A large area 100 channel PICOSEC Micromegas detector with sub 20 ps time resolution

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MPGD2022 - The 7th International Conference on Micro Pattern Gaseous Detectors, December 11-16., 2022.

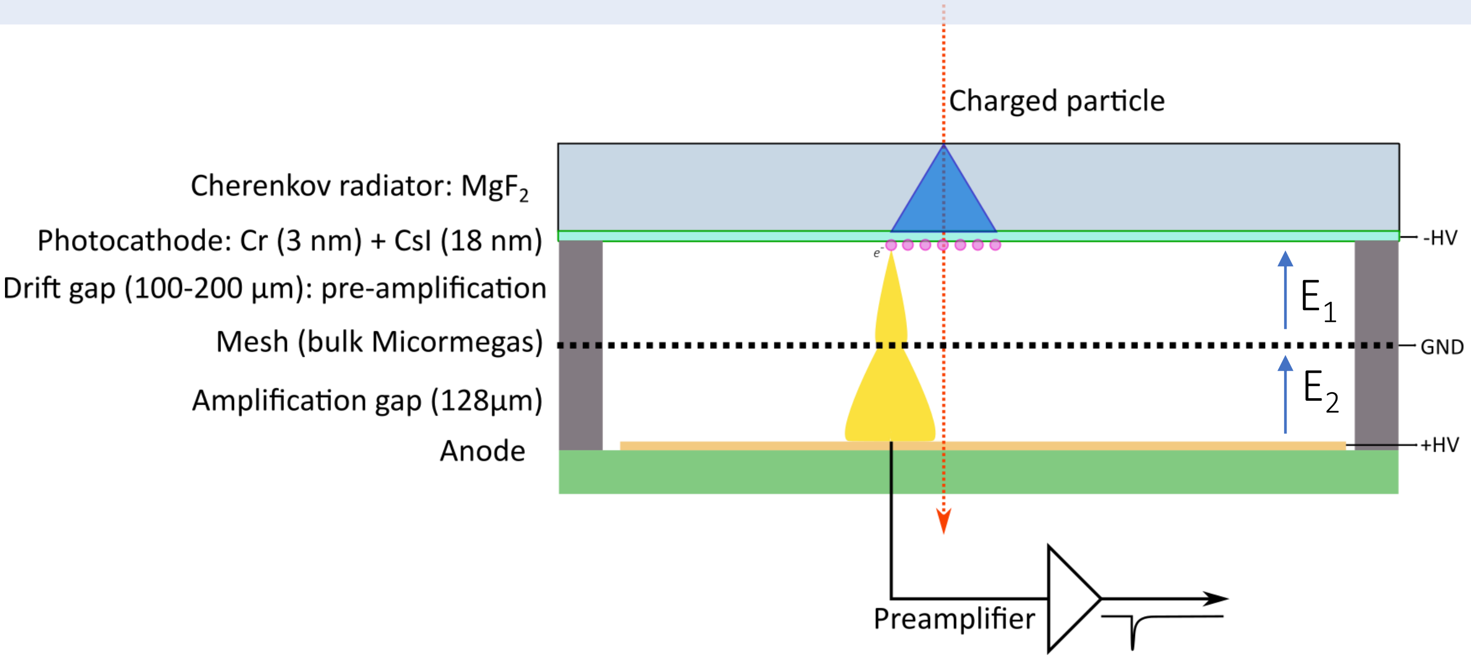
Weizmann Institute of Science, Rehovot, Israel

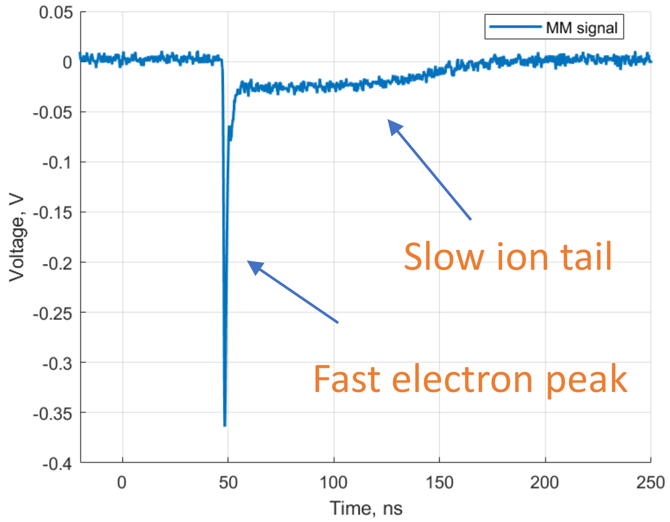
PICOSEC Micromegas

EP R&D

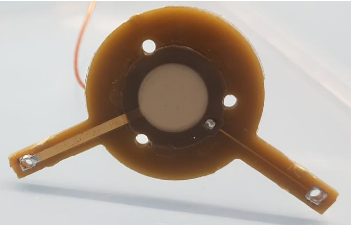
CERN

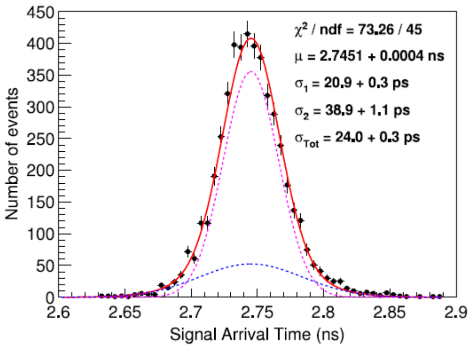
PICOSEC Micromegas detector concept





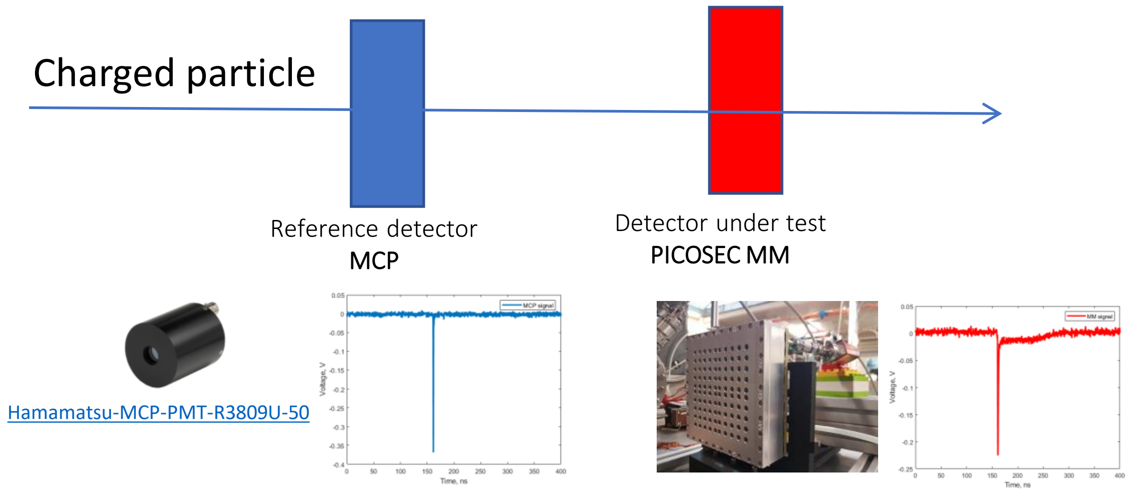
- **PICOSEC Micromegas (MM):** precise timing gaseous detector based on a Cherenkov radiator coupled to a semi-transparent photocathode and a MM amplifying structure
- **Timing resolution:** order of tens ps.
- **Cherenkov radiator:** passage of relativistic charged particle creates UV photons.
- **Photocathode:** conversion of UV photons into electrons. All the e^- created at the same z position.
- **Preamplification region:** preamplification of electrons in high drift field region (E_1~20 - 40 kV/cm).
- **Amplification region:** final electron amplification in high electric field (E_2 ~20-30 kV/cm).
- **Two component signal:** fast electron peak (~ 600 ps) and slow ion tail (~ 100 ns).
- **Proof of concept:** first single pad detector prototype ->**time resolution below 25~ps.**

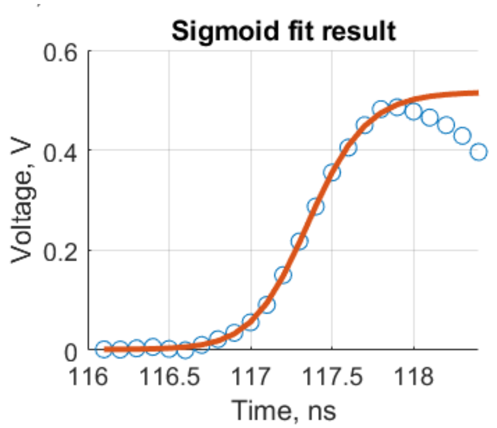


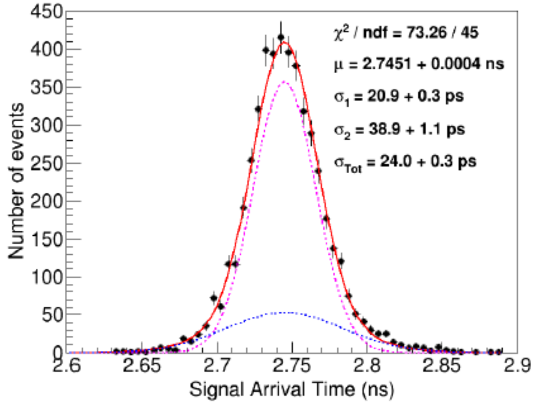


Bortfeldt, J., et al. "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector." *NIM A* 903 (2018): 317-325.

Timing properties: Signal Arrival Time (SAT) and time resolution







- Reference time with better precision than the PICOSEC is needed to quantify the precision of PICOSEC timing.
- Sigmoid function is fitted to the leading edge of the electron peak. Temporal position of the signal is calculated at 20% CF.
- **Signal arrival time (SAT):** the difference between PICOSEC and reference detector timing marks.
- **Time resolution** of the detector is defined as standard deviation of SAT distribution.

Towards PICOSEC MM detector for HEP experiments

Successful proof of concept- **PICOSEC can achieve timing ≈24 ps for MIPs.**

Next steps: Multiple directions in detector development

Large area coverage
Developemnt of large area prototypes and readout electronics

Detector optimisation
Detector fields
Operating gas
Gaps thickness

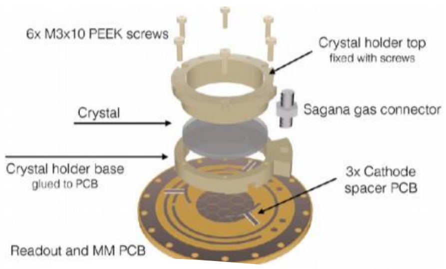
- Development of a large area 100 channel detector.
- Development of a 100 ch. readout electronics.
- Timing a large area detector.
- Detector timing improvement.

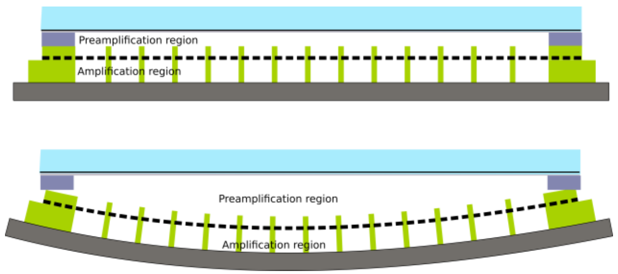
Improvement of stability
Development of detector prototypes with resistive MM

Robustness
Research on various photocathode materials

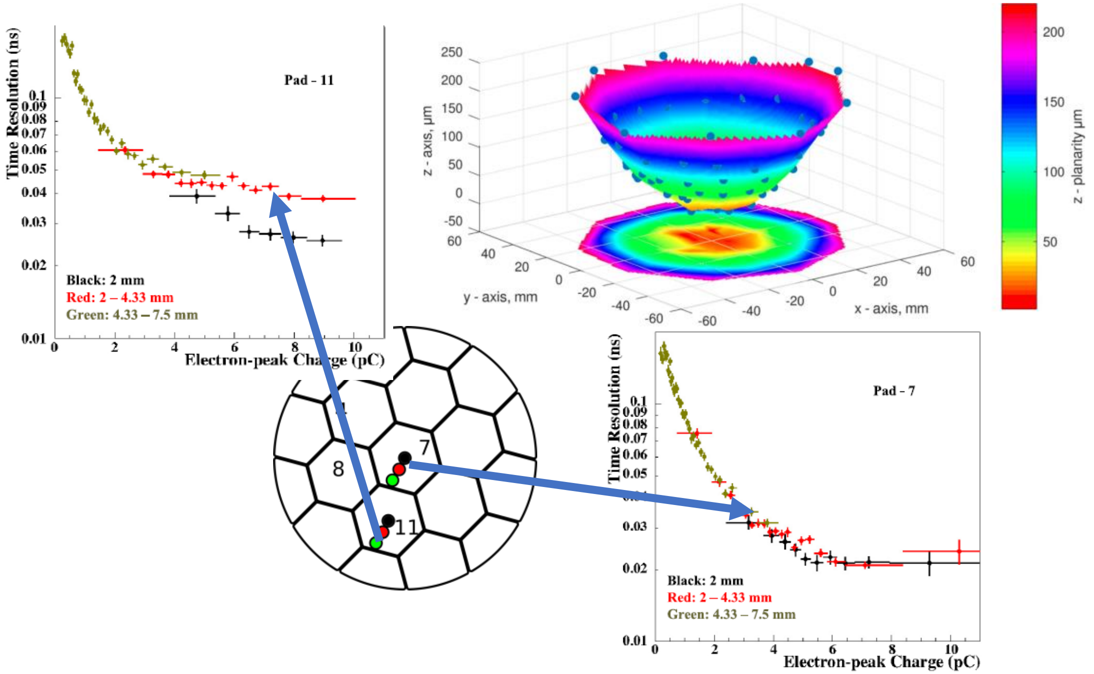
See next talk by M. Lisowska
https://indico.cern.ch/event/1219224/contributions/5130512/

Challenges in large area PICOSEC detector



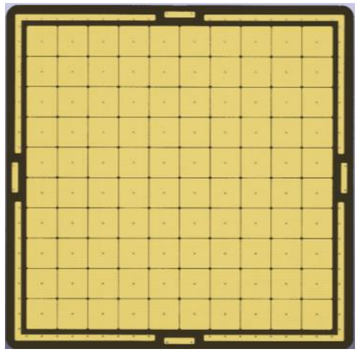


- **Drift region:** similar thickness (~110 - 220 um) and electric field as amplification.
  - Uniformity of the drift gap thinckness is important for uniform detector response.
  - Change in a drift gap thickness -> change in the **drift field** and **length** of preamplification avalanche evolution. This would affect detector gain and timing performance.
- **First 19 ch. prototype** of **ϕ=3.6 cm** active area: Observed decrease in timing performance depending on the position of MIP passing. Good timing response only after applying corrections using hit position.
  - Source of error → non-uniformity of the drift field gap **->**due to the **attachment to the chamber** & **non flatness of the board itself.**
  - Measured **deformations** in the range of **30 μm** in the active area. Gap height difference of **15 μm** will result in a time error of **100 ps**



Aune, S., et al. "Timing performance of a multi-pad PICOSEC-Micromegas detector prototype." NIM A 993 (2021): 165076.

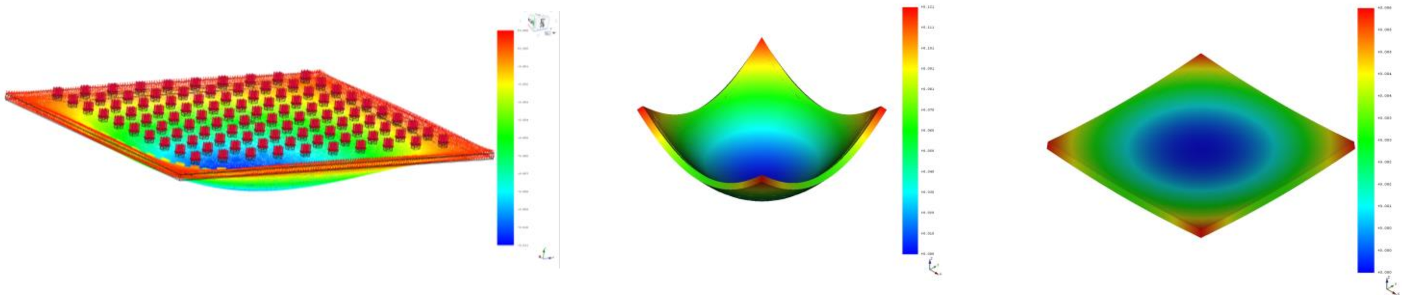
- **NEW MULTICHANNEL PROTOTYPE : can be tiled, 100 channels, 10 cm x 10 cm active area, 10μm flatness over entire area.**
- Deformations will be even more pronounced for larger area.
- **MAIN CHALLENGE**: make detector with uniform gaps (below 10 μm) over the entire 10 cm x 10 cm active area.



Development of a 100-channel detector for a large area coverage

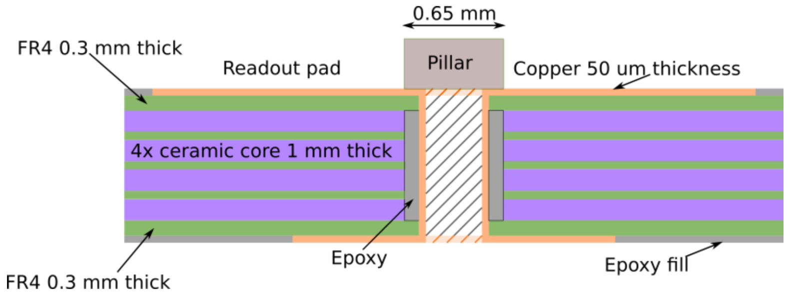
Structural mechanics simulations of MM board

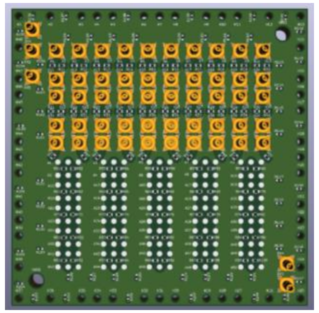
Simulations of pogo pins pressure and mesh tension influence on board planarity.



Design of Micromgeas, Outer board and gas chamber.

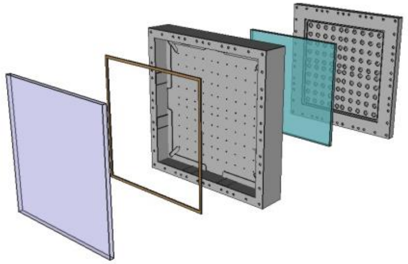
MM BOARD design: use more rigid (ceramics instead FR4) and thicker MM board material (4 mm instead 2 mm).

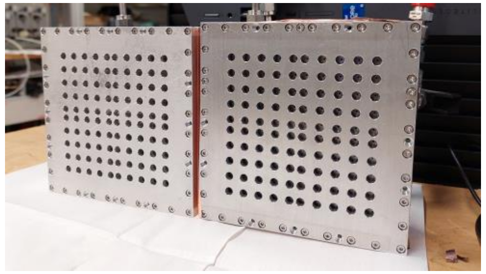




A. Utrobicic, RD51 Coll.meeting https://indico.cern.ch/event/911950/contributions/3912064/

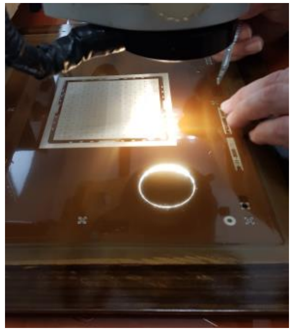
CHAMBER: mechanically decouple MM board and MgF2 crystal to avoid deformations due to the attachment

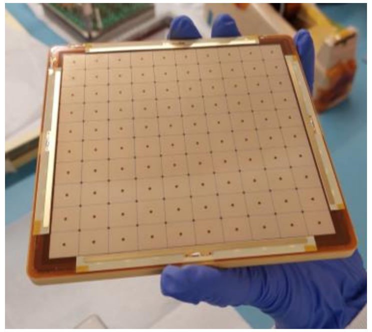




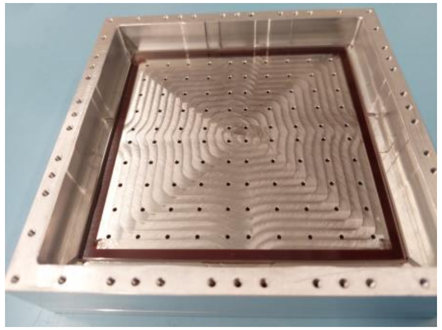
A. Utrobicic, RD51 Mini week: https://indico.cern.ch/event/989298/contributions/4225012/

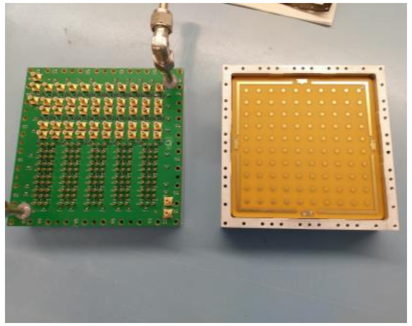
Micromegas production @ CERN MPT Workshop

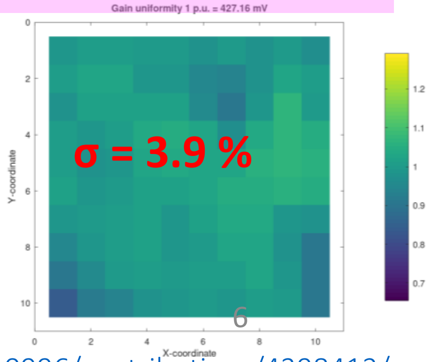




Assembly / first lab tests and detector calibration







A. Utrobicic, RD51 Coll. Meeting: https://indico.cern.ch/event/1040996/contributions/4398412/

Timing response of 100 ch. prototype with 200 μm drift gap and CsI photocathode

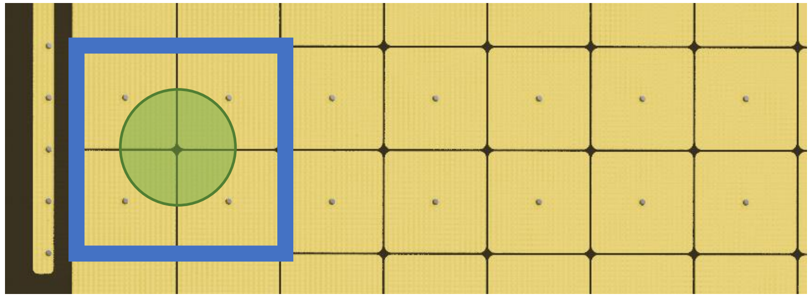
Horizontal and vertical scan of PADs:

- Preliminary results show uniform time response over the pads for signals in the center of the pad over 5 mm x 5 mm area). Time resolution below 25 ps for all measured pads.

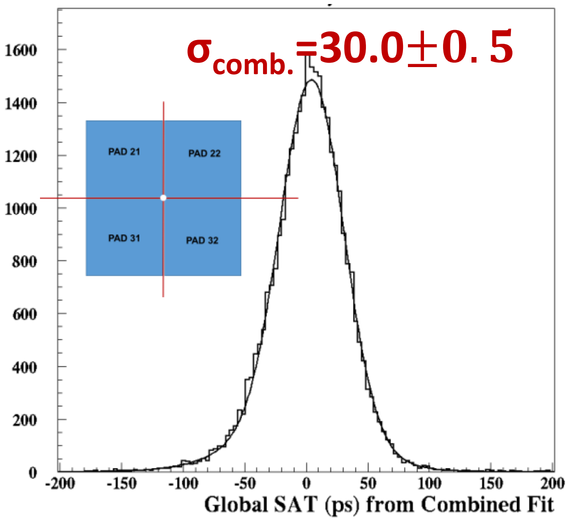
Time resolution, CsI photochatode, V_{CAT} 500 V **Preliminary**												
PAD	03	06	12	13	15	16	17	18	20	26	36	41
σ, ps	24.6	24.1	24.6	23.9	22.1	22.9	24.7	23.0	23.0	23.9	23.9	24.0

A. Utrobicic, RD51 collaboration meeting:
https://indico.cern.ch/event/1071632/contributions/4612229/

Signal sharing

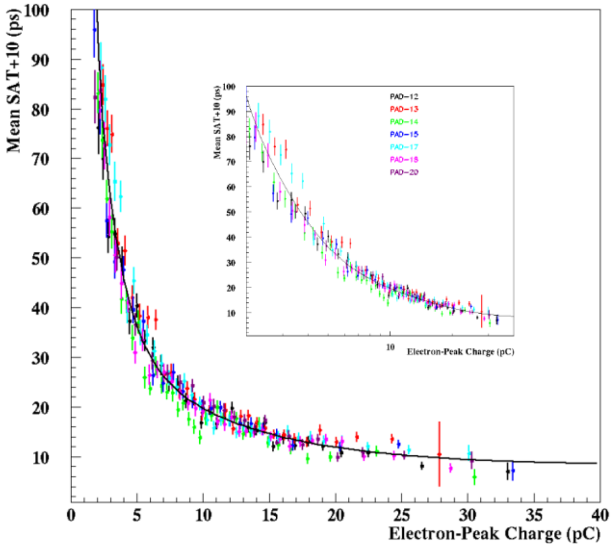


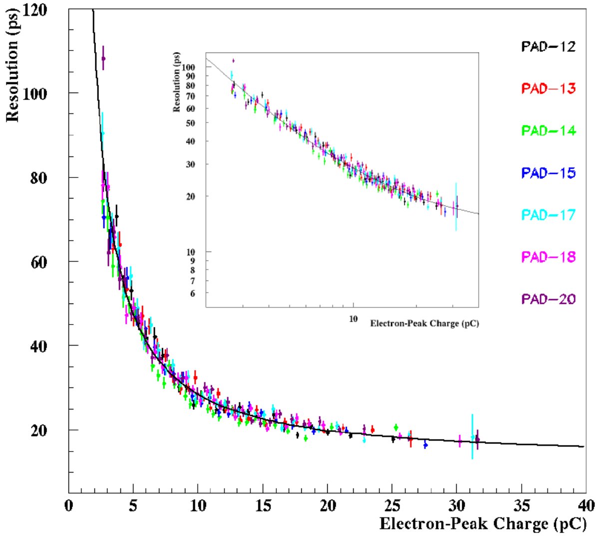
$$\hat{t}_{comb} = \frac{1}{\sum_{i=1}^{N} \frac{1}{R^2(q_i)}} \cdot \sum_{i=1}^{N} \frac{t^i_{SAT} - W(q_i)}{R^2(q_i)}$$



Dependence of the timing properties on the e-peak charge (time-walk)

- All pads have almost the same dependencies on the e-peak charge for SAT -> uniform drift field and the 'global' time walk correction can be used.
- The dependance of the time resolution on the e-peak charge is very similar for all pads.





Maniatis, I. (2022). *Research and development of Micromegas detectors for New Physics searches* (Doctoral dissertation)

Analysis by A. Kallitsopoulou, I M. Maniatis and S. Tzamarias (Aristotle University of Thessaloniki)

8

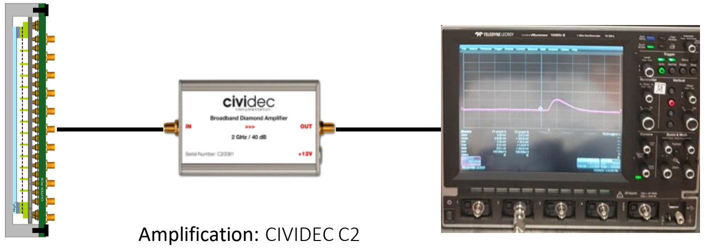
R&D on readout electronics suitable for large area coverage and precise timing

PICOSEC Micromegas readout electronics requirements and developments

Requirements:

- High bandwidth (min. 400 MHz), gain in range 40 dB, low noise
- Very low power dissipation (on area 10 cm x 10 cm, 100 channels needed)
- Small size (must fit over 10 mm x 10 mm pad with the clearance to another channel)
- On top of this it needs to be spark resistant.
- Moving to large number of channels present challenge for preamplifier design with low power dissipation, size and cost.

Currently used Picosec FE and Data Acquisition:



Amplification: CIVIDEC C2 (40 dB, 2 GHz), https://cividec.at

Digitization: LECROY WR8104 oscilloscopes operated at 1.0 GHz, 10 GSamples/s.)

RF pulse amplifier for CVD diamond particle detectors ([C. Hoarau et al 2021 JINST 16 T04005](https://cividec.at)): low noise, single polarity supply, high gain, fast rise time, low price, standard components, small dimensions…

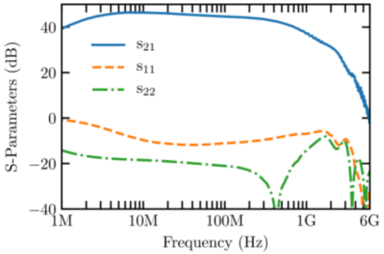


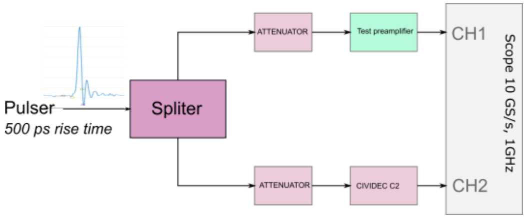
Figure 6: Layout 3D drawing of LNA.

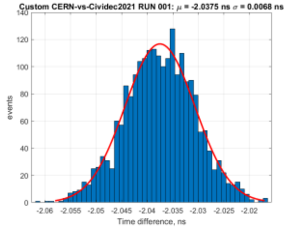
- Performance very promising only no discharge protection and the time resolution stated in the paper was in range of 40 – 100 ps.
  - This was motivation for development of custom-made amplifier for PICOSEC detector with integrated discharge protection: development of 10 channel preamplifier boards started at CERN and in parallel 2 prototypes were ordered from LPSC.

Custom made 10 channel preamplifier board for PICOSEC MM detector

- Gain **38.5dB** @100MHz
- HF -3dB cut-off **650 MHz,** LF -3dB cut-off **4 MHz**
- Input impedance **44 Ohm**
- Negative pulses linear up to **-1 V.**
- Tested to sparks by shorting the input at 350 V bias.
- Power dissipation **75 mW** per ch., Single supply **4 V.**

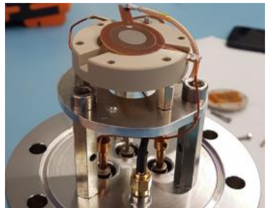
Timing test with pulser

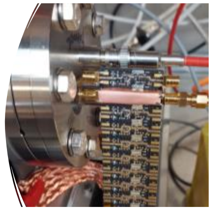


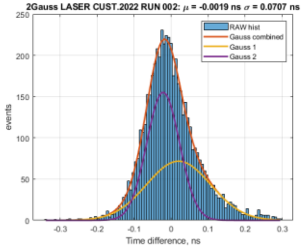


σ = 6.8 ps

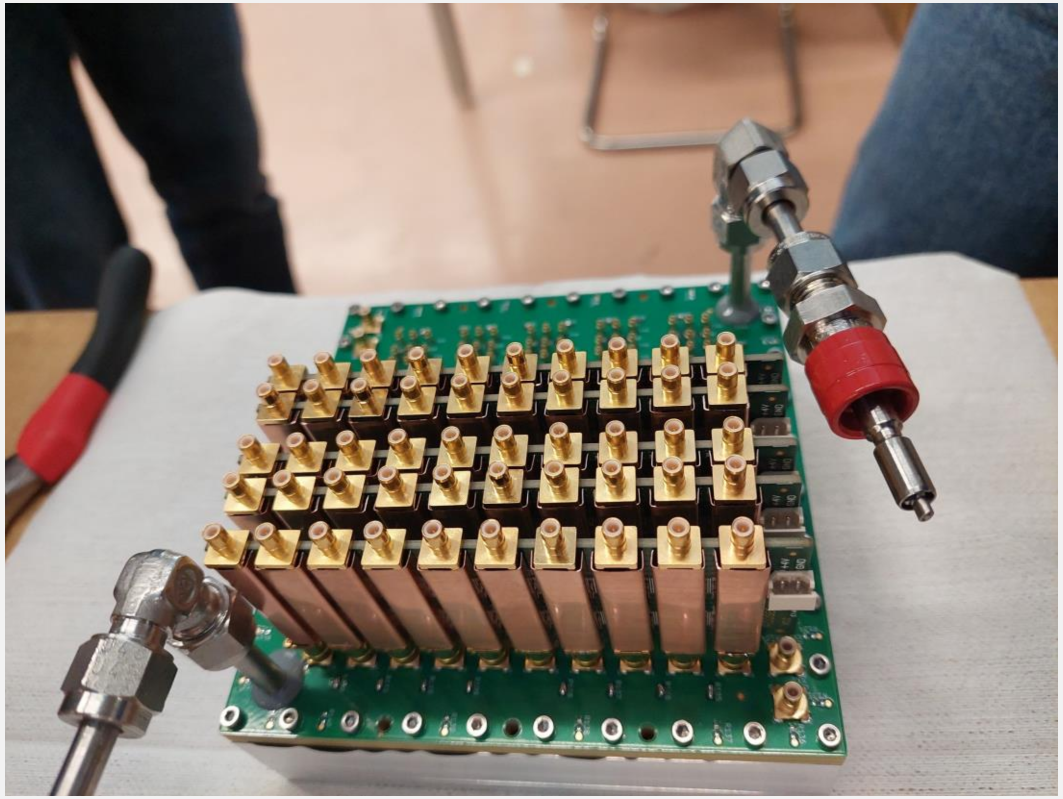
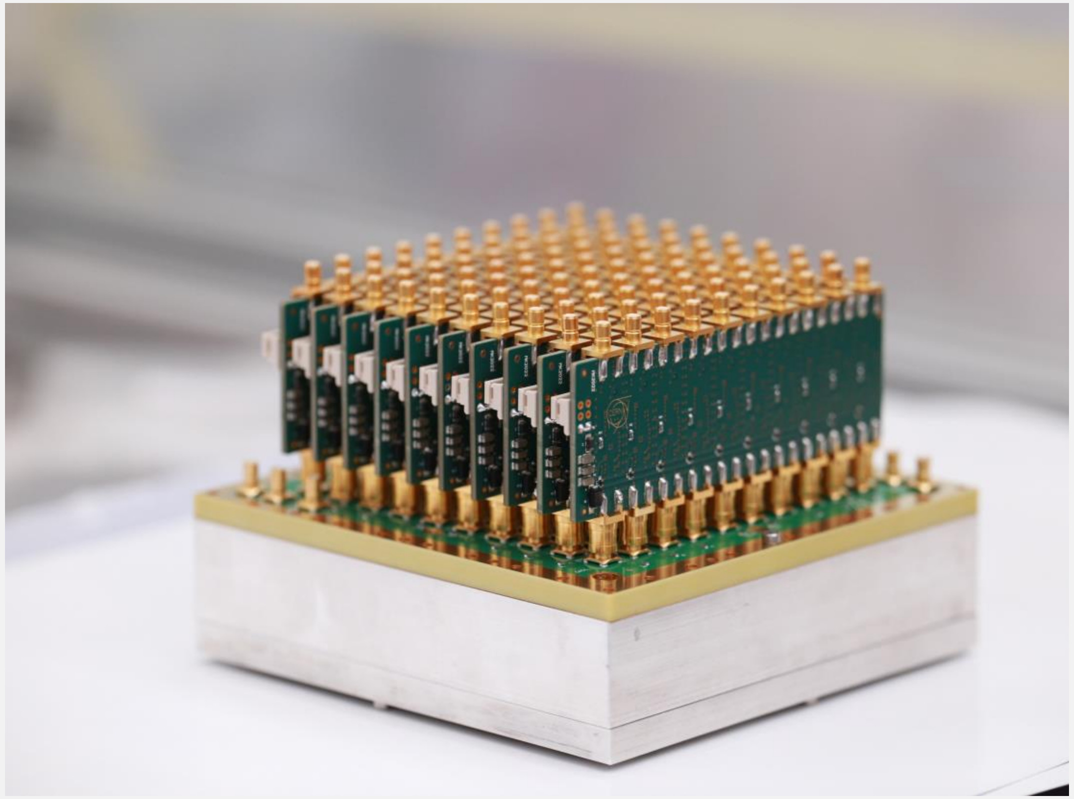
Timing test with laser (connected on single channel detector): single photoelectron time response



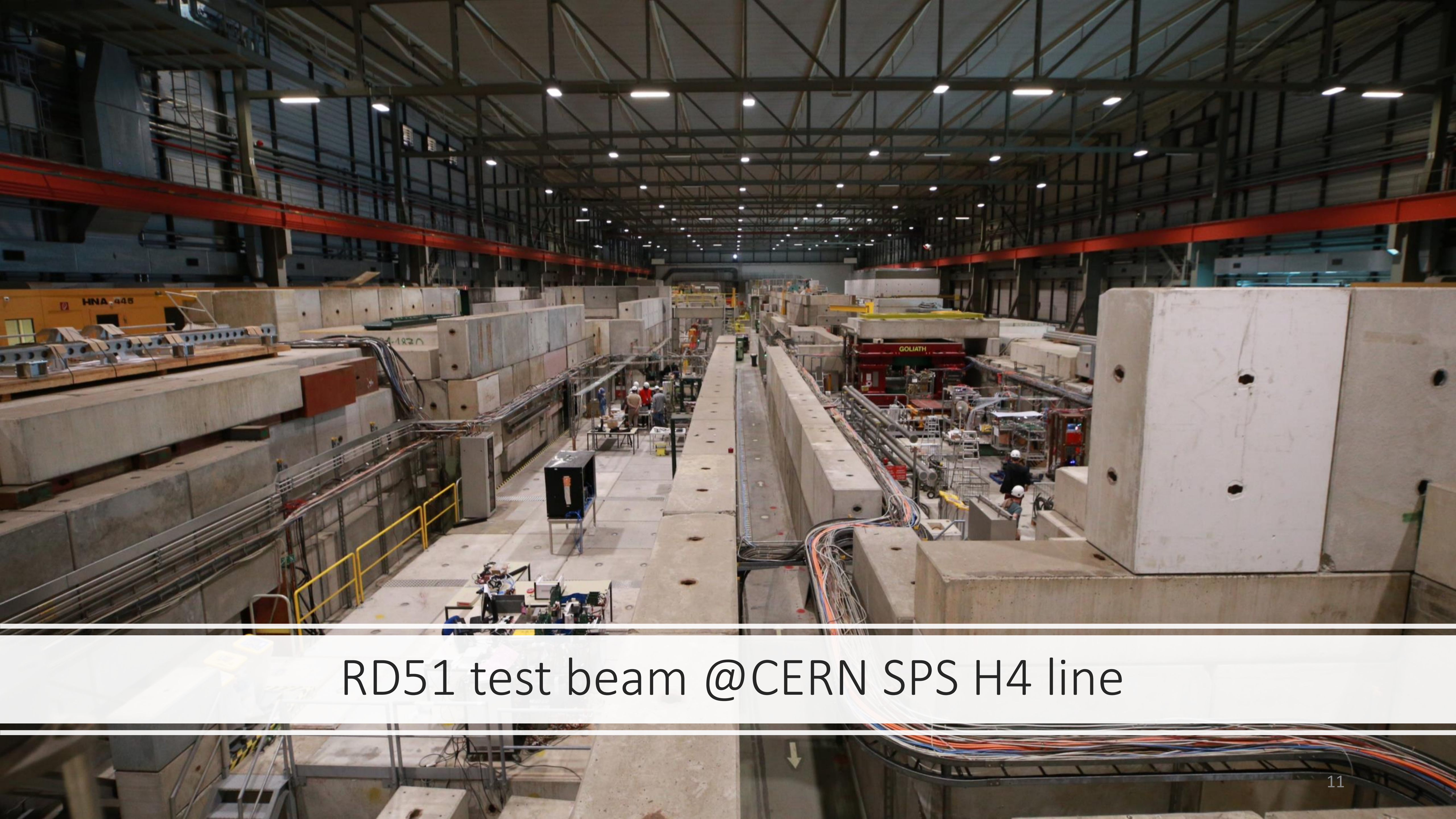




σ_{SPE} = 70.7 ps

Successful lab tests-> Copy / Paste x 100 ☺ ->Timing test

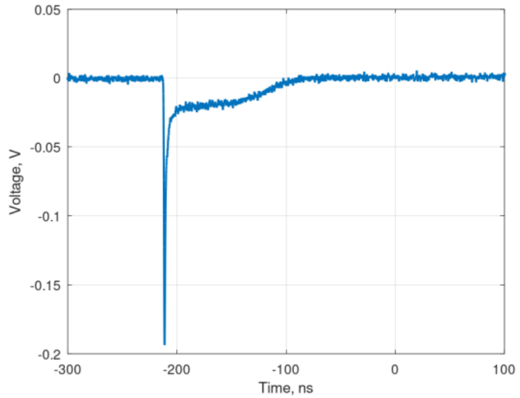


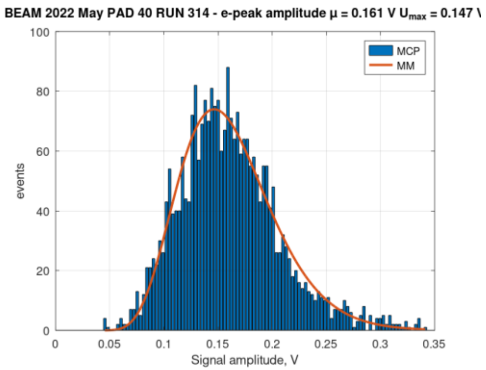
RD51 test beam @CERN SPS H4 line

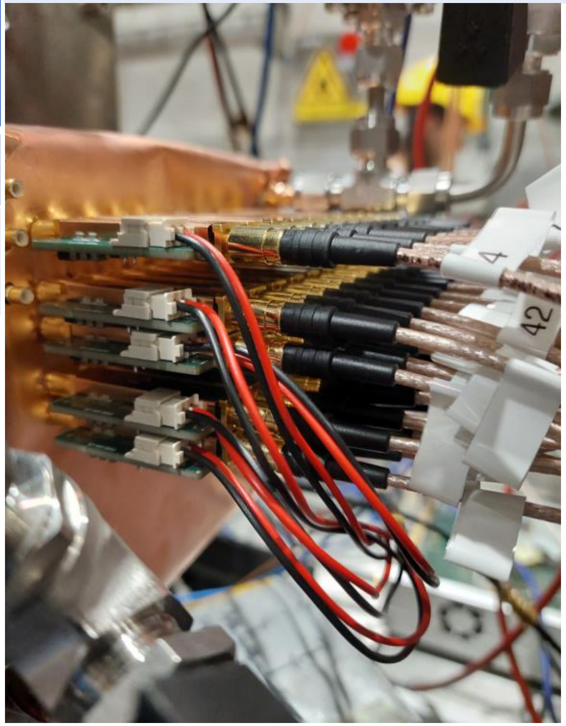
Timing response over the detector surface with custom made preamplifier

Time resolution within the center of the pad (4 mm x 4 mm), 220 µm drift gap, CsI, Vc = -485 V, Va = +275 V, preamp. Cards **Preliminary**										
PAD	12	13	15	18	22	23	25	26	31	36	40
RMS,ps	21	18.6	20.1	18.7	18.2	18.9	20.2	20.3	21.2	20.7	20.1

	21	18.6		20.1			18.7		
	18.2	18.9		20.2	20.3				
21.2					20.7				20.1

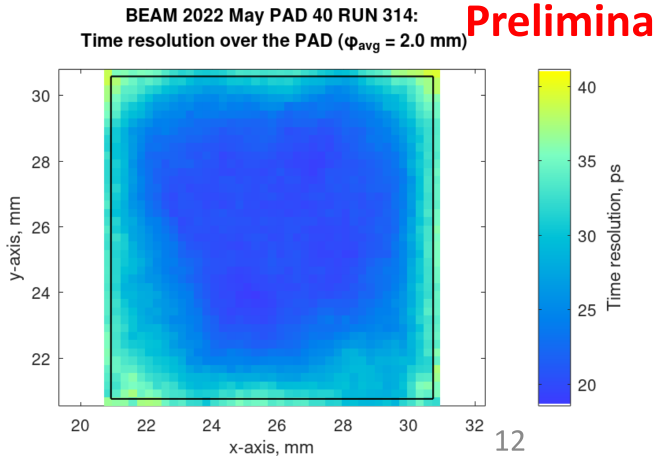




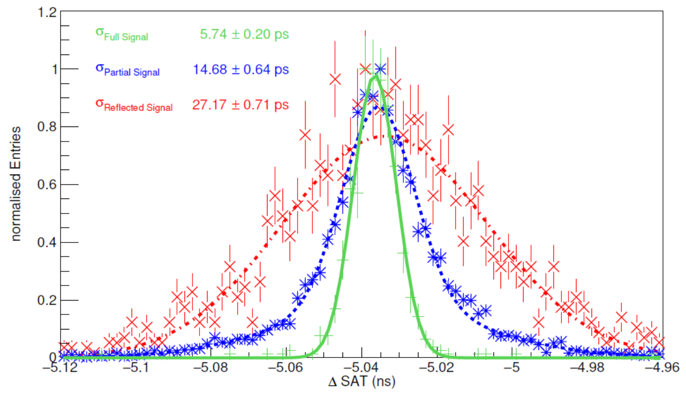


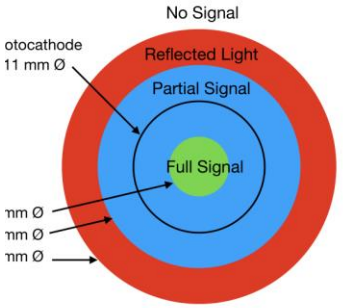
- Uniform time response over the pads for signals in the center of the pad over 4 mm x 4 mm area
- Time resolution (RMS) is in a range 18.2 – 21.2 ps for all measured pads.
- **Custom preamplifiers do not degrade detector performance.**
- Preamplifiers were **operating stable** with fast rise time signals (~ 800 ps) and no visible reflections/oscillations (cables to PADs eliminated).
- Moderate gain suitable for PICOSEC MM detector.

Preliminary



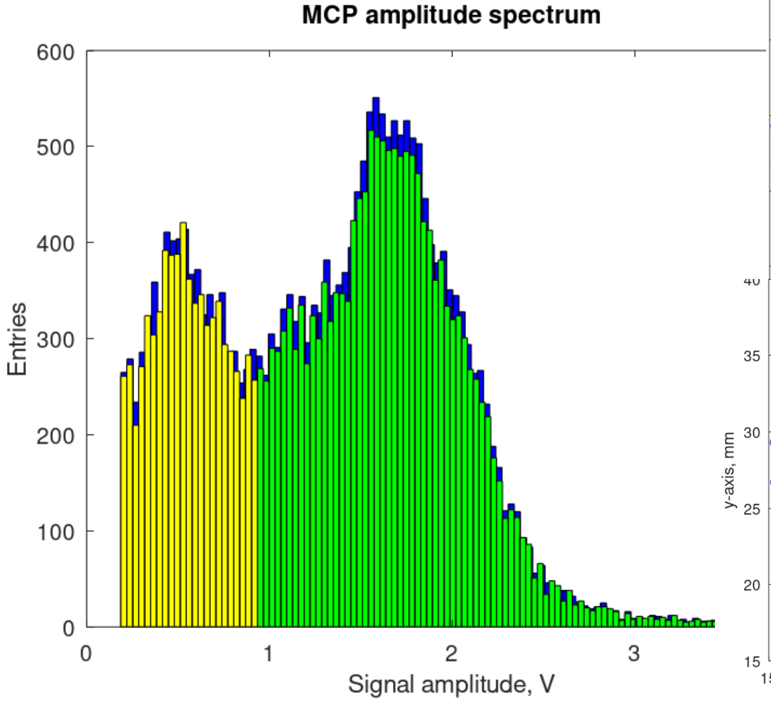
Challenge in timing a large area detector

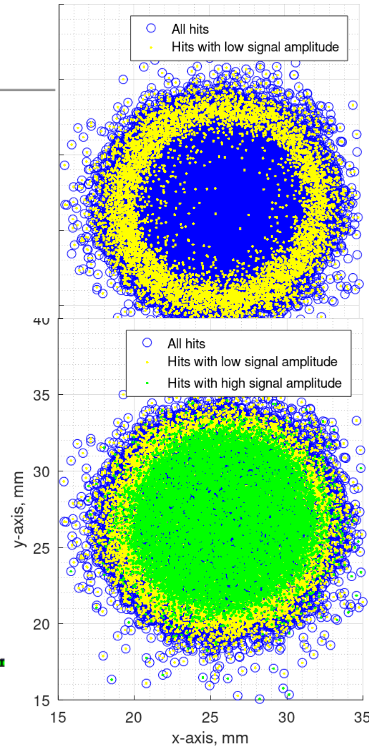




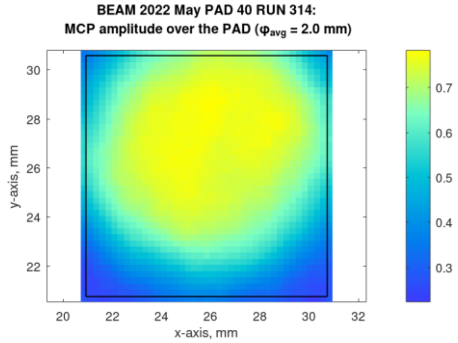
Bortfeldt, Jonathan, et al. "Timing performance of a micro-channel-plate photomultiplier tube." *NIM A* 960 (2020): 163592.

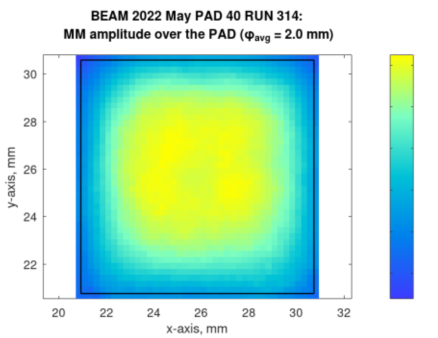
Sohl, Lukas. "Spatial time resolution of MCP–PMTs."

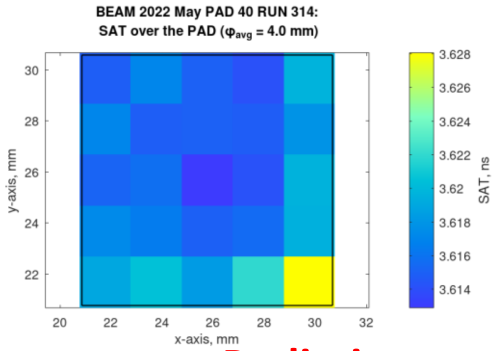




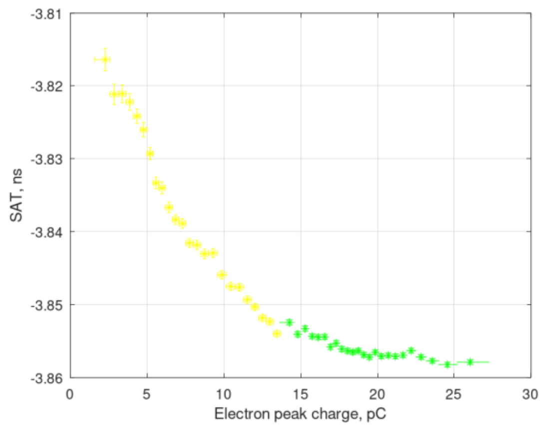
- ➢ MCP-PMT (MCP Hamamatsu R3809U-50) time response is best within 11 mm diameter.
- ➢ MCP (Φ 11 mm) is not fully covering the PAD (1cm x 1 cm)
- ➢ This is influencing Picosec timing measurements at not well covered regions (corners/edge) where non-uniformity in SAT is mostly visible.

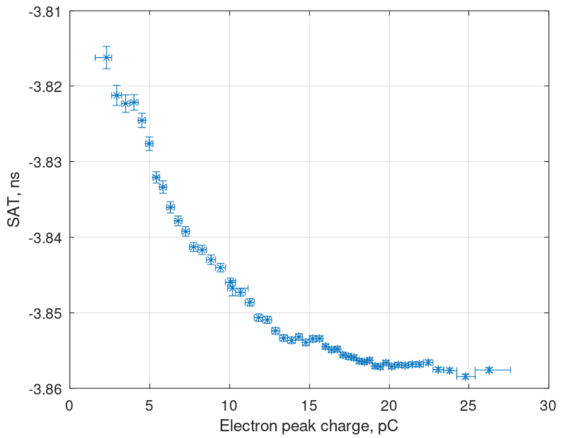






Preliminary

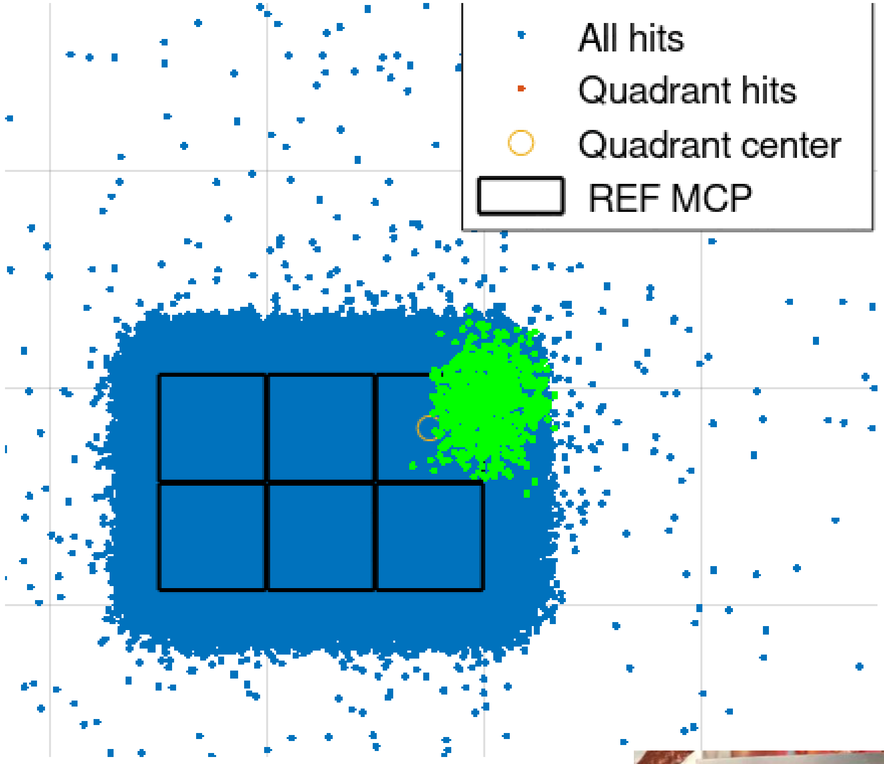




Automated scan method

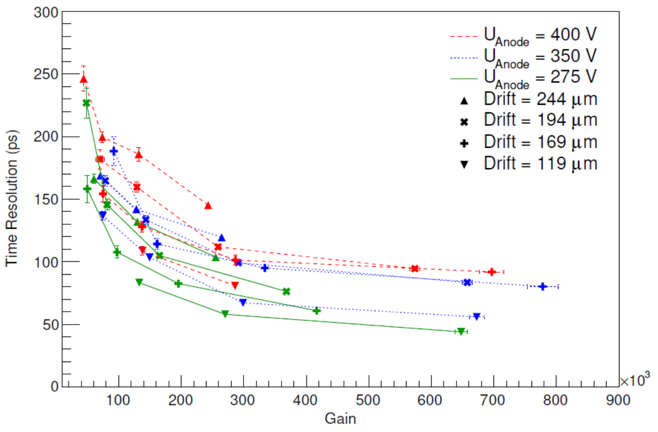
How to minimize the effect of the nonuniformity of reference detector in large area timing measurements:

- Uniformity: Omitting small MCP signals (with larger time walk). Trigger on large signal to have only events with small time walk.
- Cover larger area: MCP mounted on a movable stage and scans the entire pad area.
- This way whole PAD area can be characterized. Also, multiple pads or entire detector active area can be studied. Beneficial for signal sharing studies.

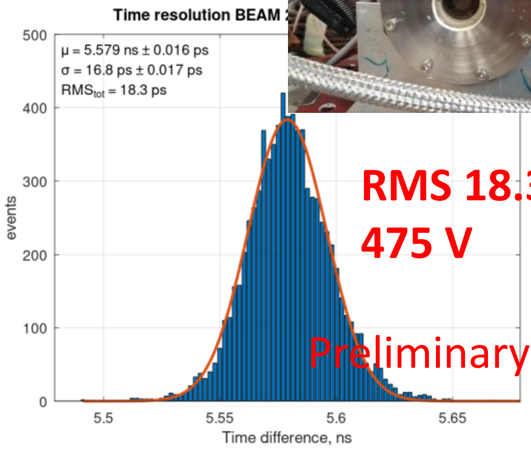


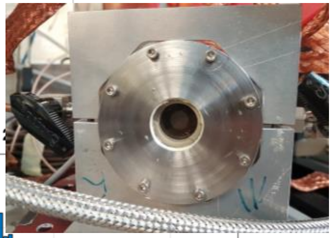
Improving detector timing

- Preliminary results for single channel thin drift gap (110 μm) prototype (SACLAY,) show excellent time resolution of 50 ps for single p.e and 18.3 ps for MIP measurements in the center of the pad (5 mm x 5 mm).



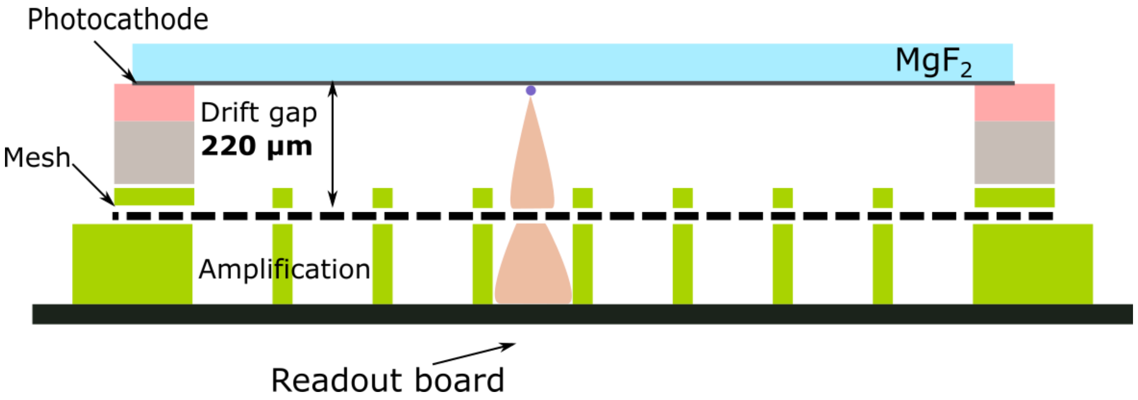
Sohl, L., et al. JINST 15.04 (2020): C04053.

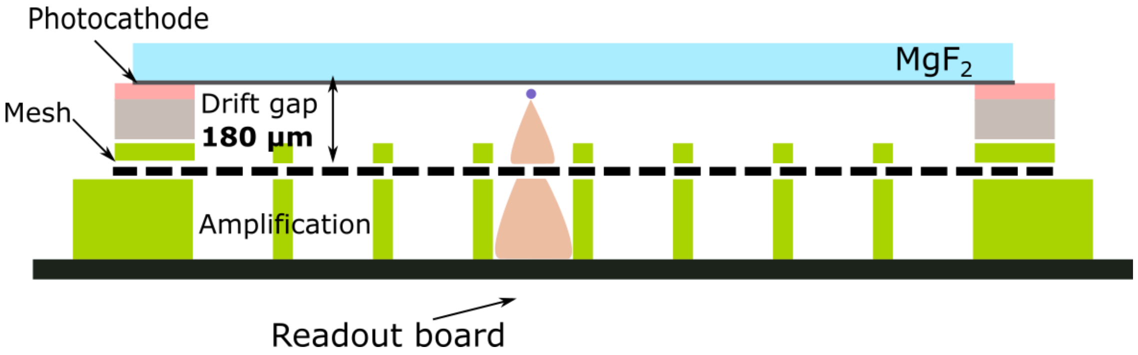


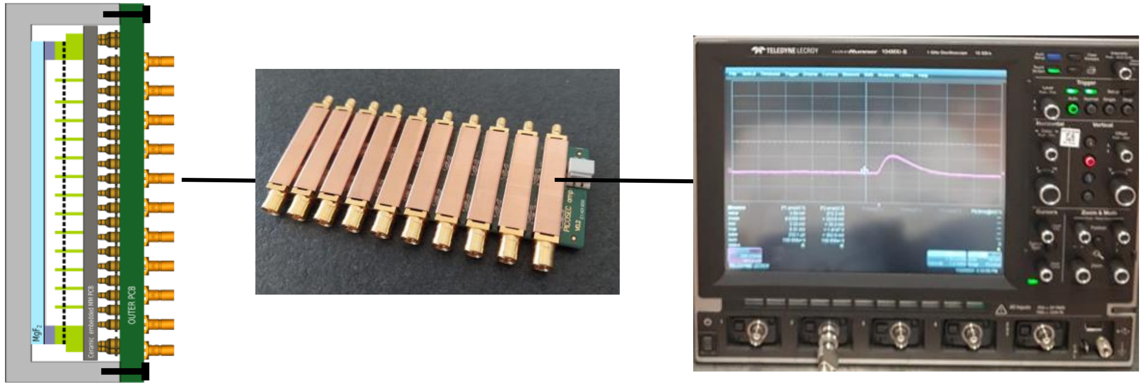


Saclay, T. Papaevangelou

Reducing the drift gap (220->180 μm) of 100 channel large area PICOSEC detector







- Automated scan of thin gap 100 ch. prototype
- Custom preamplifiers
- Oscilloscopes
- 10 different pads measured.

Test beam July 2022: 2 x 4 pads scan

1	2	3	4	5	6	7	8	9	10
11	22	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	43	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

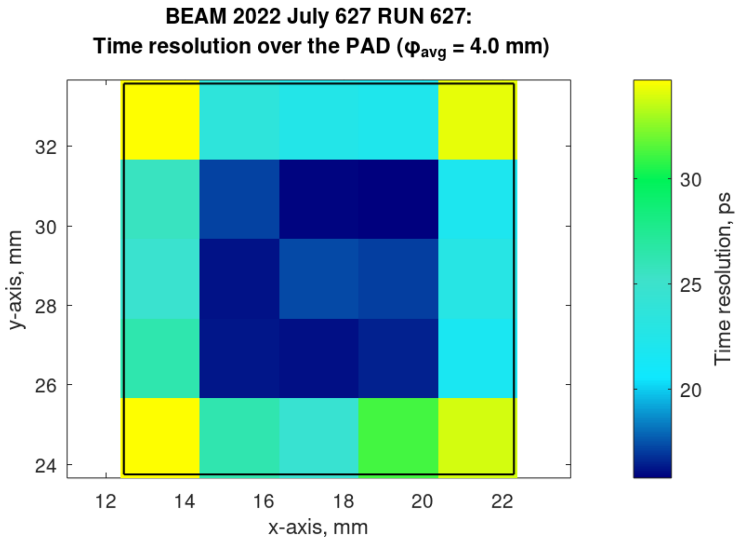
Test beam October 2022: 6 pads scan

1	2	3	4	5	6	7	8	9	10
11	22	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	43	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

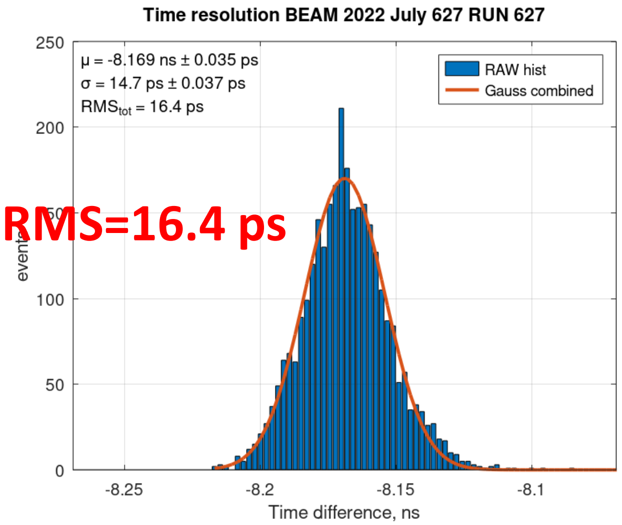
RD51 test beam July 2022: 2 x 4 pads scan

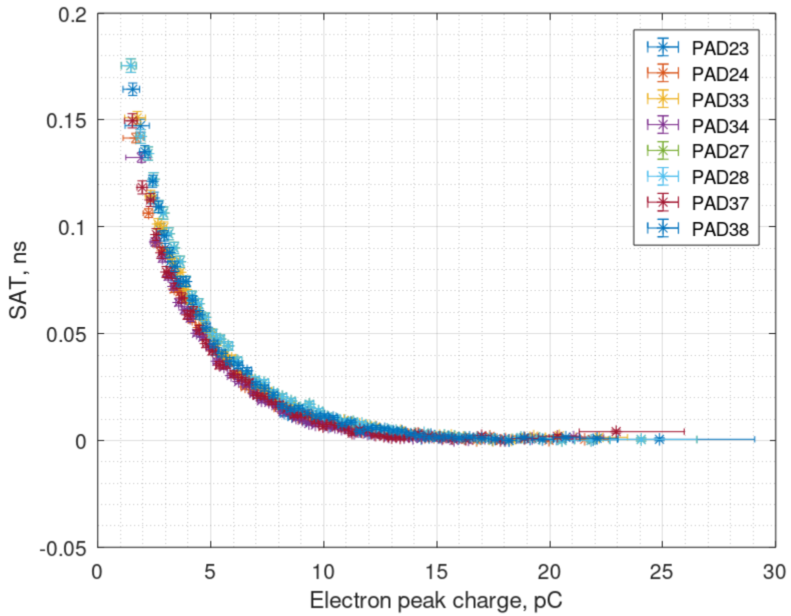
Preliminary results

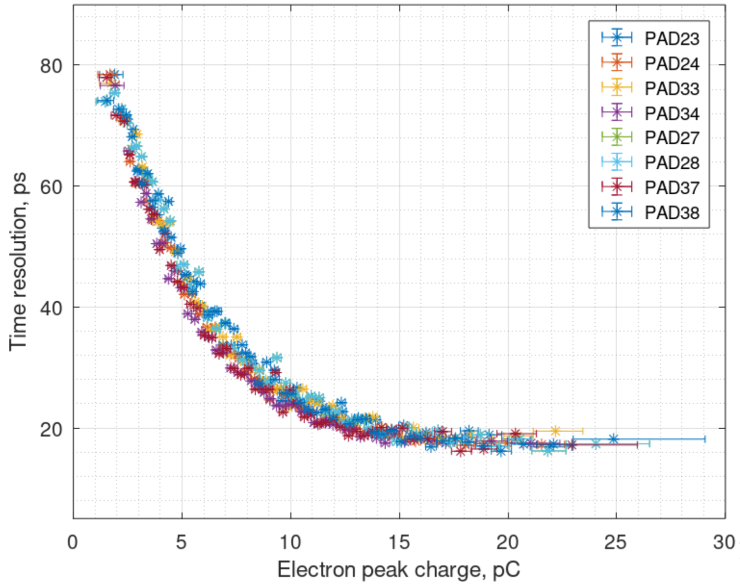
2D plot of time resolution over the **pad 28** (1 cm x 1 cm area)



Time resolution within 4 mm x 4 mm square







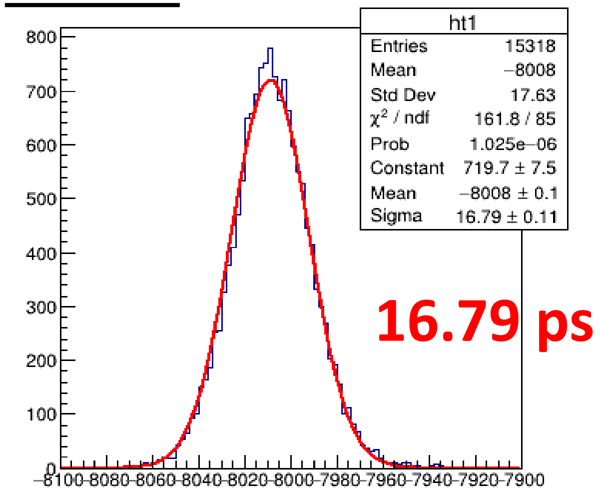
Time resolution within the center of the pad (4 mm x 4 mm), 180 μm drift gap, Vc = -465 V, Va = +275 V, preamp. Cards

PAD	23	24	33	34	27	28	37	38
RMS,ps	17.4	17.1	17	17.9	17.2	16.4	17.1	16.6

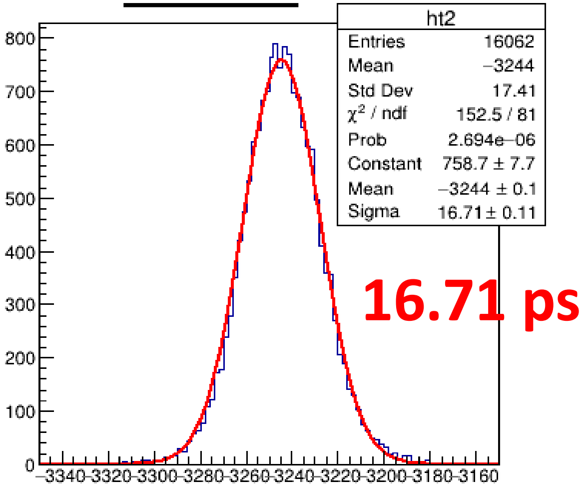
- All measured pads have time resolution below 18 ps in the pad central region.
- Signal Arrival Time and time resolution have similar dependance on e-peak charge for all measured pads.

RD51 test beam October 2022: 6 pads scan, V_c=-460 V, V_a=+275 V

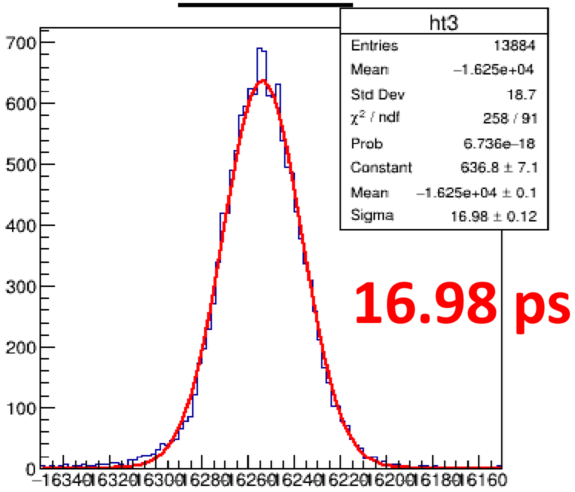
Pad 27

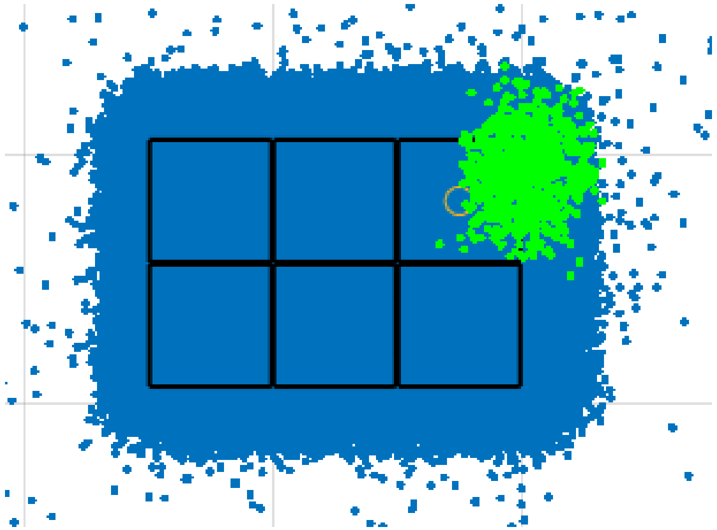


Pad 28

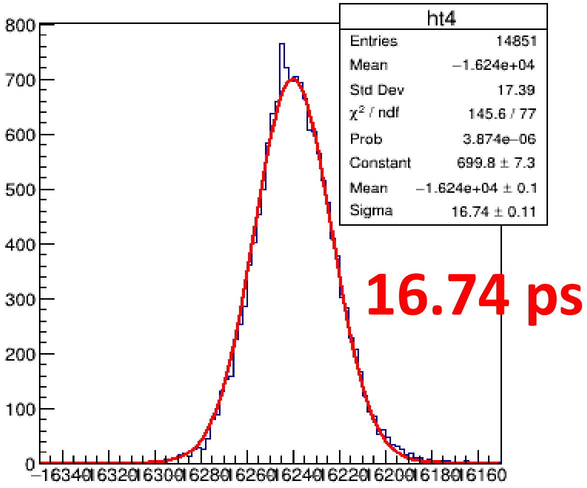


Pad 29

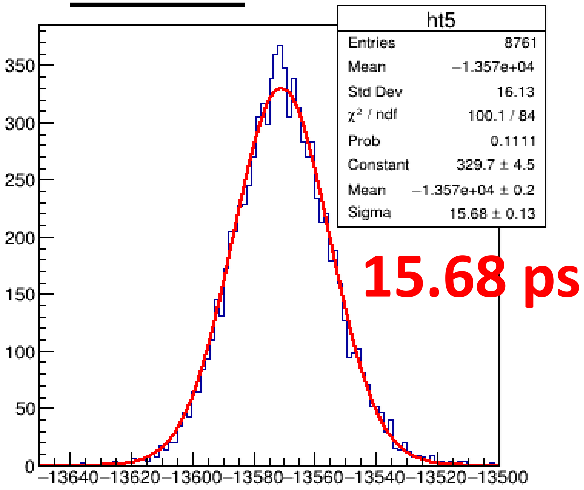




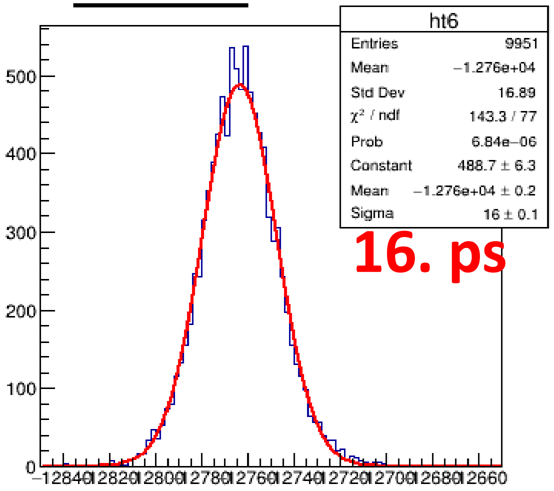
Pad 37



Pad 38



Pad 39



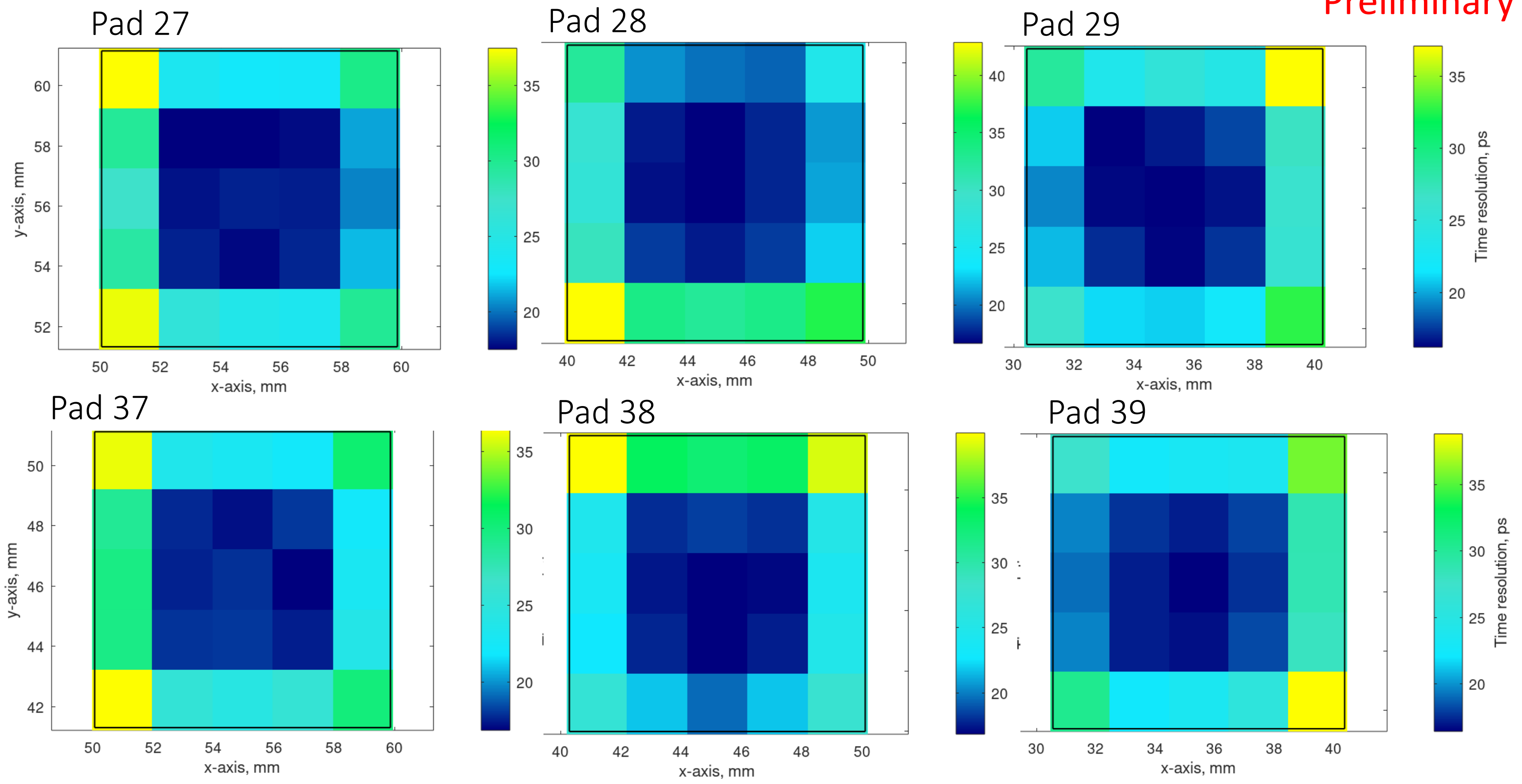
Time resolution in the 4 mm x 4 mm center pad region is below 17 ps for all measured pads.

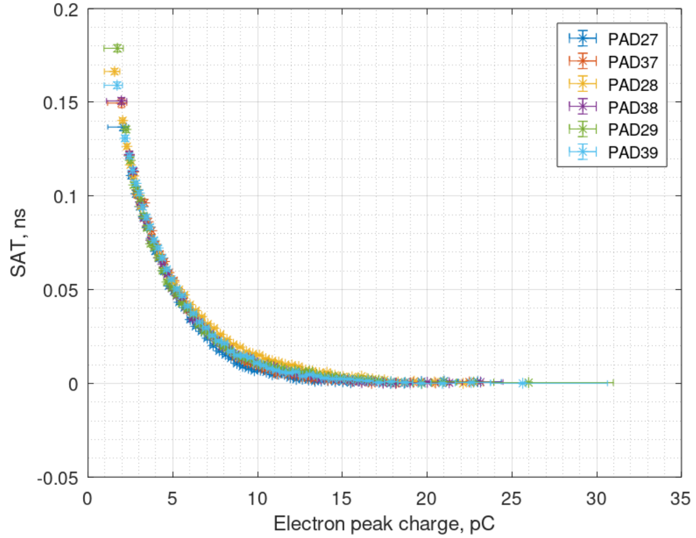
Preliminary results

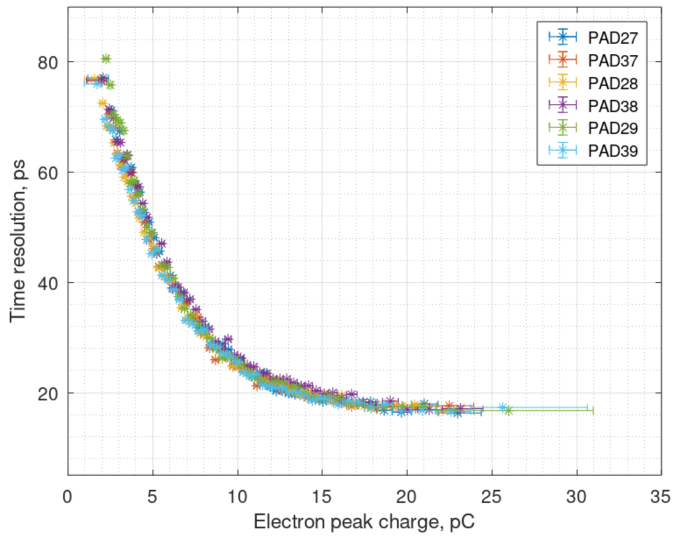
Analysis by Y.Angelis,E.Chatzianagnostou, A. Tsiamis & Spyros Tzamarias (Aristotle University of Thessaloniki)

Time resolution within the pad and dependence of the timing properties on the e-peak charge (time-walk)

Preliminary results



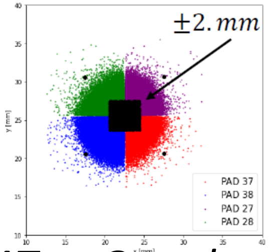




- Time resolution is uniform and below 20 ps in the center of all scanned pads.
- Signal Arrival Time and time resolution have similar dependance on e-peak charge for all measured pads.

Analysis of signal sharing: analytical method

by Y.Angelis,E.Chatzianagnostou, A. Tsiamis & Spyros Tzamarias
Aristotle University of Thessaloniki

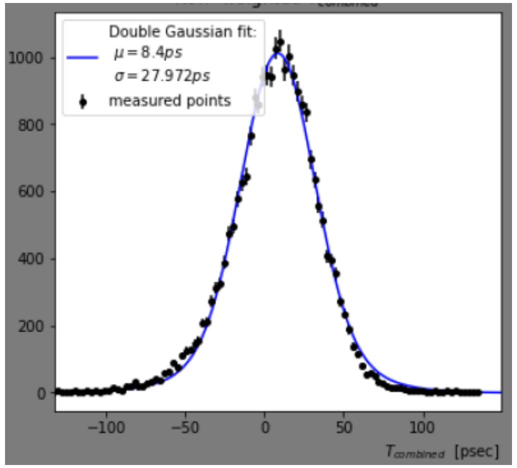


Using global parametrization functions for SAT vs Q and time resolution vs Q.

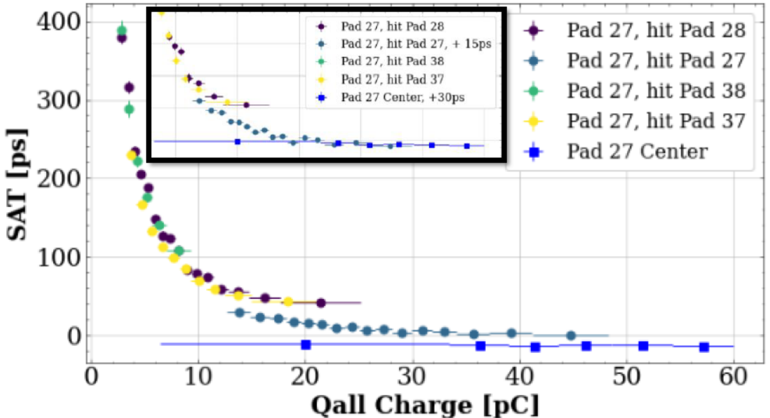
$$S\ (q\ ) = \exp\left(p^0\, q\ + p^1\ \right) + \exp\left(p^2\, q\ + p^3\ \right) + p^4$$

$$\chi^2 = \sum_{k=1,2,3,4} \frac{[T_{comb} - (t^k - S\ (q^k))]^2}{R^2\ (q^k)}$$

σ = 28.0 ± 0.8 ps



Parametrize time walk effect for each observed pad k, with respect to the hit pad j (max. fraction of charge in sharing)

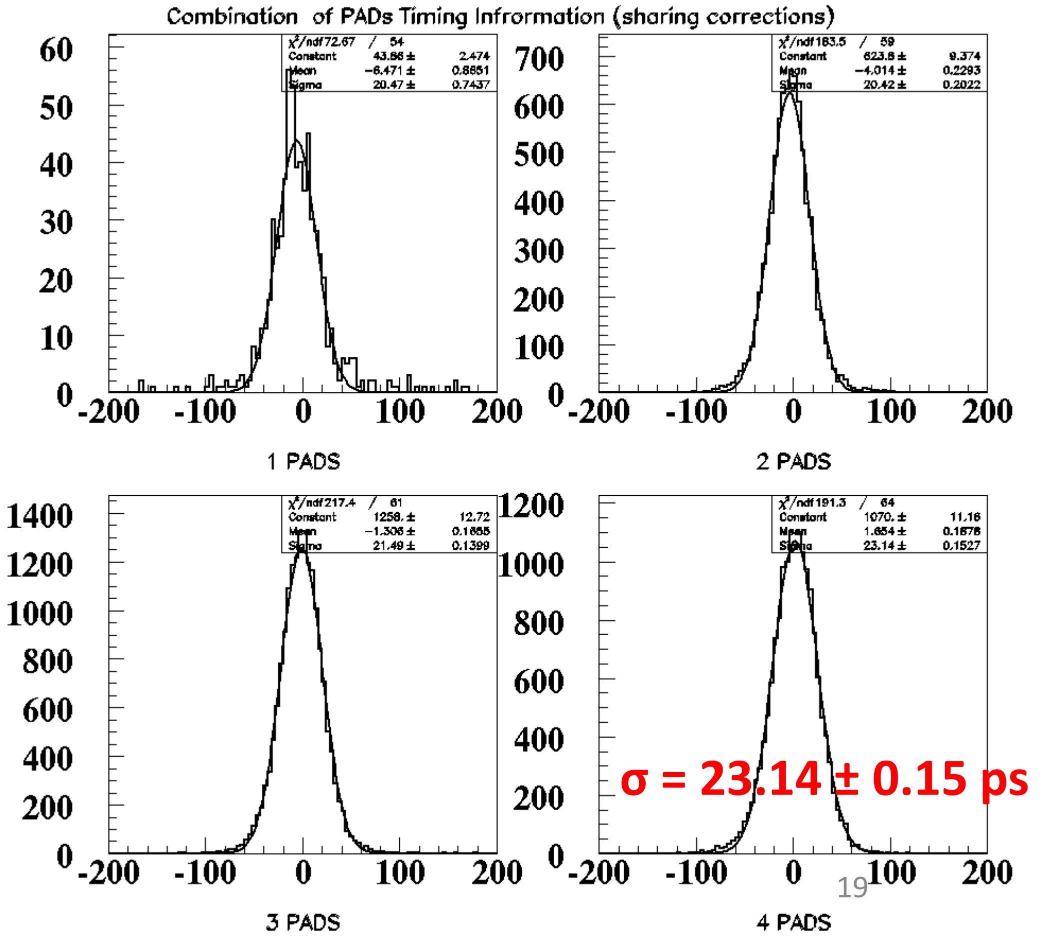


$$S_{kj}(q^k) = \exp\left(p^0_{kj} q^k + p^1_{kj}\right) + \exp\left(p^2_{kj} q^k + p^3_{kj}\right) + p^4_{kj}$$

$$R_{kj}(q^k) = \exp\left(r^0_{kj} q^k + r^1_{kj}\right) + \exp\left(r^2_{kj} q^k + r^3_{kj}\right) + r^4_{kj}$$

Redefining χ^2 estimator

$$\chi^2 = \sum_{k=1,2,3,4} \frac{[T_{comb} - (t^k - S_{kj}(q^k))]^2}{R^2_{kj}(q^k)}$$



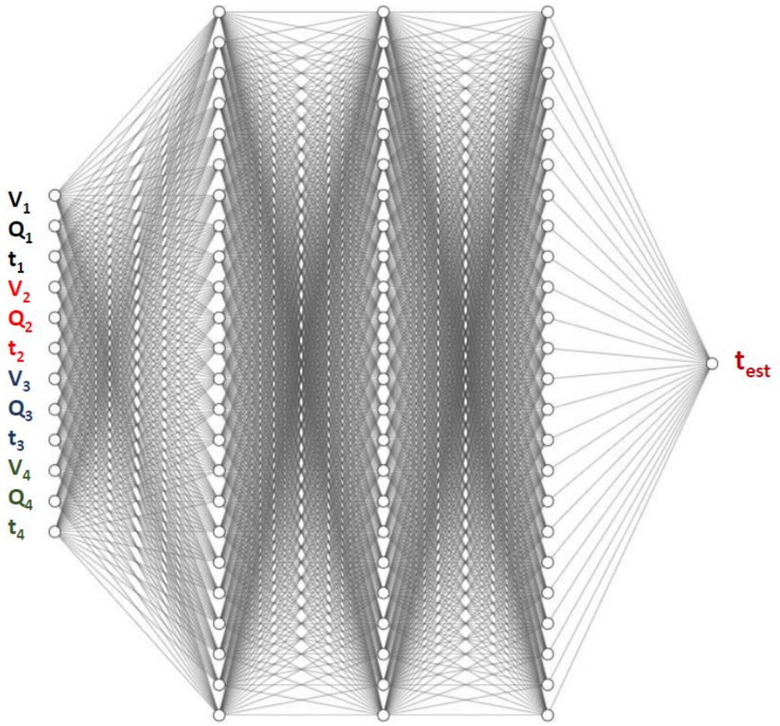
σ = 23.14 ± 0.15 ps

Analysis of signal sharing: ANN

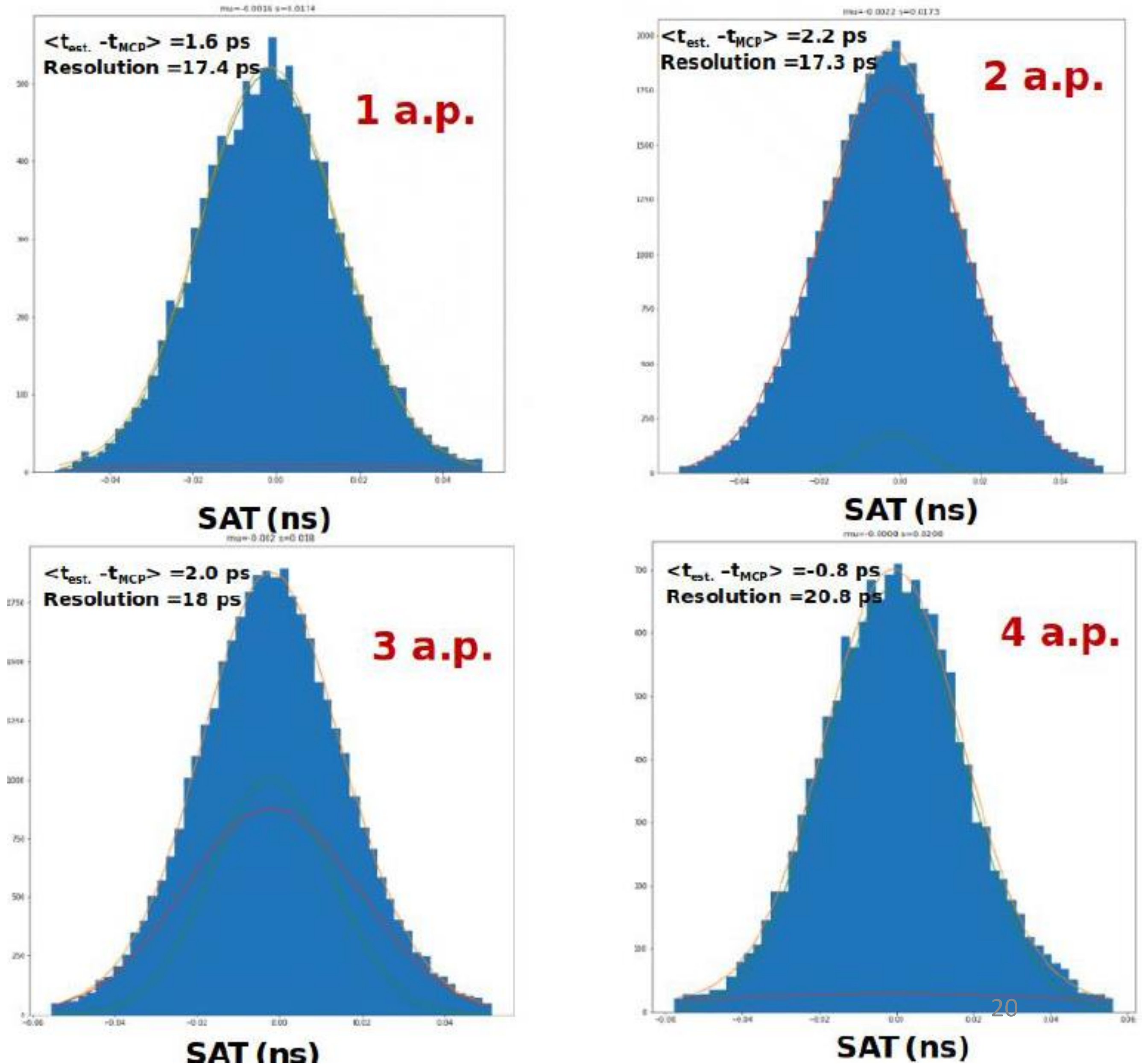
by Y.Angelis,E.Chatzianagnostou, A. Tsiamis & Spyros Tzamarias
Aristotle University of Thessaloniki

Time resolution near the common cross point area for 1, 2, 3, or 4 active pads:

Using input vector of voltage, charge and time from signal processing for all 4 pads.
Neural network training on fraction of data set.
Neural network analysis on remaining data set.



σ^{4pads} = 20.8 ps



Conclusion

- After intensive R&D activities on 100 channel Picosec detector (simulations, design, production, initial tests, and successful commissioning with MIP at SPS H4 beamline) research activities were continued towards multi-channel readout system, large area timing measurements, and detector optimization..

✓ Low noise, low-power, **fast custom-made amplifiers** were adopted for PICOSEC and tested in the lab and on the beam:

  ✓ Do not dominate the jitter and time resolution slightly improves. 100 channels were produced, and a full detector was equipped and tested with a SAMPIC digitizer.

✓ **Automated scan** method was successfully implemented for large area timing measurements.

  ✓ Successful scan of 2 x 4 and 6 pads with oscilloscopes and ~90 pads with Sampic digitizer.

✓ Improvement in the **detector timing performance** by reducing drift gap thickness (220 μm->180 μm):

  ✓ Time resolution in the pad center improves from ~ 24 ps -> ~ 17 ps.

  ✓ Time resolution for signal sharing between four neighboring pads improves from ~30 ps -> ~ 23.14 ps (analytical method) or 20.8 ps (ANN)

- R&D still ongoing: robustness, stability, detector optimization .... See next talk by M. Lisowska https://indico.cern.ch/event/1219224/contributions/5130512/

Acknowledgments ☺

Huge thanks to

- **Christophe Hoarau**, LPSC, original amplifier design
- **Marinko Kovacic** (UNIZG FER), design of 10 channel amplifier cards, optimization for Picosec detector
- **Rui De Oliveira, Antonio Teixeira, Olivier Pizzirusso and Bertrand Mehl**, CERN MPT workshop, Micromegas board
- **Miranda VAN STENIS, Ouassim Heribi and Thomas SCHNEIDER**, CsI photocathodes and housings.
- **Jihane Maalmi and Dominique Breton, SAMPIC**
- **RD51 Picosec Micromegas Coll.** task force ☺.

RD51 PICOSEC Micromegas Collaboration

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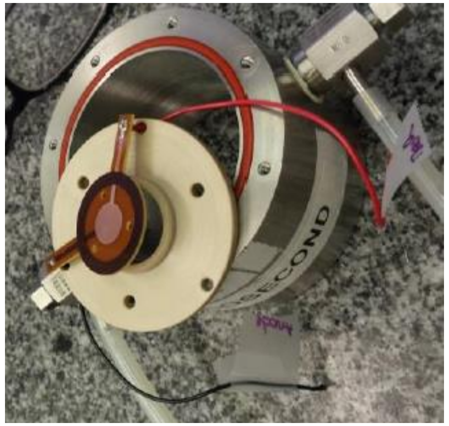
PICOSEC Micromegas

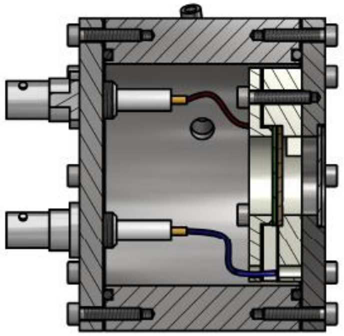
Thank you for your attention ☺

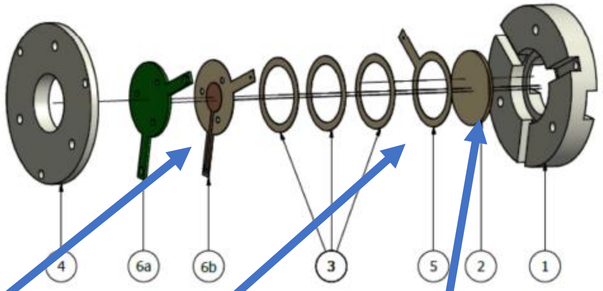
backup

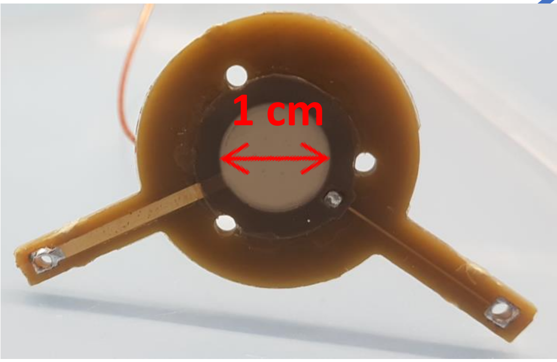
Proof of concept - First PICOSEC MM single channel prototype

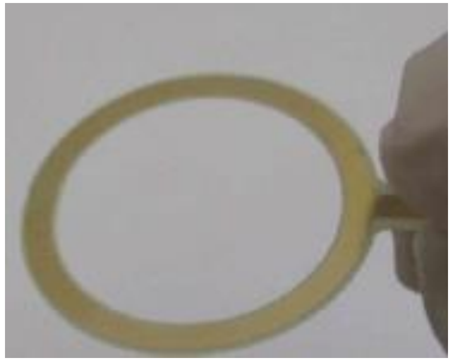
- Bulk Micromegas
  - **1 cm** diameter active area.
- Drift/preamplification region
  - 200 μm thick drift region.
- Cherenkov radiator and photocathode
  - 3 mm thick **MgF_2**
  - 5.5 nm **Cr**
  - 18 nm **CsI**
- Operating gas
  - 80% Ne + 10% CF_4+ 10%C_2H_6
  - Pressure: 1 bar

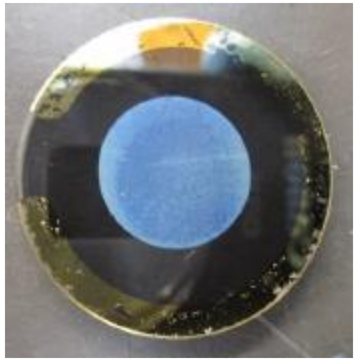












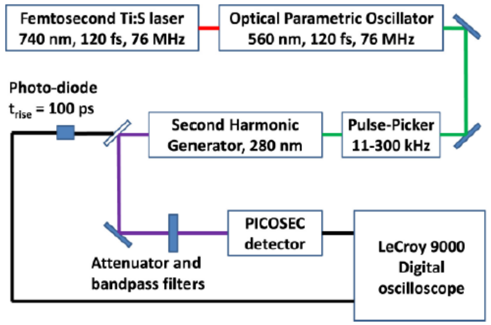
F.J. Iguaz PM2018, https://agenda.infn.it/event/17834/contributions/83199/attachments/60308/71340/113-Slides-iguaz_gutierrez-20180528_FJIguaz_PM2018_PICOSEC.pdf

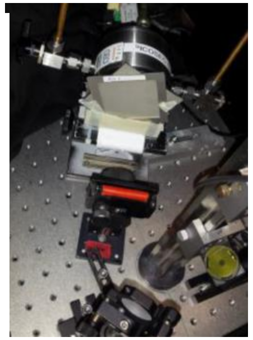
Time response studies: with MIPs and single photoelectron

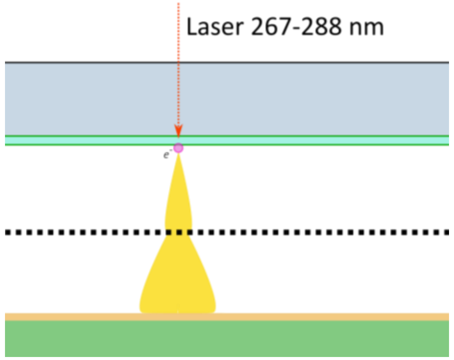
Laser test

Pulsed laser @ The FLUME Laser setup at LYDIL Laser laboratory at CEA Saclay

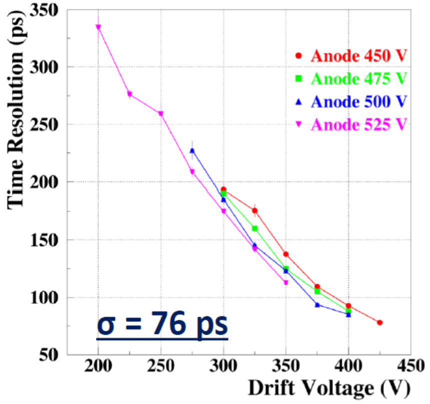
Single p.e response: systematic detector studies (E-fileds / gaps / gas mixtures…)

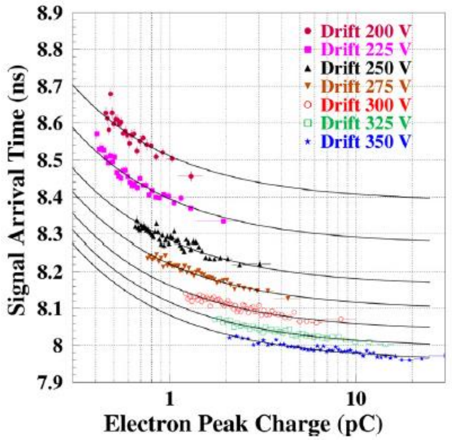






- Time resolution for single p.e. (200 µm drift gap) : 76.0 ± 0.4 ps.



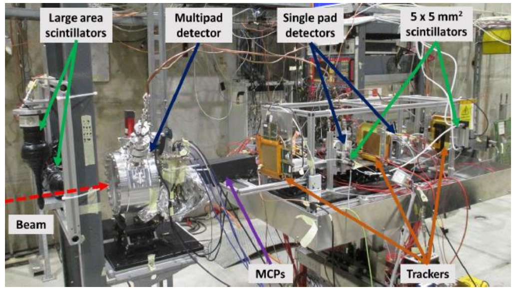


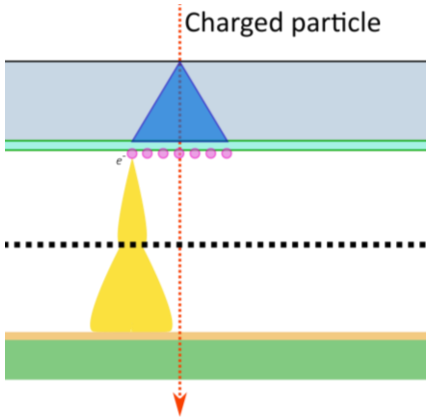
Bortfeldt, J., et al. "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector." *NIM A* 903 (2018): 317-325.

Beam test

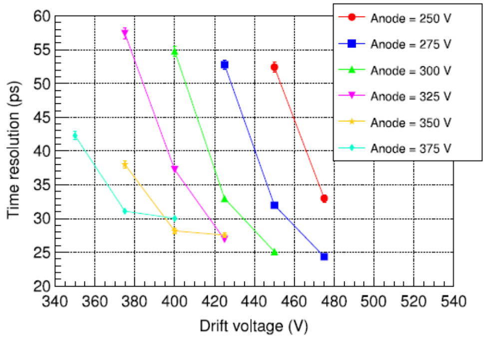
150 GeV muons @ CERN SPS H4 secondary beamline

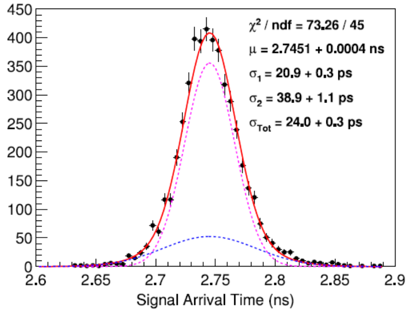
MIPs response





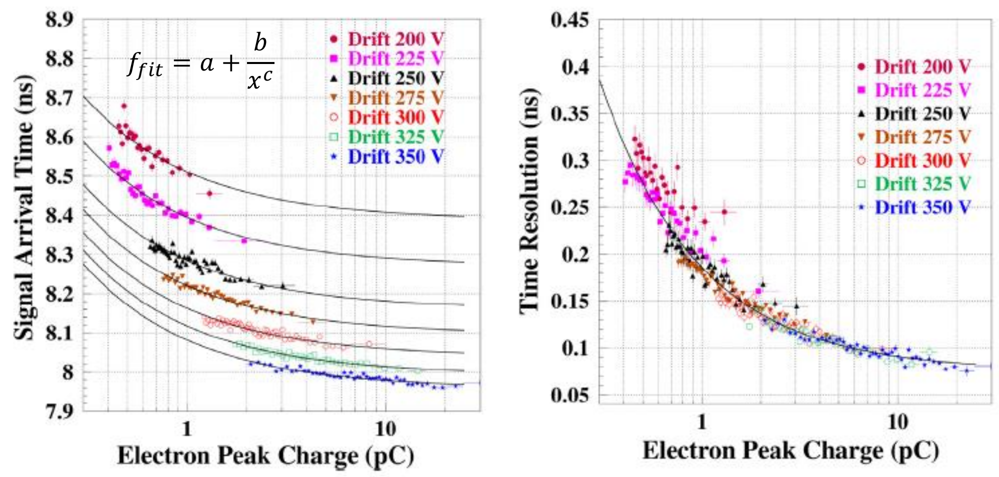
- Beam tests @ CERN SPS H4 secondary beamline.
- Time resolution of 24.0 ± 0.3 ps for 150 GeV muons



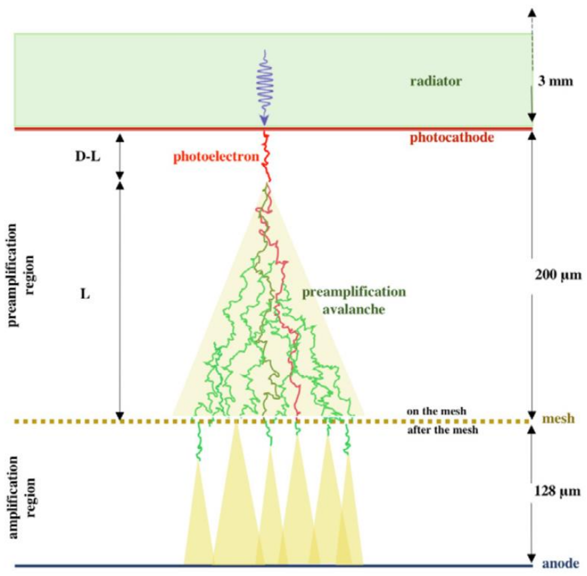


- Time resolution improves significantly with higher drift field.

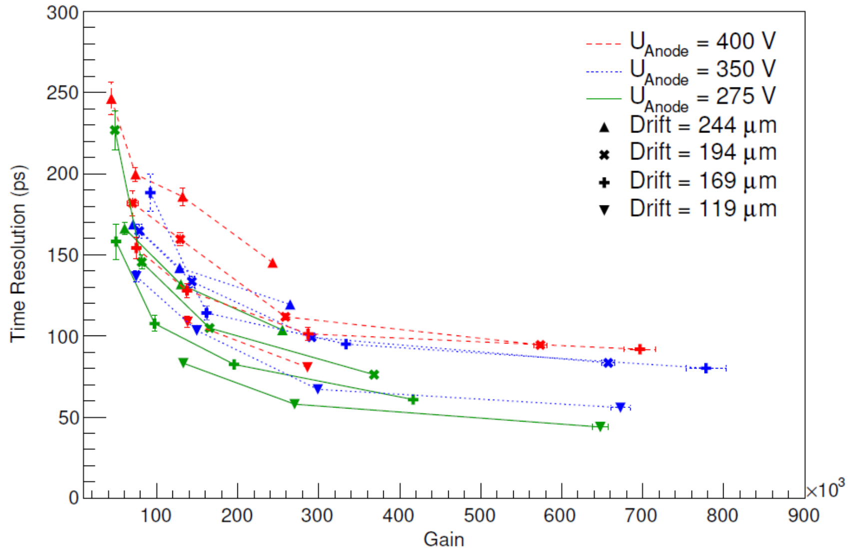
Impact of the drift region to the timing properties



[Bortfeldt, J., et al. "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector." *NIM A* 903 (2018): 317-325.]()



[Bortfeldt, J., et al. NIM A 993 (2021): 165049]()



[Sohl, L., et al. JINST 15.04 (2020): C04053.]()

- Both simulations and measurements show that Signal Arrival Time has a dependence on e-peak charge:
  - **For longer SAT** → smaller e-peak charge
  - **For lower drift field** → longer SAT
- Both SAT and resolution can be improved if drift field is increased.
- Longer pre-ionization path add delay in SAT.
- Earlier avalanche onset → better timing.
- More recent measurements show time resolution **< 50 ps** at single p.e. with a shorter drift gap (120 µm).
- **Preamplification/drift region has the dominant influence on timing.**