Precise charged particle timing with the PICOSEC detection concept

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on behalf of the PICOSEC collaboration

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RD51 PICOSEC-Micromegas Collaboration

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Outline

PICOSEC detection concept: precise timing with Micromegas-based detector

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

Towards a robust, large-area detector: resistive Micromegas, photocathodes and scaling-up

Picosecond timing needs

High Luminosity Upgrade of LHC

ATLAS/CMS simulations: ~150 vertexes/crossing

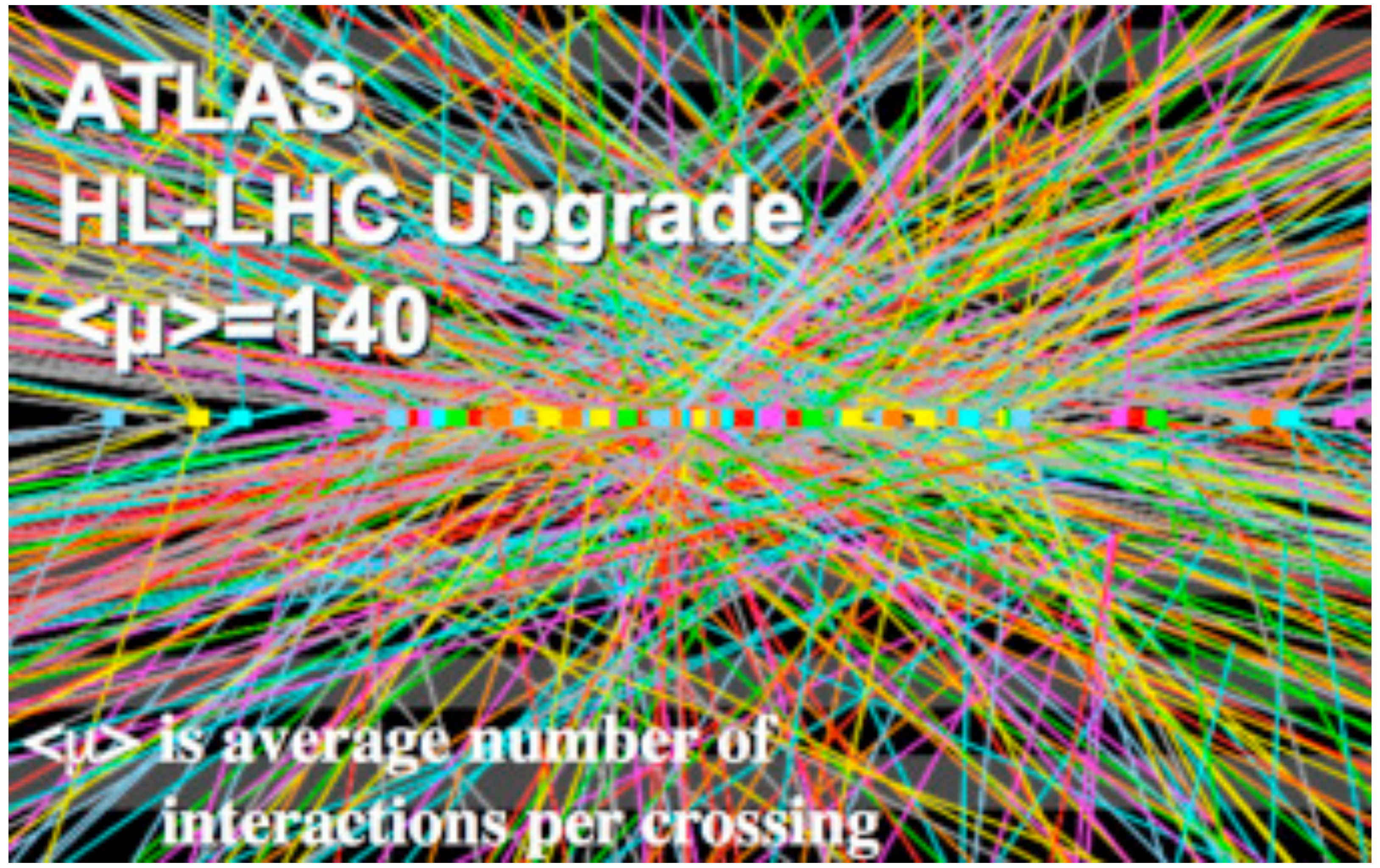
To mitigate pile-up and separate particles coming from different vertices:

- 3D tracking of charged particles is not sufficient
- Exploit precise timing to separate tracks

Tens of ps timing + tracking info required

Precise timing detector:

- Tens of ps timing precision
- Large surface coverage
- Resistance against ageing

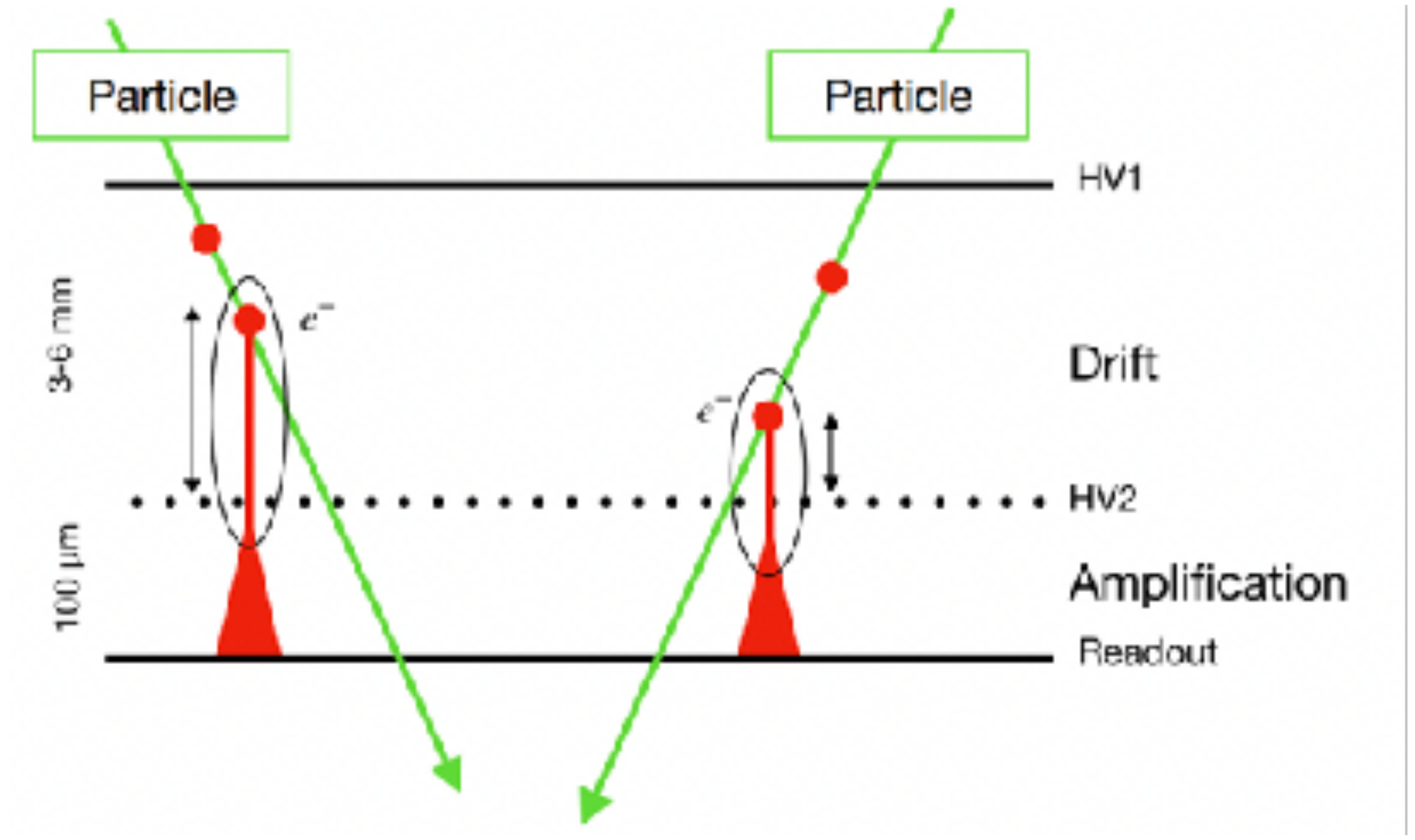


PID techniques: Alternatives to RICH methods, J. Va'vra, NIMA **876** (2017) 185-193, https://dx.doi.org/10.1016/j.nima.2017.02.075

Limitations of conventional gaseous detector

Conventional Micromegas:
Giomataris Y. et al., NIMA 376 (1996) 29

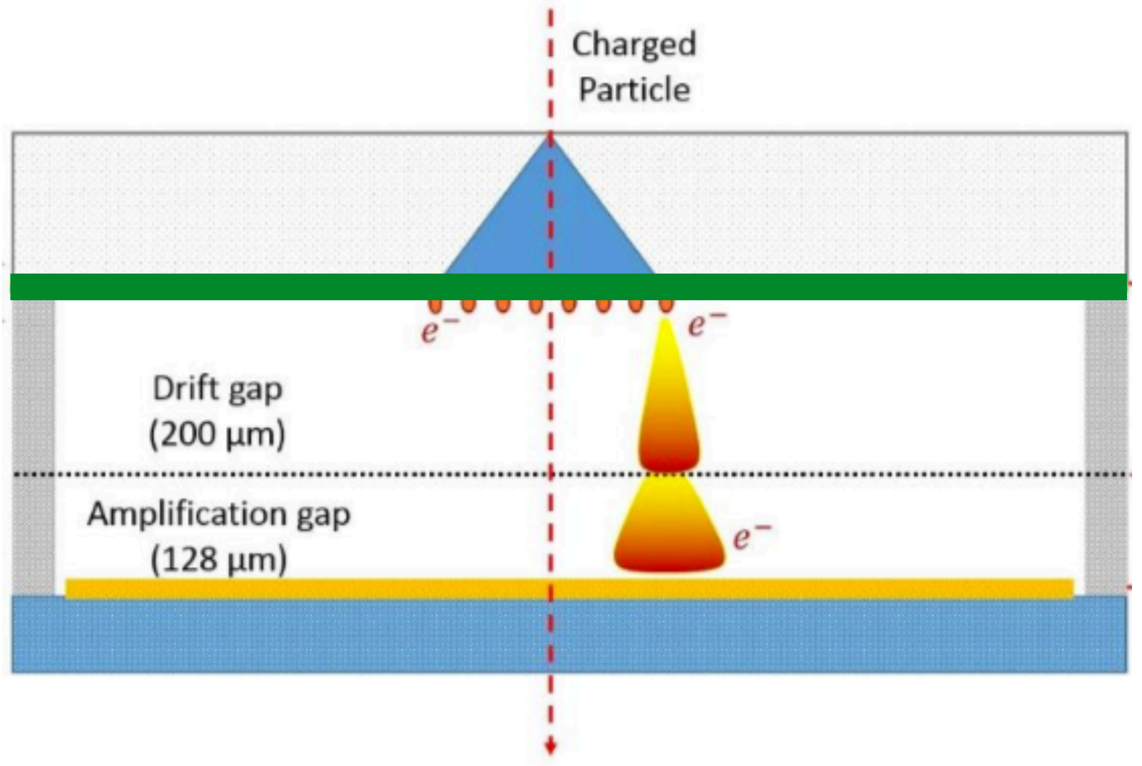
Primary electrons produced along trajectory in drift region -> millimetres difference
Timing jitter of ≈ ns



PICOSEC-Micromegas:
https://doi.org/10.1016/j.nima.2018.04.033

Cherenkov radiator + Photocathode + Micromegas

Primary electrons at photocathode -> well-defined location
Timing jitter of ≈ tens of ps



PICOSEC detection concept

Precise timing with Micromegas

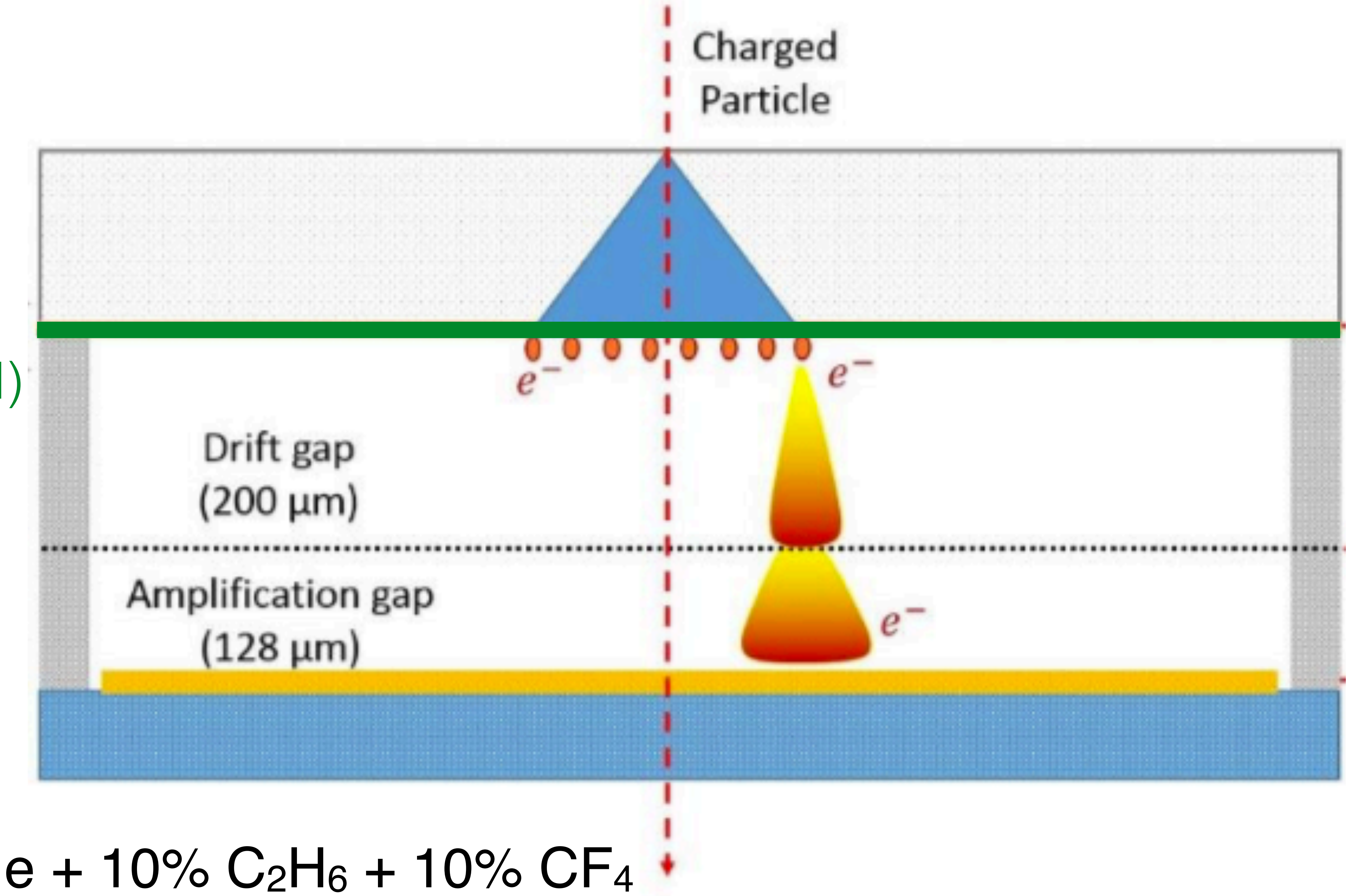
PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector
J. Bortfeldt et. al. (RD51-PICOSEC collaboration), Nuclear. Inst. & Methods A 903 (2018) 317-325

Cherenkov radiator
(3 mm MgF_2)

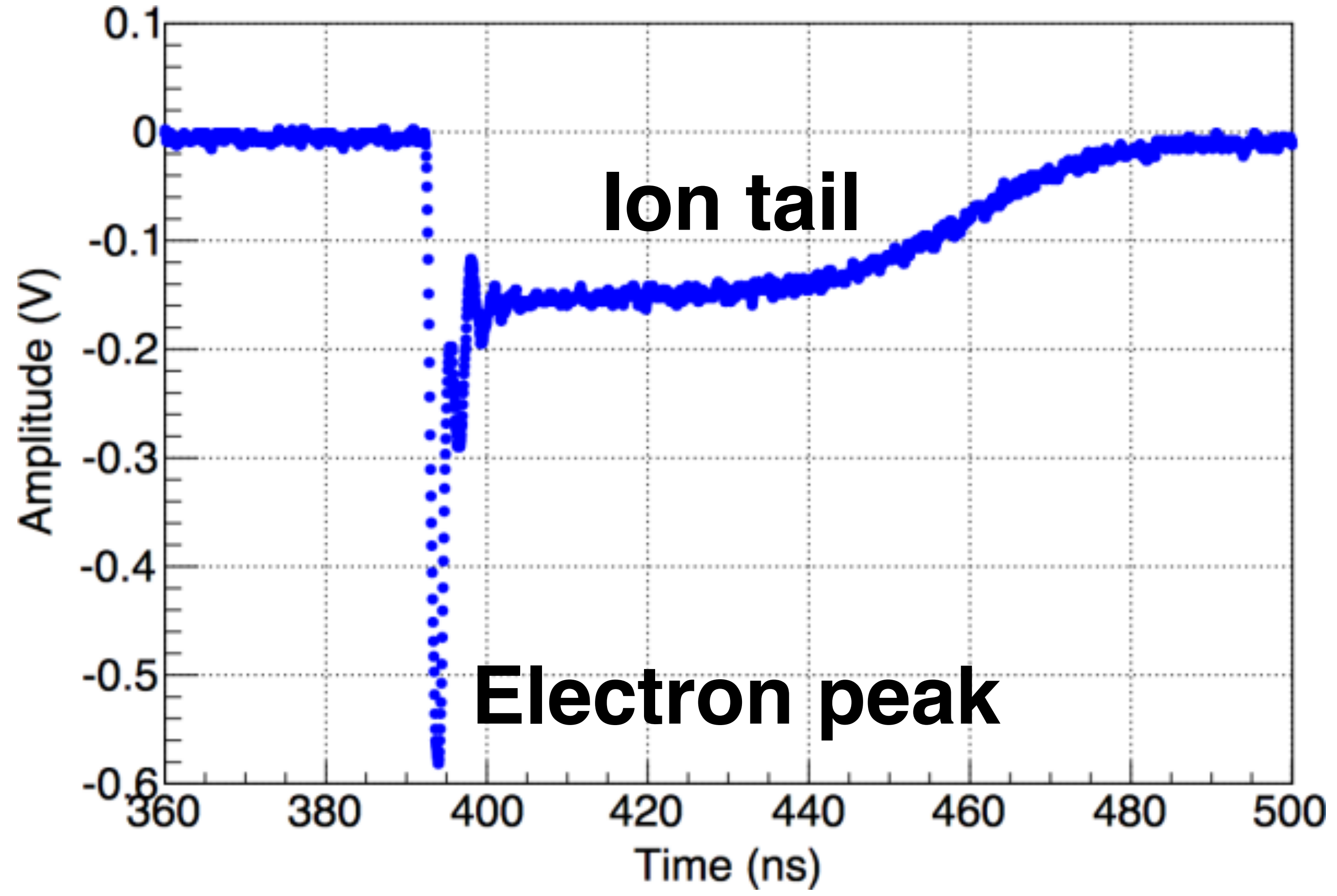
Photocathode
(3 nm Cr + 18 nm CsI)

Drift gap
(Pre-amplification)

Micromegas
(Amplification)



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

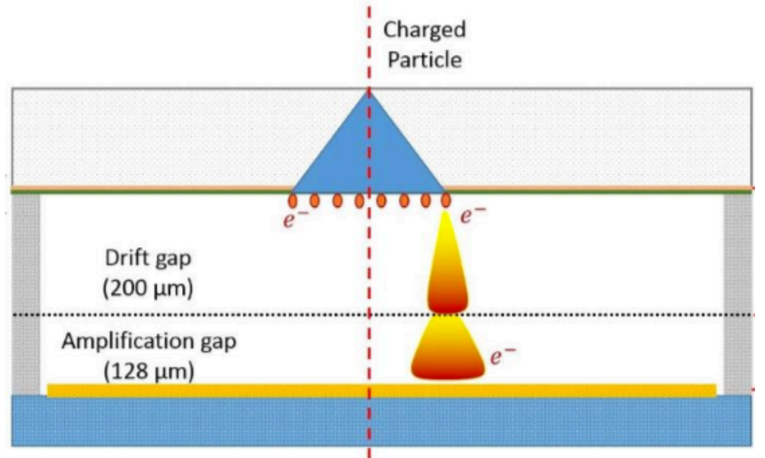


- **Signal with two distinct components:**
  Electron peak: fast (≈0.5 ns)
- Ion tail: slow (≈100 ns)

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

PICOSEC detection concept

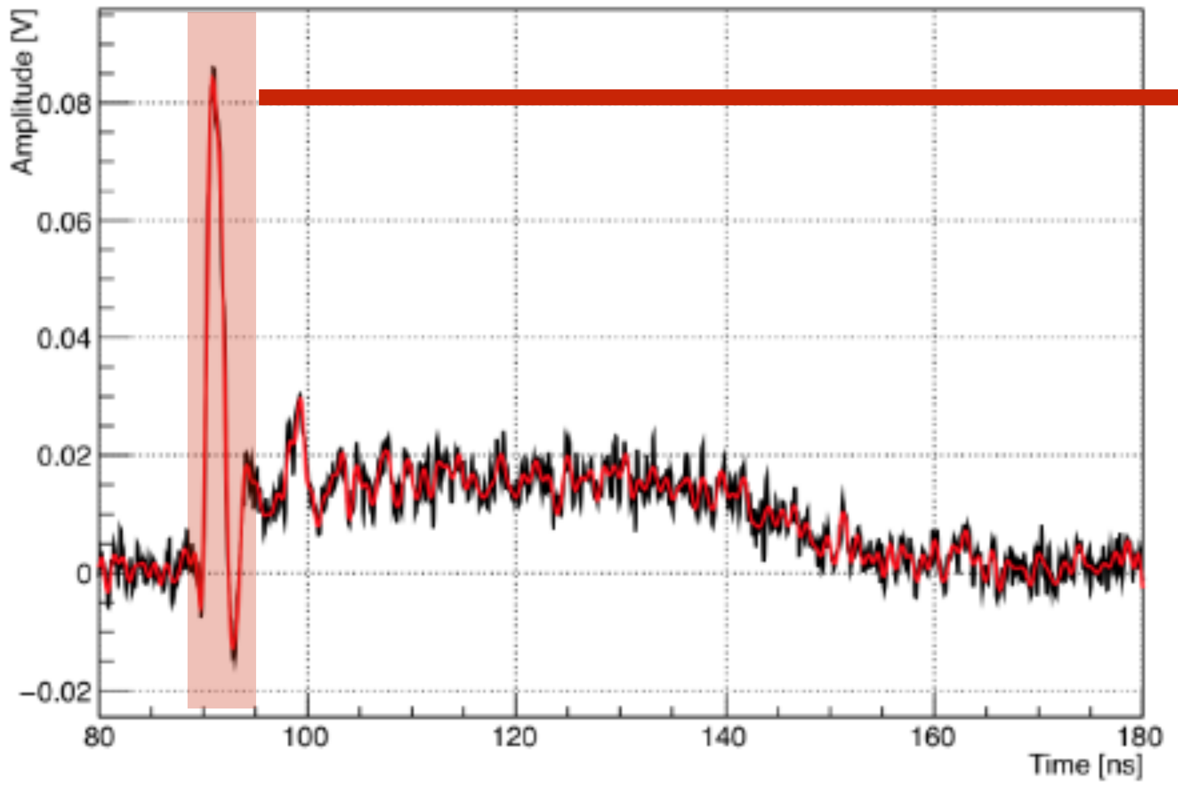
Precise timing with Micromegas



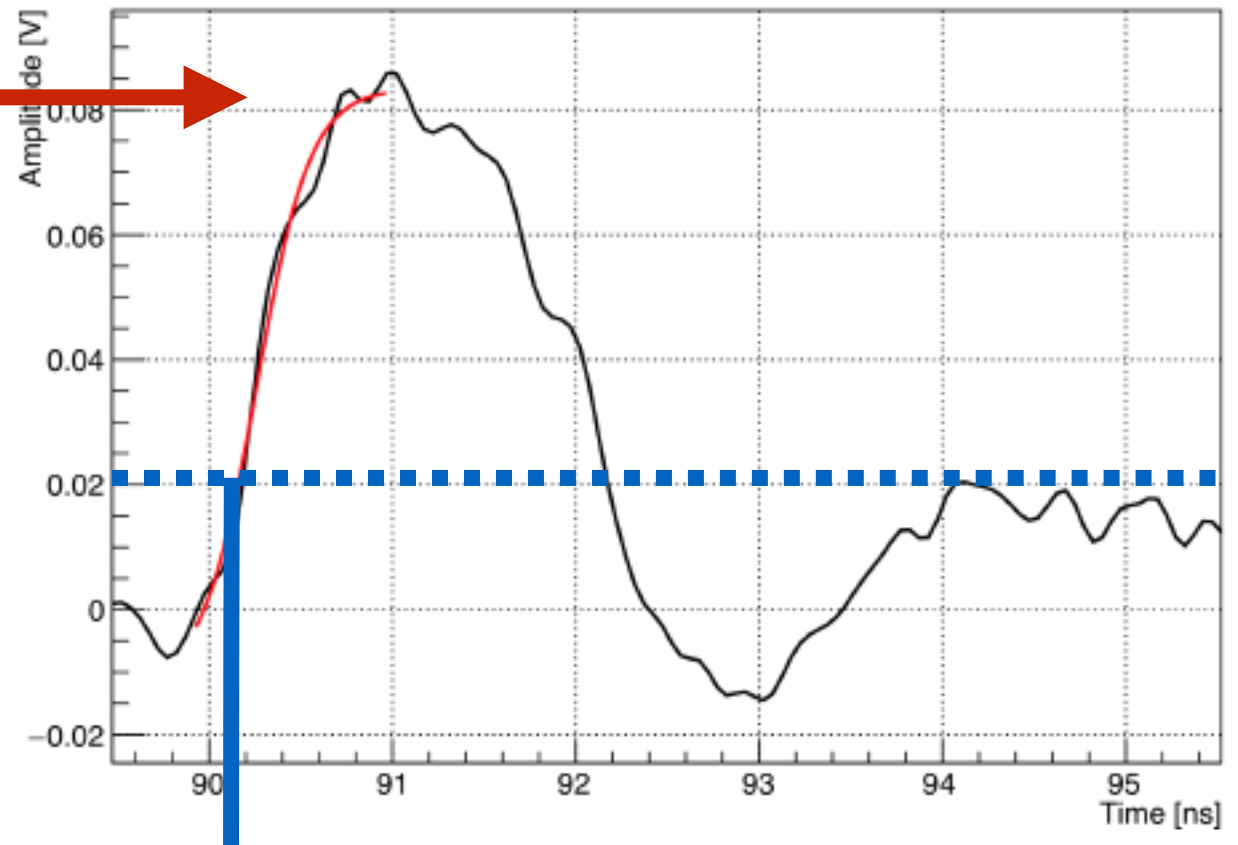
Preamplification of induced signal with CIVIDEC preamp

Digitized by 2.5GHz LeCroy oscilloscope @ 20GSamples/s = 1 sample / 50 ps

Recorded waveform

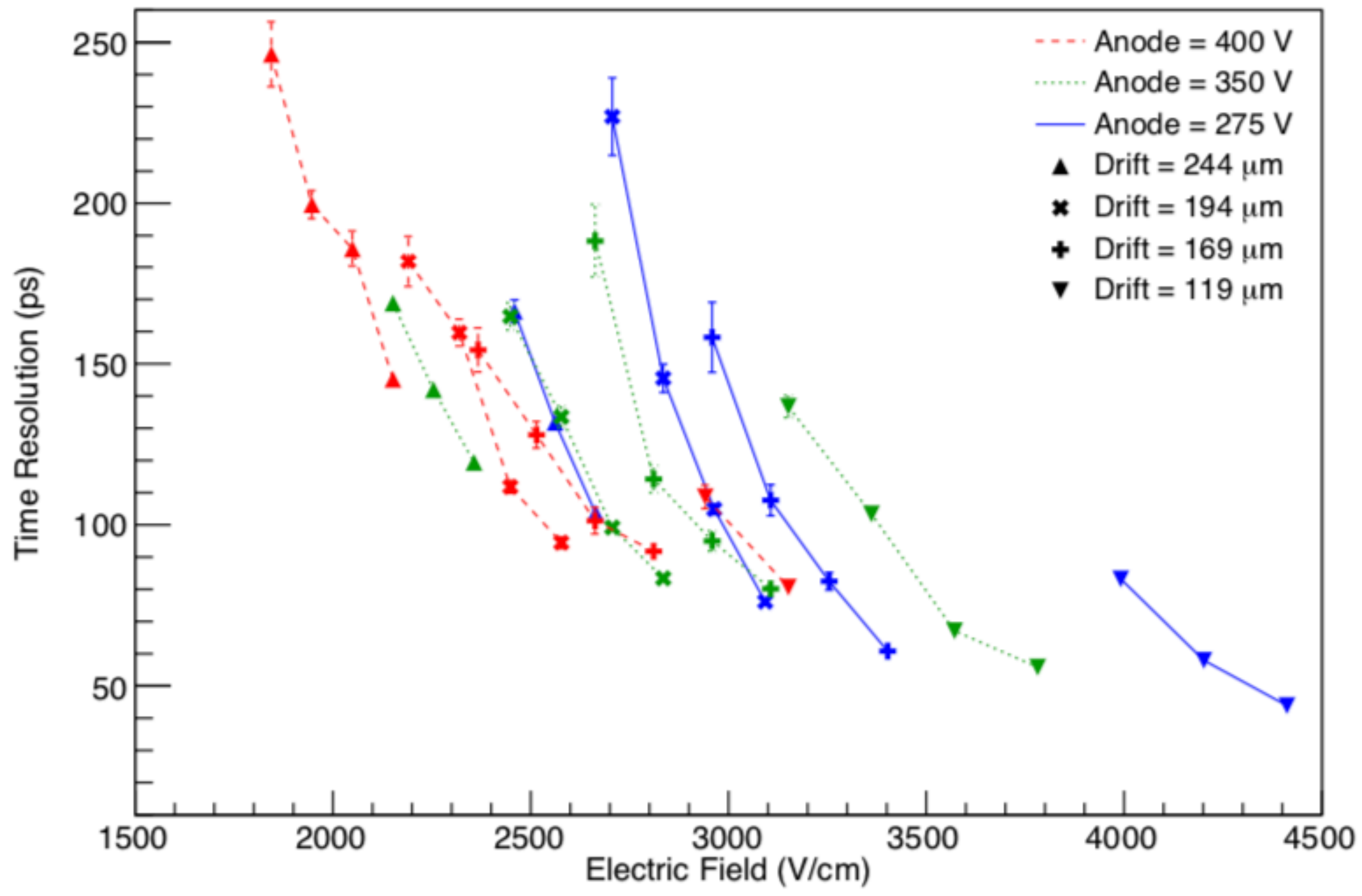


Zoom: electron peak



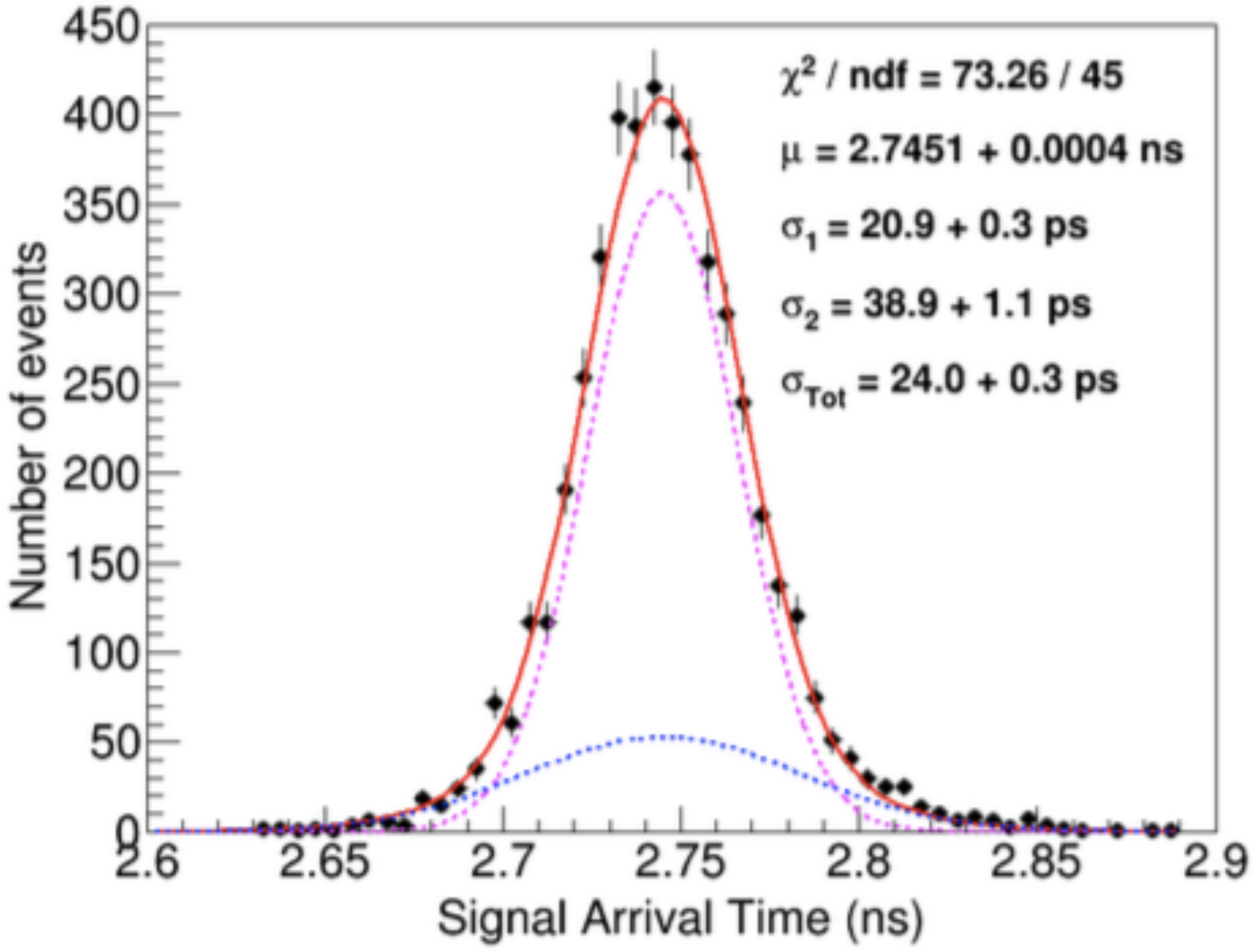
Constant Fraction Discrimination (**CFD**) at 20% on the fitted noise-subtracted e-peak

Single photoelectron studies



<50 ps single photoelectron timing resolution

MIP test beam measurements



24 ps MIP timing resolution

Single photoelectron studies

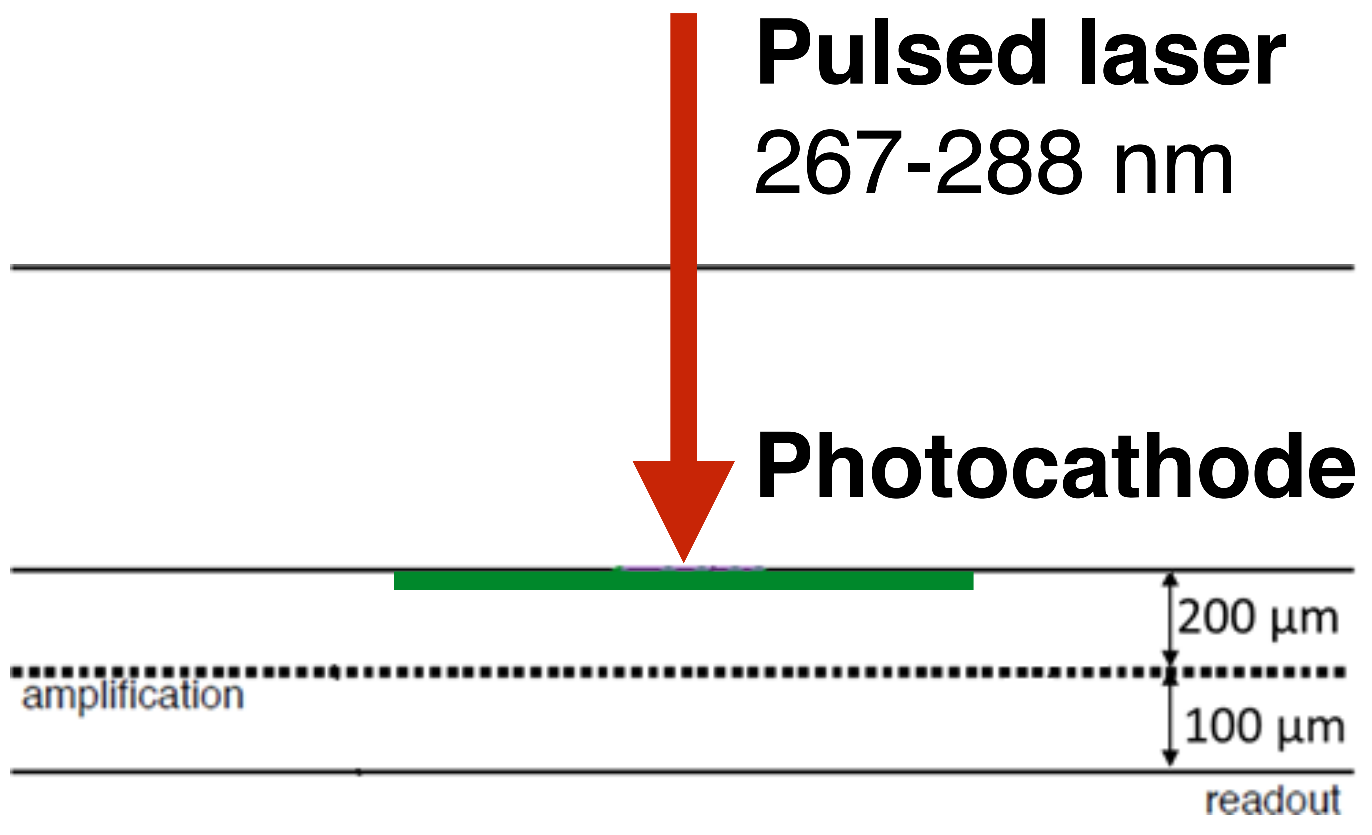
Pulsed laser at IRAMIS facility (CEA Saclay)

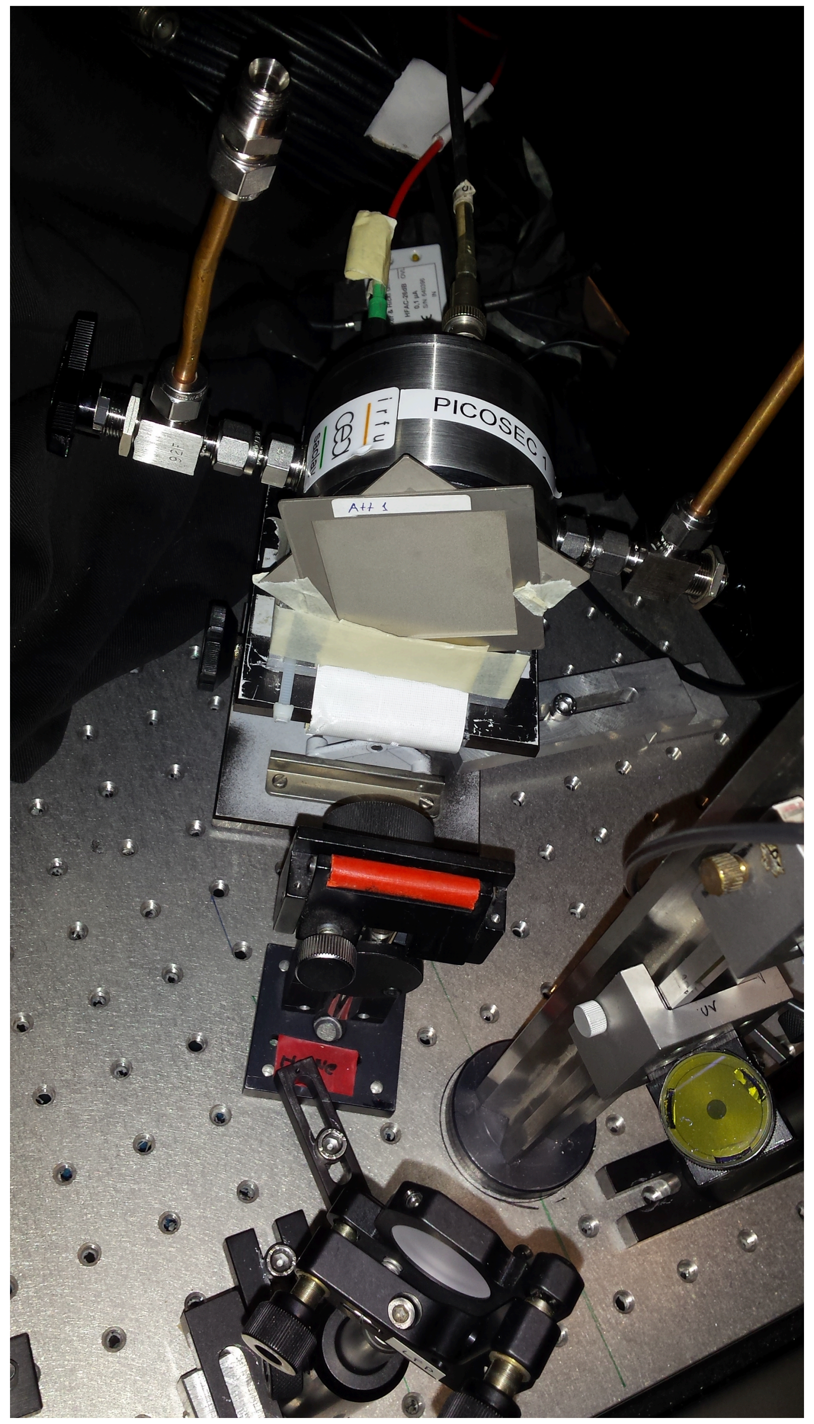
Detailed detector response studies in well-controlled conditions: direct production of primary electrons at photocathode.

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

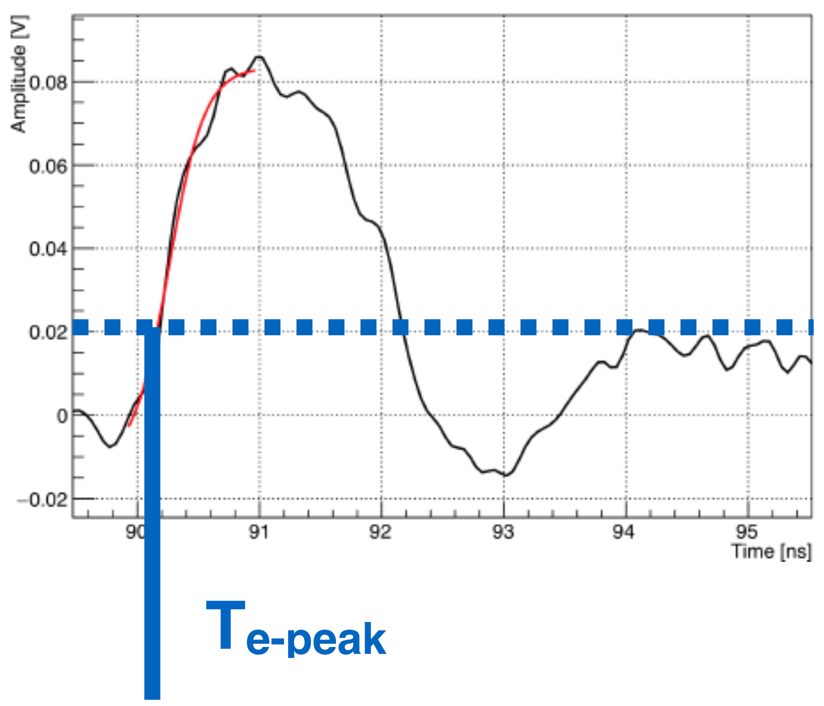
Allows for systemic studies and optimisations of
- Drift field strength
- Amplification field
- Gas mixtures

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



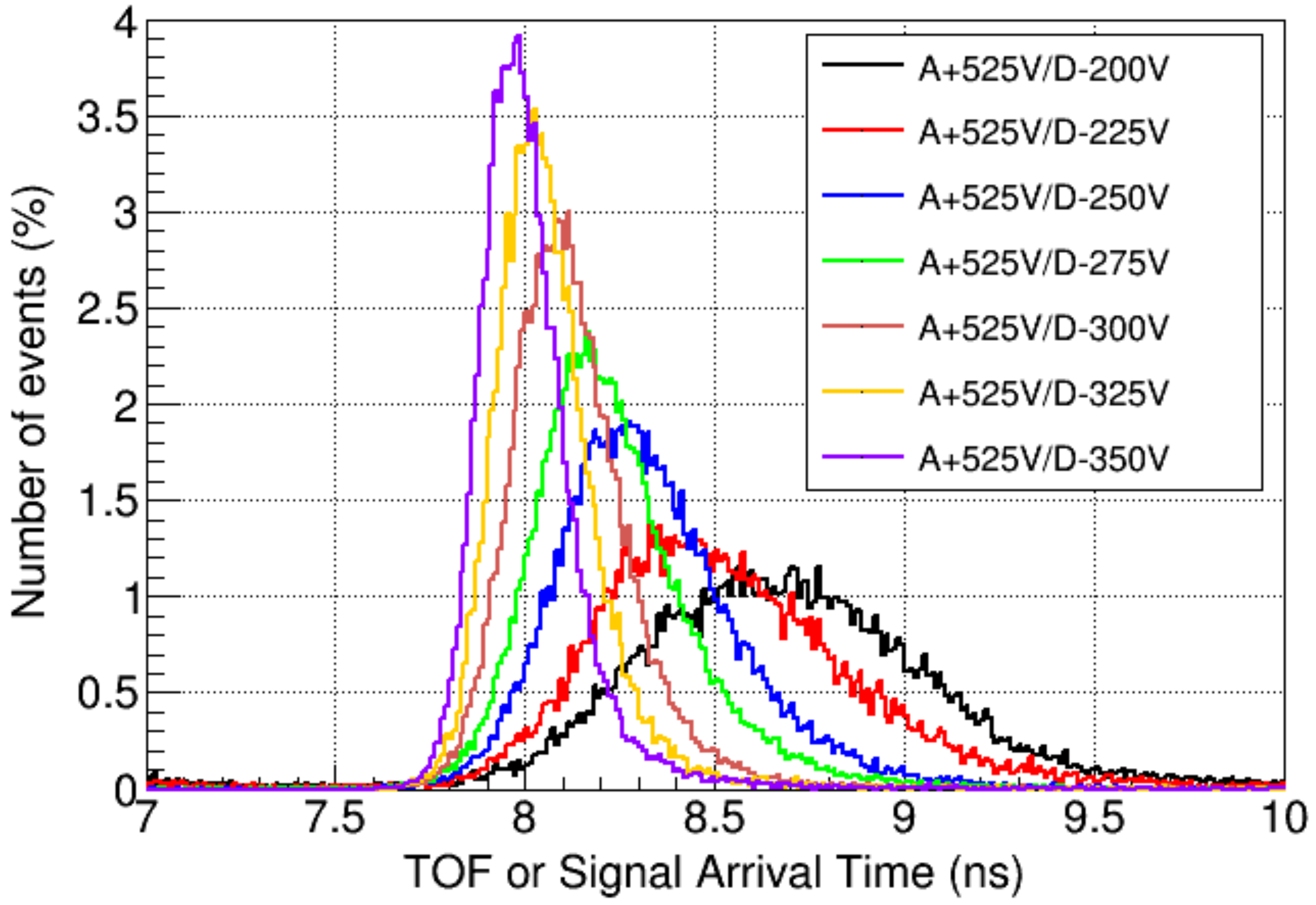


Detector response



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

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



SAT distribution exhibits tail at higher values

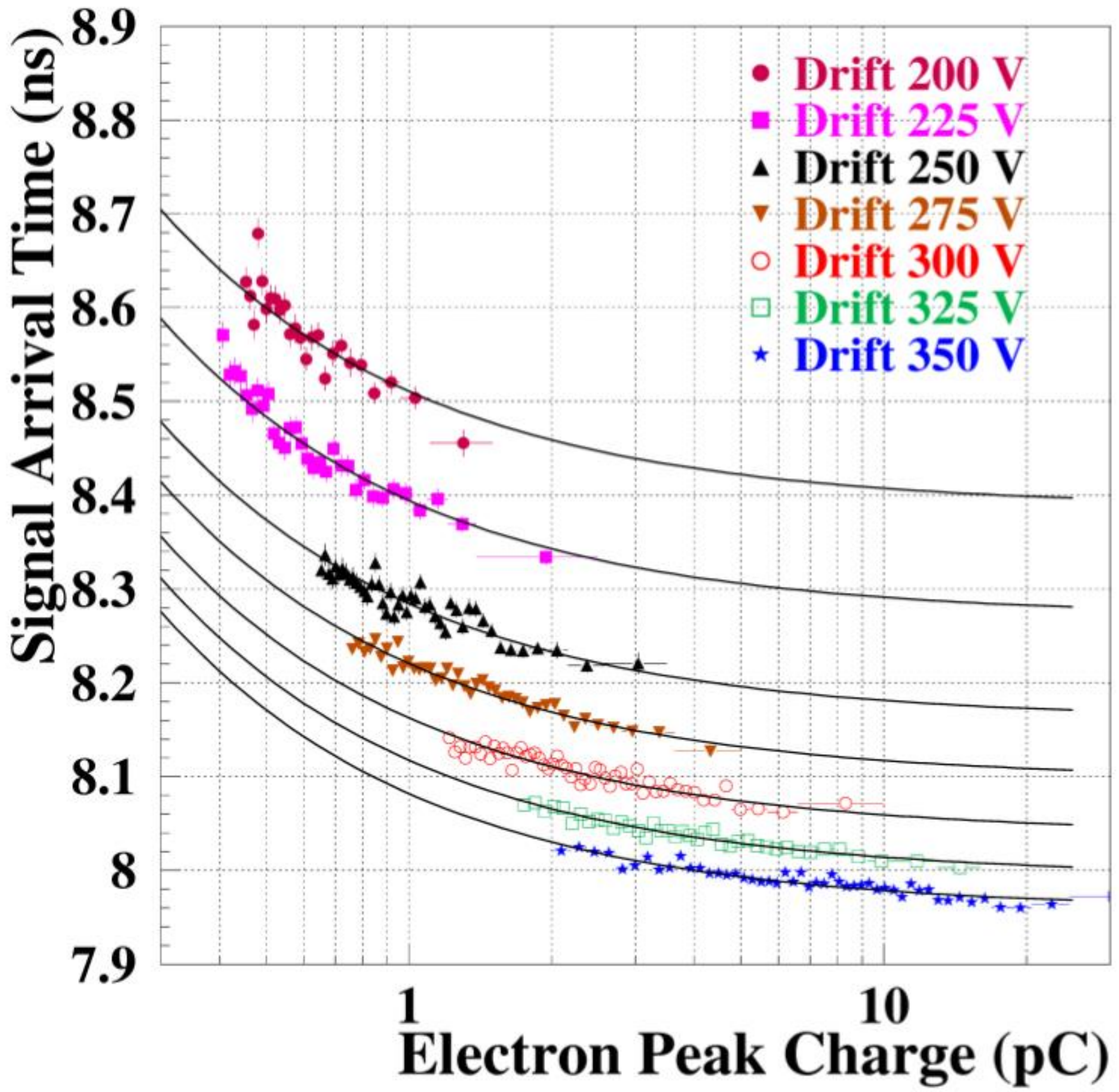
https://indico.cern.ch/event/716539/contributions/3246636/

Detector response

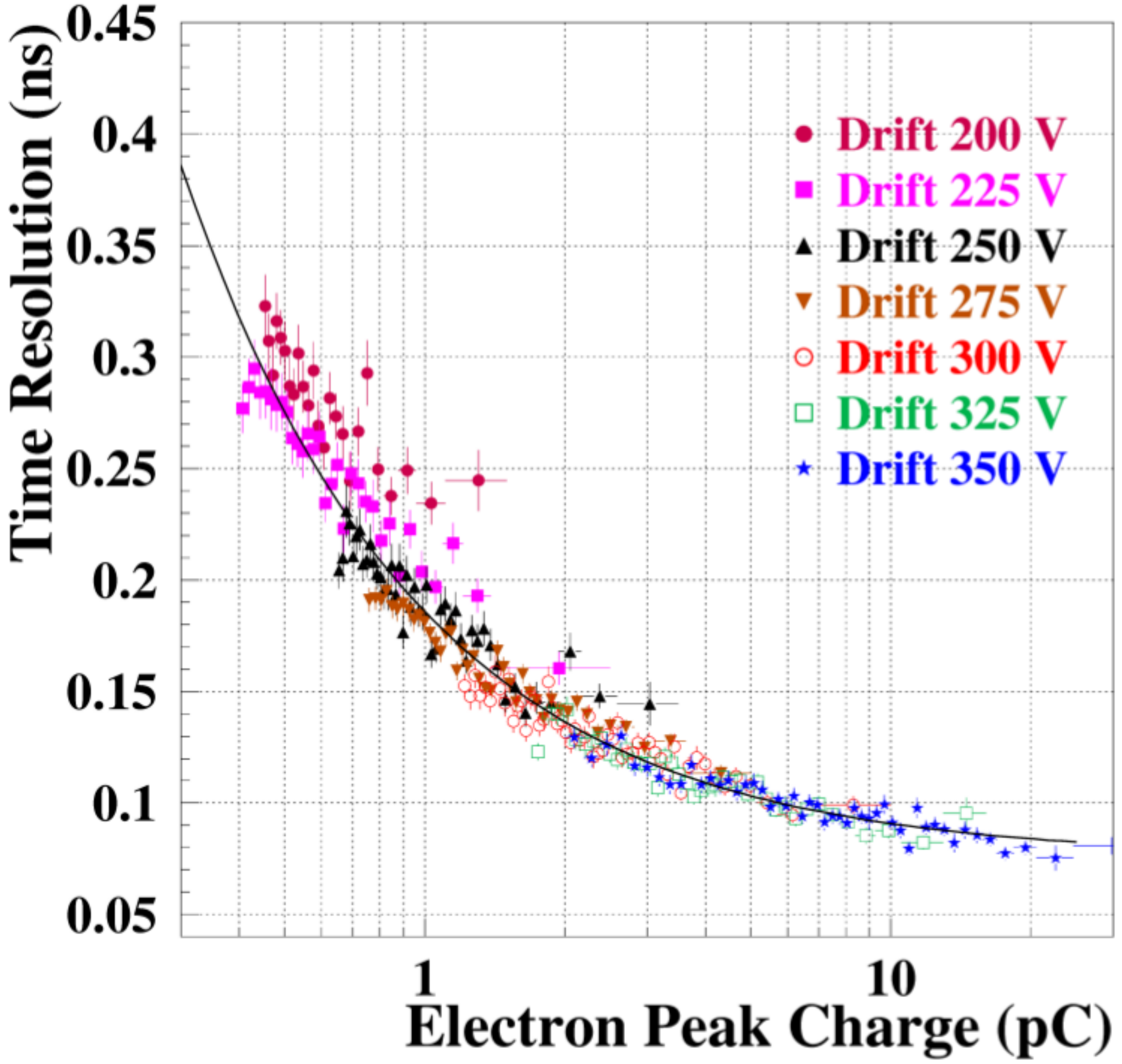
Correlation of signal arrival time and pulse amplitude

Time resolution depends primarily on e-peak charge

Signal arrival time



Time resolution



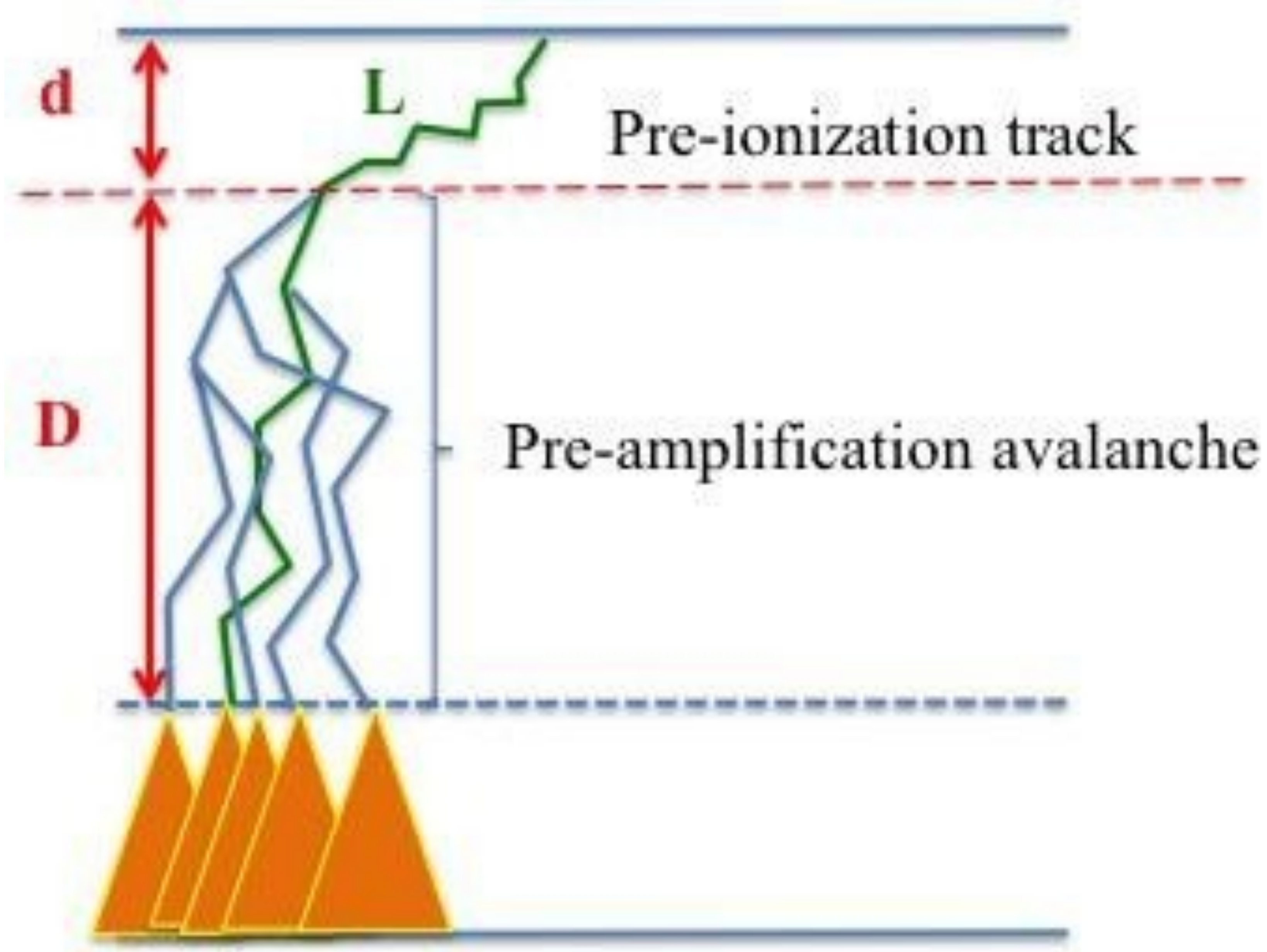
https://indico.cern.ch/event/716539/contributions/3246636/

Detector response

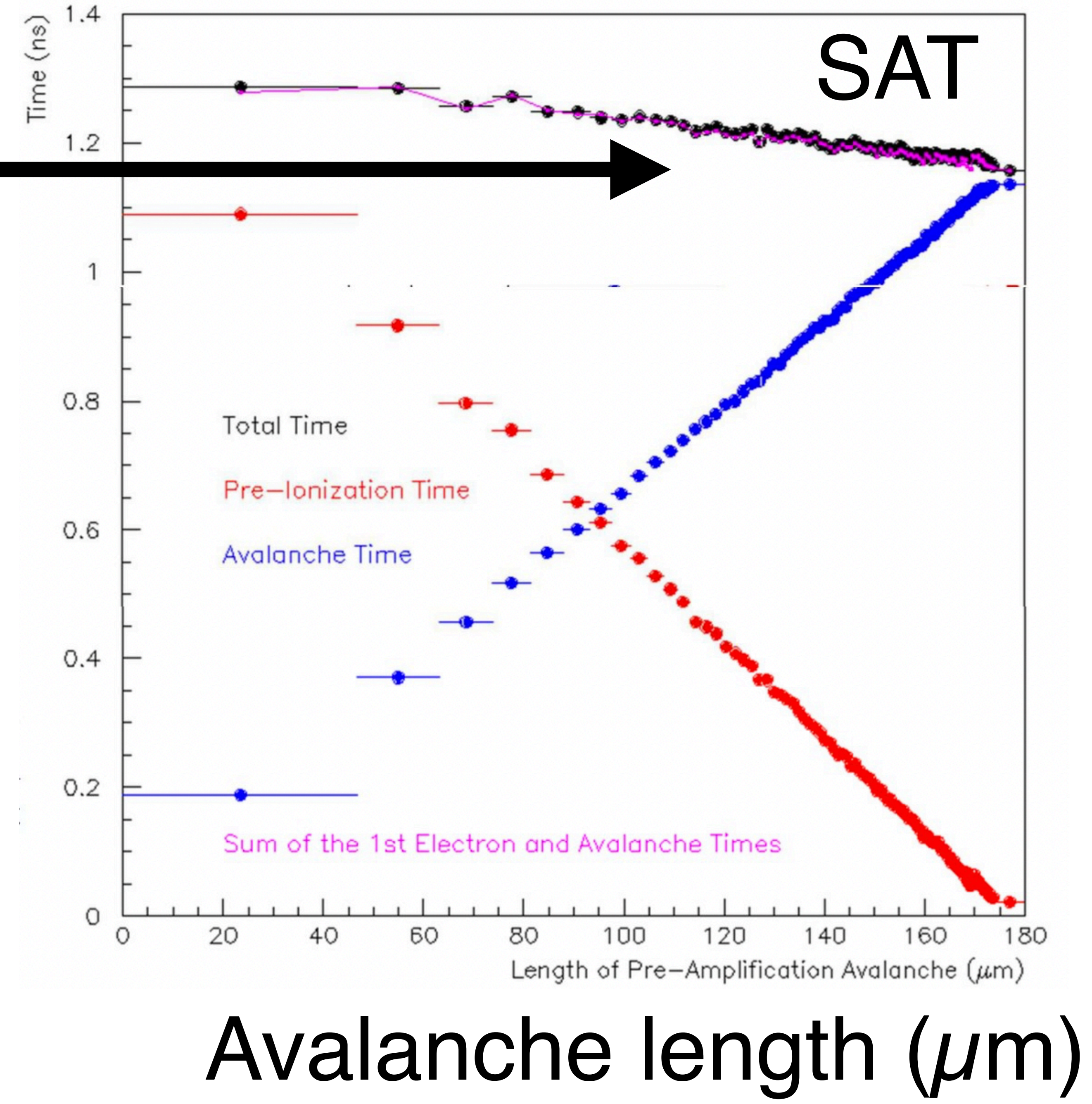
Time resolution depends primarily on e-peak charge

SAT depends on e-peak size:

- bigger pulses -> lower SAT
- higher drift field -> lower SAT



Location of first ionisation determines length of avalanche

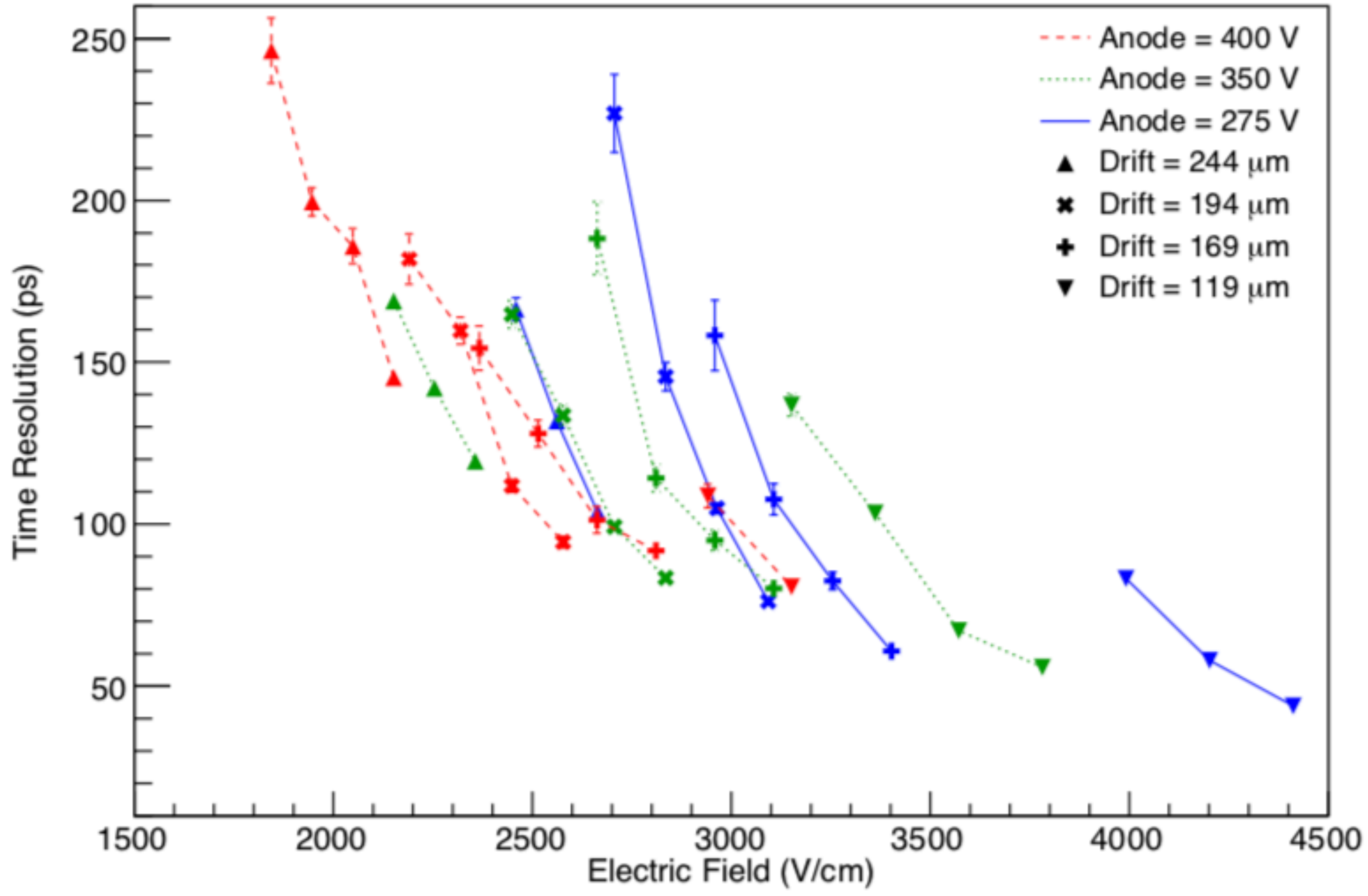


Longer avalanches result in bigger e-peak charge
SAT reduces with e-peak charge

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/

Single photoelectron studies

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



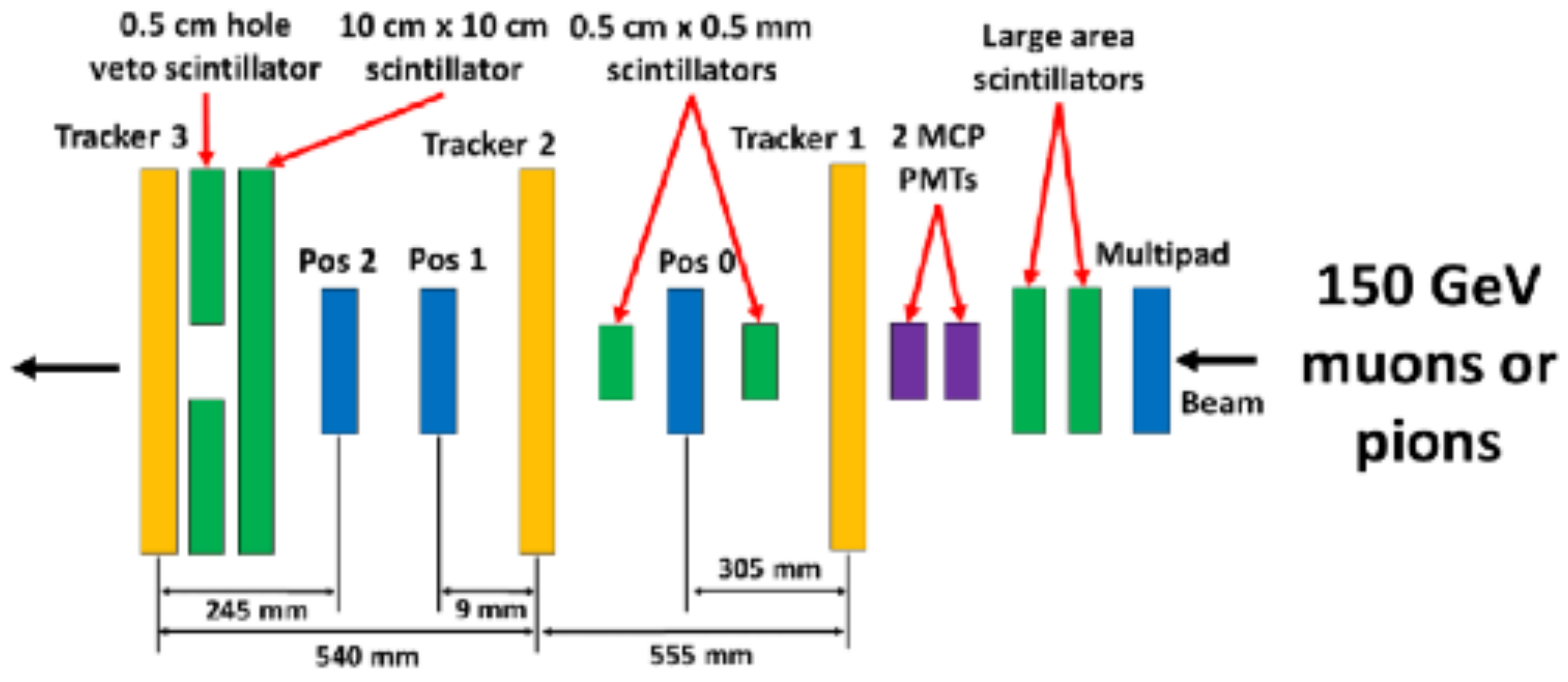
L. Sohl, et al., Single photoelectron time resolution studies of the PICOSEC-Micromegas detector, JINST Proc. of the 15th Topical Seminar on Innovative Particle and Radiation Detectors 2019, InPress (2020)

Time resolution improves with electric field

Smaller drift gap has better performance at same gain

Shorter drift time of the first electron before starting an avalanche gives a better time resolution

MIP beam tests



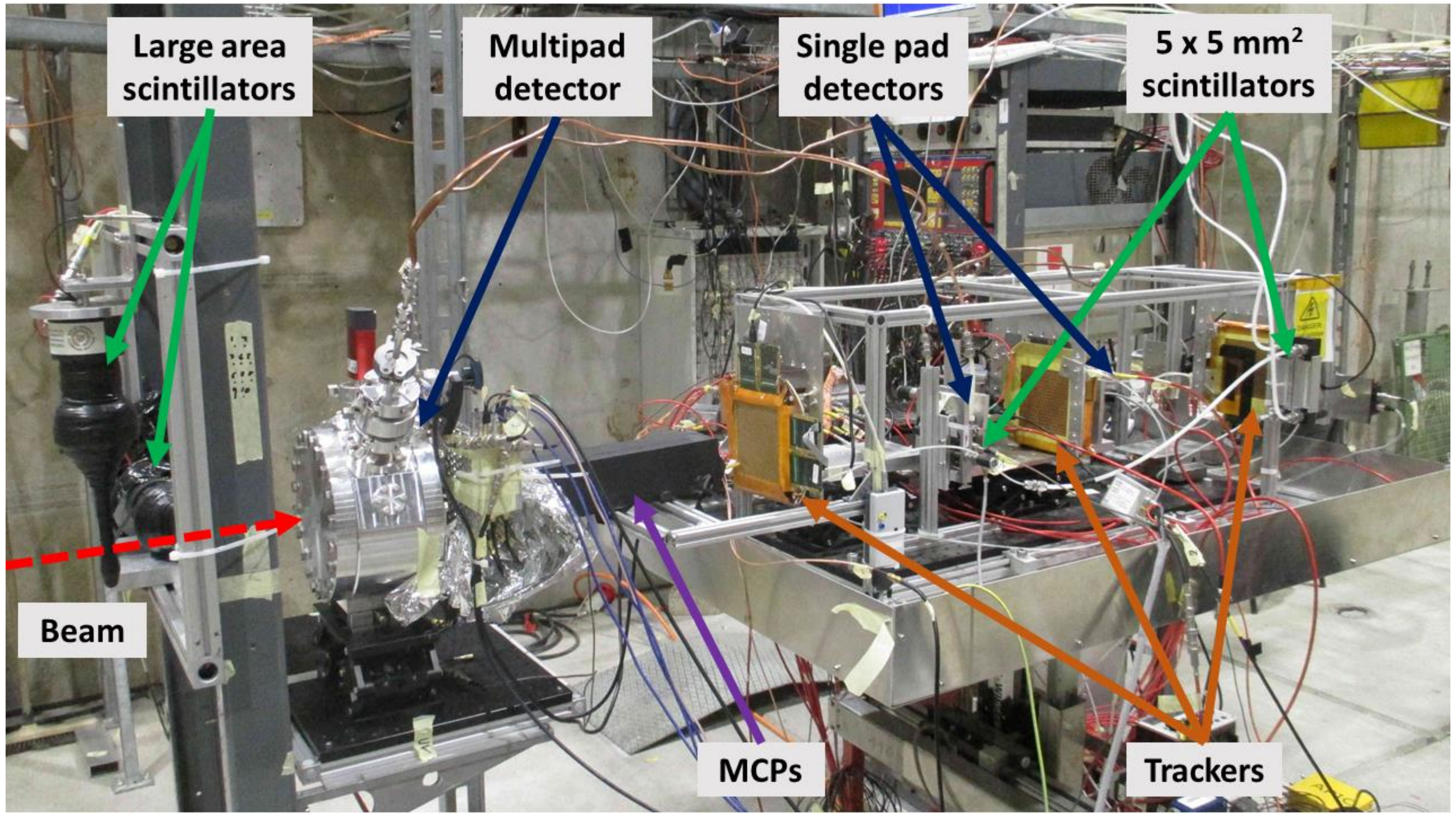
Completed several beam test campaigns at CERN SPS H4 beam line
150 GeV muons and pions

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

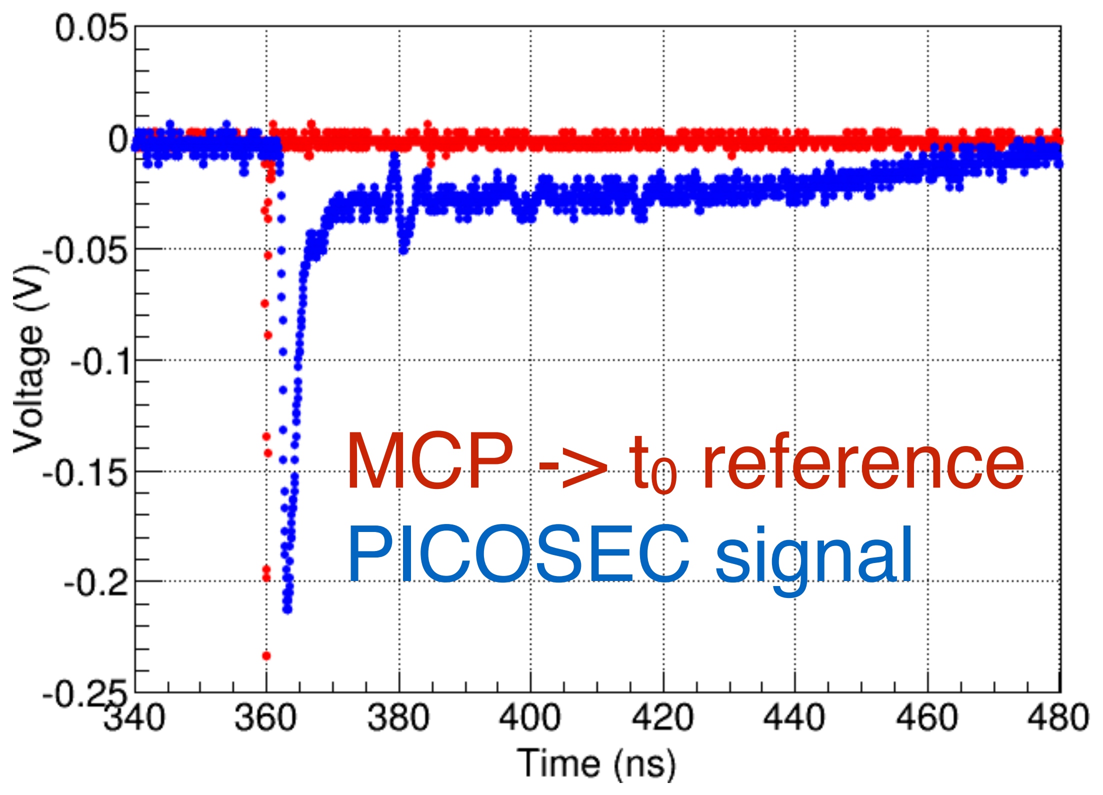
Scintillator as DAQ trigger to select tracking regions

Tracking system with triple-GEMs (40 μm precision)

CIVIDEC preamp + 2.5 GHz oscilloscopes



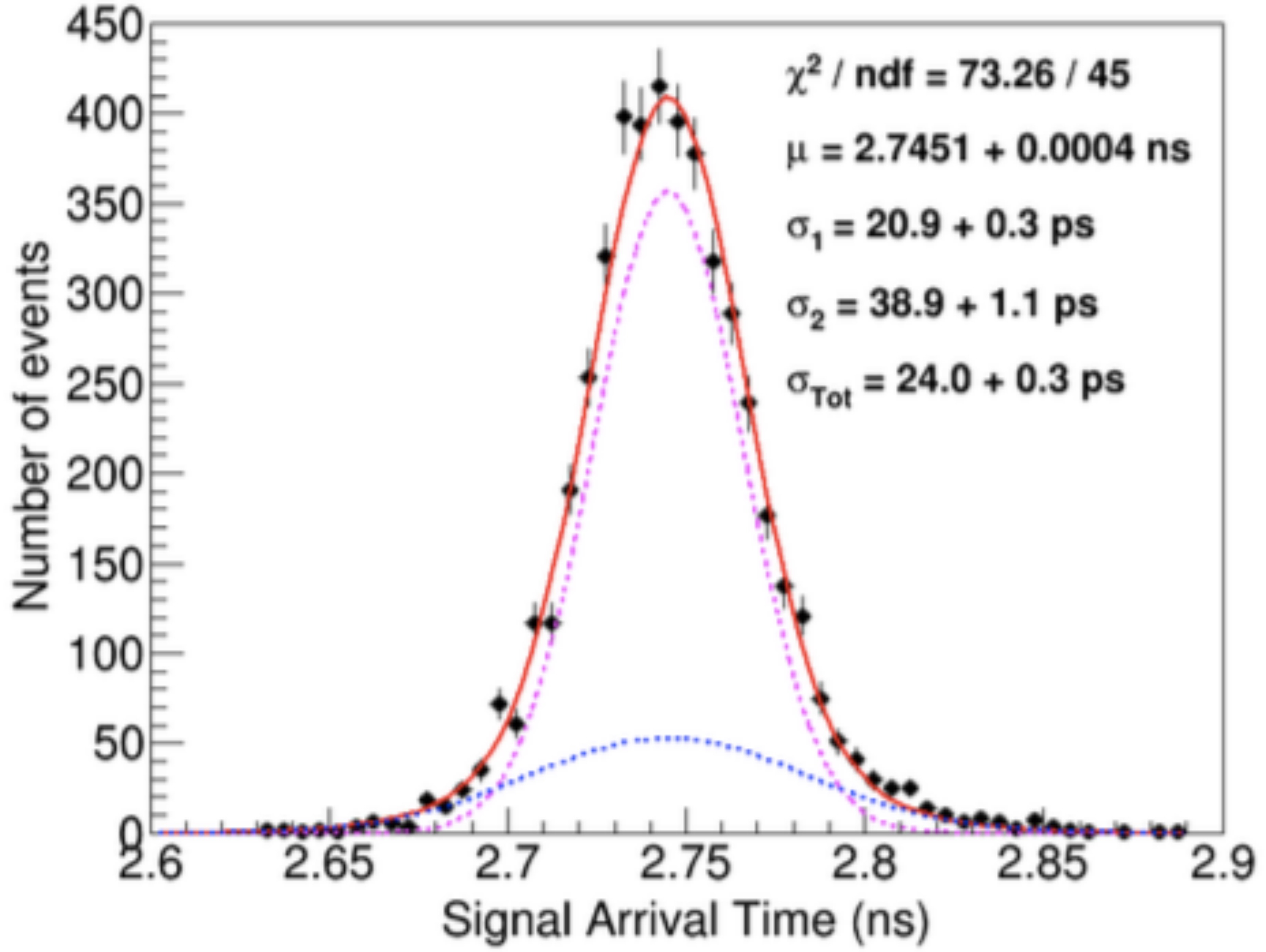
MIP beam tests

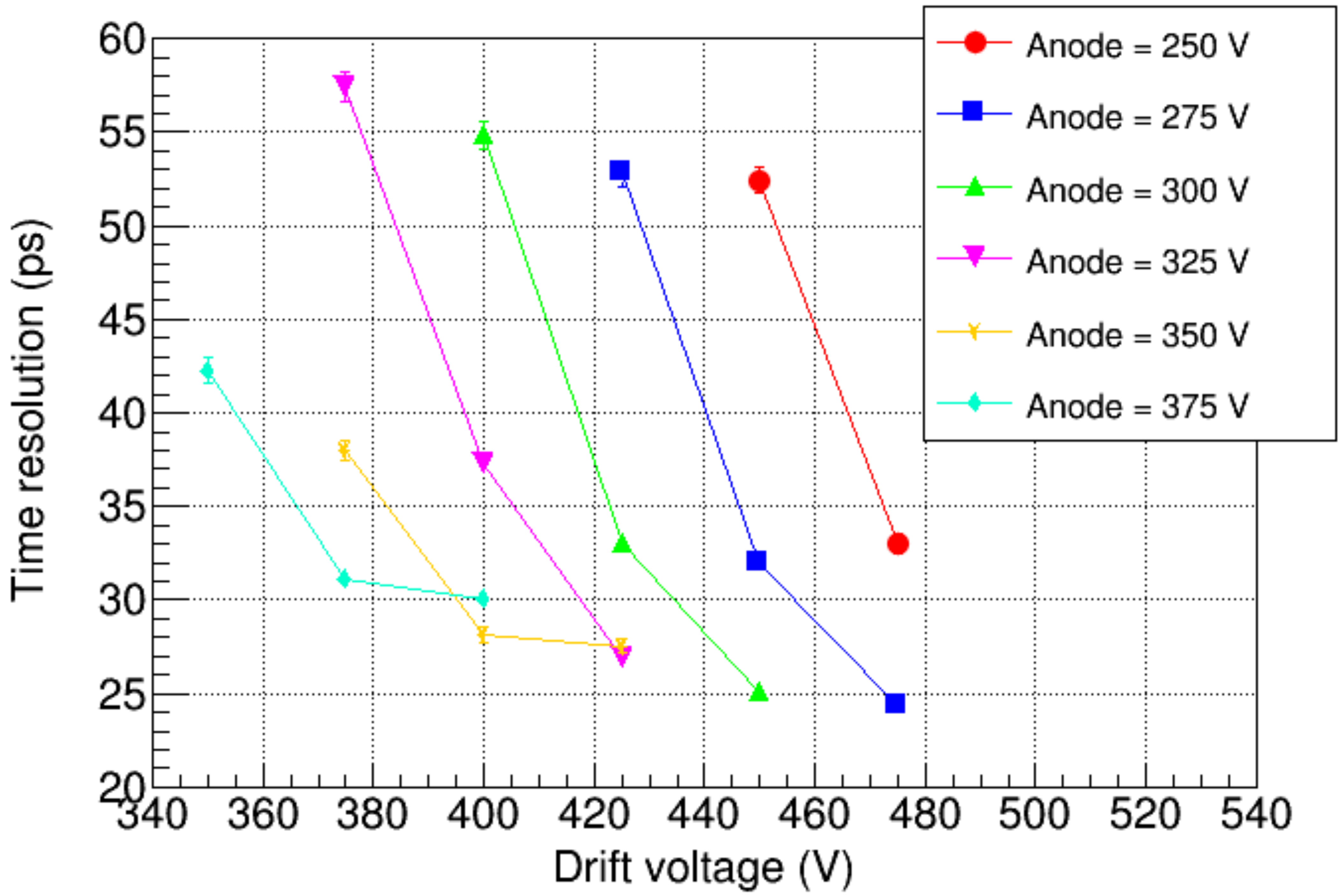


Time resolution for 150 GeV muons: 24 ps

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

Mean number of photoelectrons per muon = 10.4 ± 0.4



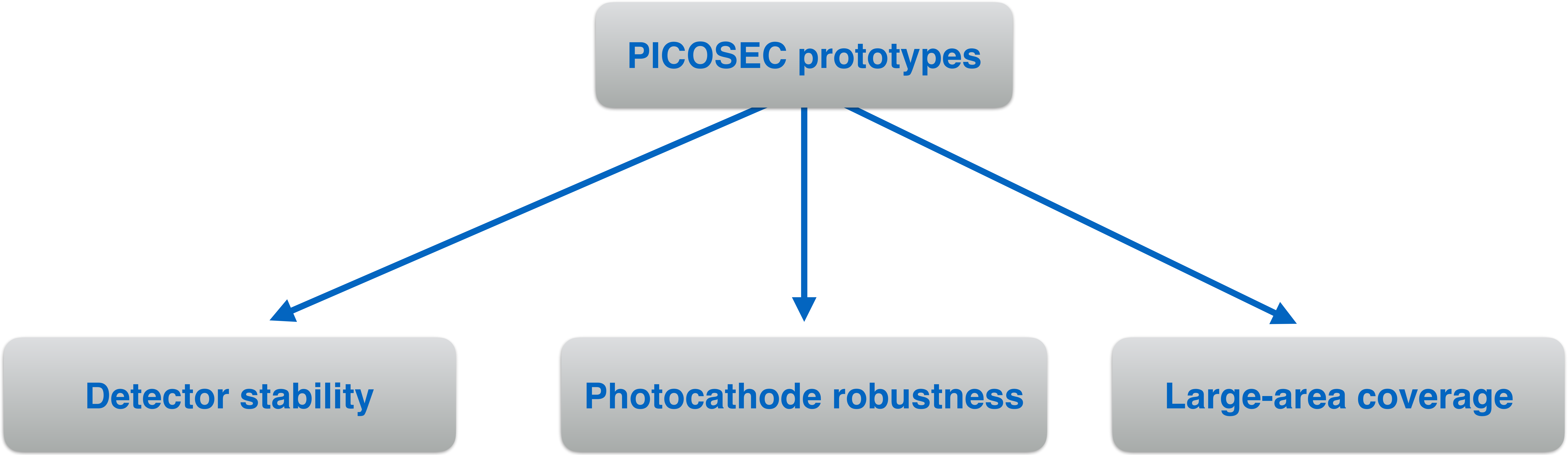


Next steps

Towards a robust, large-area detector

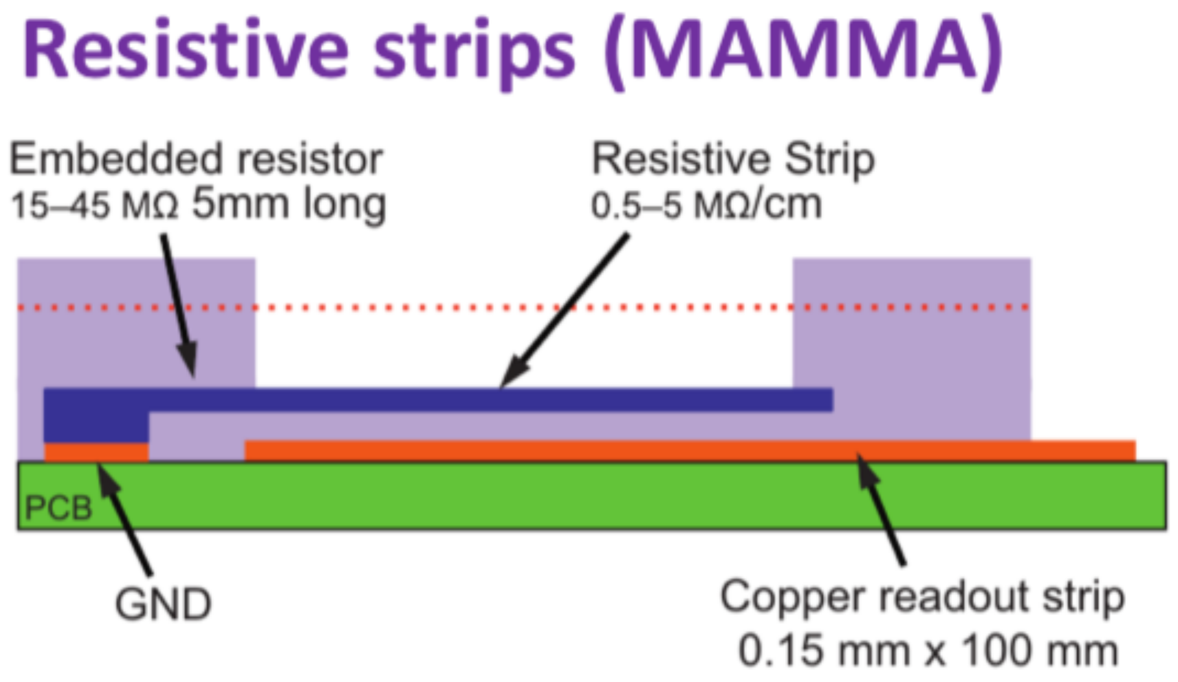
Towards a robust, large-area detector

Based on promising timing precision achieved in beam tests, the PICOSEC collaboration is working towards an applicable detector by addressing robustness of Micromegas and photocathodes as well as scaling up to cover larger areas.



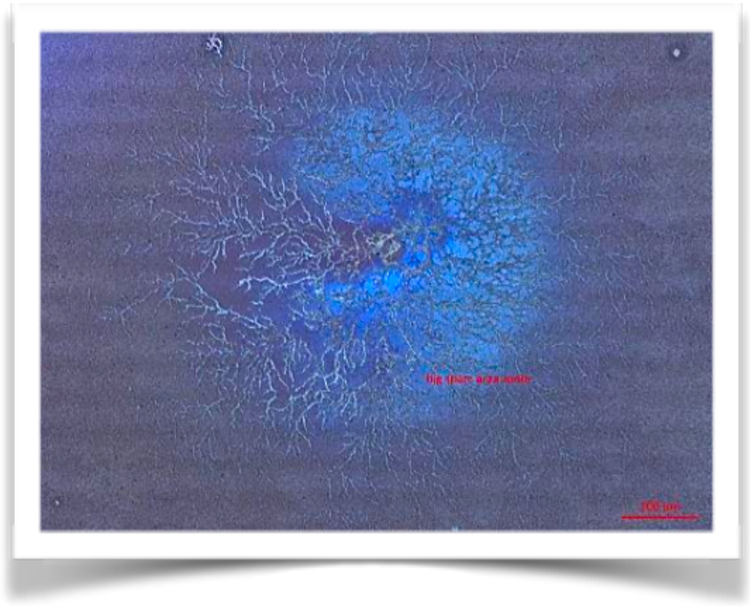
Towards a robust, large-area detector

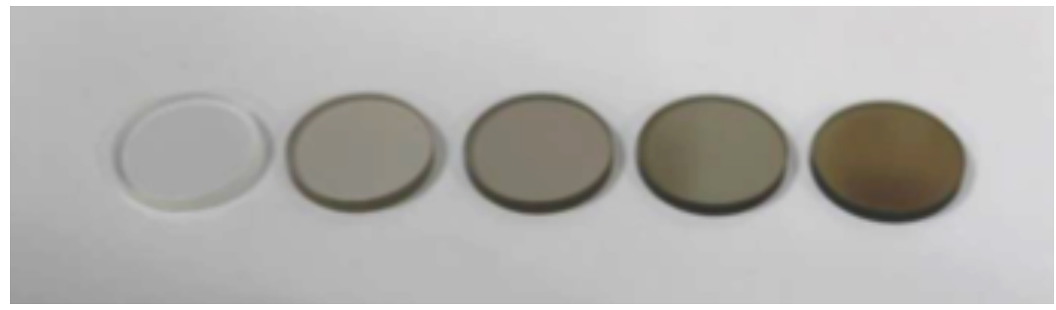
Detector stability
Resistive Micromegas



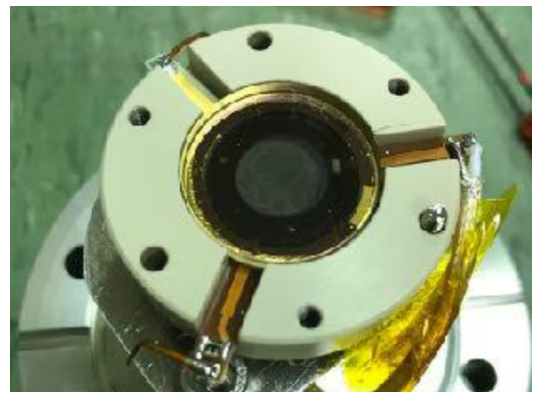
T. Alexopoulos *et al.*, *NIMA* **640** (2011) 110-118.

Photocathode robustness

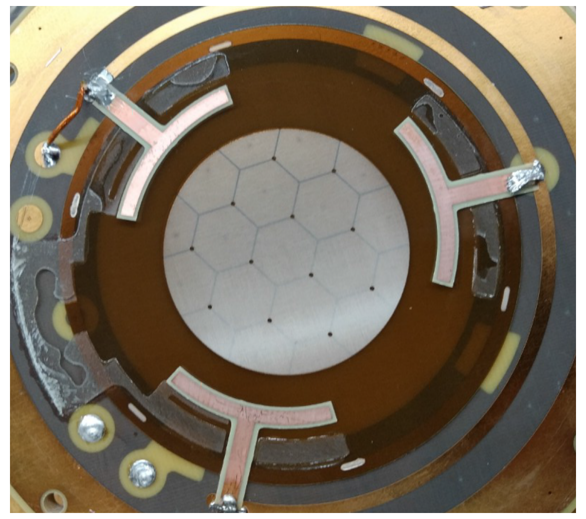




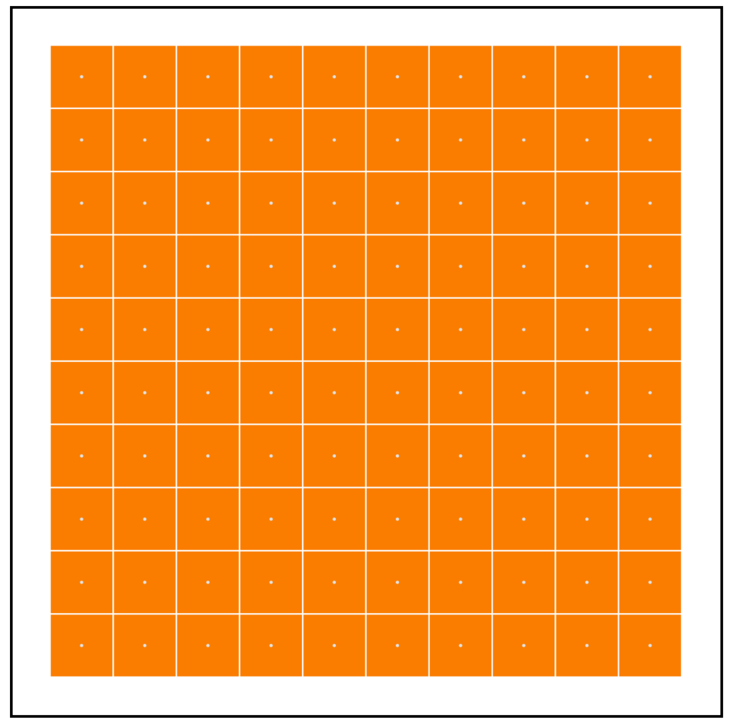
Large-area coverage
From single pad to multi-pad module



Single pad (2016)
⌀1 cm



Multi pad (2017)
⬡ 1 cm



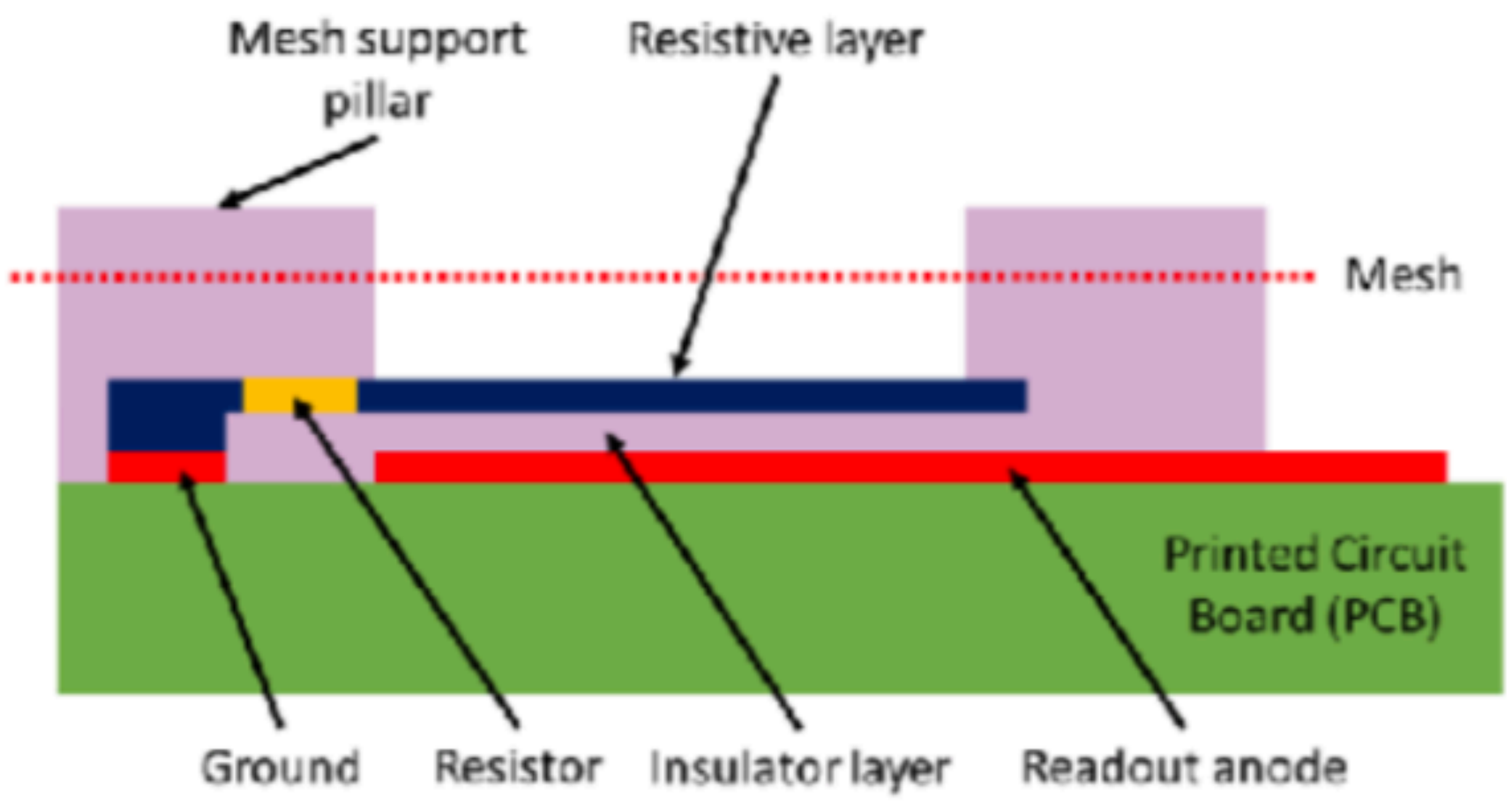
10x10 module
◻ 1 cm

Detector stability
Resistive Micromegas

Limiting destructive effect of discharges but employing resistive elements for readout anodes

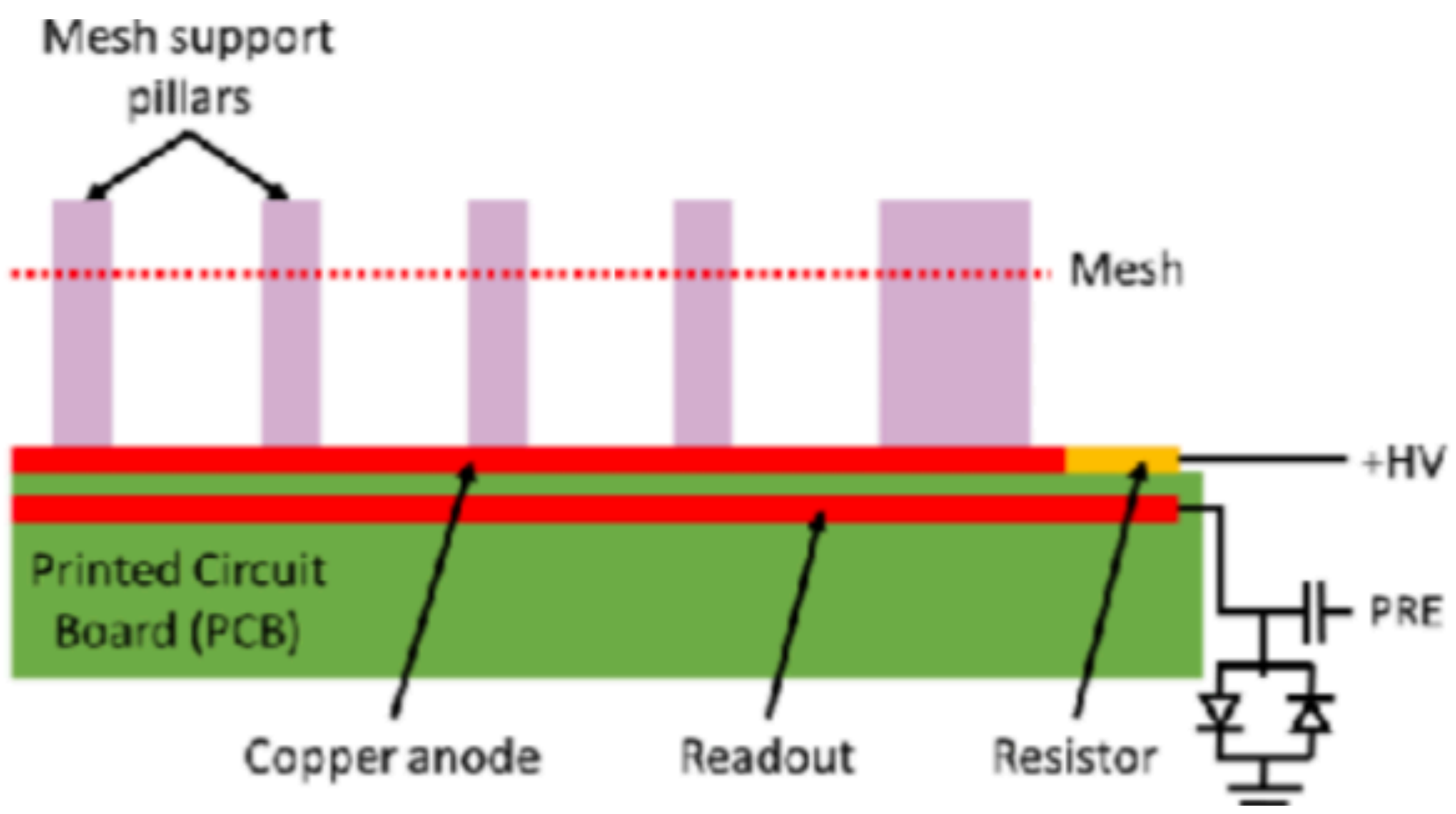
Two design approaches tested and evaluated in beam test campaigns

Resistive strips (MAMMA)



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

Floating strips (COMPASS)

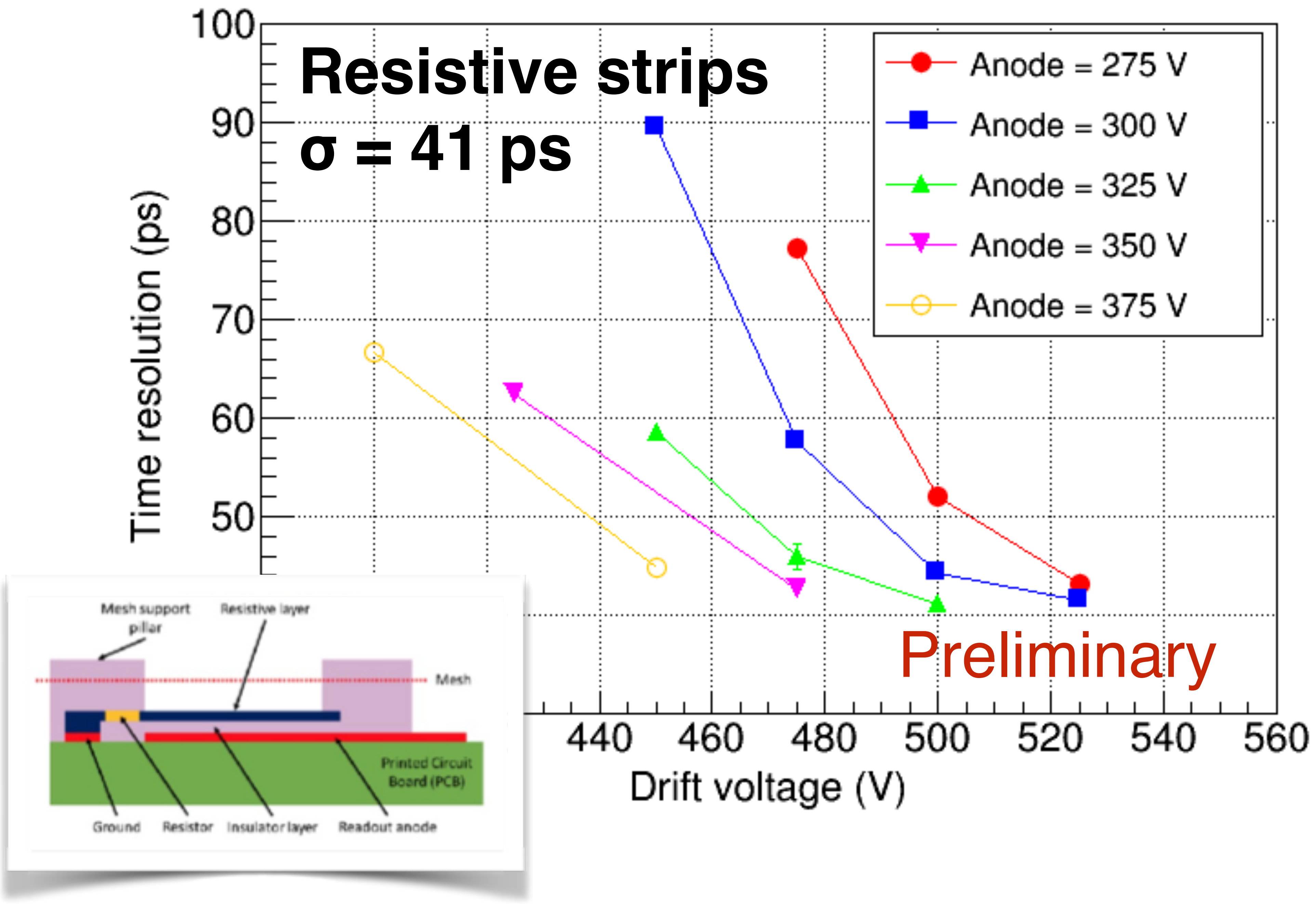


Detector stability

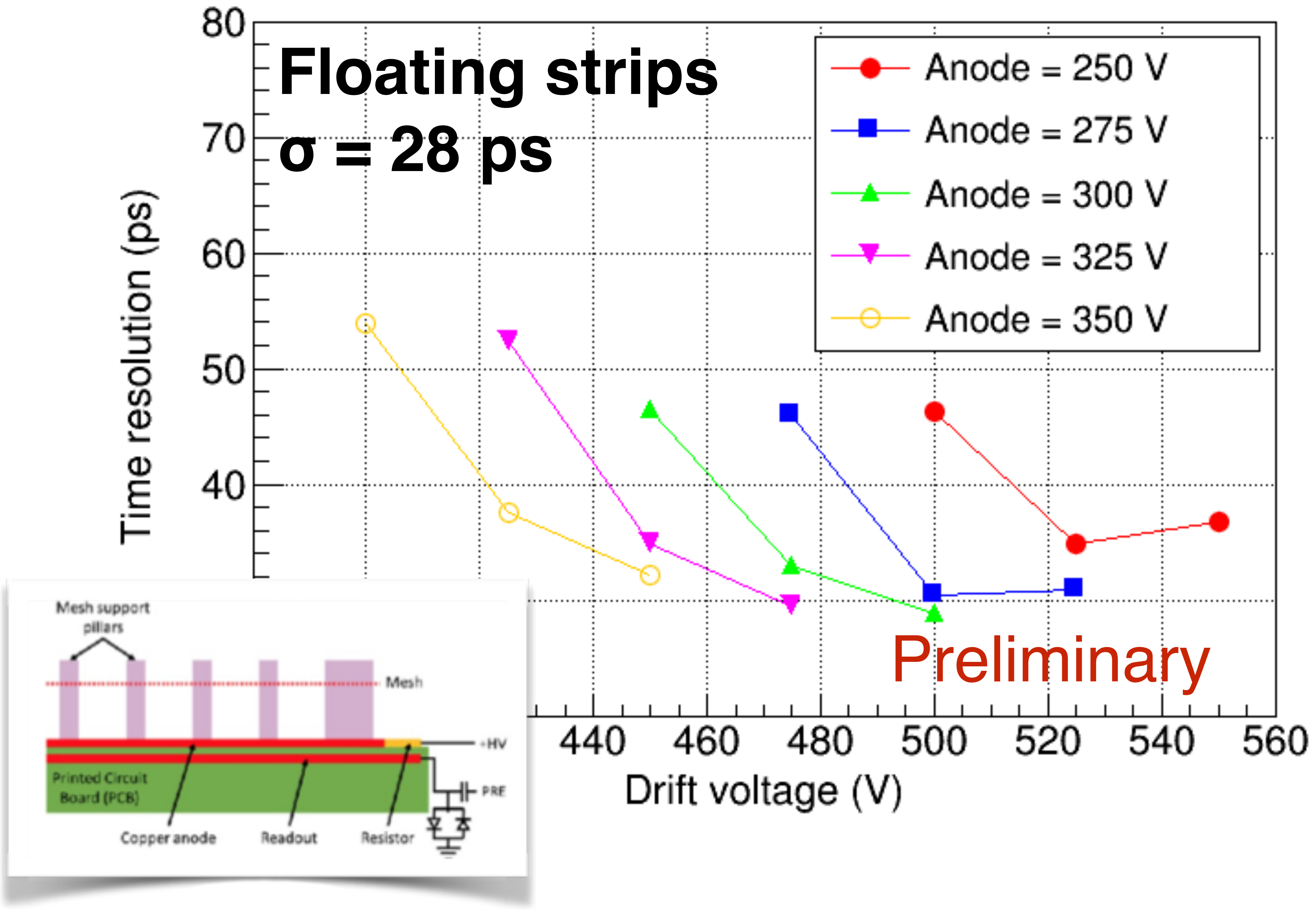
Resistive Micromegas

Achieved time resolution close to PICOSEC bulk readout.

Stable operation in intense pion beam



41 MΩ/sq



25 MΩ

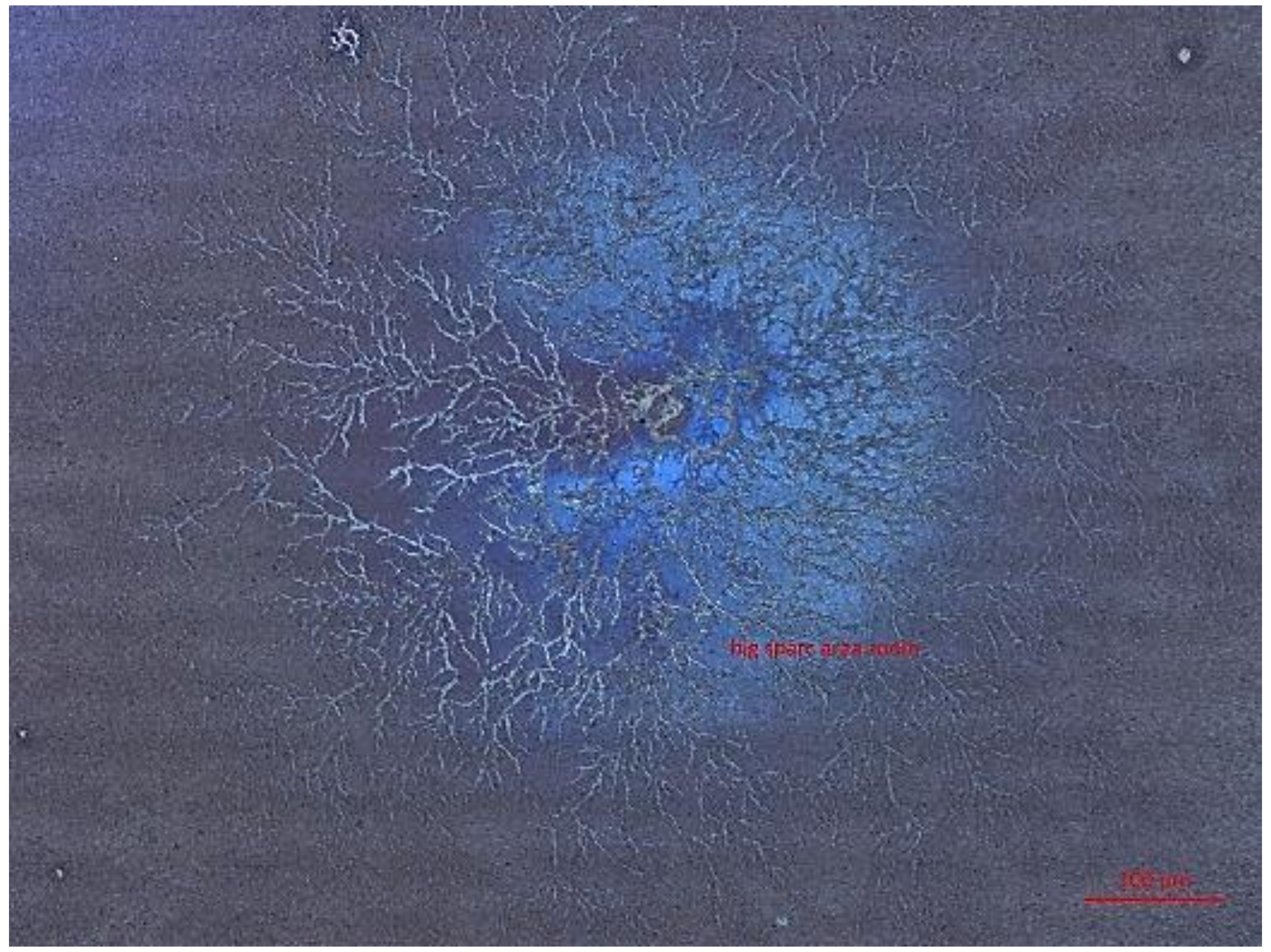
Photocathode robustness

Problems with CsI

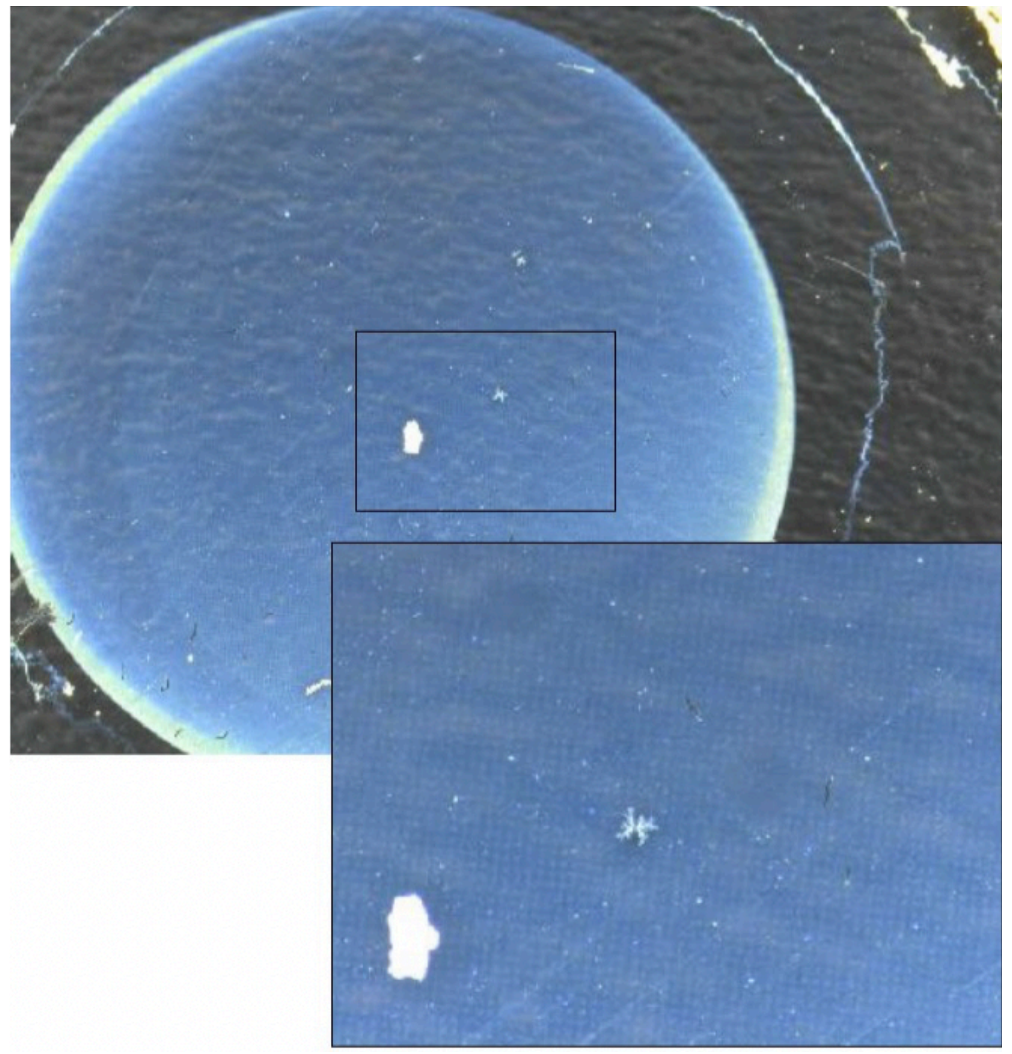
Standard PICOSEC photocathode: 18 nm CsI + 3 nm Cr

CsI sensitive to humidity, ion backflow and sparks

CsI photocathode after spark



Ion backflow on CsI



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

Protection layers (MgF_2, LiF, …)

Minimise effect of ion back flow while preserving high QE

Alternative photocathodes

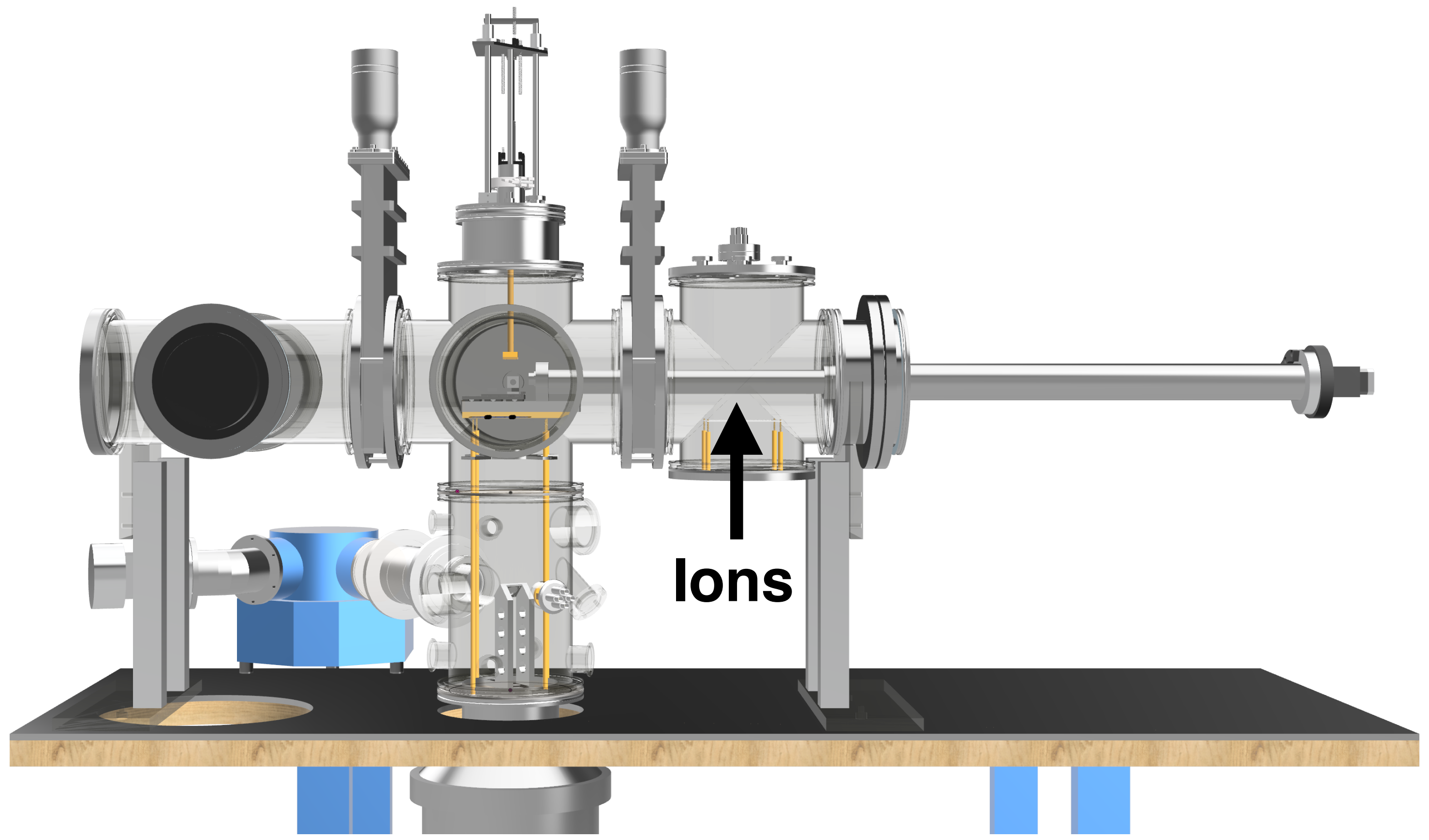
Metallic, DLC, B_4C, nano diamond powder, CVD diamond, …

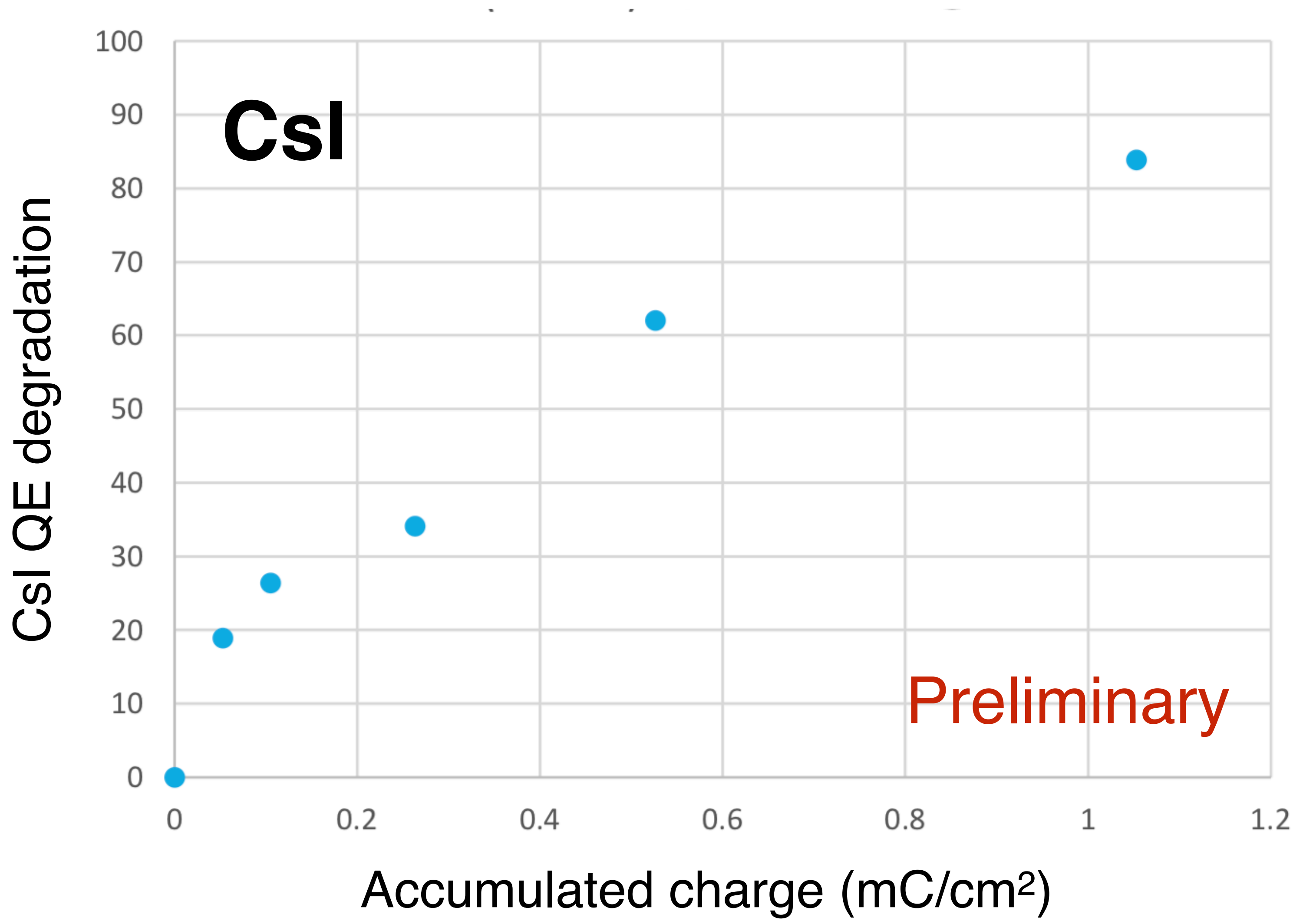
Inherently robust materials with lower QE

Photocathode studies

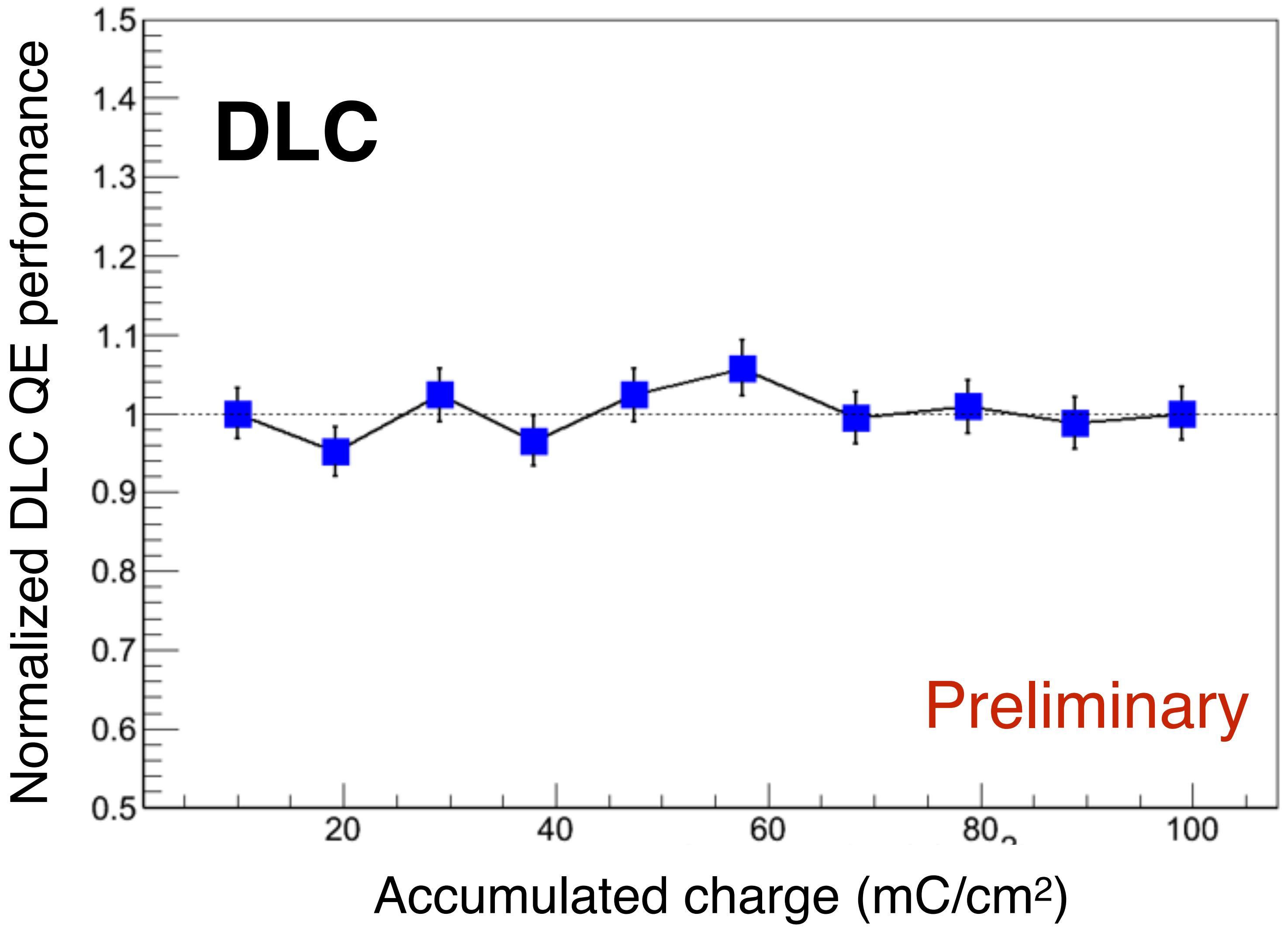
Dedicated setups to study photocathode QE and possibility to quantify degradation under ion bombardment

Several materials and approaches being studied





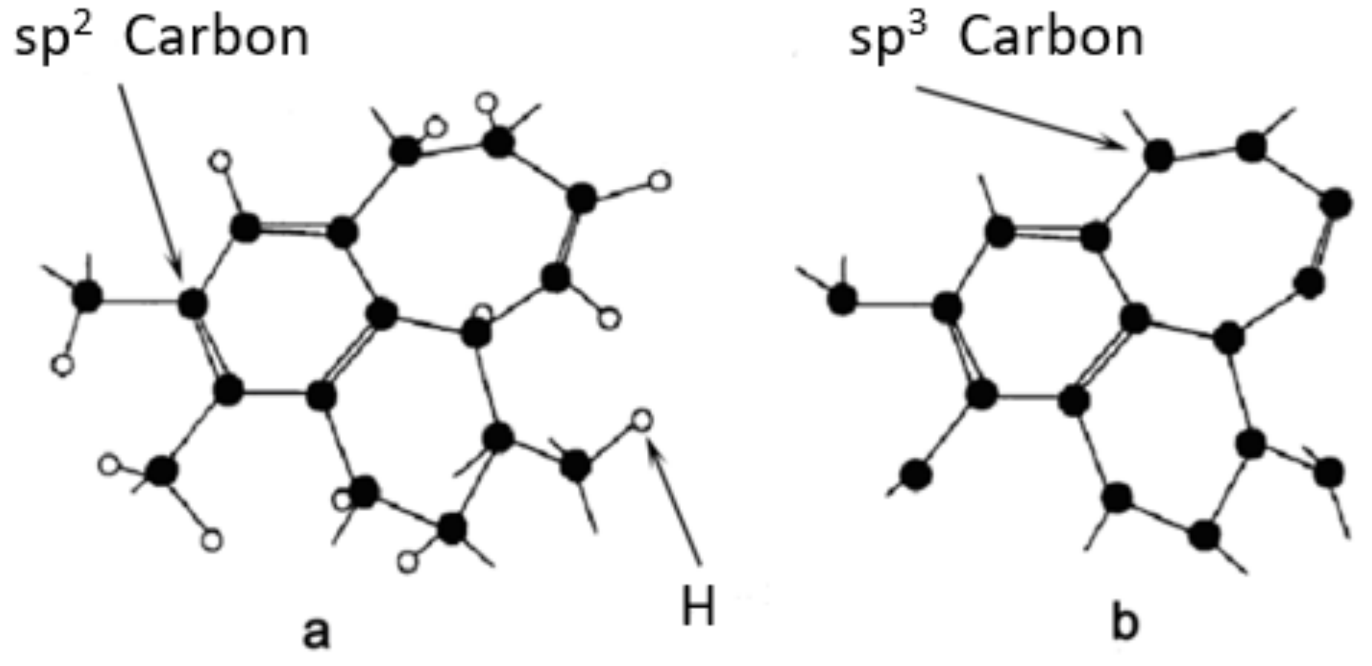
M. Lisowska, ASSET - Photocathode characterisation device, RD51 Mini-Week February 2020, https://indico.cern.ch/event/872501/contributions/3726017

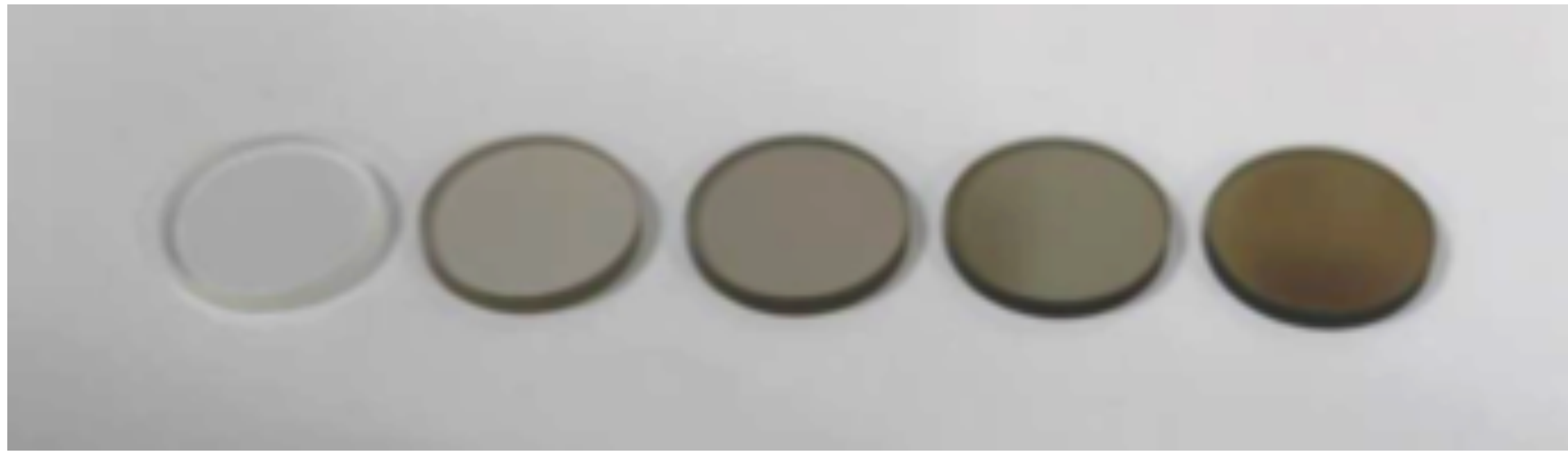


X. Wang, Recent photocathode and sensor developments for the PICOSEC Micromegas detector, MPGD 2019 https://indico.cern.ch/event/757322/contributions/3387110

Photocathodes: DLC

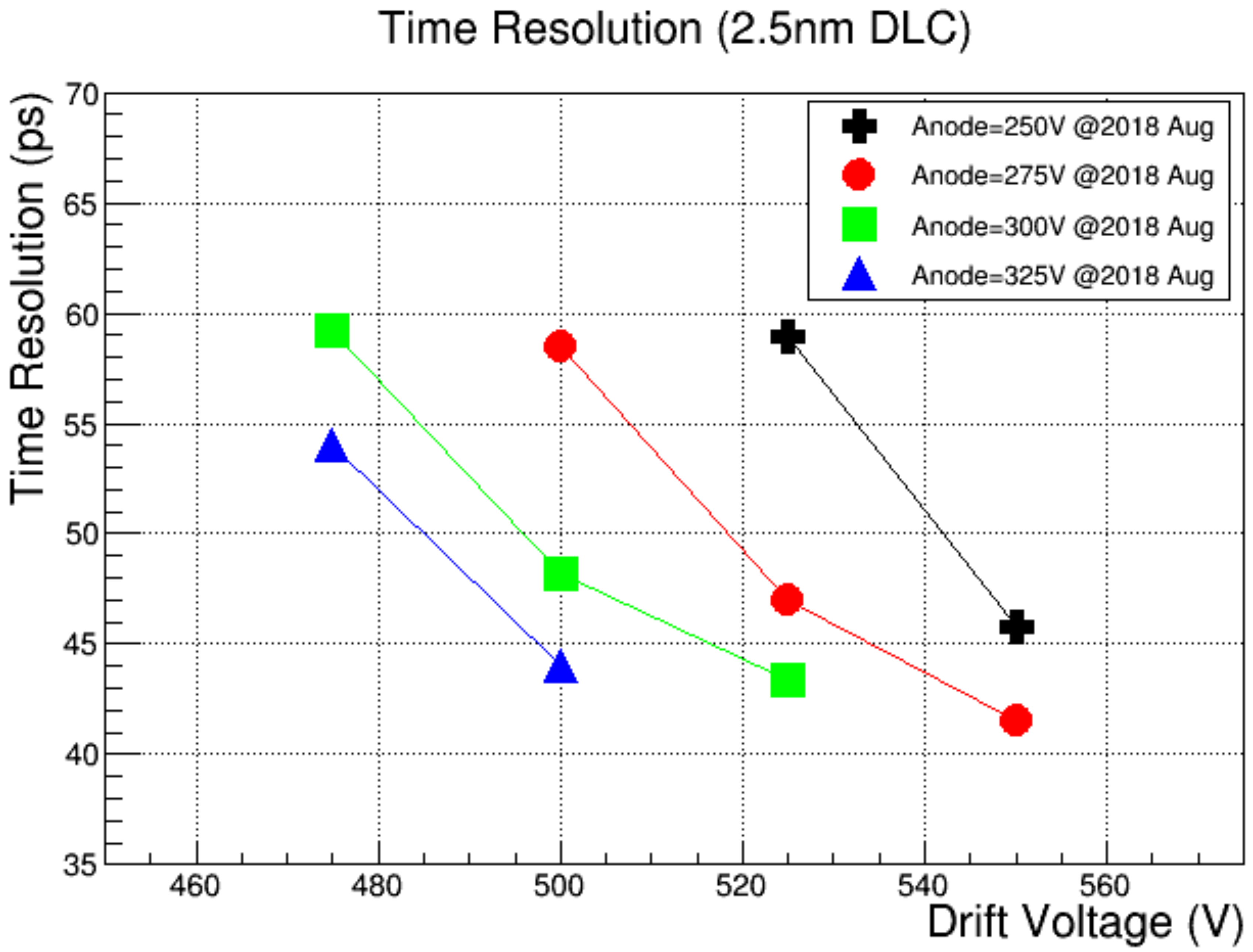
Diamond-like carbon (DLC) is a robust material which may also be used as photocathode.



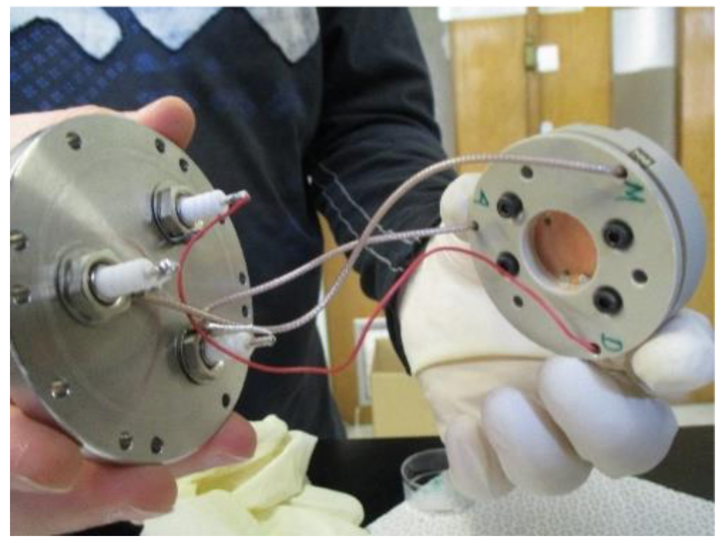


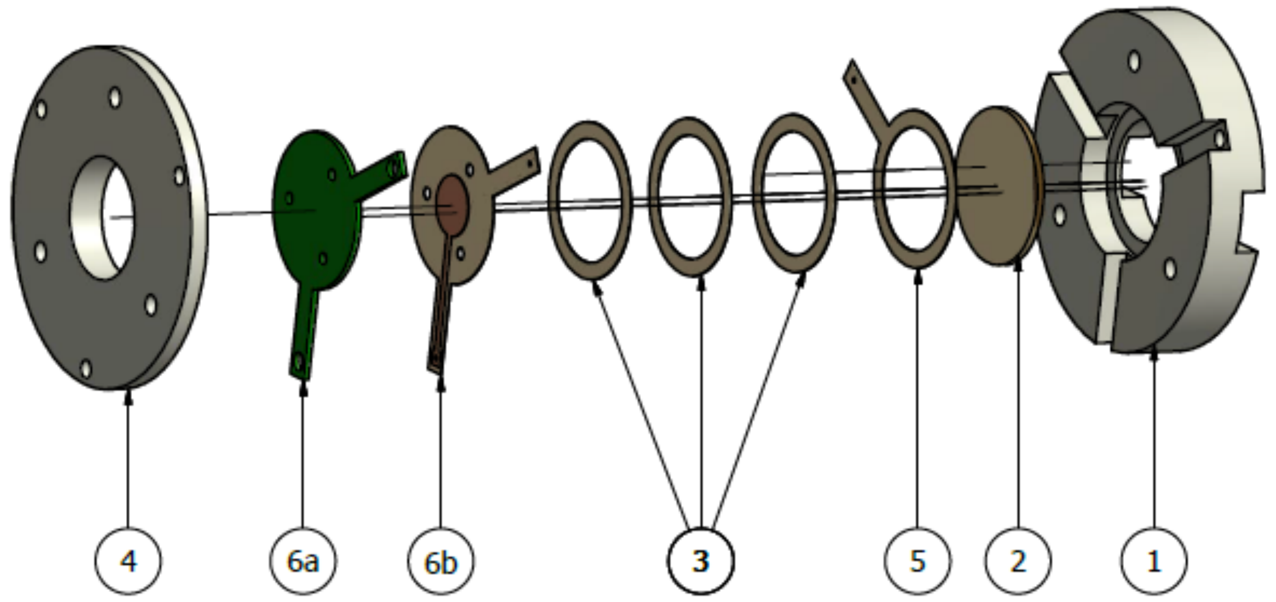
https://indico.cern.ch/event/709670/contributions/3020862/attachments/1672921/2684467/

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



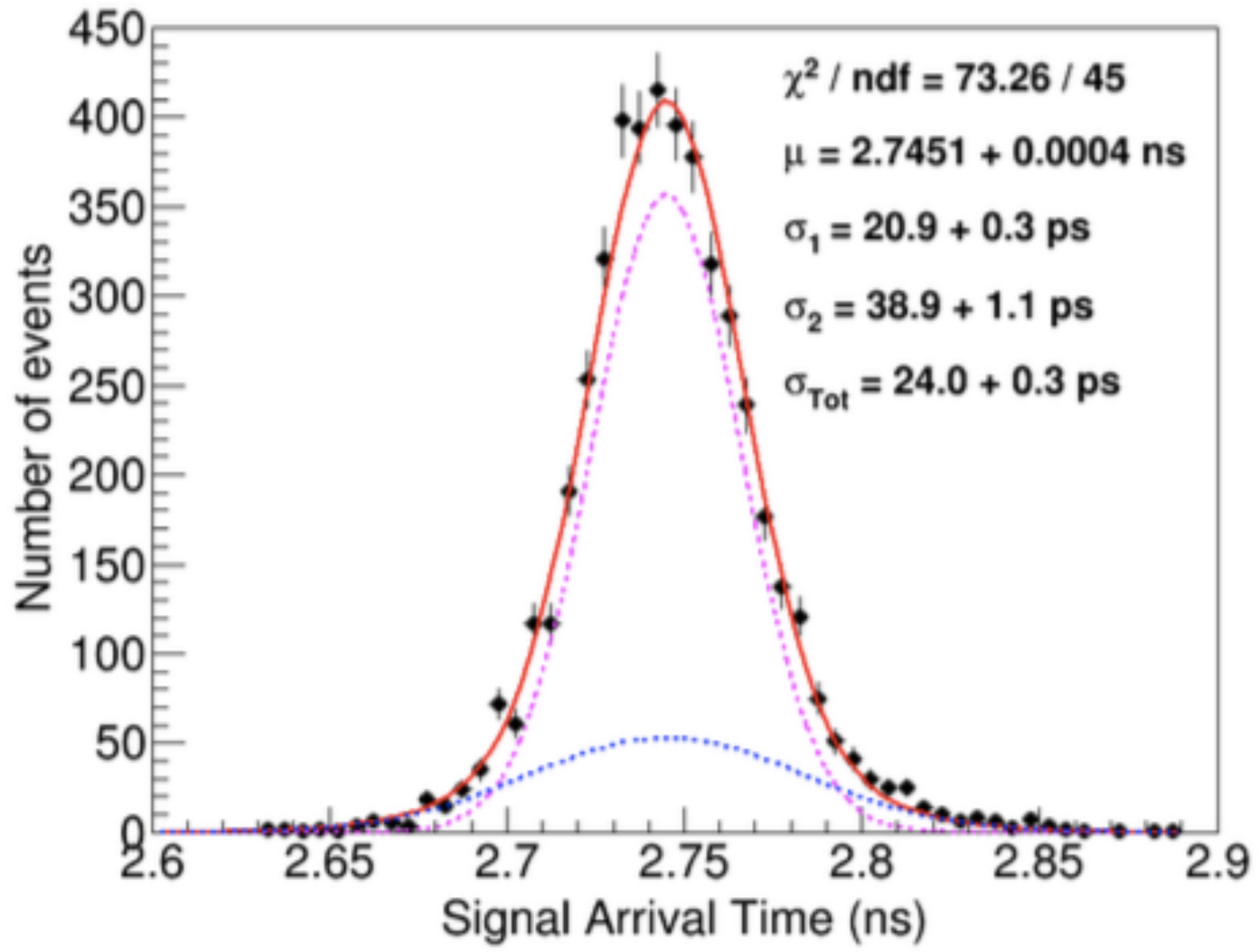
Large-area coverage
Scaling up multi-channel PICOSEC

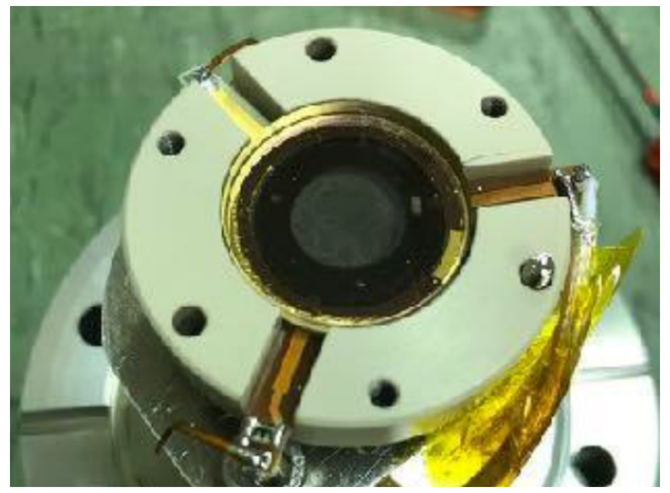




1 cm diameter PICOSEC prototype was used for laser studies and in test beam campaigns

Simple, single-channel readout





Single pad (2016)
⌀1 cm

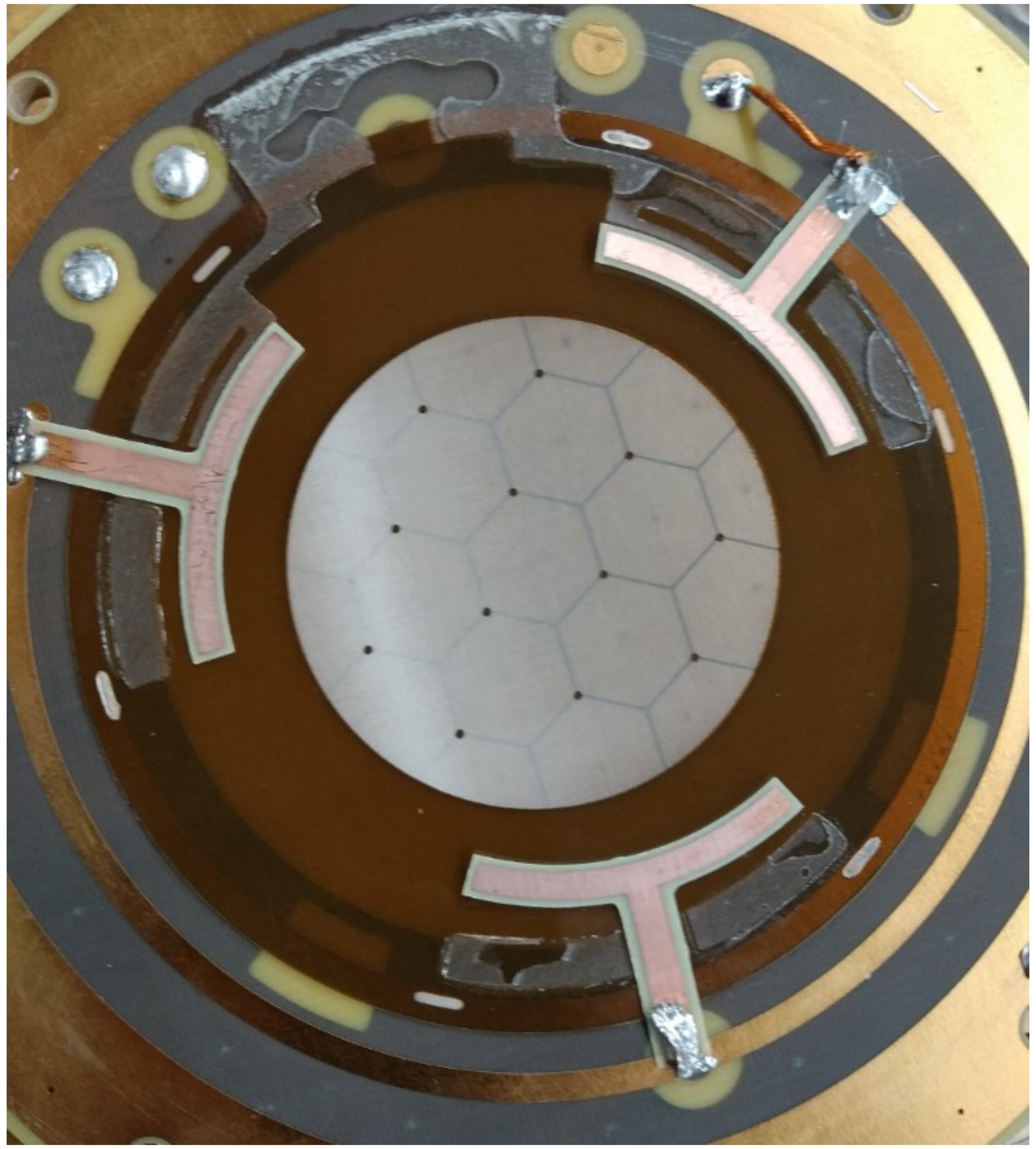
Multi pad (2017)
⬡ 1 cm

10x10 module
□ 1 cm

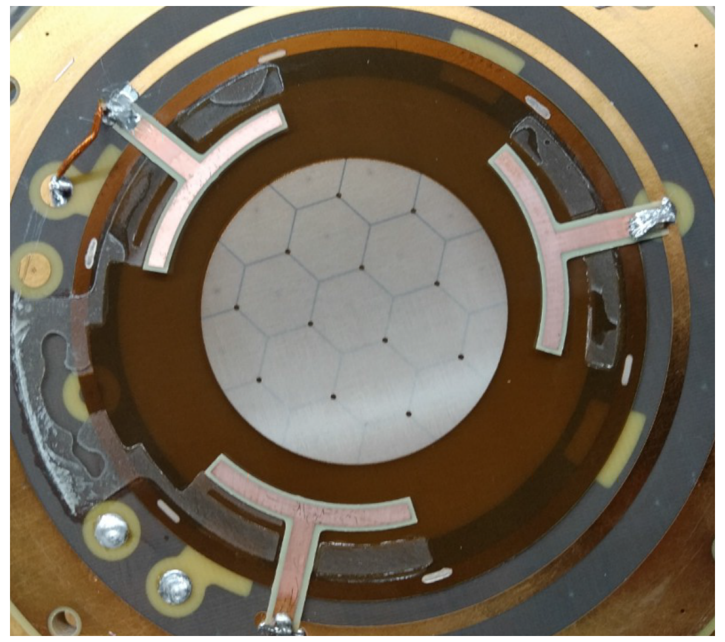
Large-area coverage

Scaling up multi-channel PICOSEC

Multi-pad prototype was evaluated in test beam campaigns and timing resolution for signal shared across multiple pads was studied



Single pad (2016)
⌀1 cm

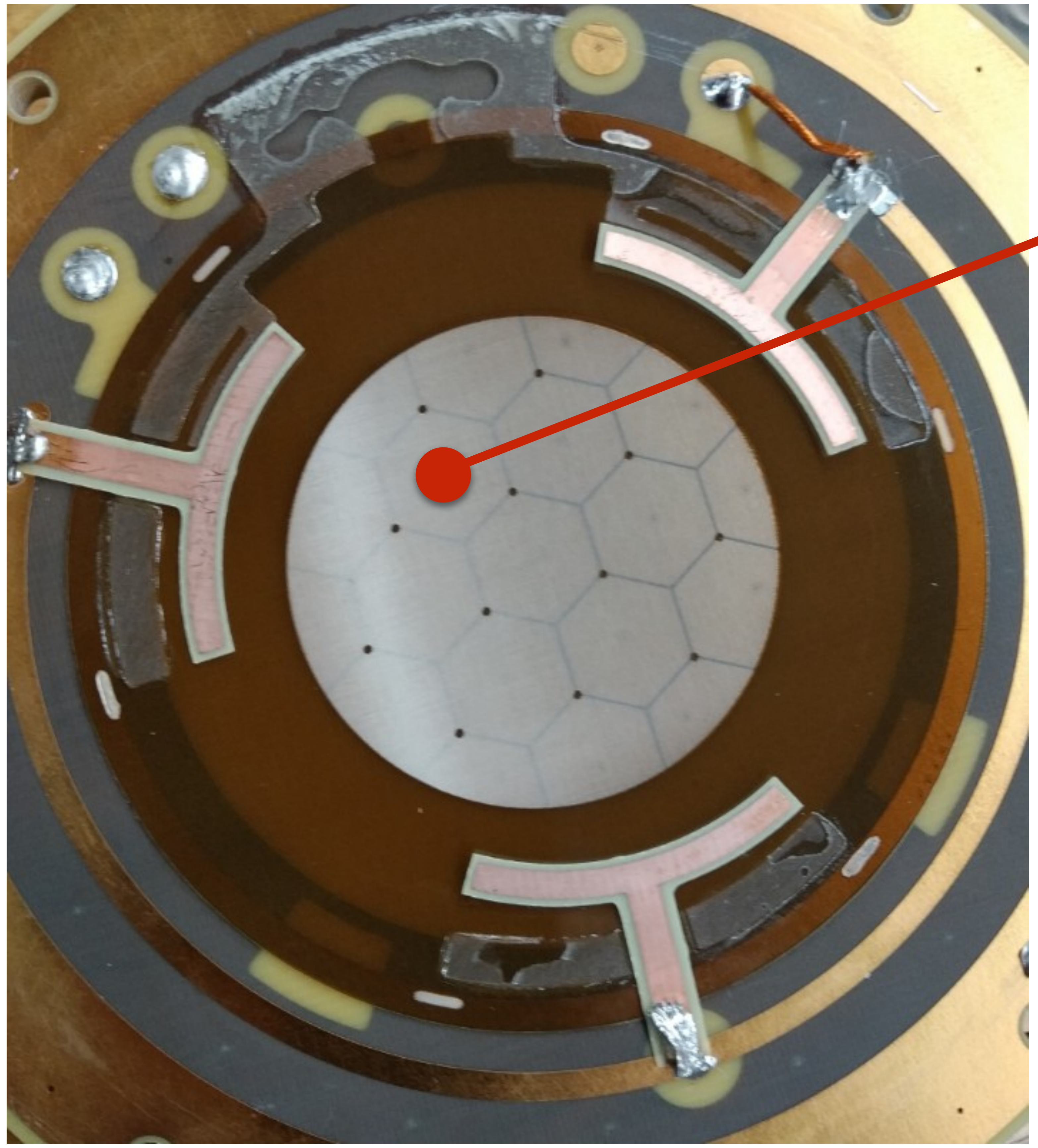


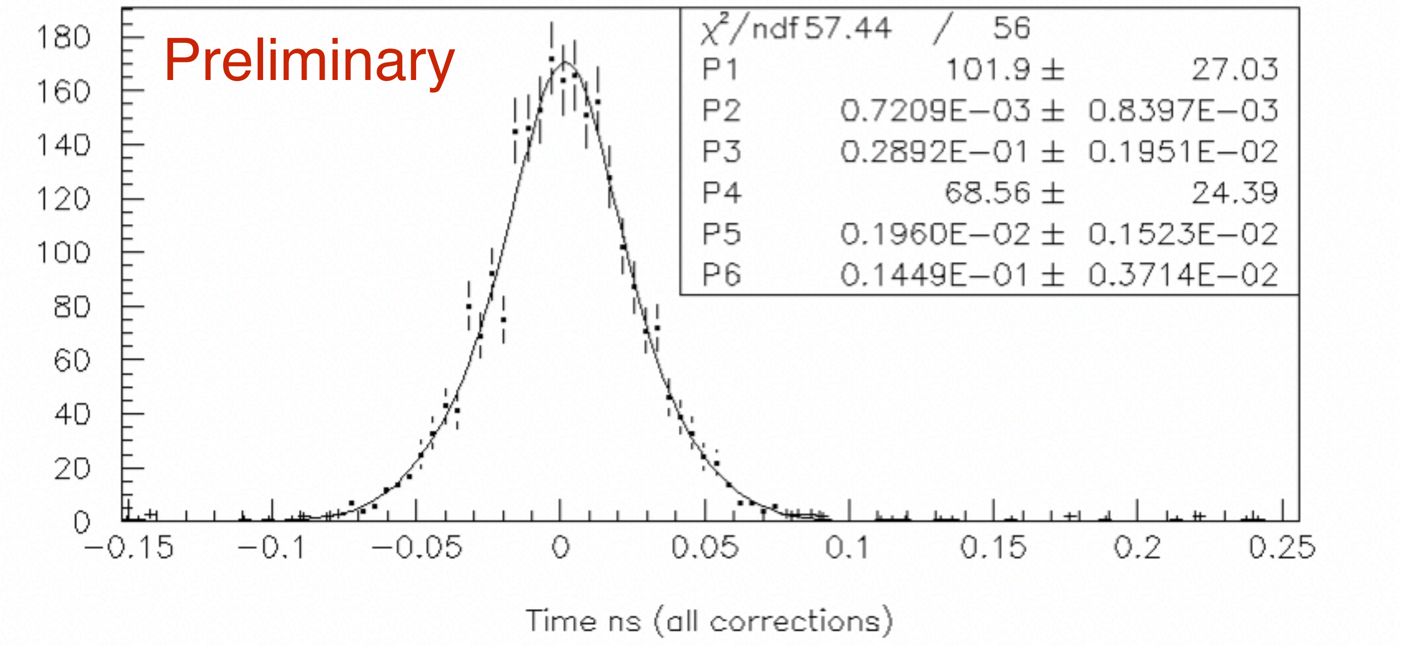
Multi pad (2017)
⬡ 1 cm

10x10 module
□ 1 cm

Large-area coverage

Scaling up multi-channel PICOSEC



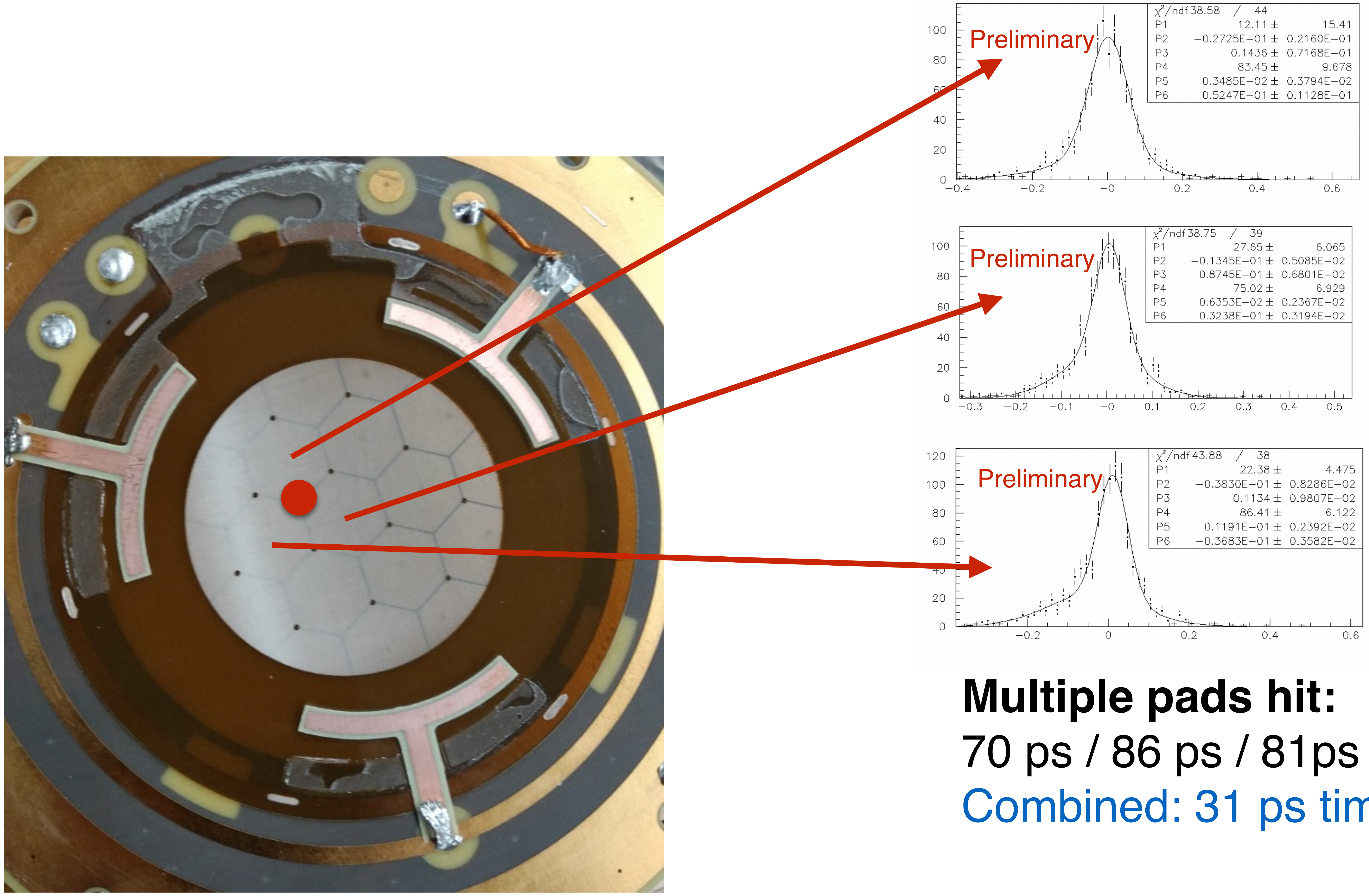


Single pad hit:

25 ps timing resolution for all pads

Large-area coverage

Scaling up multi-channel PICOSEC



Multiple pads hit:

70 ps / 86 ps / 81ps timing resolution

Combined: 31 ps timing resolution

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

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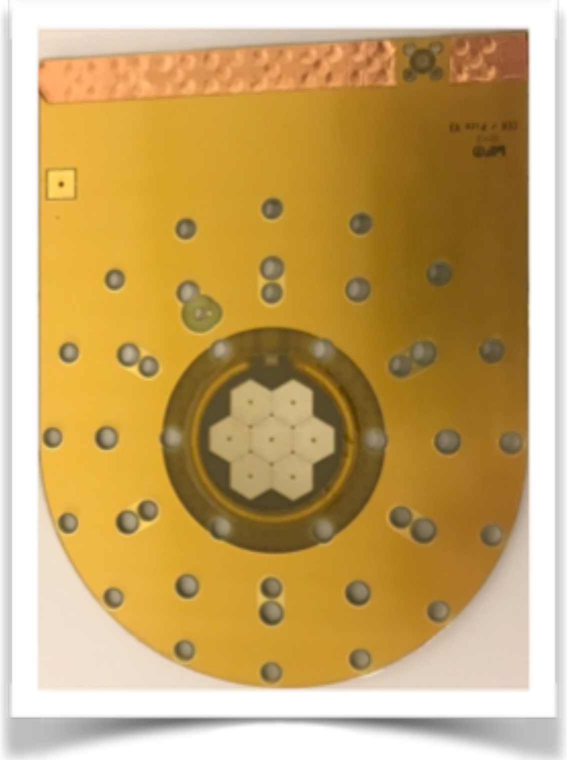
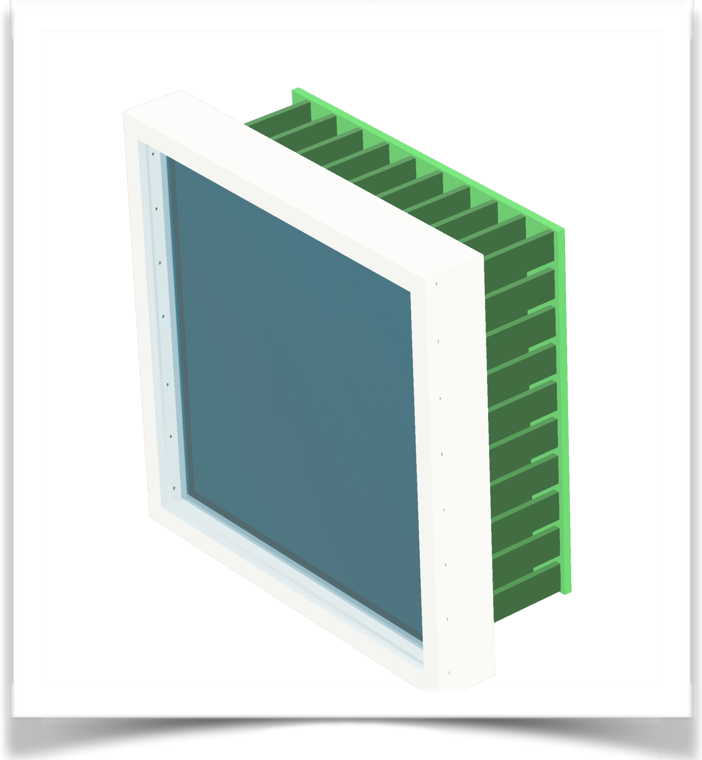




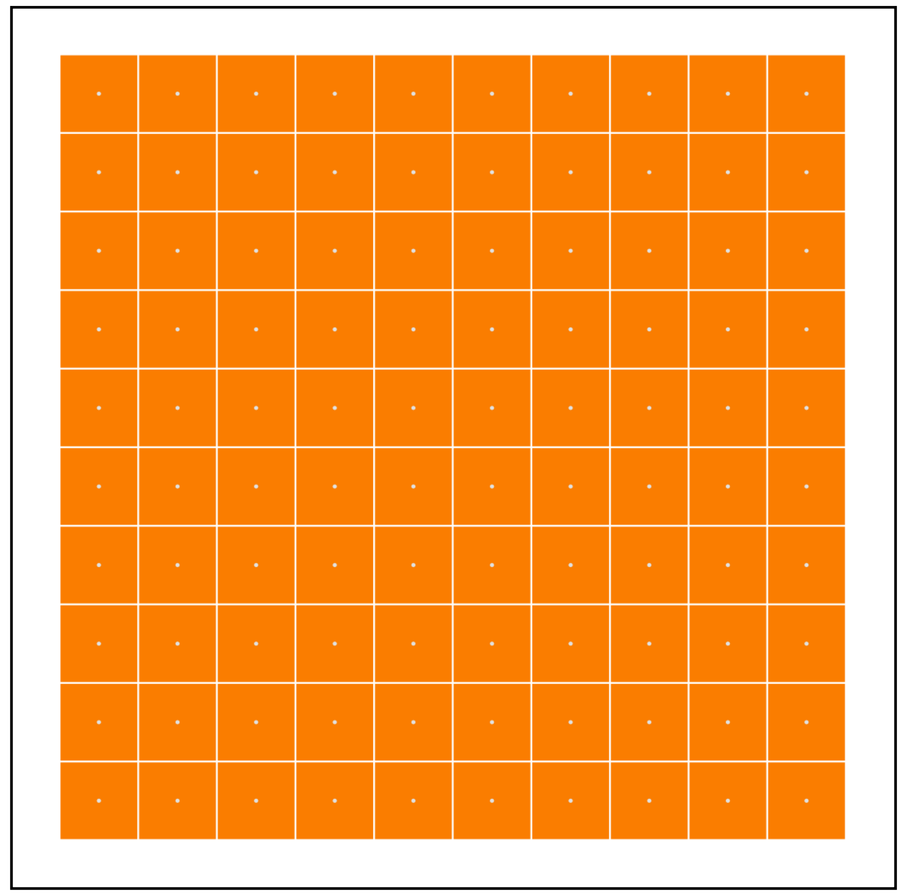
Several variants of multi-channel PICOSEC prototypes in development / under test

Addressing challenges associated with scaling to larger areas:

- Signal routing and sharing across pads
- Multi-channel amplifiers and digitisers
- Resistive multi-pad anode
- Detector uniformity
- Large Cherenkov radiators
- Mechanics to preserve precise gaps
- Compact detector vessel
- …

Single pad (2016)
⌀1 cm

Multi pad (2017)
⬡ 1 cm



10x10 module
□ 1 cm

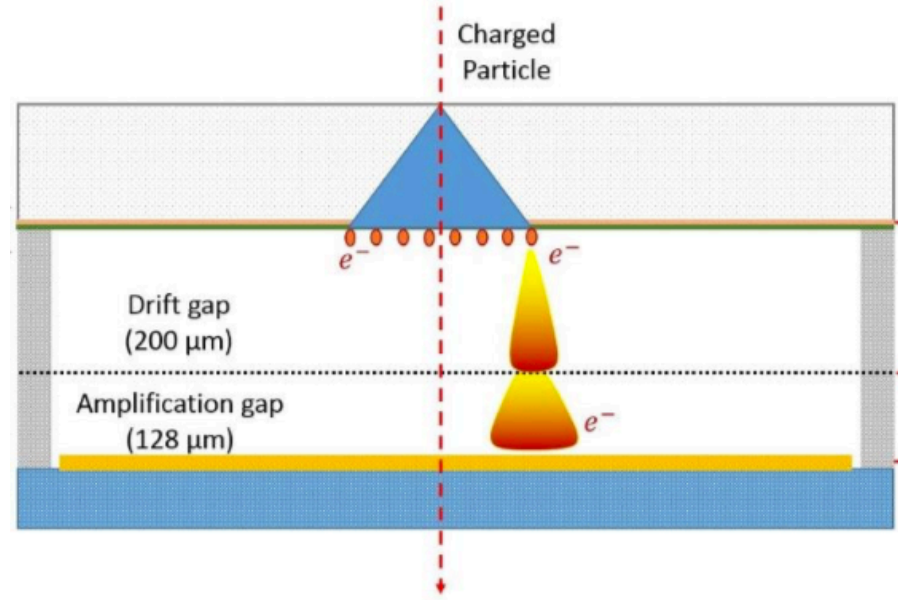
Summary

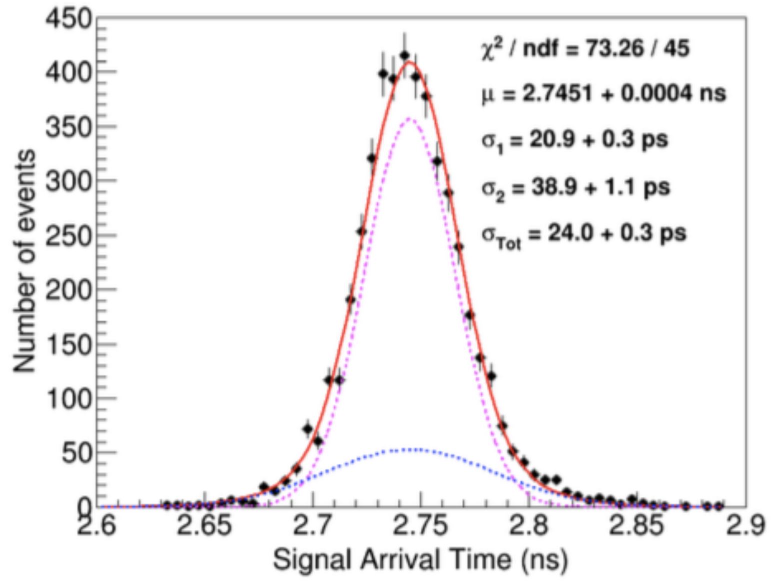
The PICOSEC detection concept achieves high timing precision of up to 24 ps for MIPs.

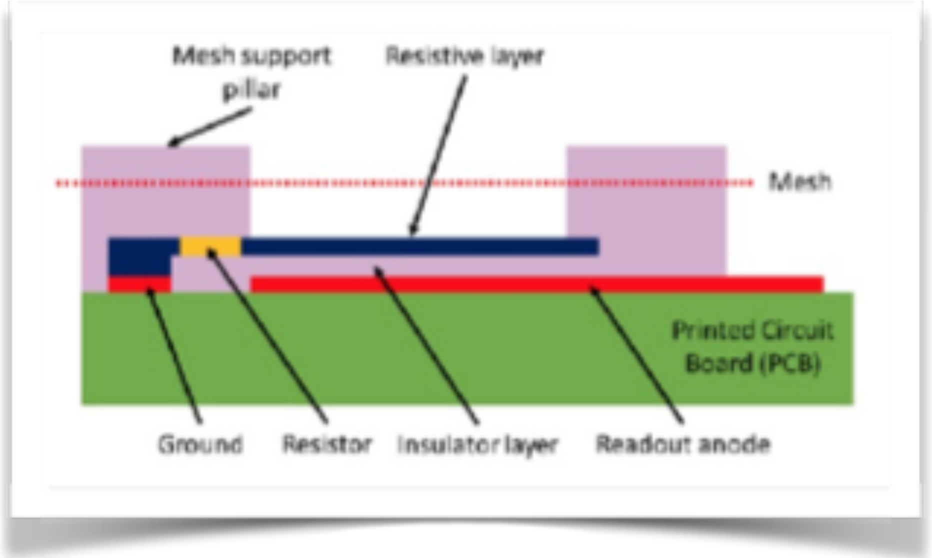
Beam tests (muons, pions) and **laser tests (single-electron response)** have been conducted to systematically study and optimise the detector performance.

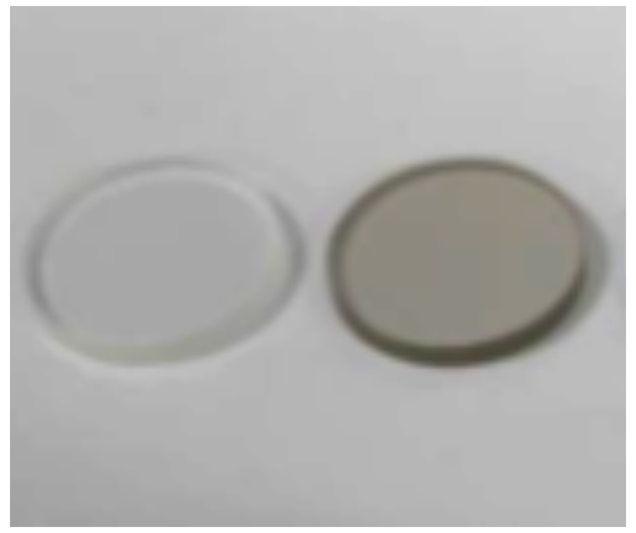
Detailed **detector response simulations** provide an in-depth understanding of detector physics and signal formation.

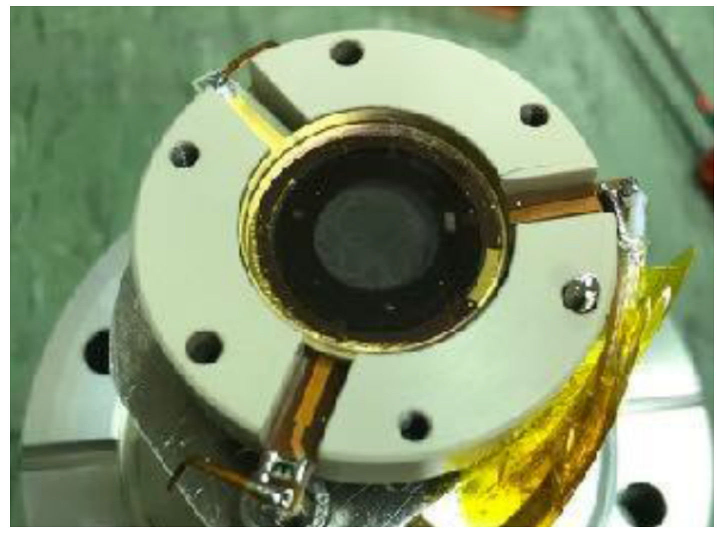
Detector robustness, **photocathodes** and **large-area coverage** are pursued towards a robust, larger-area PICOSEC precise timing detector.

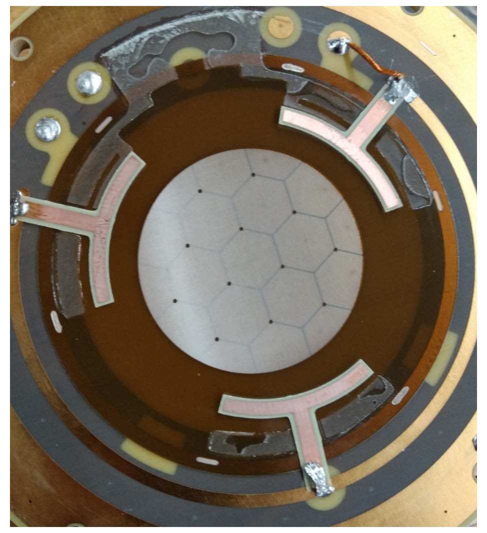








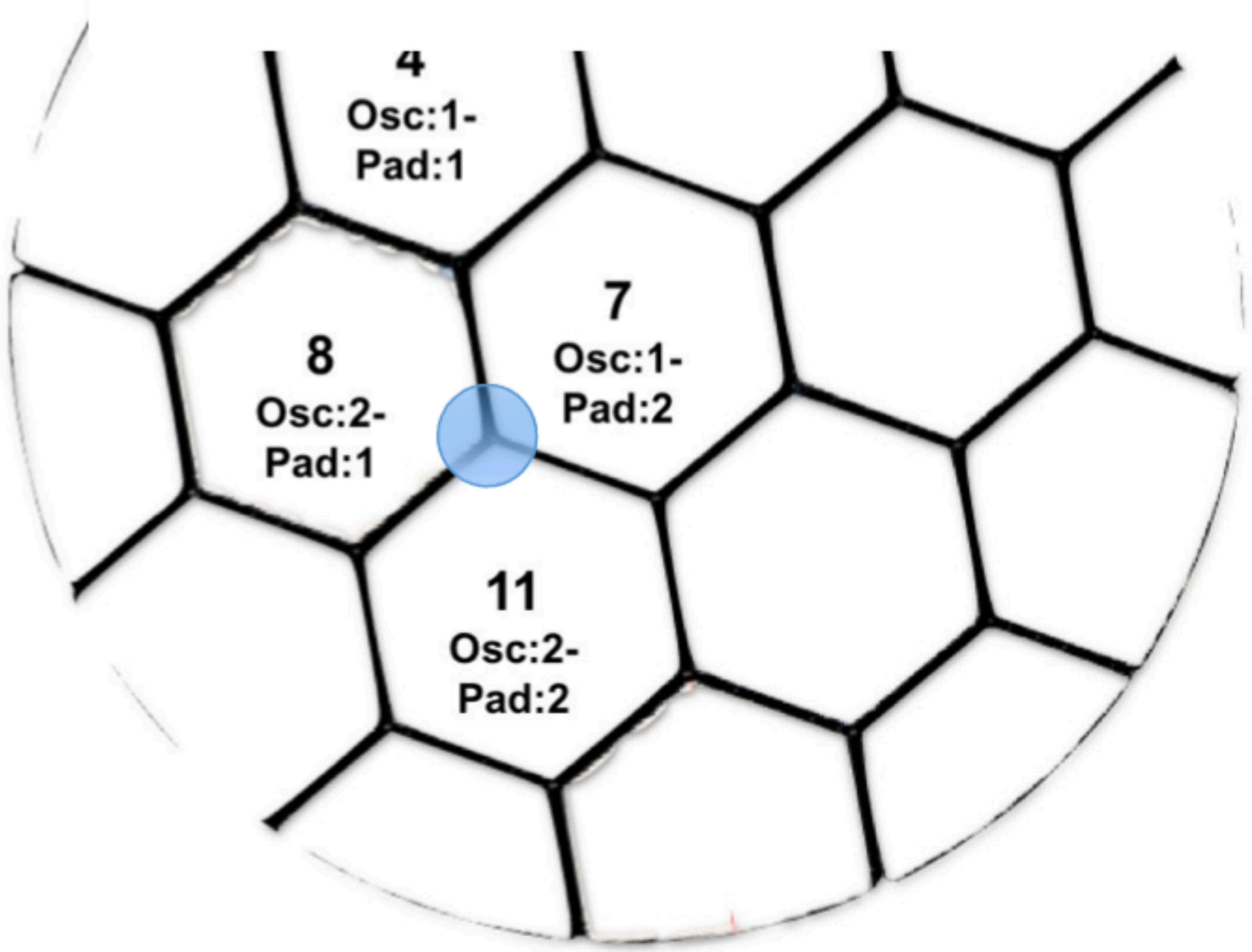




Backup

Combining multi-pad hits

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

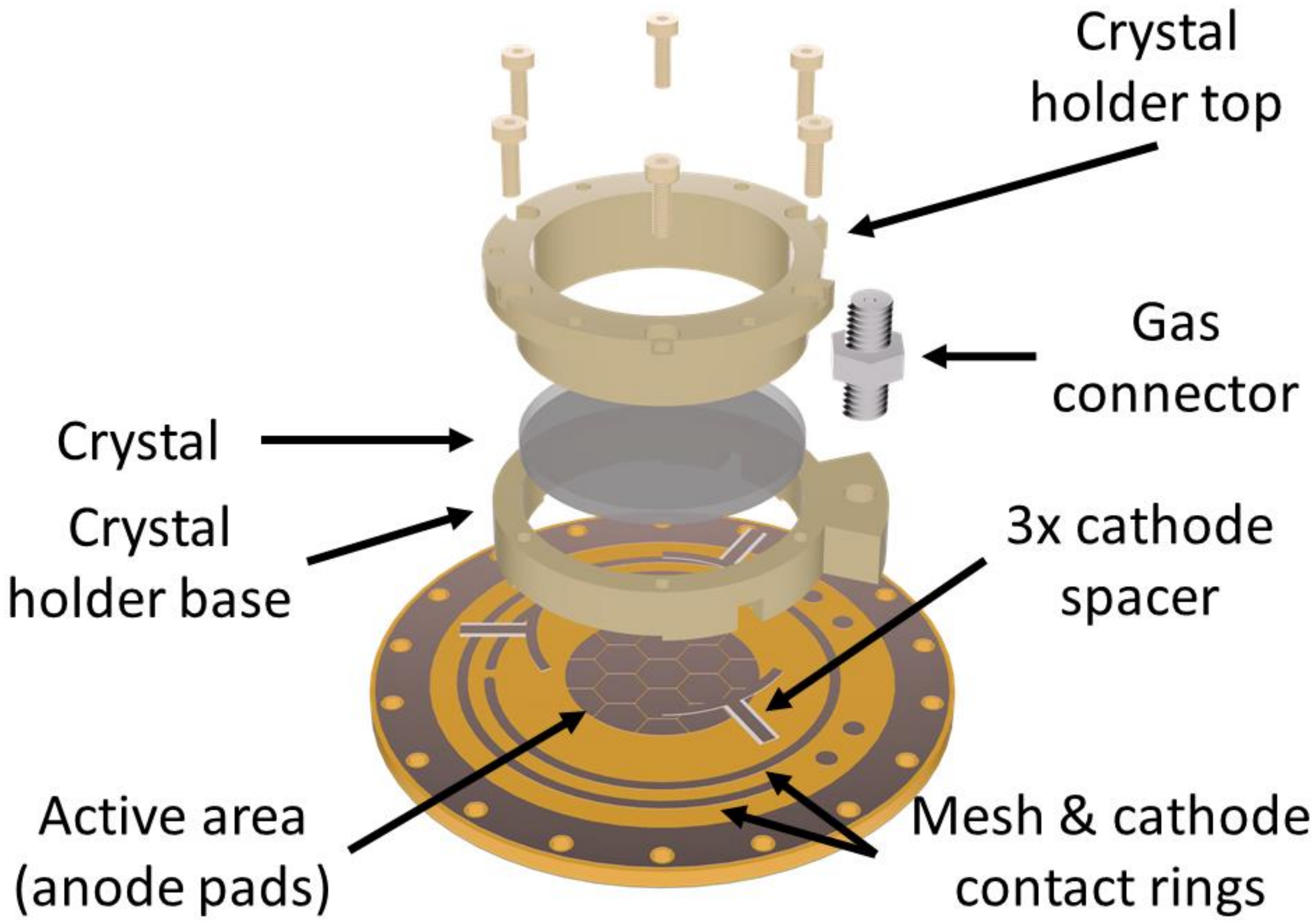


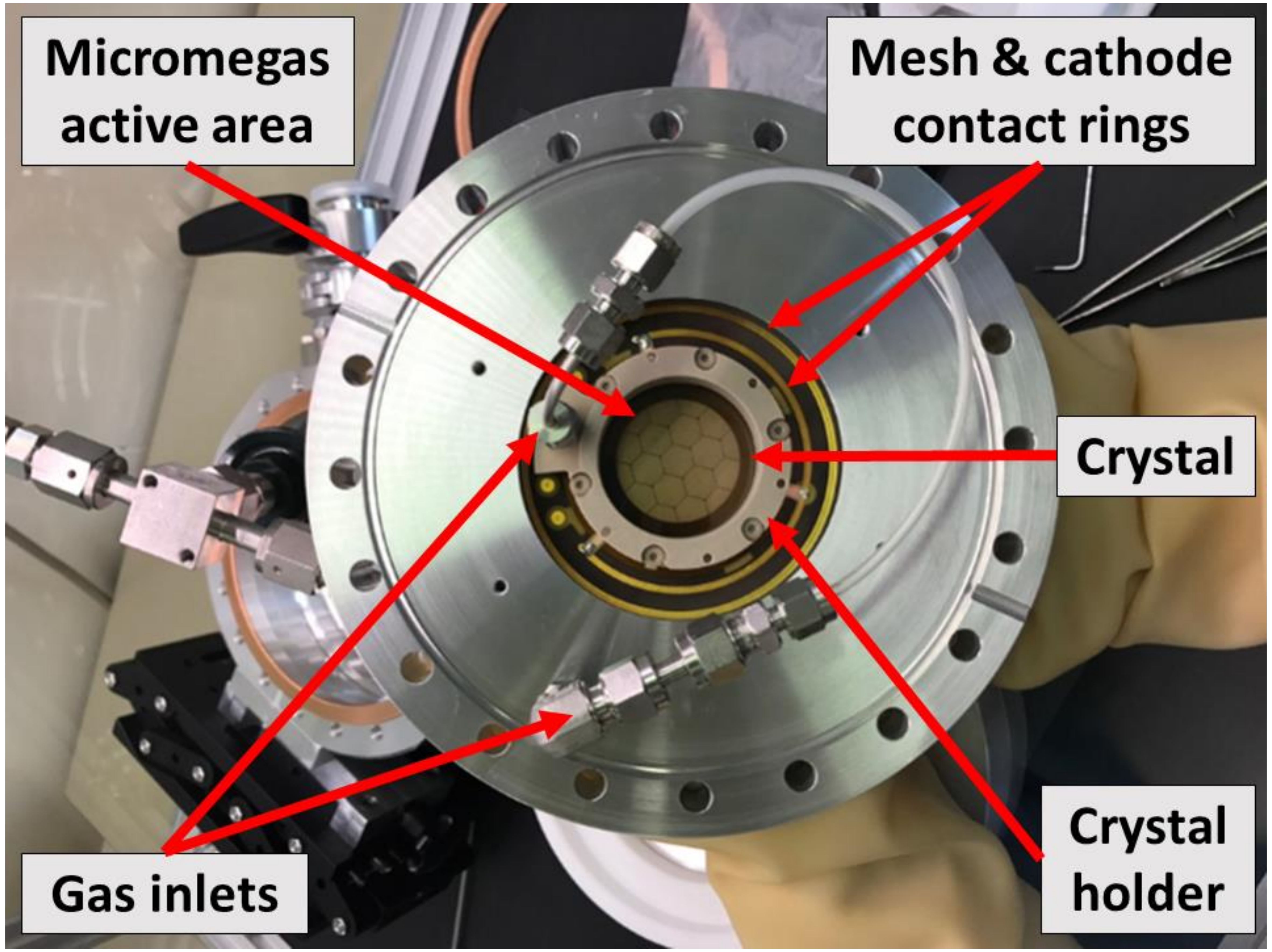
Gas studies

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

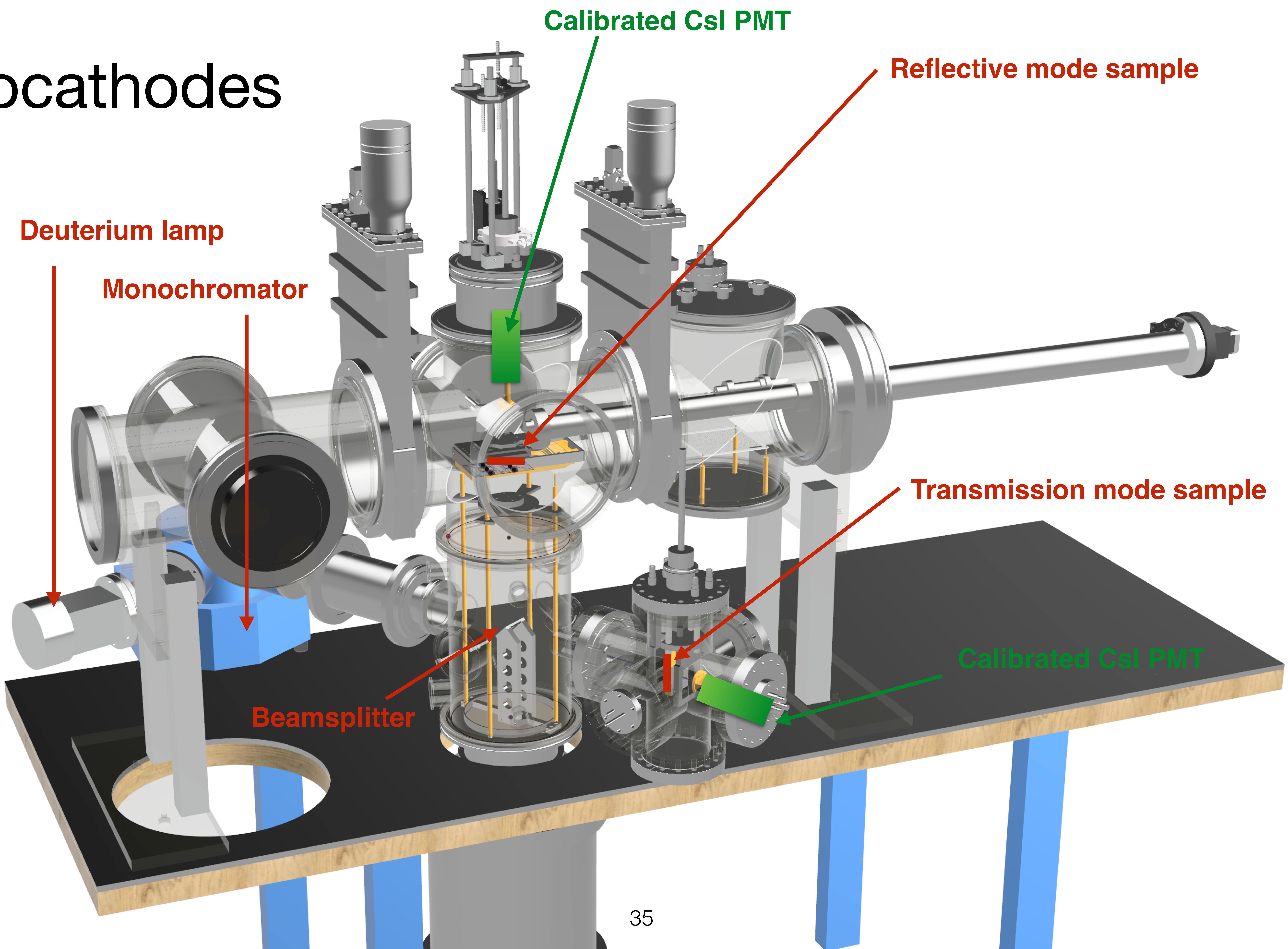
L. Sohl, Overview on recent PICOSEC-Micromegas developments and performance tests, RD51 Mini-Week February 2020, https://indico.cern.ch/event/872501/contributions/3726013/

Multi-pad prototype

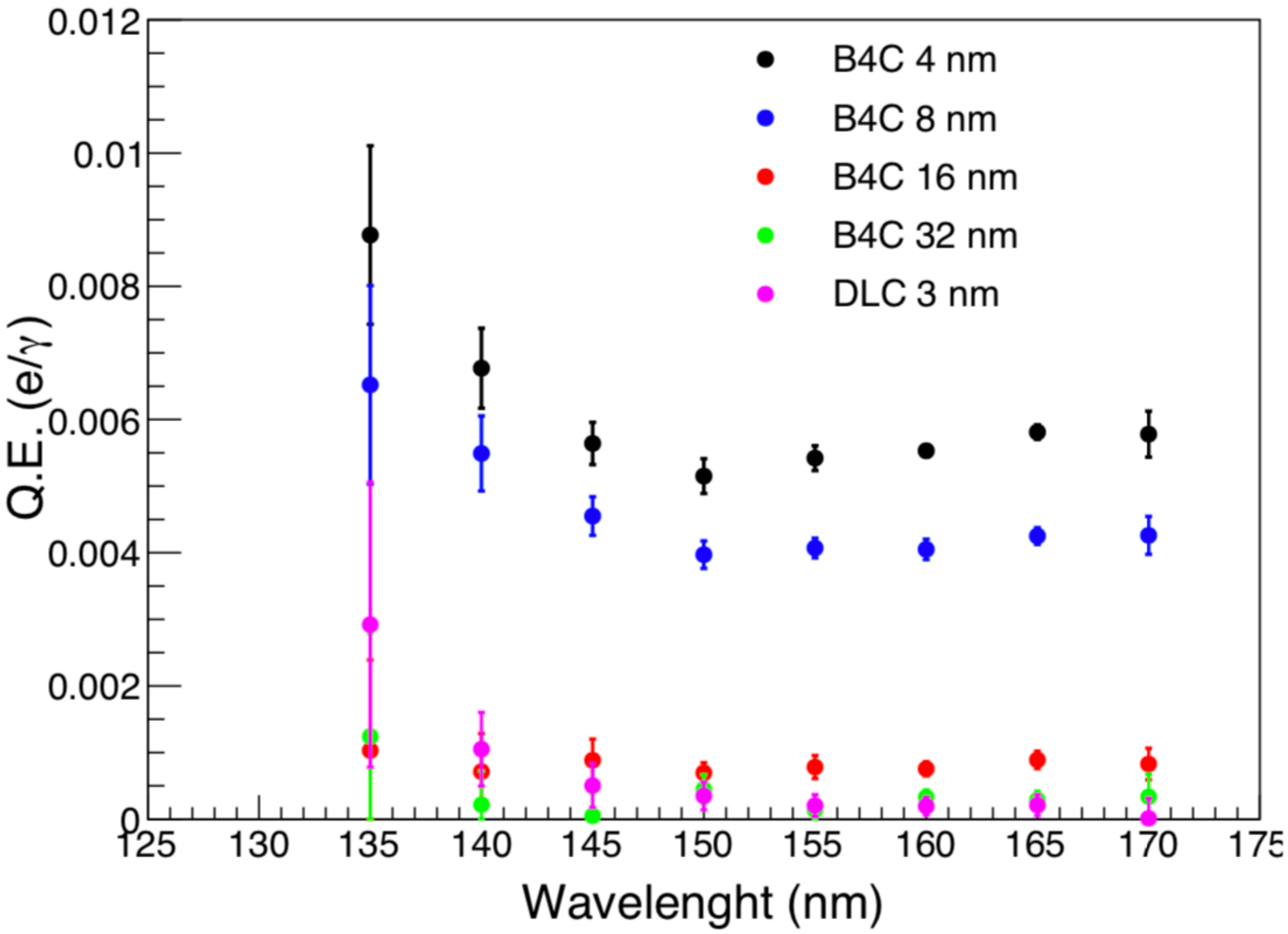




Photocathodes



Gas studies



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