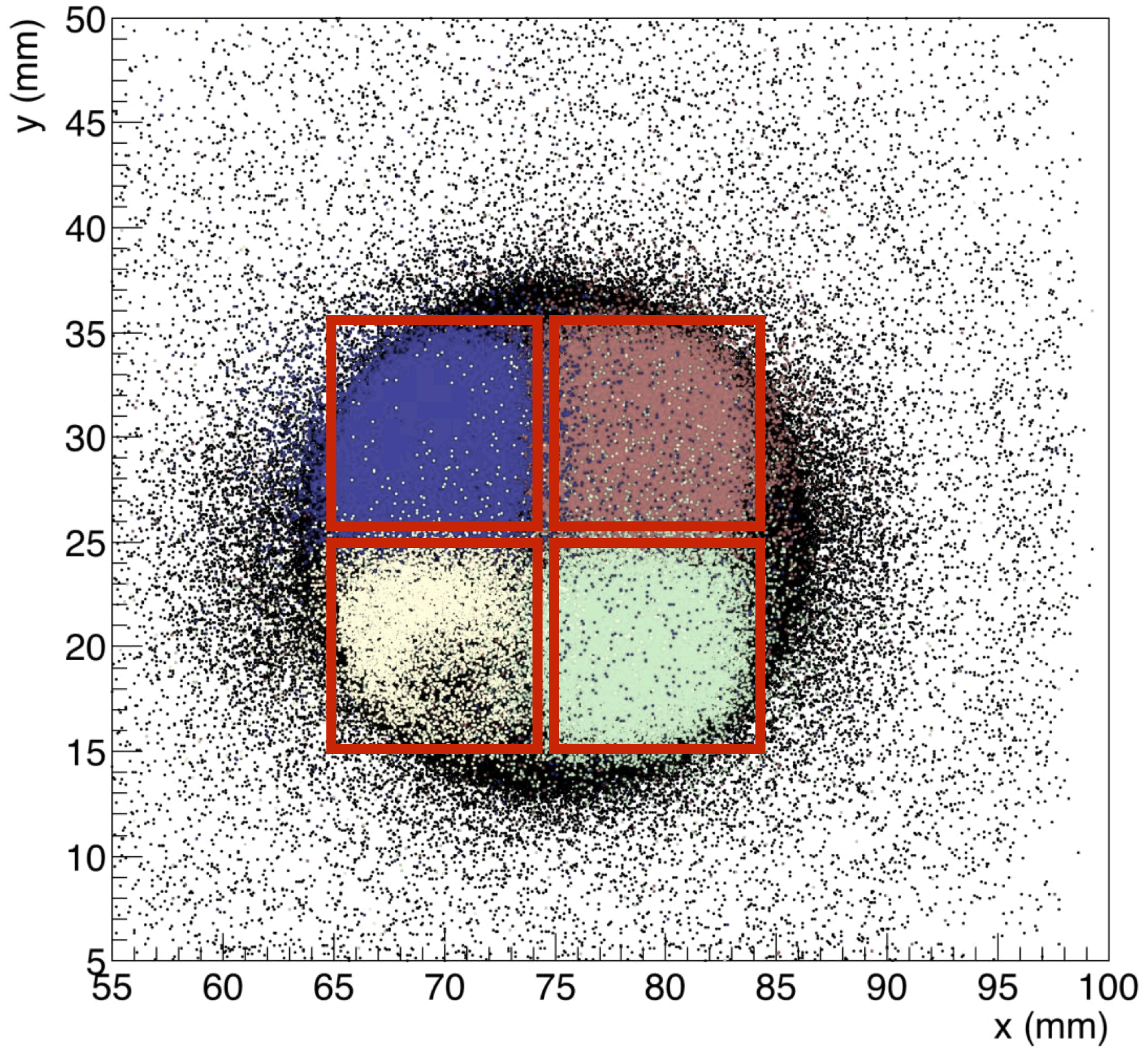
A. Utrobičić

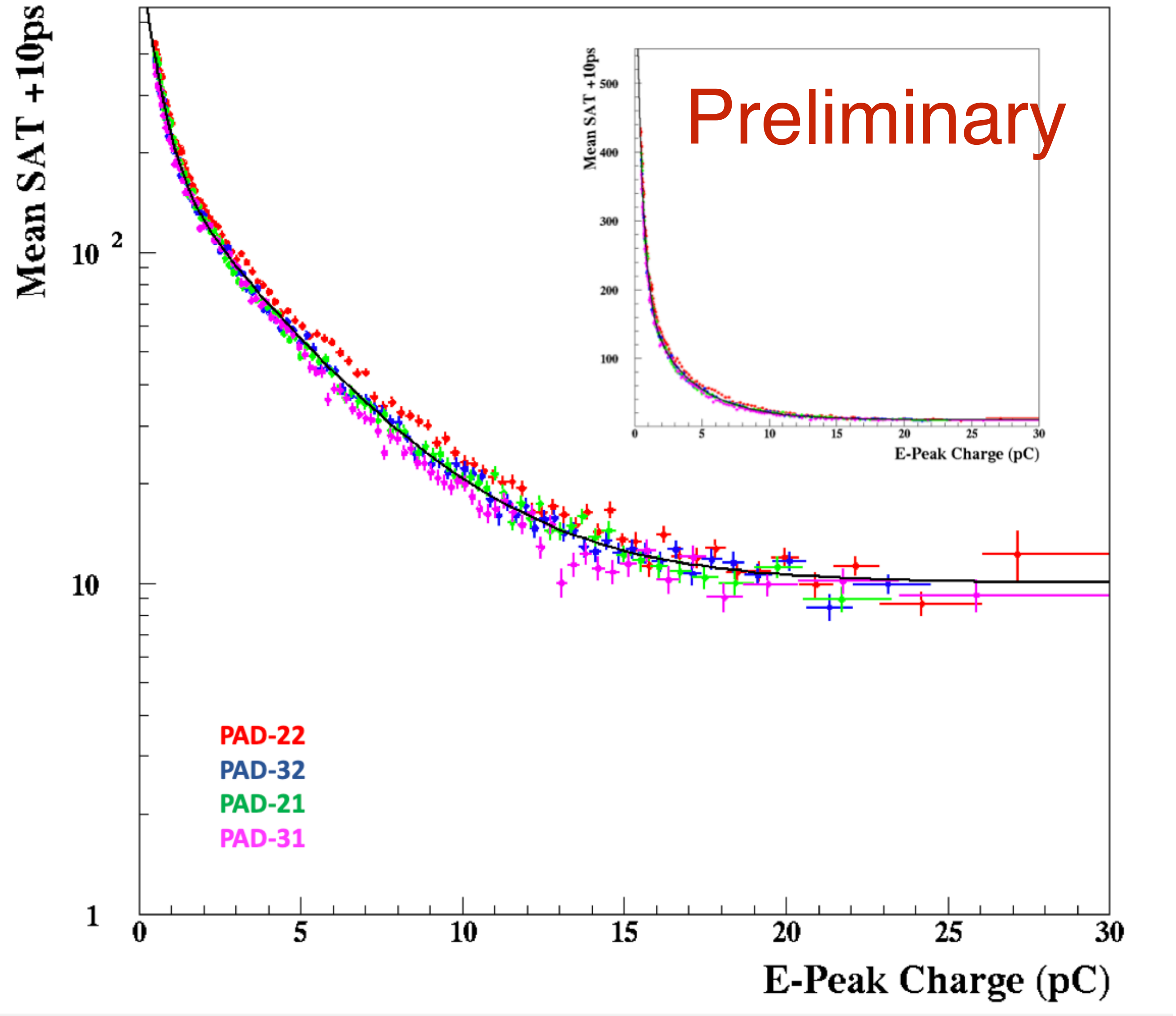
Signal sharing

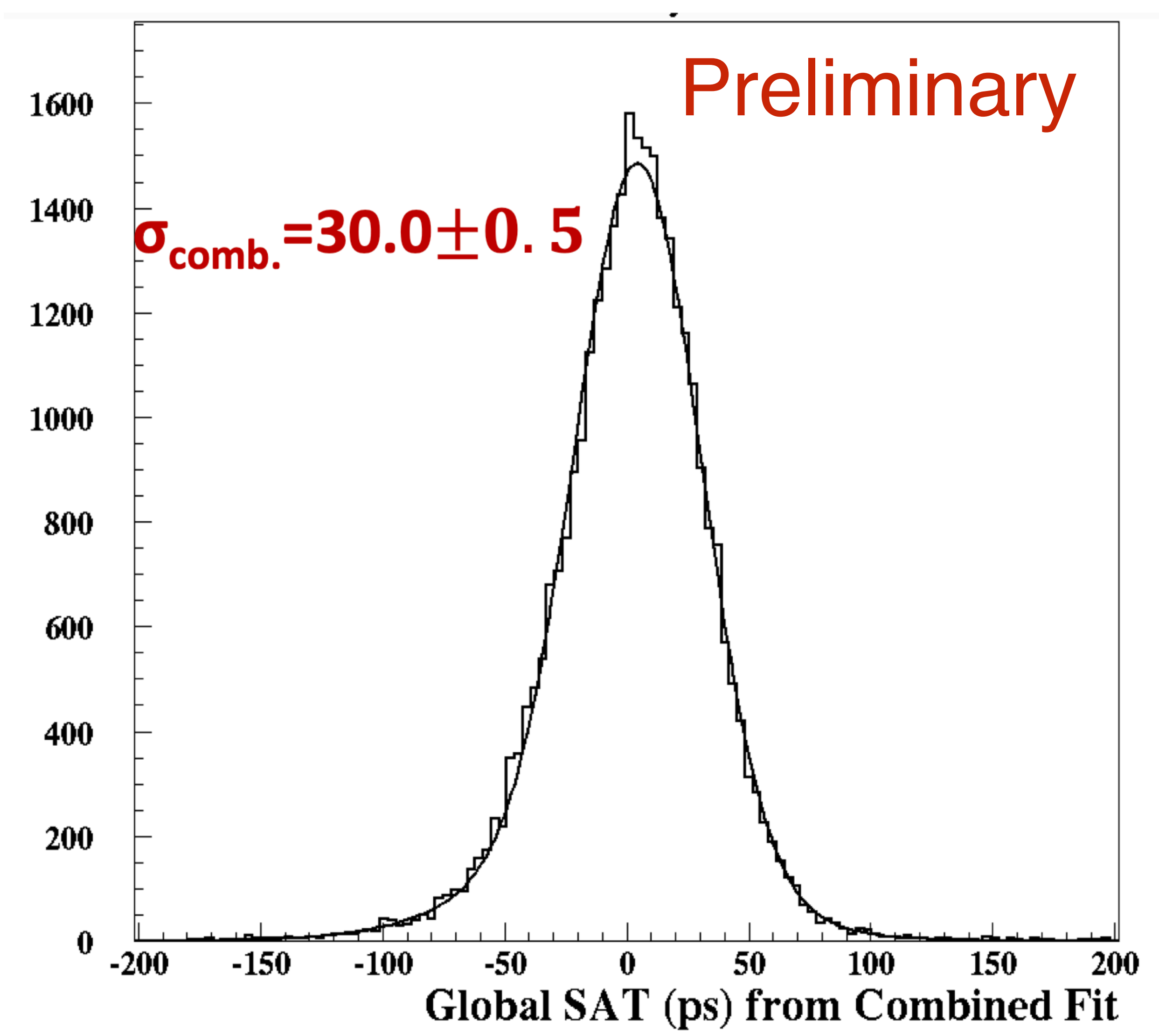
Detector shows uniform response and different anode pads exhibit the same trend of signal-arrival-time as function of electron peak charge → **universal time walk correction**

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/

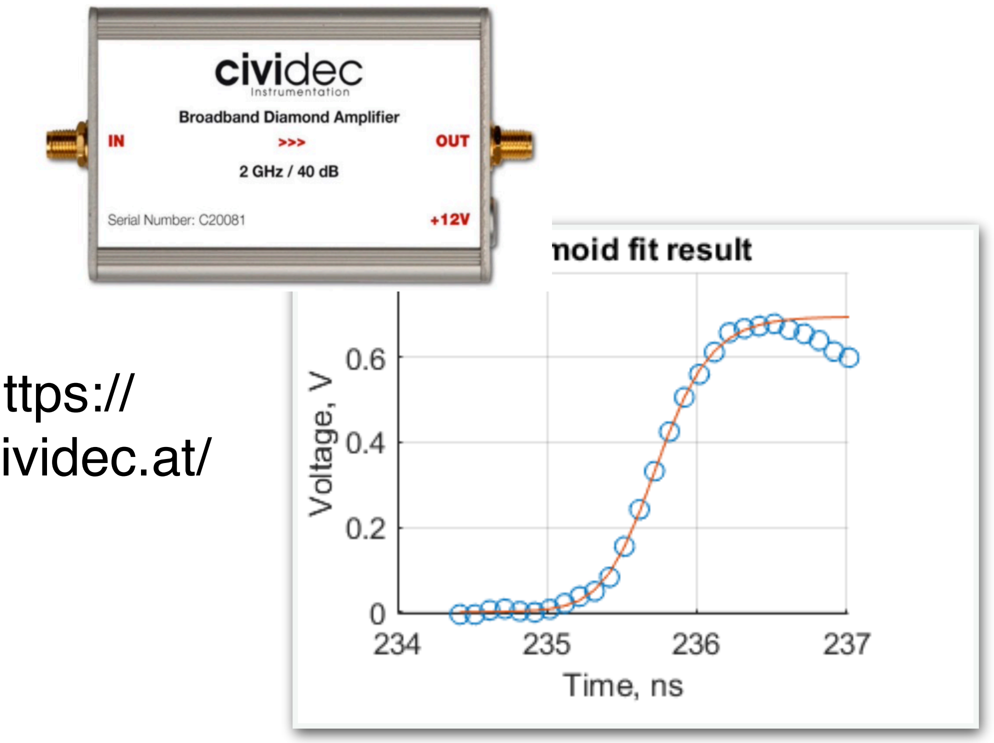
Schematic not drawn to scale

Readout electronics

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

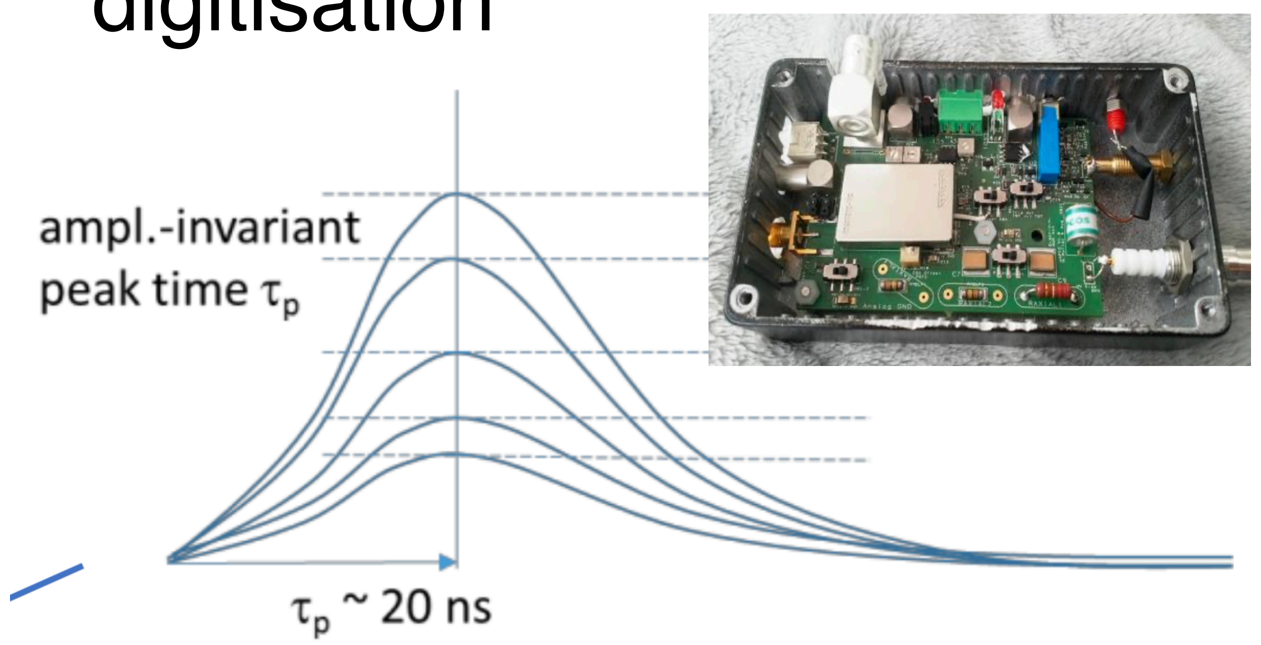
Detector → **Preamplifier** → Digitisation

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



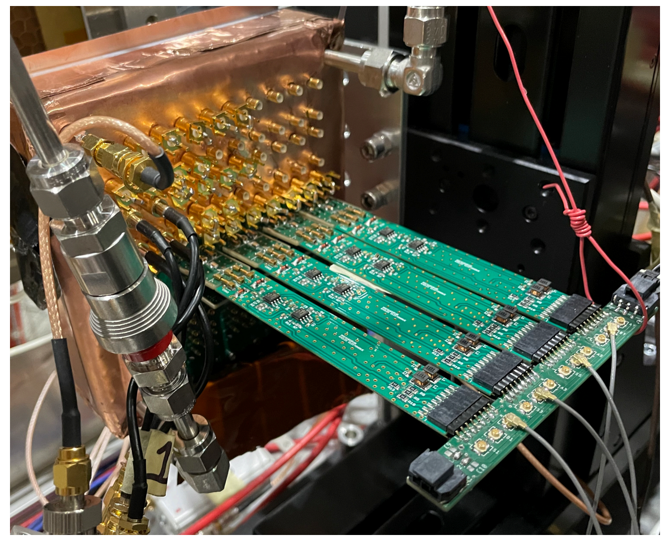
https://cividec.at/

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



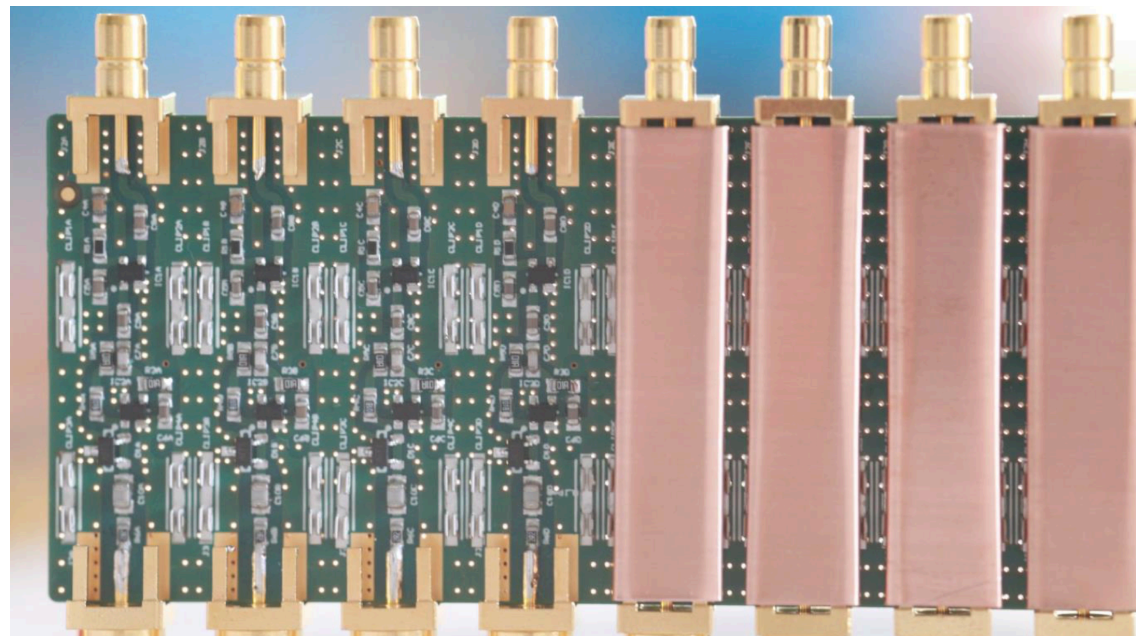
CSA-shaper, H. Muller, CERN

Custom preamplifiers (P. Legou, CEA Saclay)
- Fast risetime, low noise, moderate gain
- Good timing resolution
- Different circuits being tested and optimised



Preamp card, 10x10 module

Custom high-bandwidth amplifiers (A. Utrobicic, M. Kovacic, University of Zagreb)
- Bandwidth ≈ 625 MHz with 38.5db@100MHz
- Low power consumption of 78mW/channel



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

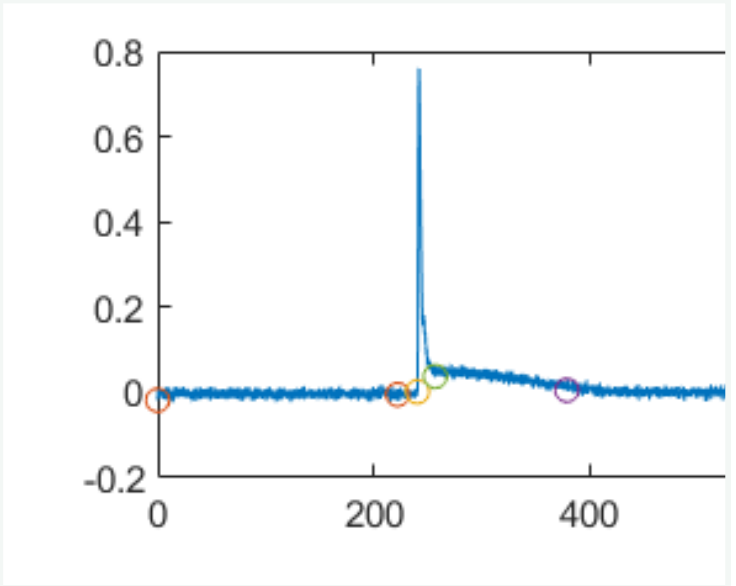
Readout electronics

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

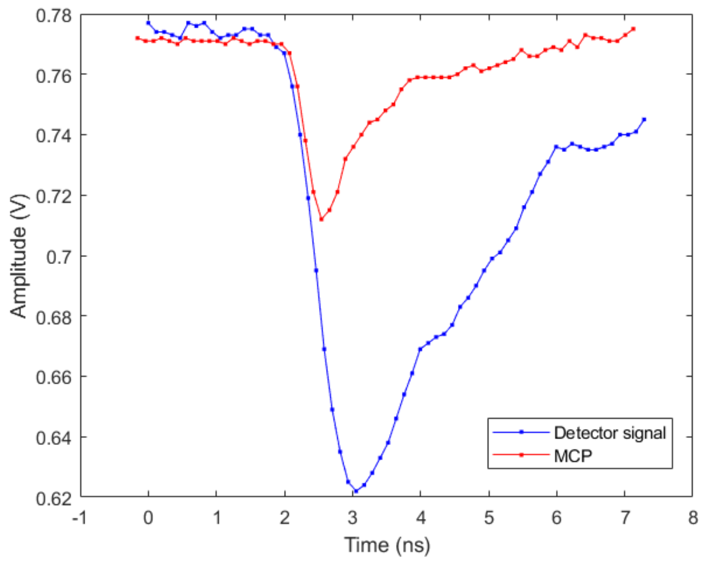
- Record full waveform (electron + ion)



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.)

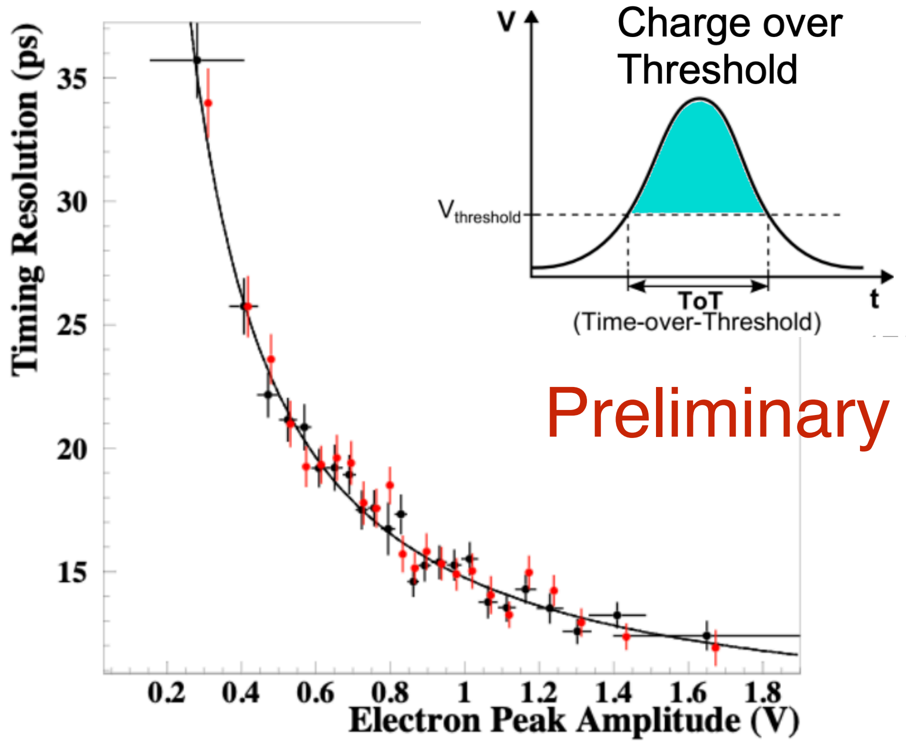


Waveforms recorded at 8.5 GS/s

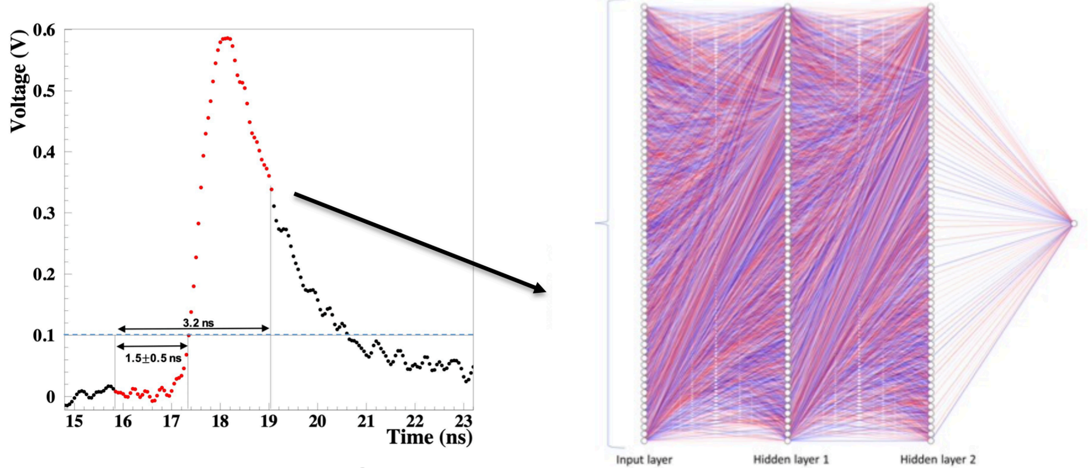
Alternative approaches:

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

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



Artificial NN to extract time from rising edge



A. Tsiamis, PSD 12

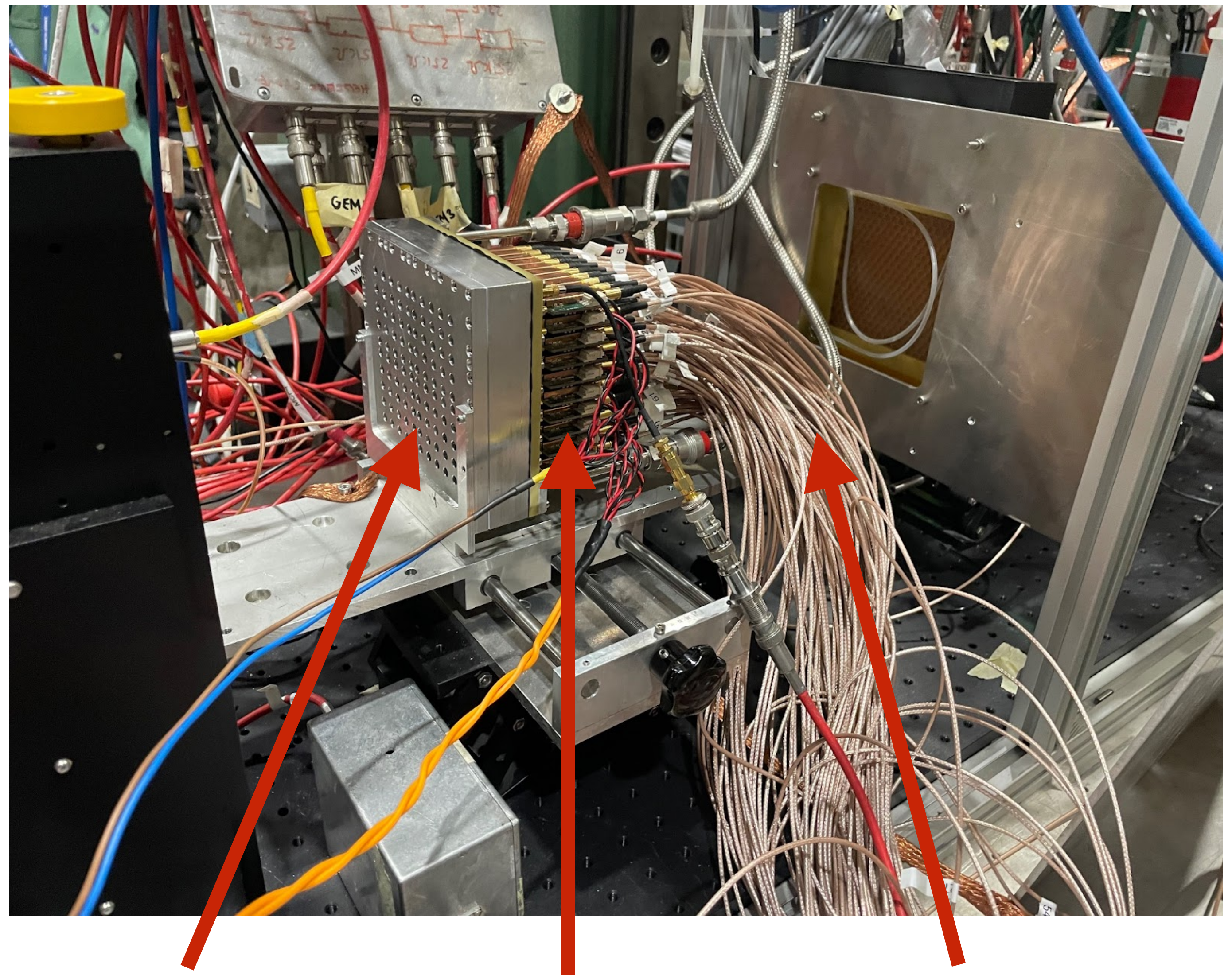
→ 64 samples as input, ≈reproduce time resolution with only **5 GS/s**

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

100CH PICOSEC readout: custom preamp + SAMPIC

Readout of 10x10 pad Multipad PICOSEC with custom preamplifier cards and SAMPIC digitisation

Characterised in muon test beam with reference MCP-PMT scanned across full active area

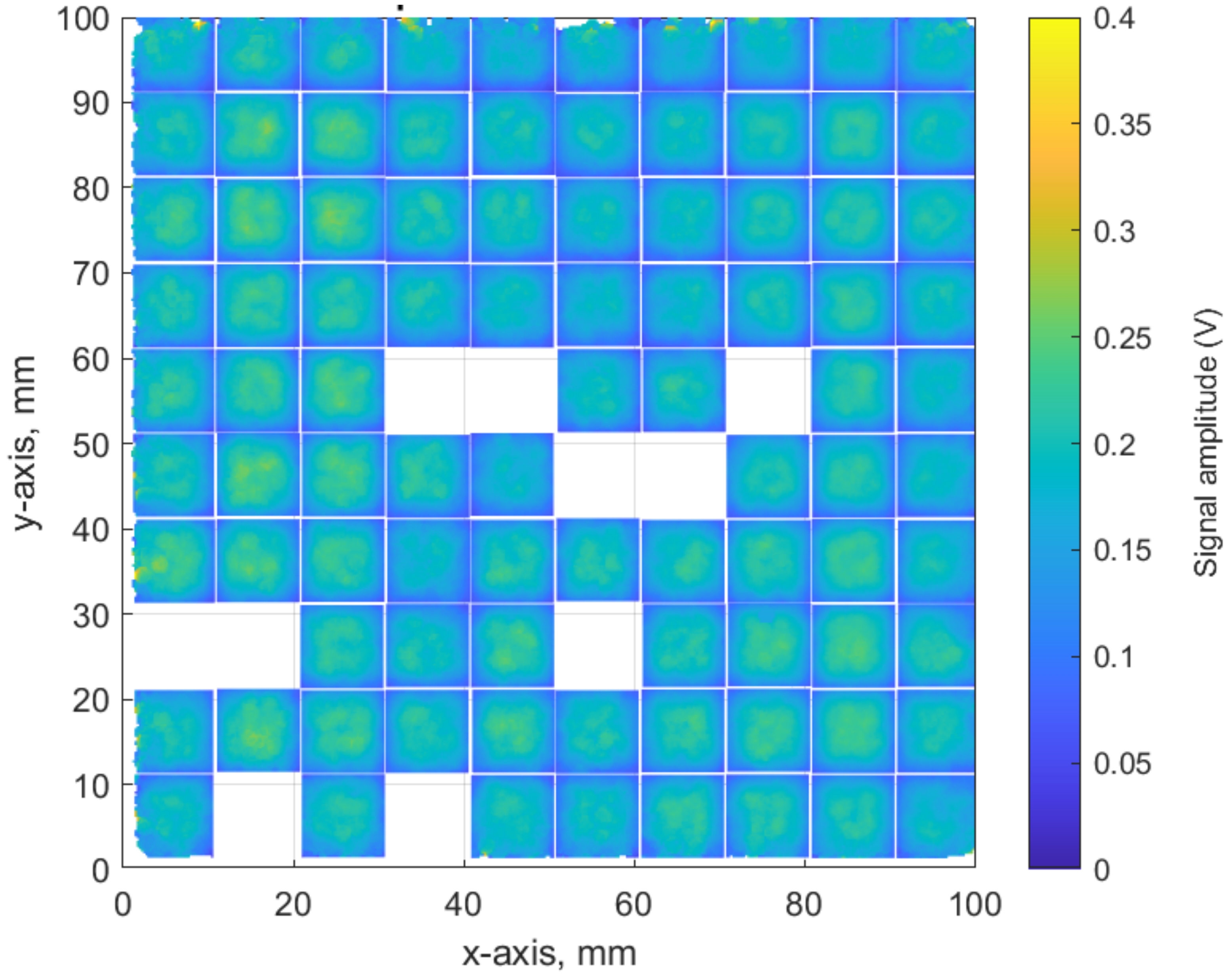


10x10 Multipad PICOSEC

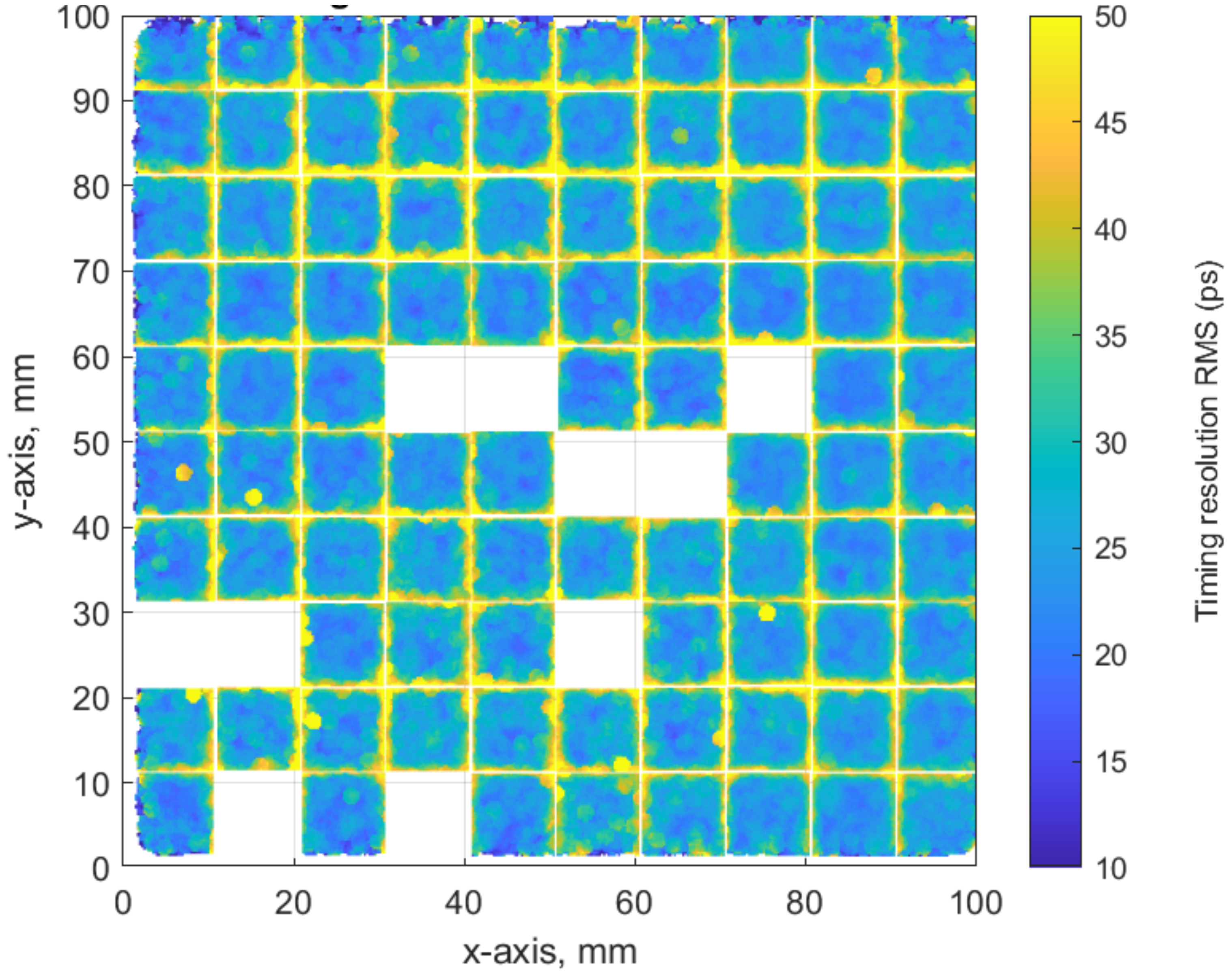
Custom preamp cards

Cables to 128CH SAMPIC

Signal amplitude per pad



Timing resolution per pad



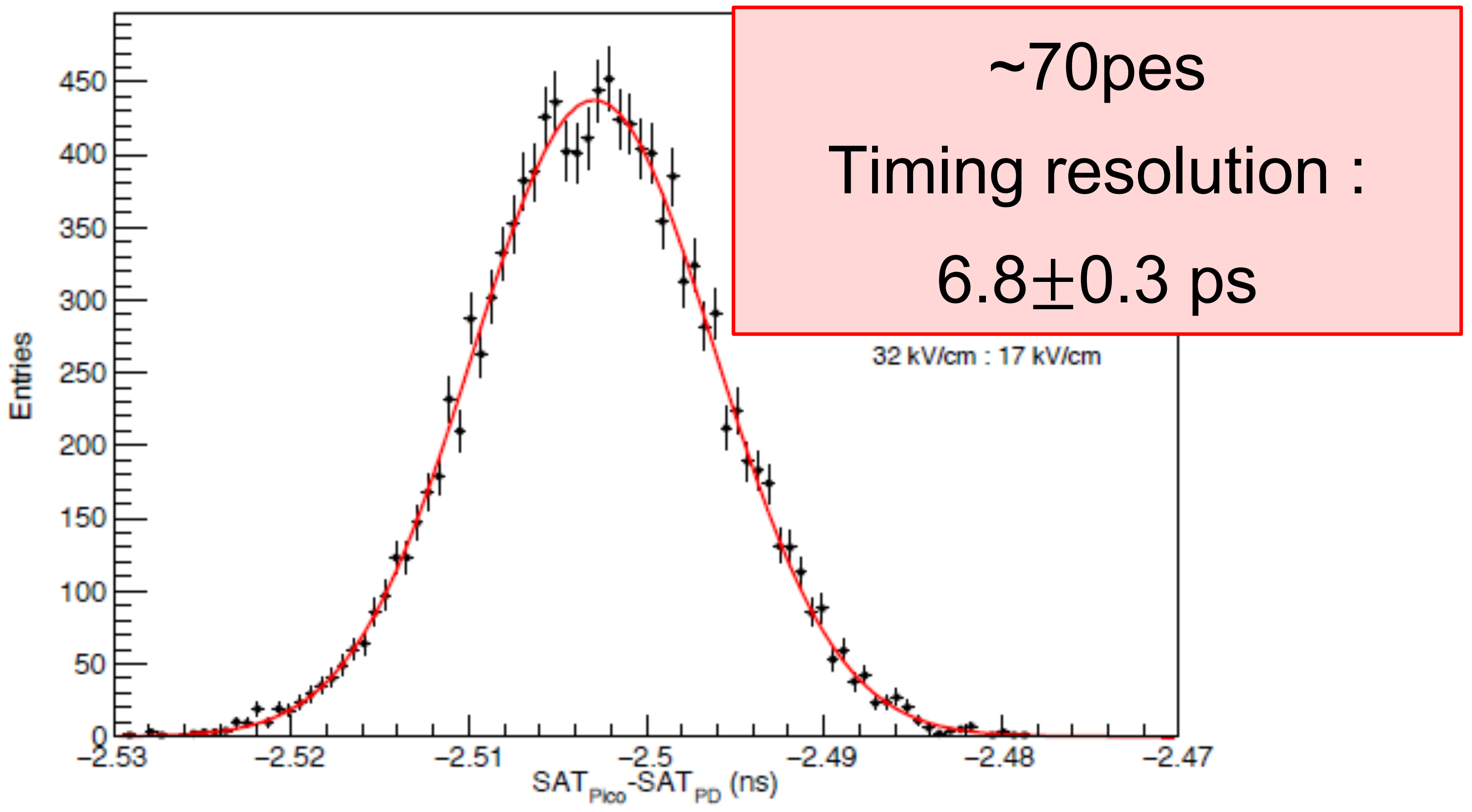
Uniform signal amplitude and time resolution across active area shows uniform detector preamplification region

Visible structure in pads is due to partially contained events and can be corrected by combining signals shared across neighbouring pads as shown for previous multipad prototype

Physics Studies & Experimental Results

Embed a PICOSEC-Micromegas layer inside an electromagnetic calorimeter after few radiation lengths absorber

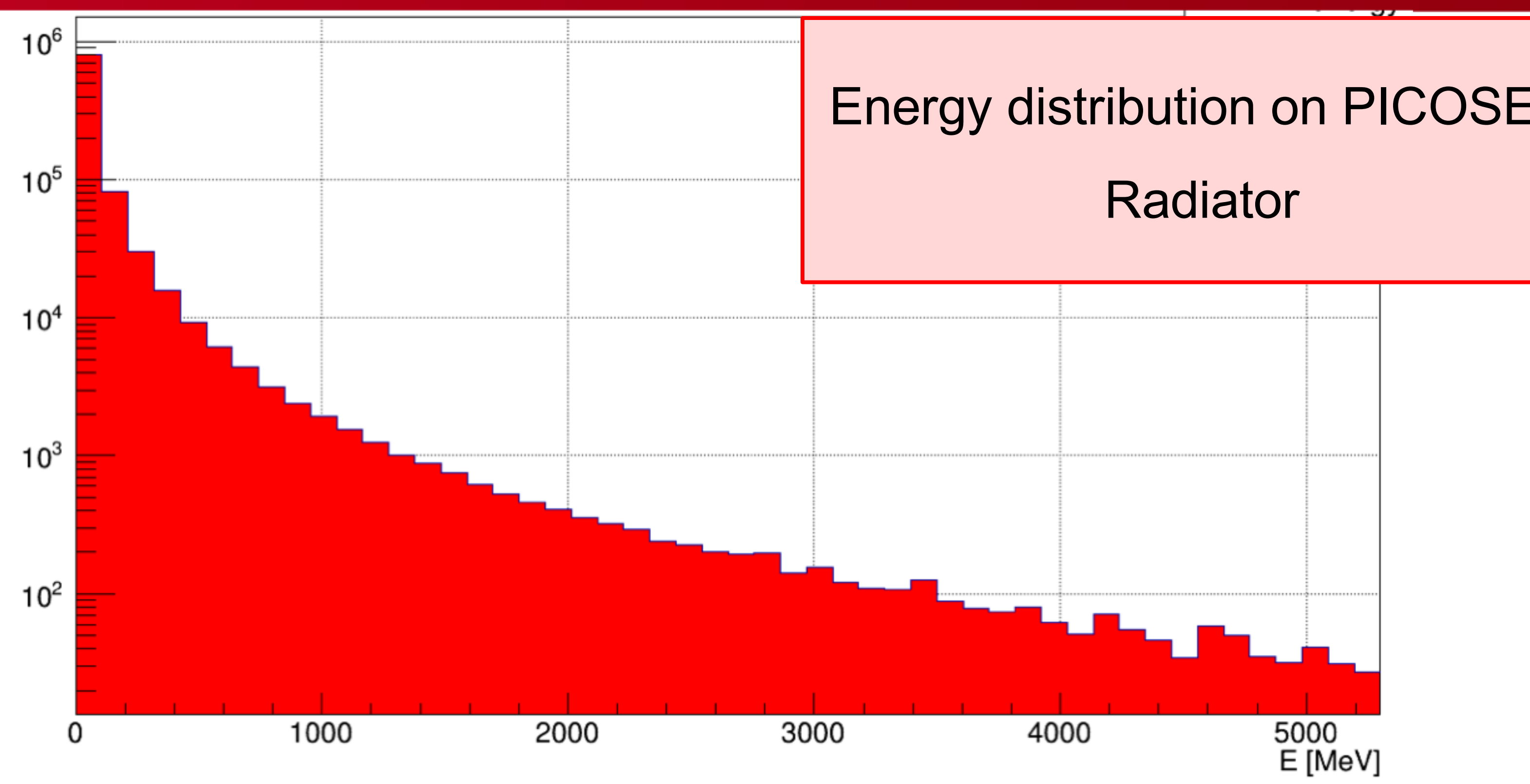
First Indications from laser test measurements @ IRAMIS /CEA



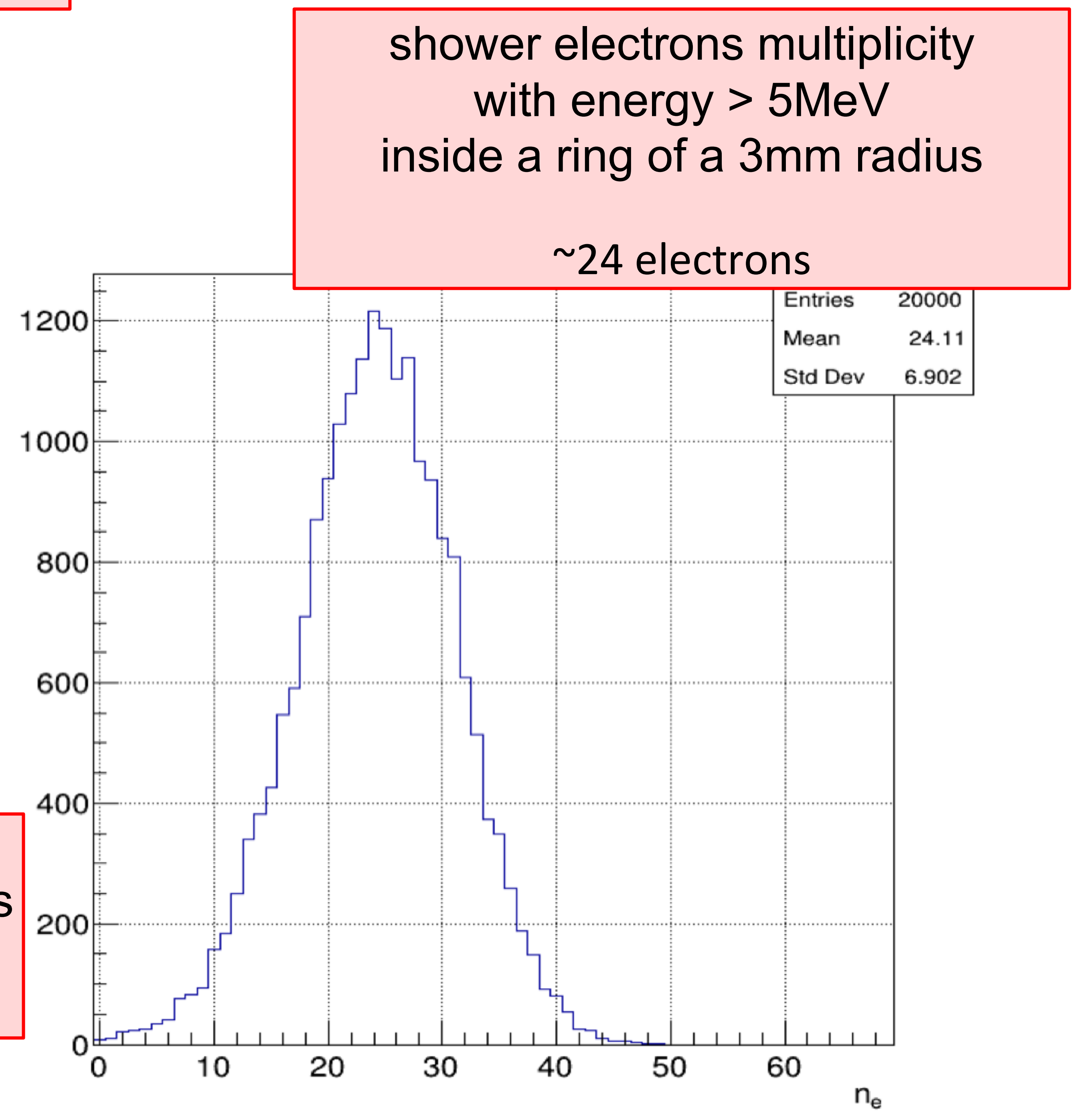
~70pes

Timing resolution :

6.8±0.3 ps



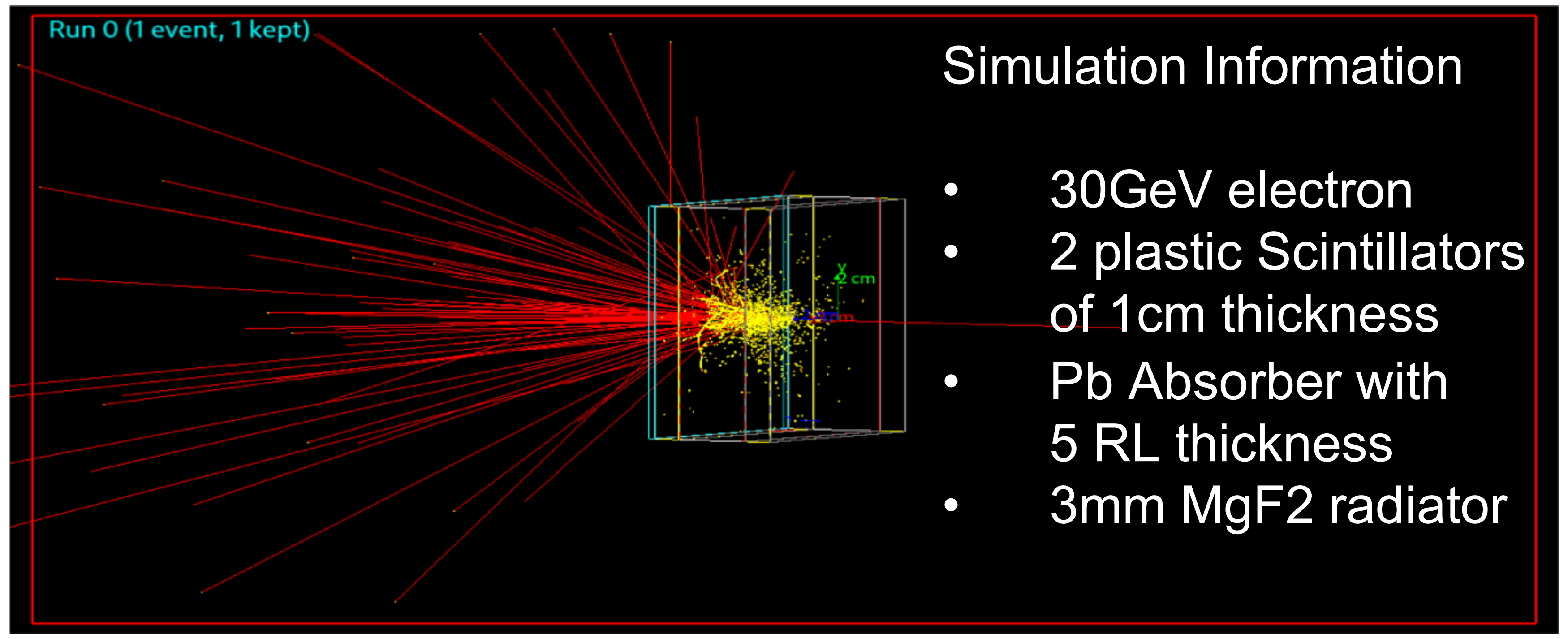
Energy distribution on PICOSEC Radiator



shower electrons multiplicity
with energy > 5MeV
inside a ring of a 3mm radius

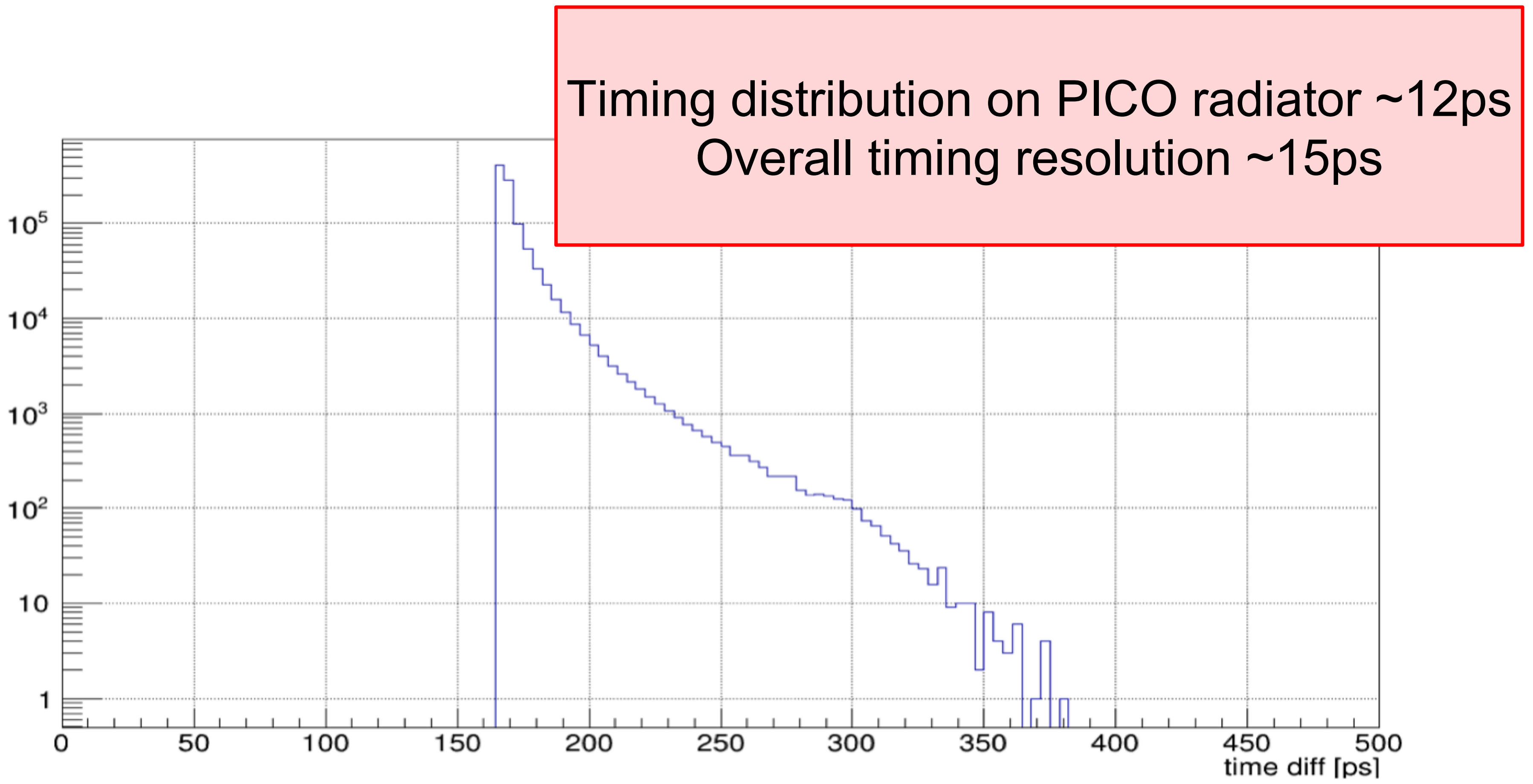
~24 electrons

First Simulation Studies with Geant4



Simulation Information

- 30GeV electron
- 2 plastic Scintillators of 1cm thickness
- Pb Absorber with 5 RL thickness
- 3mm MgF2 radiator



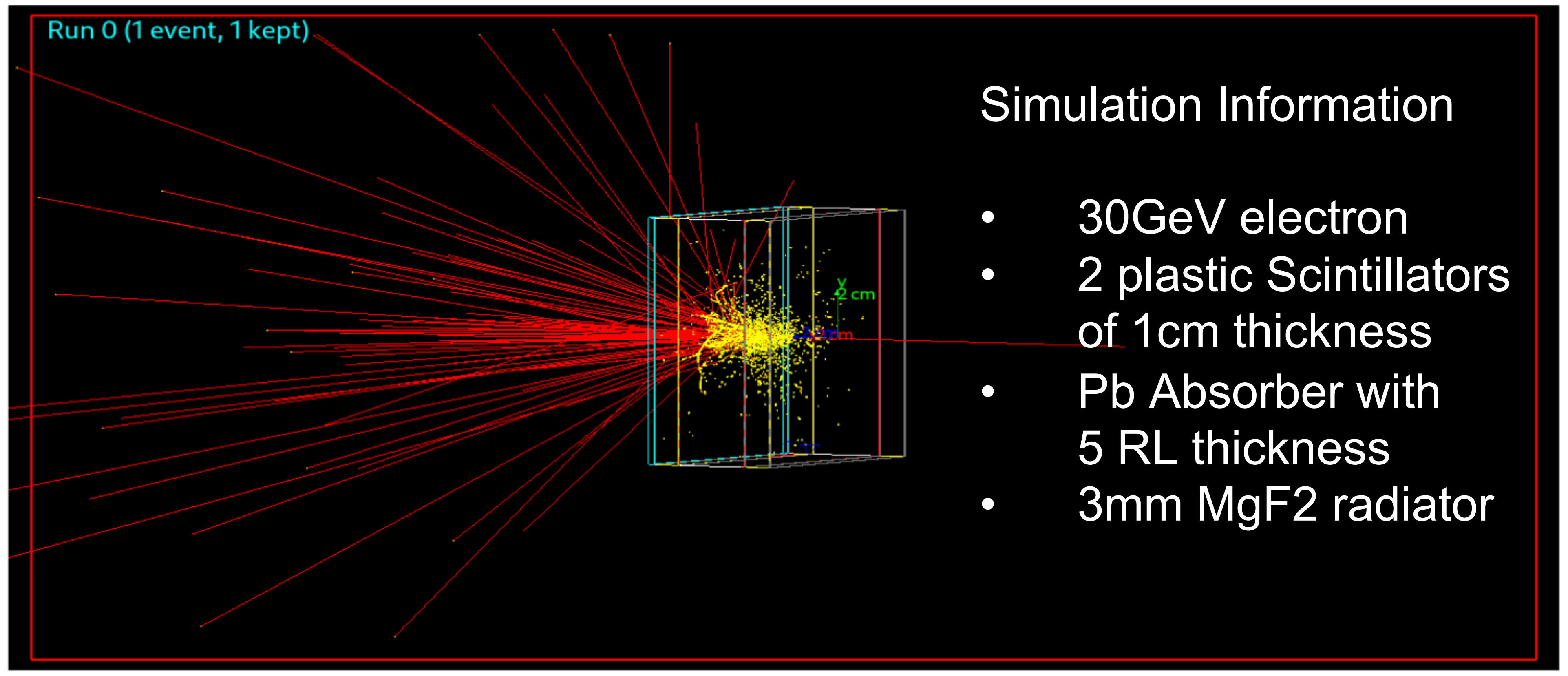
Timing distribution on PICO radiator ~12ps
Overall timing resolution ~15ps

For more info see the presentation by **A. Kallitsopoulou** *the RD51 Mini Week, CERN (7-10 Feb 2022)*
https://indico.cern.ch/event/1110129/contributions/4733737/attachments/2388605/4082733/PICOSEC_in_electron_beam.pdf

alexandra.kallitsopoulou@cern.ch

Physics Studies & Experimental Results

Most Recent Results from July 2022- Preliminary results for PICOSEC in electron beam



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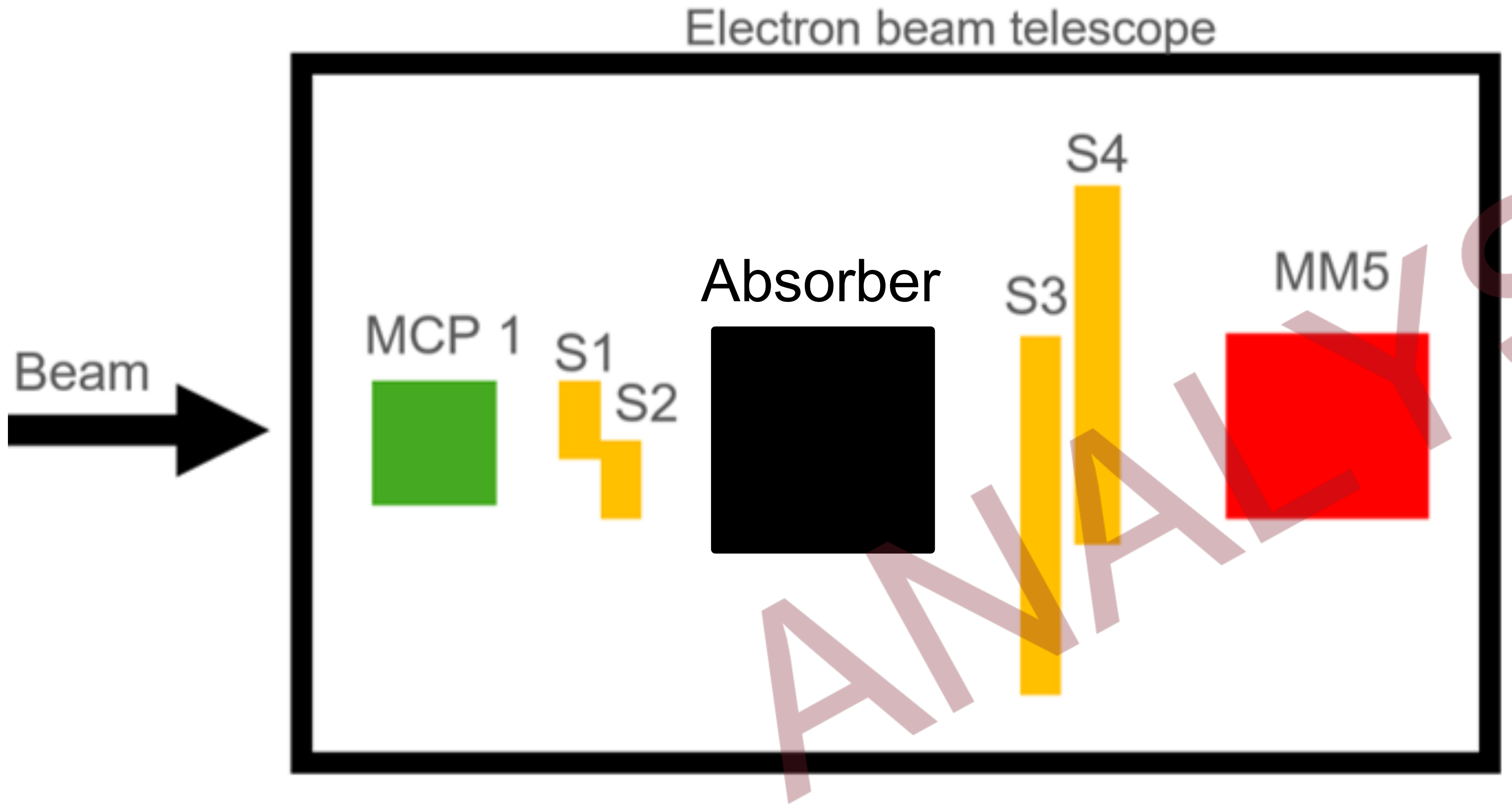
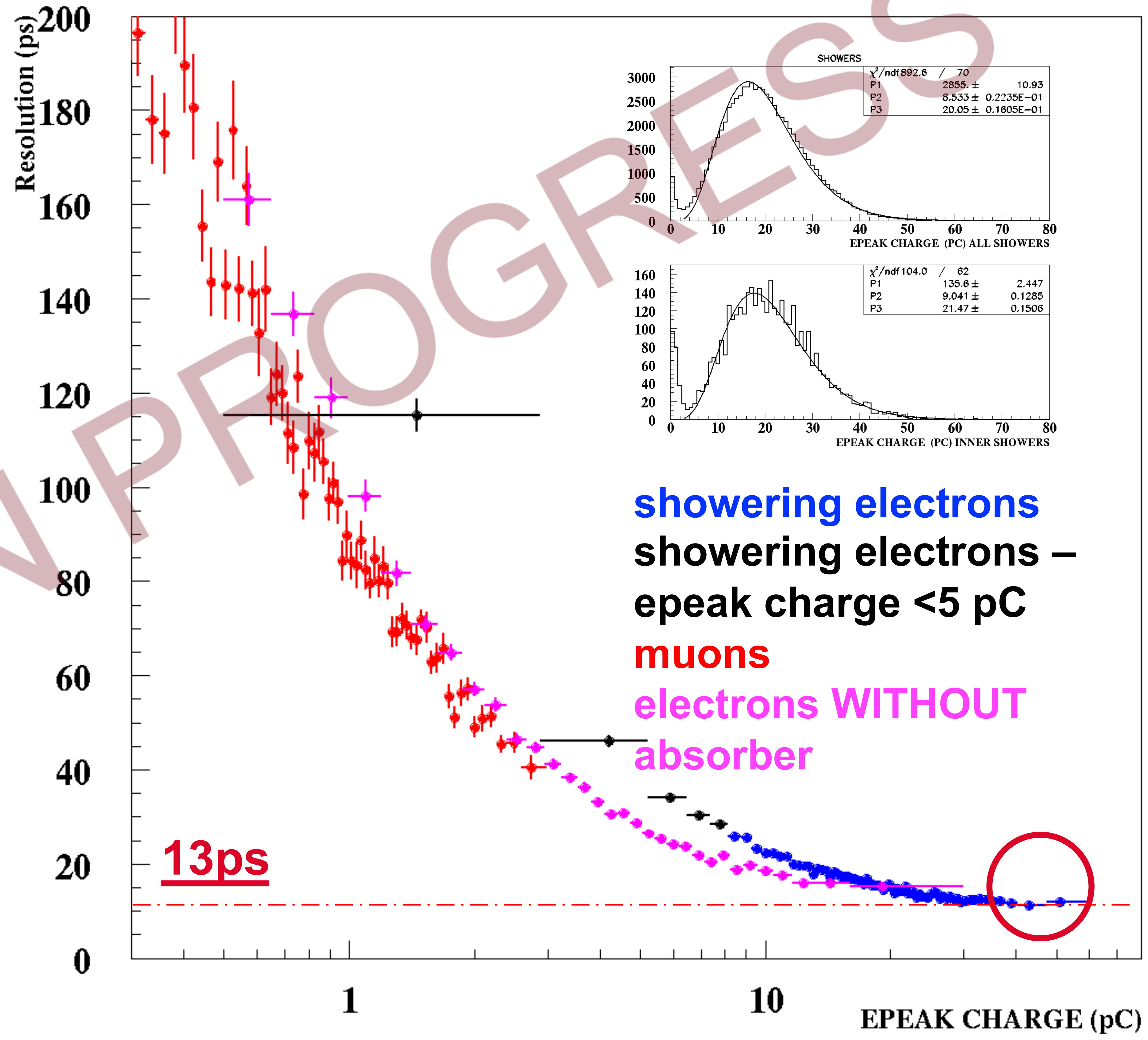
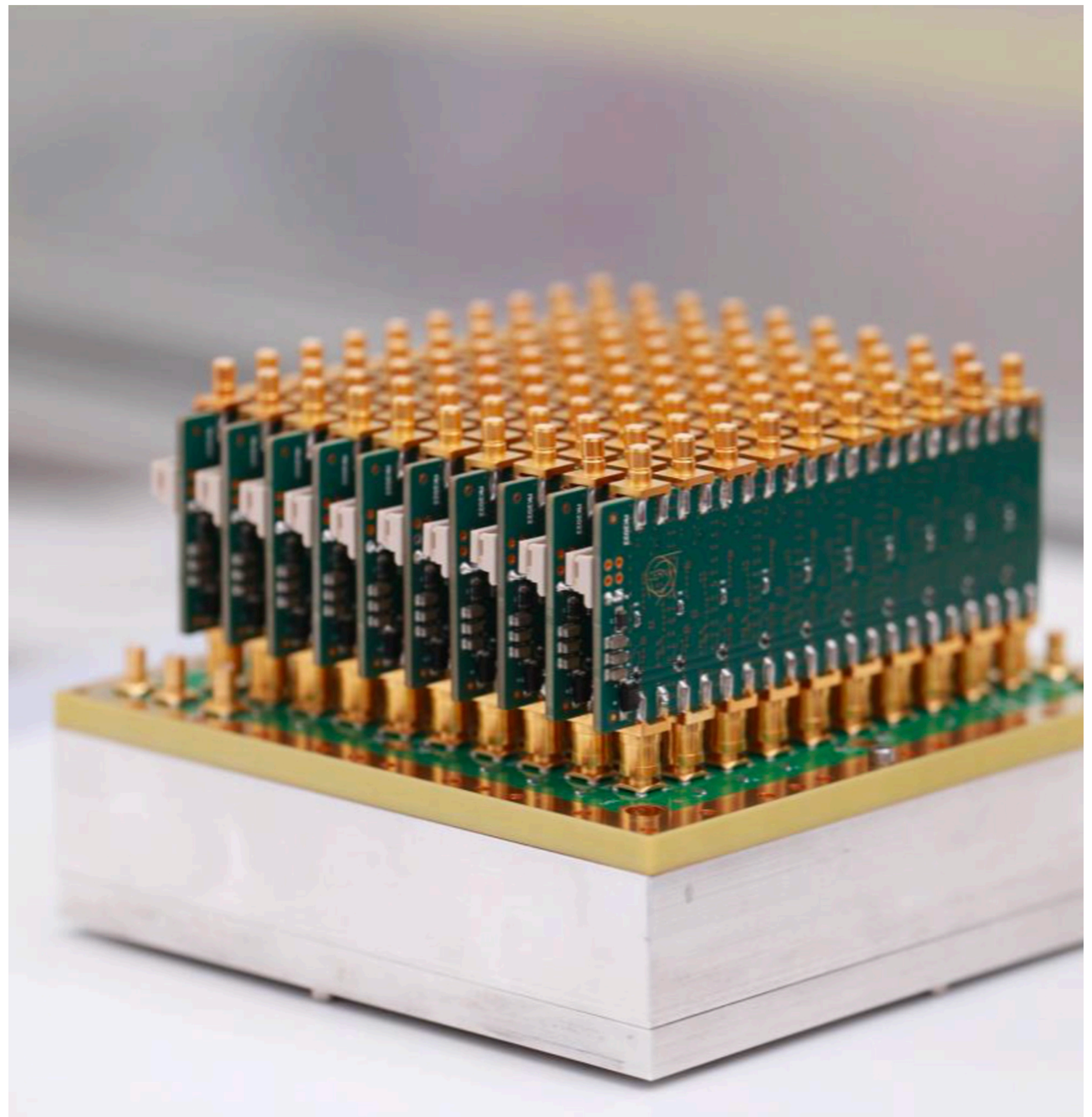




alexandra.kallitsopoulou@cern.ch

Summary

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

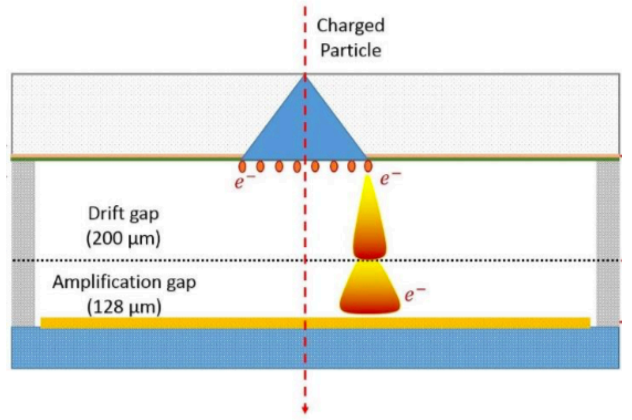


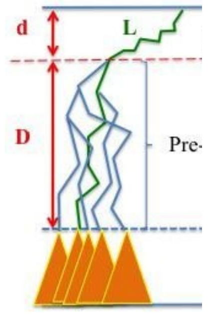
Beam tests (muons, pions) and **laser tests (single-electron response)** conducted to optimise the detector performance. **Simulations** provide an in-depth understanding of detector physics.

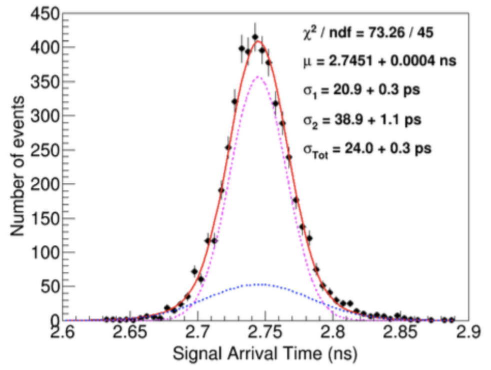
Tileable 10x10 pad detector modules have been tested in MIP test beams and provide good timing resolution also for signals shared across pads.

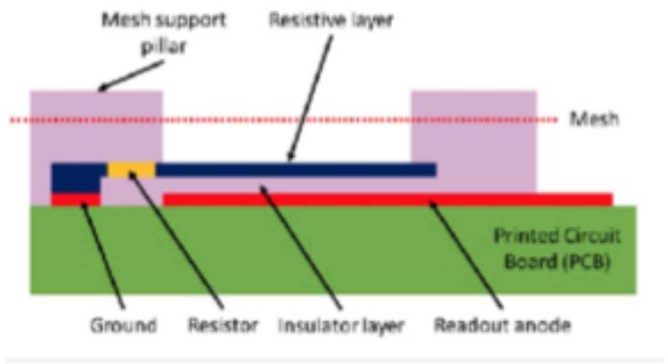
Robust photocathodes (**DLC**), **resistive multi-pad** Micromegas and scaling to **larger area coverage** are implemented in new prototypes.

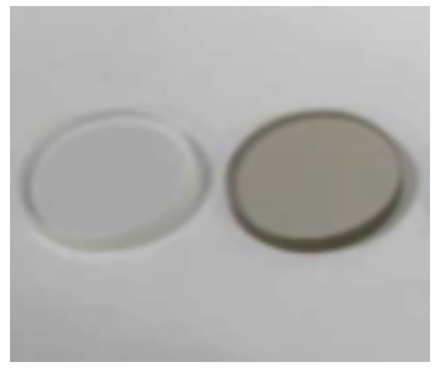
Scalable readout electronics (custom preamplifiers + SAMPIC WTDC) are developed and tested.

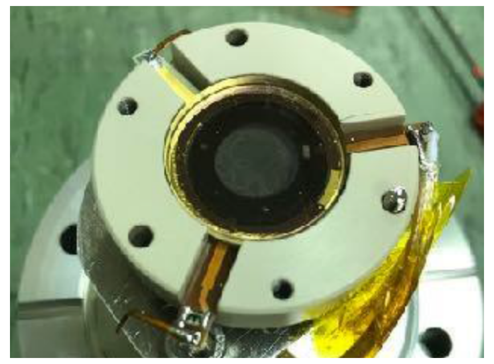


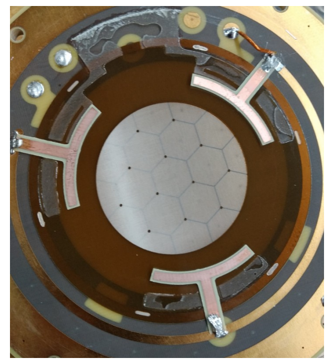


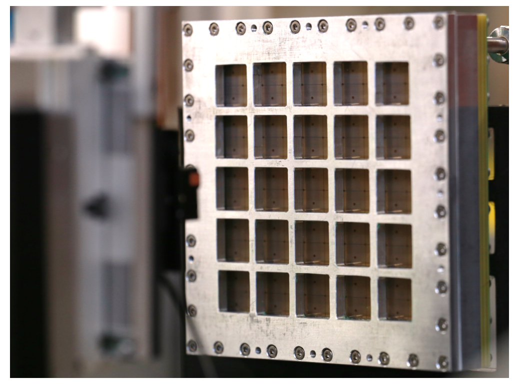


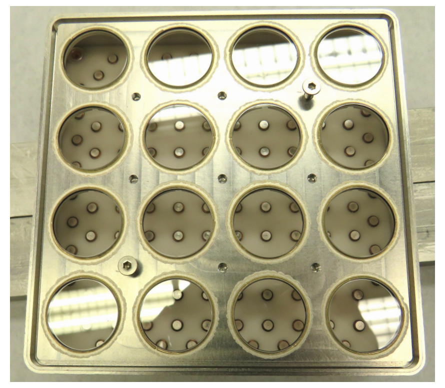


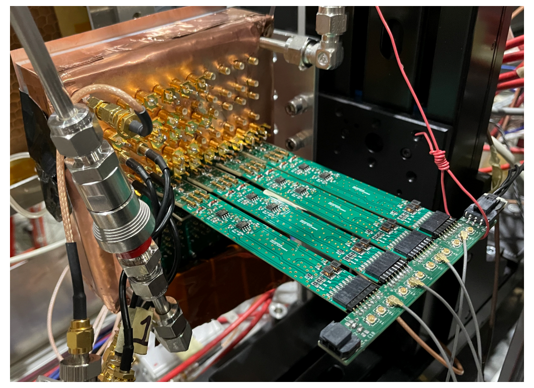












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The **PICOSEC detection** concept overcomes timing limitations of gaseous detectors and achieves high timing precision of < **25 ps** for MIPs.

Beam tests (muons, pions) and **laser tests (single-electron response)** conducted to optimise the detector performance. **Simulations** provide an in-depth understanding of detector physics.

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.

Future perspectives

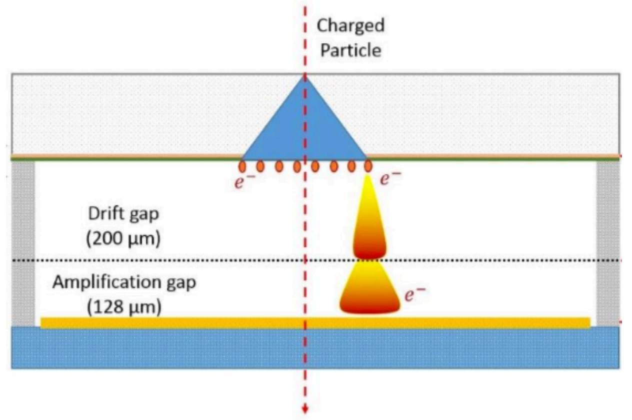
Secondary emitters: minimise material budget

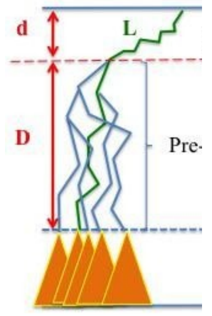
Spatial resolution: adjusting pad size, charge sharing

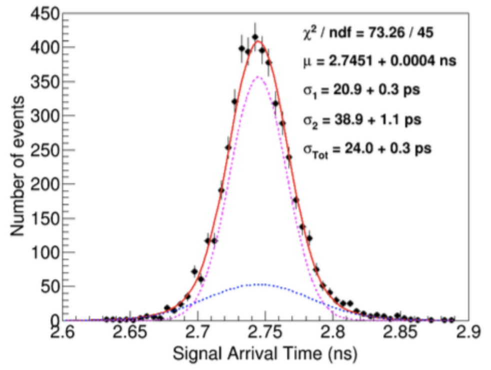
Optical readout with SiPMs

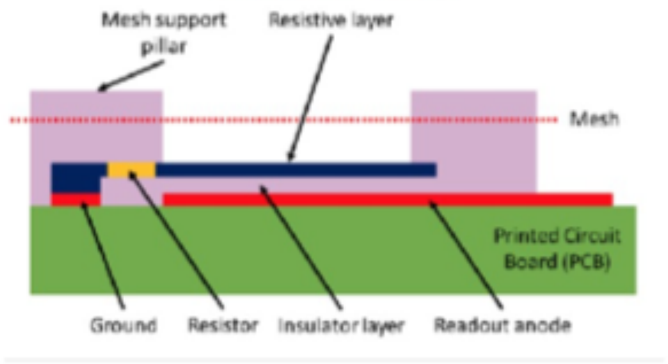
Amplification structure: optimised double/single gaps, mesh geometries/technologies, resistive multi-pad

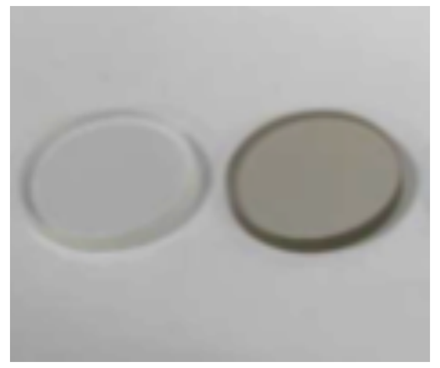
Electronics: waveform digitisation vs. threshold based timing

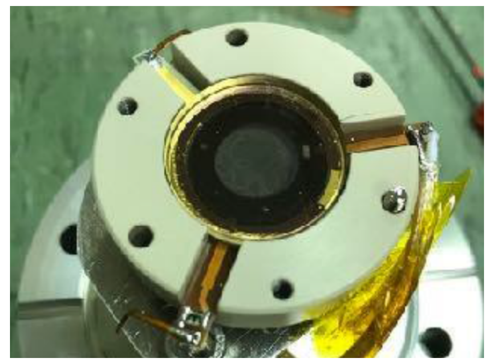


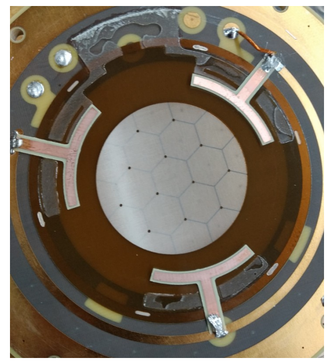


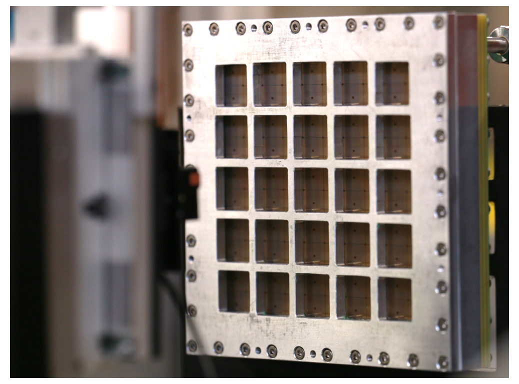


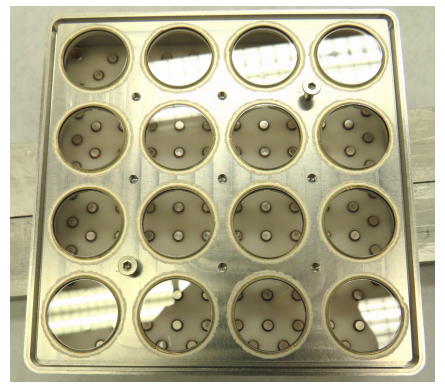


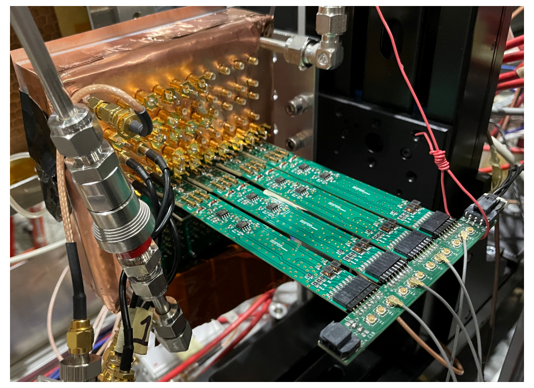












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RD51 PICOSEC-Micromegas Collaboration

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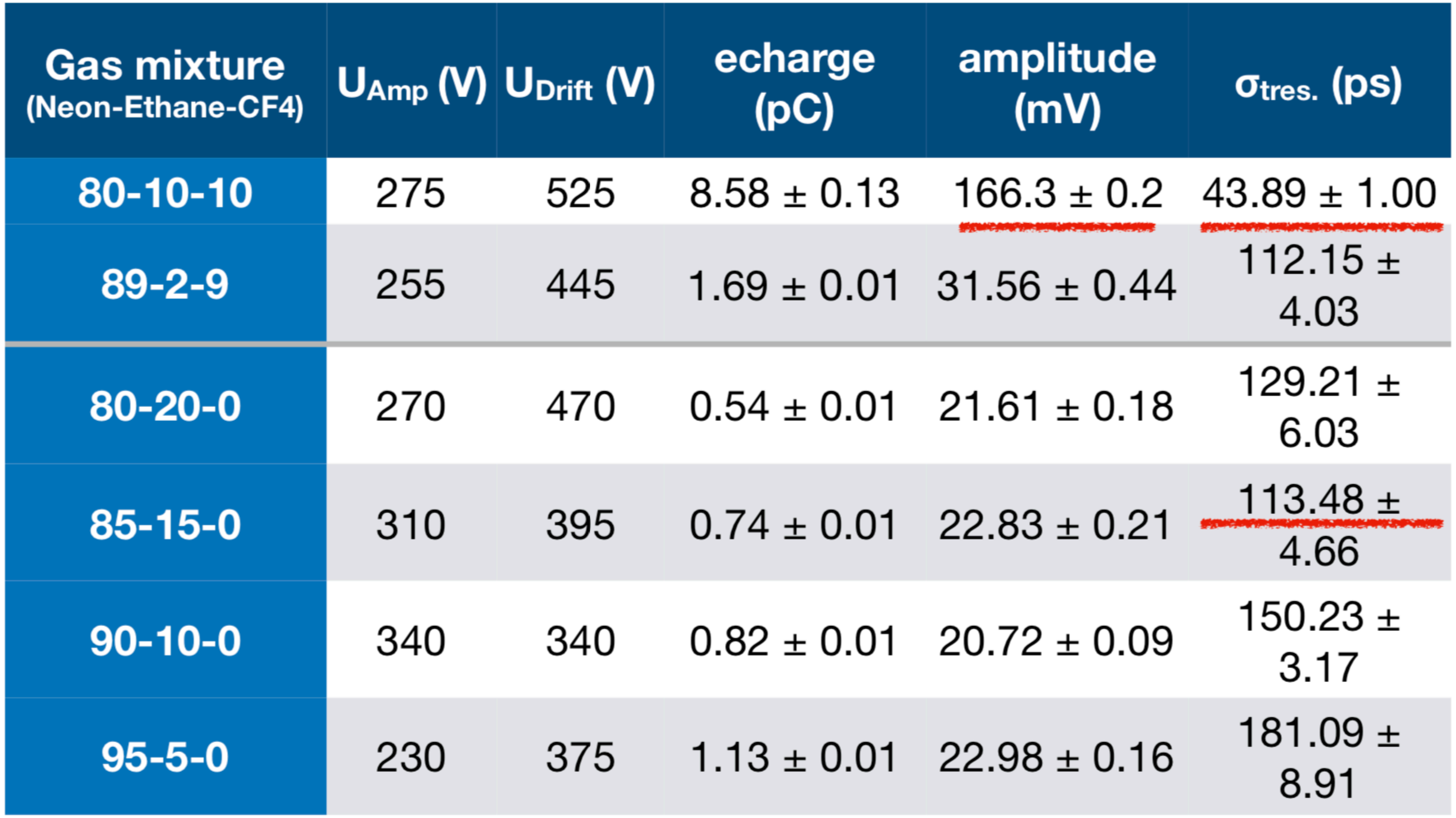
4) Now at University of Birmingham

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