AUTH CONTRIBUTION IN THE DEVELOPMENT OF THE MULTI-PAD PICOSEC-MICROMEGAS

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on behalf of the RD51-PICOSEC collaboration

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Thessaloniki, Greece
On

PICOSEC Micromegas

ARISTOTLE UNIVERSITY OF THESSALONIKI

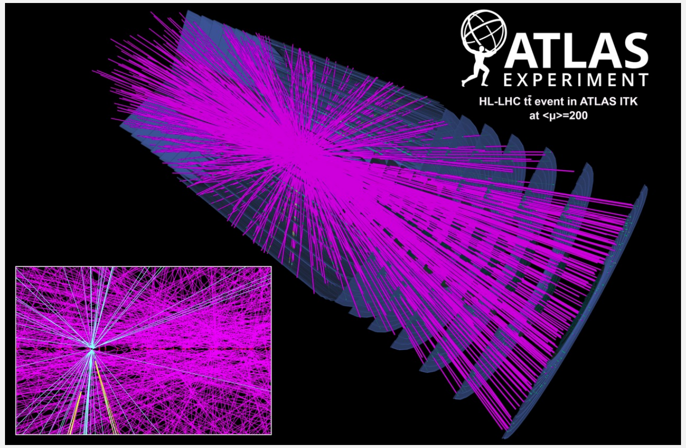
OUTLINE

- PICOSEC-MicroMegas: A fast reminder
- The multi-pad PICOSEC-Micromegas: Towards a large scale detector
  - Results from the first protype
  - An updated multi-pad PICOSEC-MicroMegas detector
- Novel timing results
- Conclusions

A FAST REMINDER

Motivation for precise timing in HEP

- In the High Luminosity LHC, ~140 "pile-up" proton-proton interactions ("vertices") in the same pp bunch-crossing
- Tracking information (3D) is not enough to associate interactions to the corresponding vertex
- Demand for precise timing detectors for physics
- Precision down to 30 ps or more
- Precise track reconstruction in the very demanding HL and very HE environments of future colliders (e.g. FCC) will require 4D treatment



Available detecting technologies

Solid state detectors

- Avalanche photodiodes (σ_t ~ 20 ps)
- Low Gain Avalanche Diodes (σ_t ~ 20 ps)
- HV/HR CMOS (σ_t ~ 80 ps)

Radiation hardness = ?
Cost = ✗

Gasseous detectors

- RPC (σ_t ~ 30 ps)
- Micro-Pattern Gaseous Detectors (σ_t ~ 4 ns)

Precise timing detector requirements:

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

A typical Micromegas detector and its limitations in the timing domain

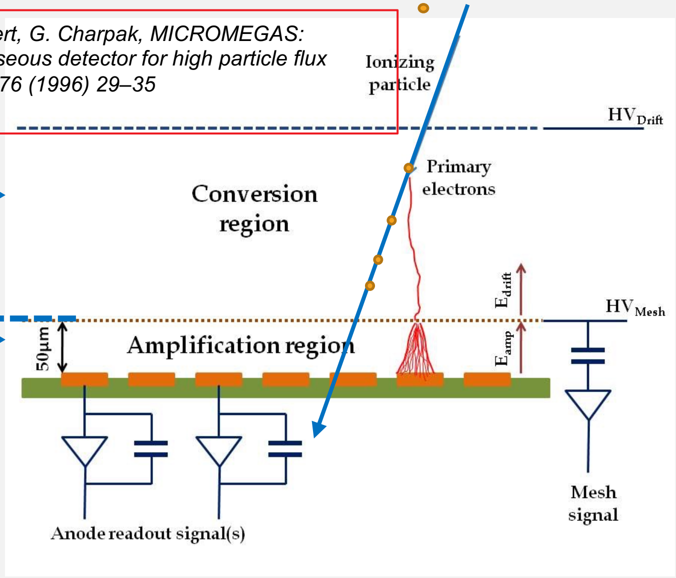
Y. Giomataris, P. Rebourgeard, J. Robert, G. Charpak, MICROMEGAS:
A high granularity position sensitive gaseous detector for high particle flux environments, Nucl. Instrum. Meth. A 376 (1996) 29–35

Drift Gap / Conversion region

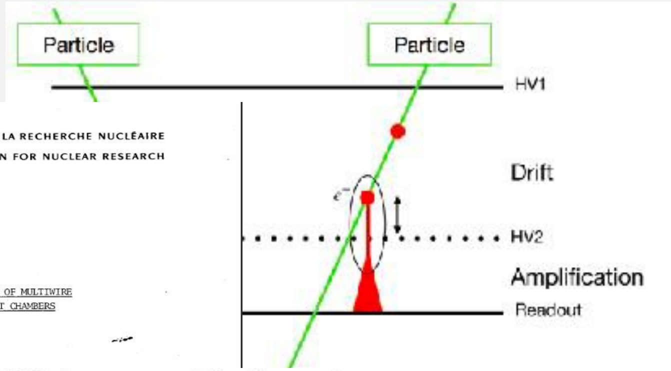
A traversing particle drift toward the readout plane ionizes gas molecules → free electrons drift

Amplification region

High electric field→ avalanche creation →moving charges induce signals



- Even though gaseous detectors performs well for spatial measurements (high spatial resolution down to tens of microns) they have limited precision in timing measurements
    - Stochastic nature of ionizations
    - Ionization start point variates → ns time jitter for 3 – 6 mm conversion region
    - Difussion effects
    - Time resolution only down to 5 ns



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PRINCIPLES OF OPERATION OF MULTIWIRE PROPORTIONAL AND DRIFT CHAMBERS

F. Sauli

Lectures
Academic Trainin
197

1977

which is represented in Fig. 8, for n = 34, as a function of the coordinate across a 10 mm thick detector. If the time of detection is the time of arrival of the closest electron at one end of the gap, as is often the case, the statistics of ion-pair production set an obvious limit to the time resolution of the detector. A scale of time is also given in the figure, for a collection velocity of 5 cm/μsec typical of many gases; the FWHM of the distribution is about 5 nsec. There is no hope of improving this time resolution in a gas counter, unless some averaging over the time of arrival of all electrons is realized.

The PICOSEC - Micromegas

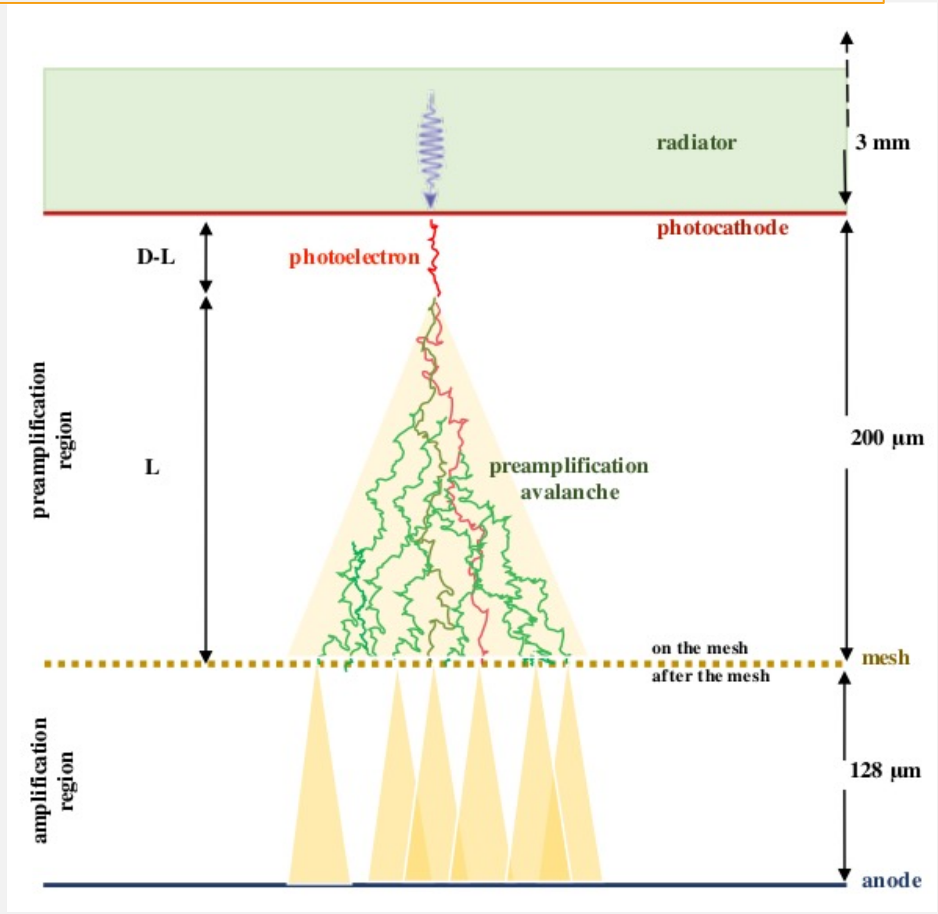
Additional parts

- Cherenkov radiator
  - A traversing particle produces Cherenkov light
- Photocathode instead of the classic cathode
  - Photoelectrons extracted from the photocathode simultaneously

Modification of detector's geometry

- Smaller drift gap
  - From a few mm to some hundreds of microns
- Higher Drift Voltage

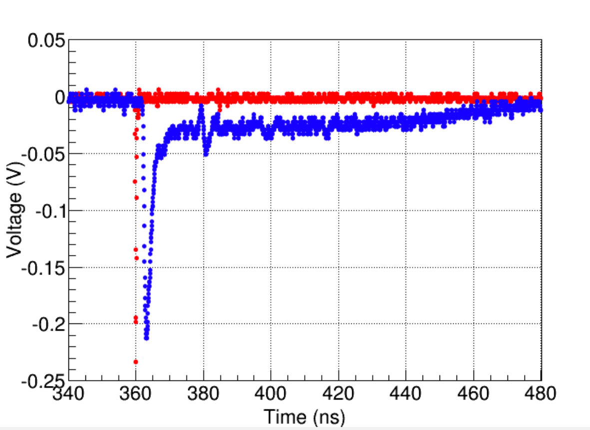
PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector J. Bortfeldt et. al. (RD51-PICOSEC collaboration), Nuclear. Inst. & Methods A 903 (2018) 317-325

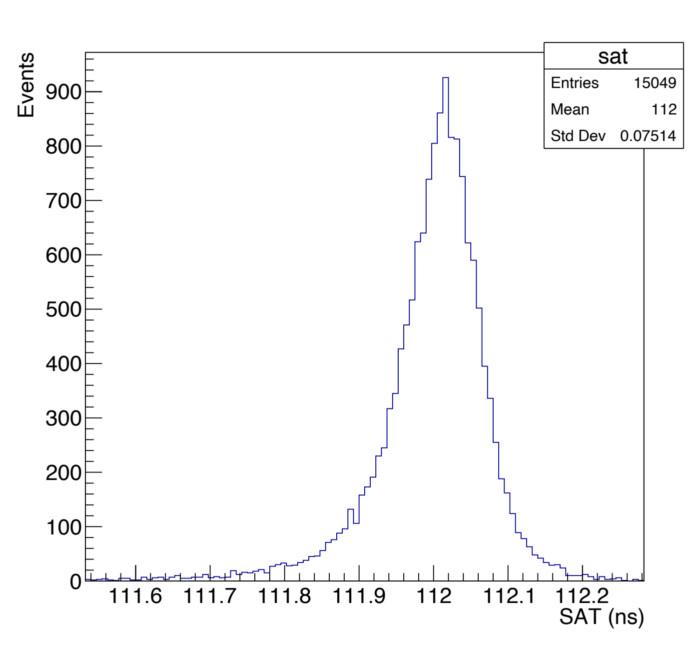


- The MIPs produce synchronous Cherenkov photons in the radiator
- The photocathode emits synchronous photoelecrtons
- Preamplification avalanche

Timing resolution calculation

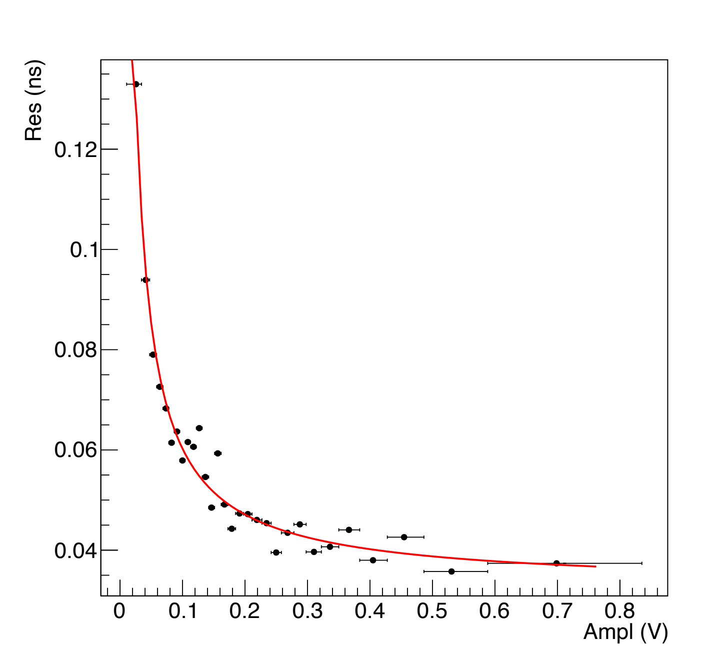
- Compare the measured time of the PICOSEC-Micromegas with a reference detector of much better resolution e.g MCP (≈ 5 ps)
- Timing of MCP's signal with the same process
- Subtract the PICOSEC-Micromegas SAT from the MCP SAT
- Time resolution = RMS[ΔSAT]





- CFD method sould not suffer from the time walk effect
  - In our data we have dependence of the ΔSAT and Resolution on the signal amplitude
  - Results from the microscopic behavior of the avalanche
    - The photoelectrons drift with different velocity than the avalanche as a whole
  - Calibration curve: $g(x; a, b, w) = a + \frac{b}{x^w}$
  - Correct all SAT values: $SAT_{pico} = SAT_{pico} - \frac{a}{V^b} + c$
  - Re-fill the ΔSAT distribution

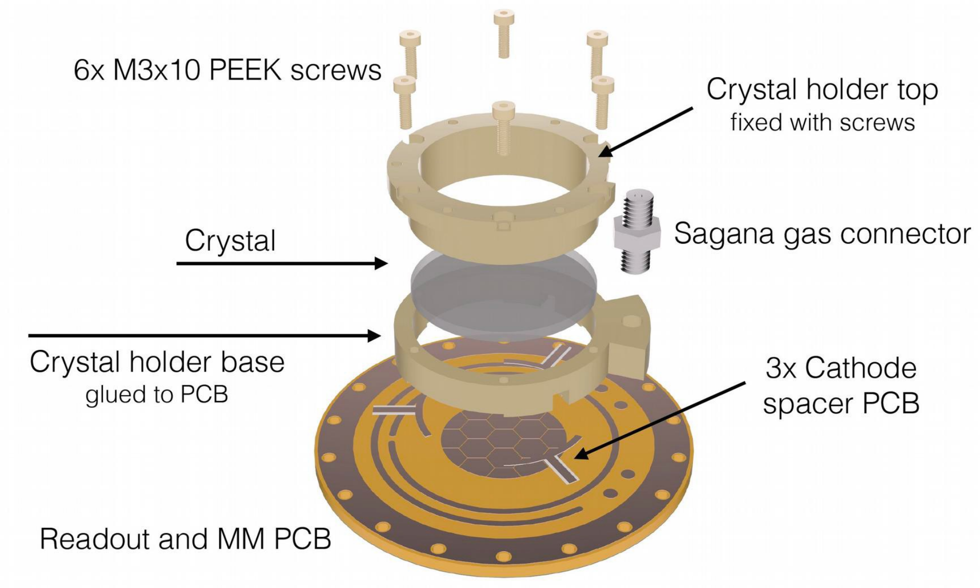
Best results: 24 ± 0.3 ps



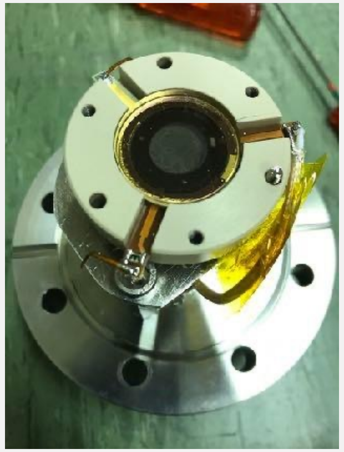
TOWARDS A LARGE SCALE DETECTOR

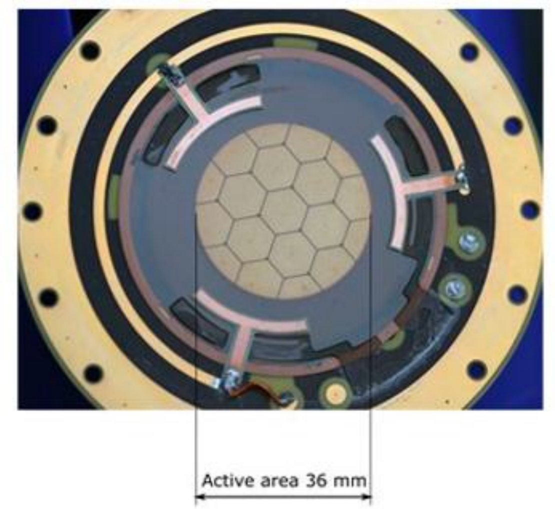
A multichannel PICOSEC – Micromegas prototype

- Big experiments like ATLAS need large scale detectors like the presented MM earlier
- The large scale PICOSEC – MM should:
    - Deliver the 25 ps resolution
    - Robust
    - Reasonable cost



- Introduced the first Multipad PICOSEC- MM
    - Similar detector configuration like the single pad:
        - MgF_2 radiator of 3 mm thickness
        - 18 nm CsI photocathode on 5.5 nm Cr
        - Bulk Micromegas
        - “COMPASS” gas
        - 220 μm drift gap
        - Hexagonal pads of 1 cm diameter

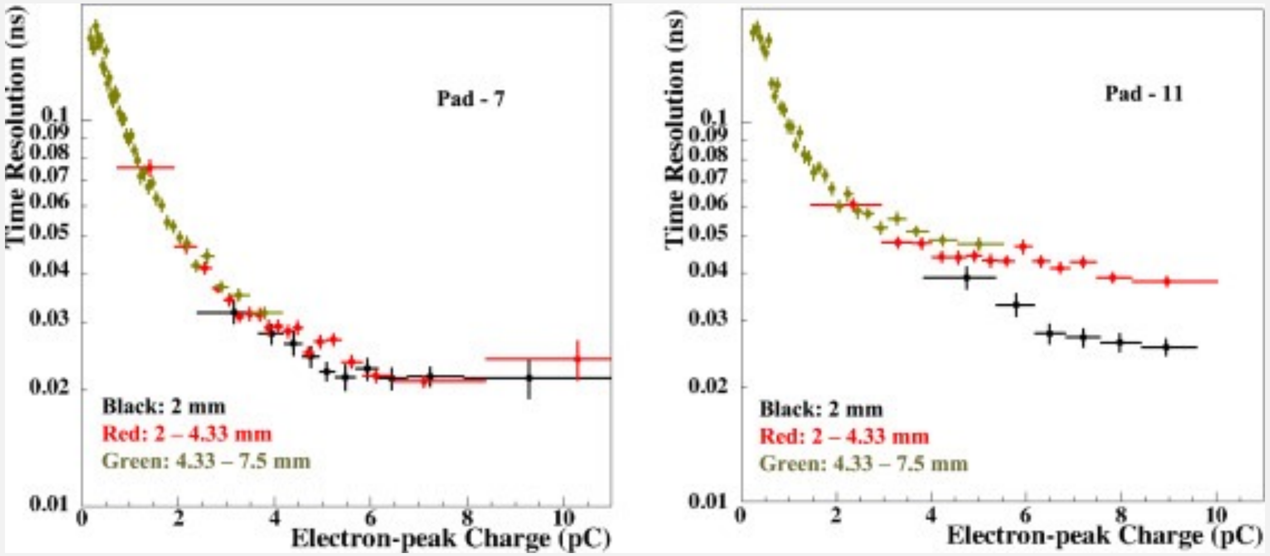


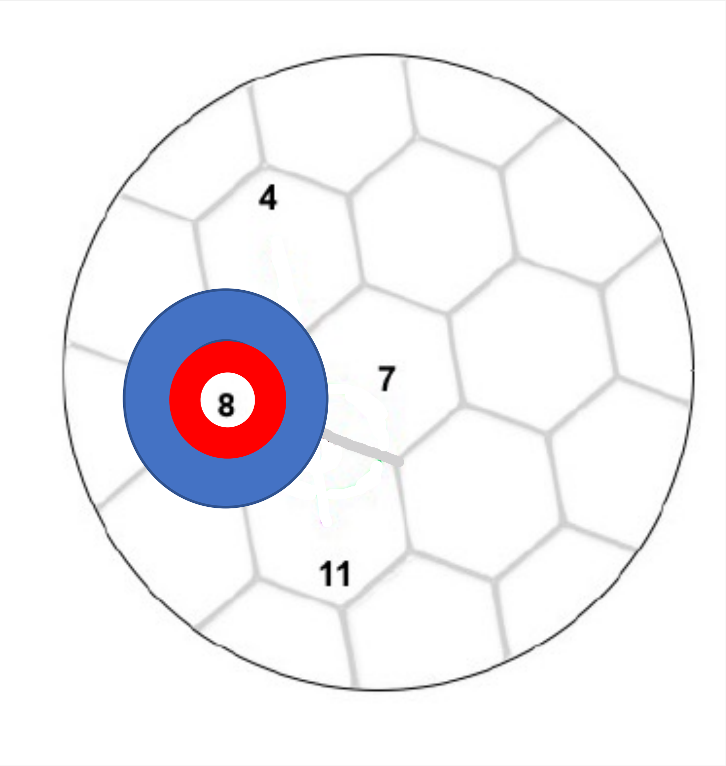


- New challenges have emerged with the proposed multi channel scheme

Flatness corrections

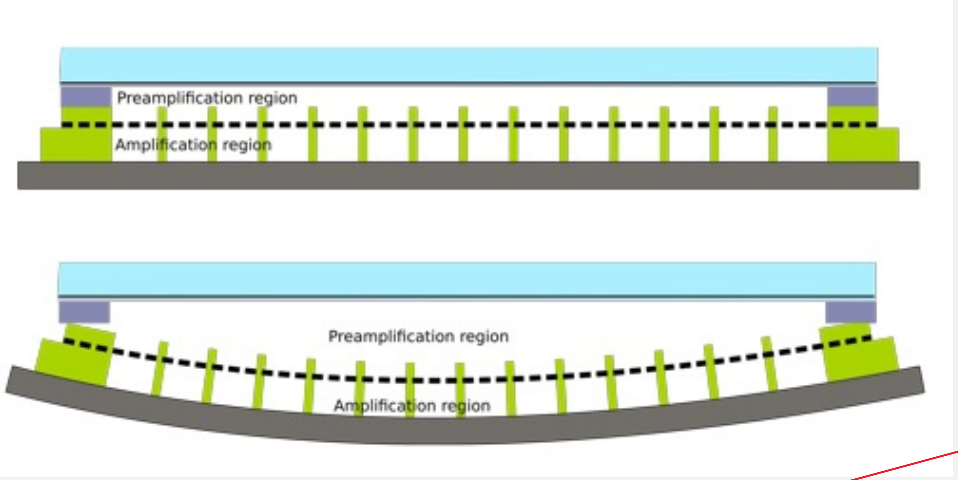
- ≈25 ps resolution nearby the pads' centers
- Scan across different pads' regions revealed SAT differences
  - Outer vs inner area on peripheral pads
- Gain non-uniformity → worse time resolution
- Pad No. 7 was less affected
- The time resolution of the central pad is an exlusive function of the Q_e
- Resolution of peripheral pads depends on both Q_e and MIP impact point

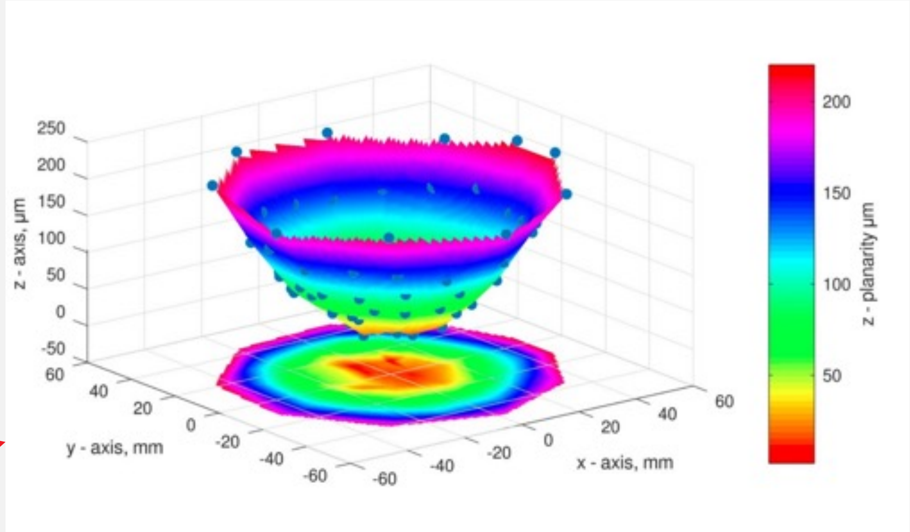




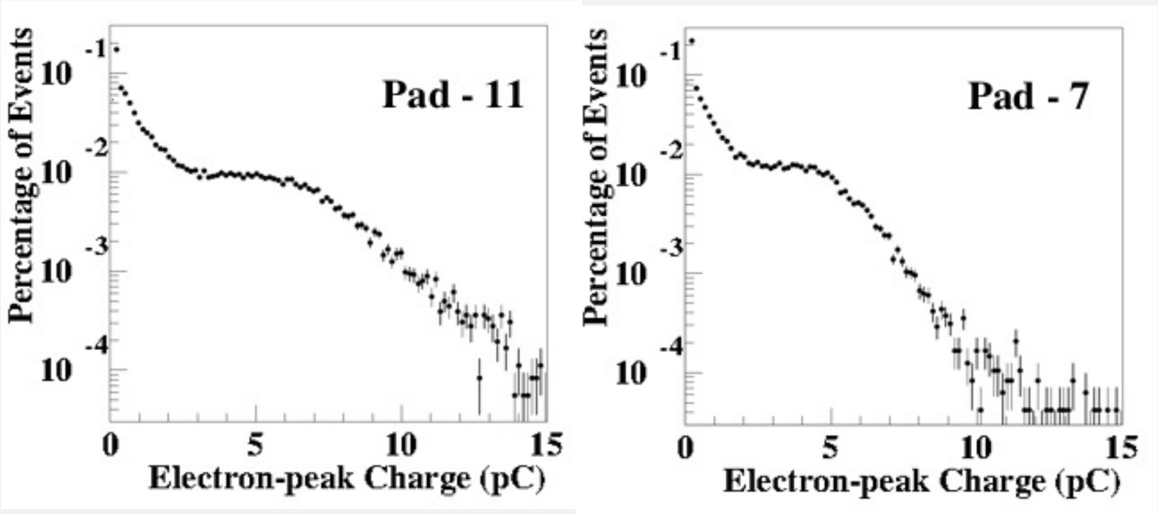
7: Central pad
4, 8, 11: Peripheral pads

The first attempt: unforeseen deformation





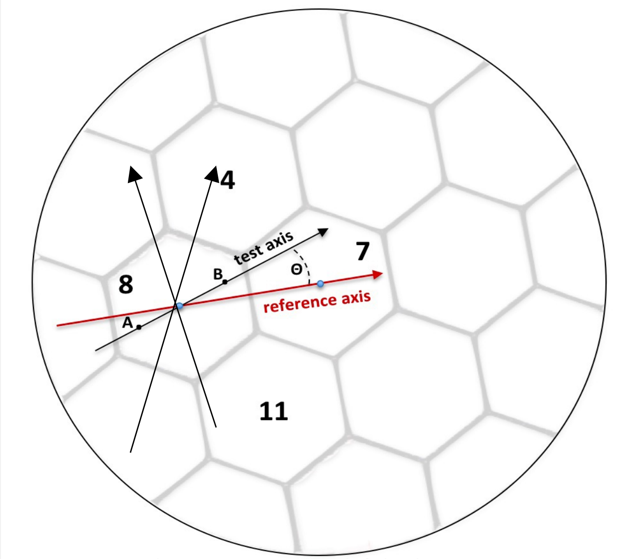
- Timing performance revealed anode deformation (confirmed later by an optical device measurement)
- Drift gap non uniformity →spatial variation of the detector gain
- Direct impact on the timing performance between pads
- Corrections applied, restored a uniform timing response over all detector active area

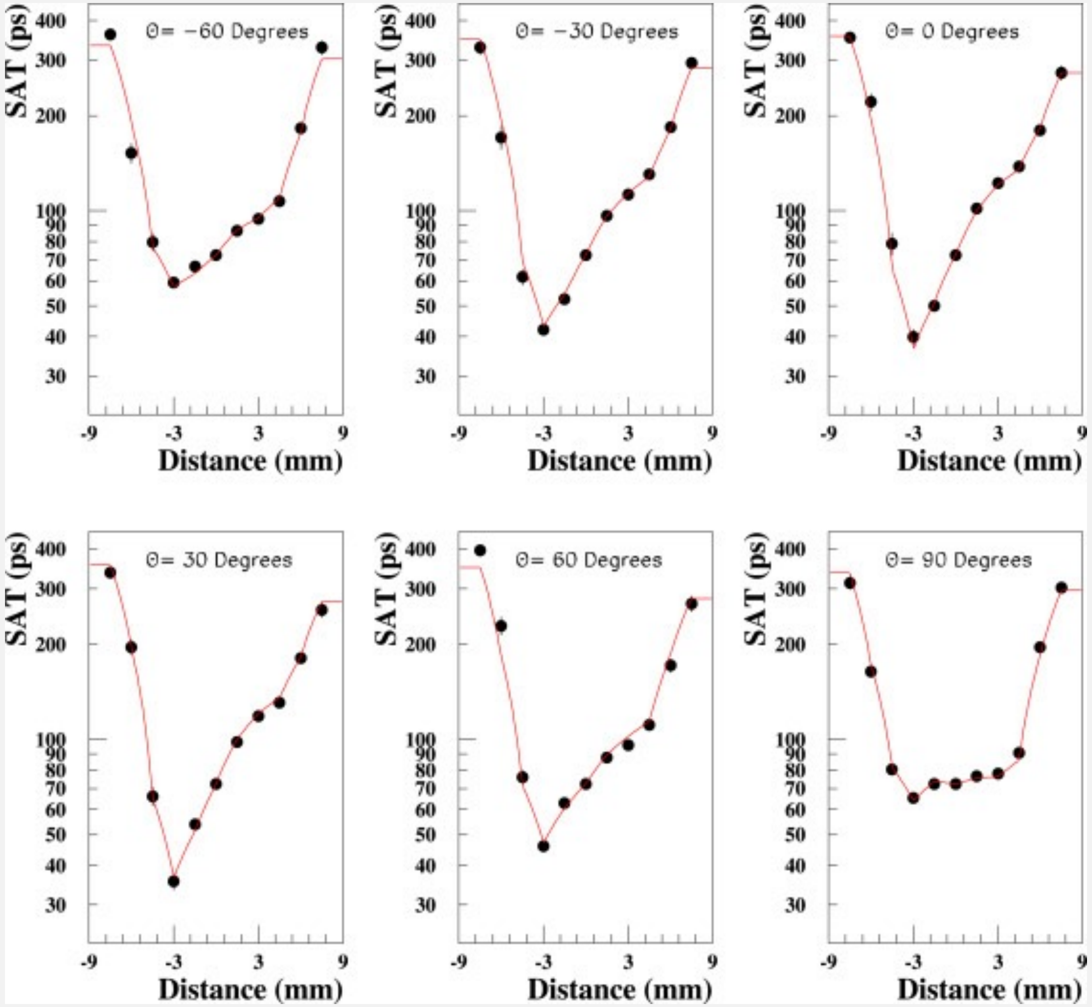


Timing performance of a multi-pad PICOSEC-Micromegas detector prototype, NIM A 933 – 2021

Flatness corrections

- Reference axis: *The axis collinear to the line segment connecting the understudy peripheral pad with the central pad centre and directing towards to the centre of the central pad*
- Measurements on seed points along several test-axis
- On each seed point collected tracks passing within 0.5 mm around it
- Signals on negative distances arrive faster than the mirroring points
- The mean SAT assymetry reflectst the spatial variation of the drift velocity
    - Maps the variation of the drift field due to deformations

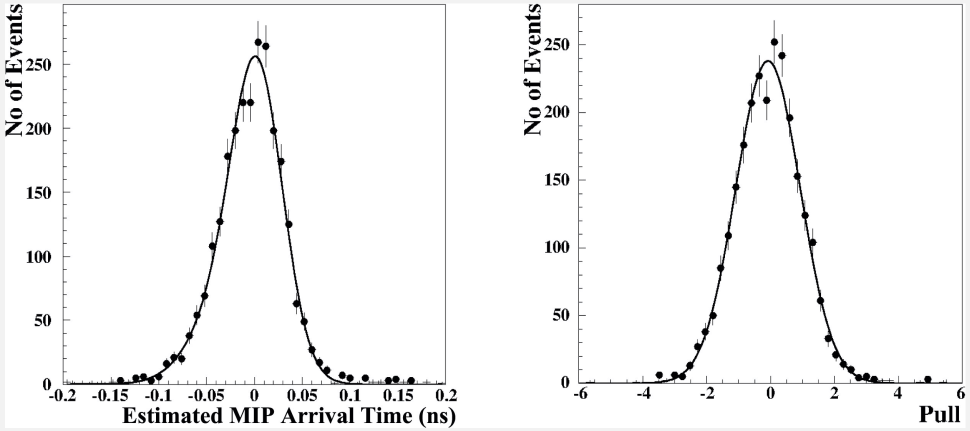




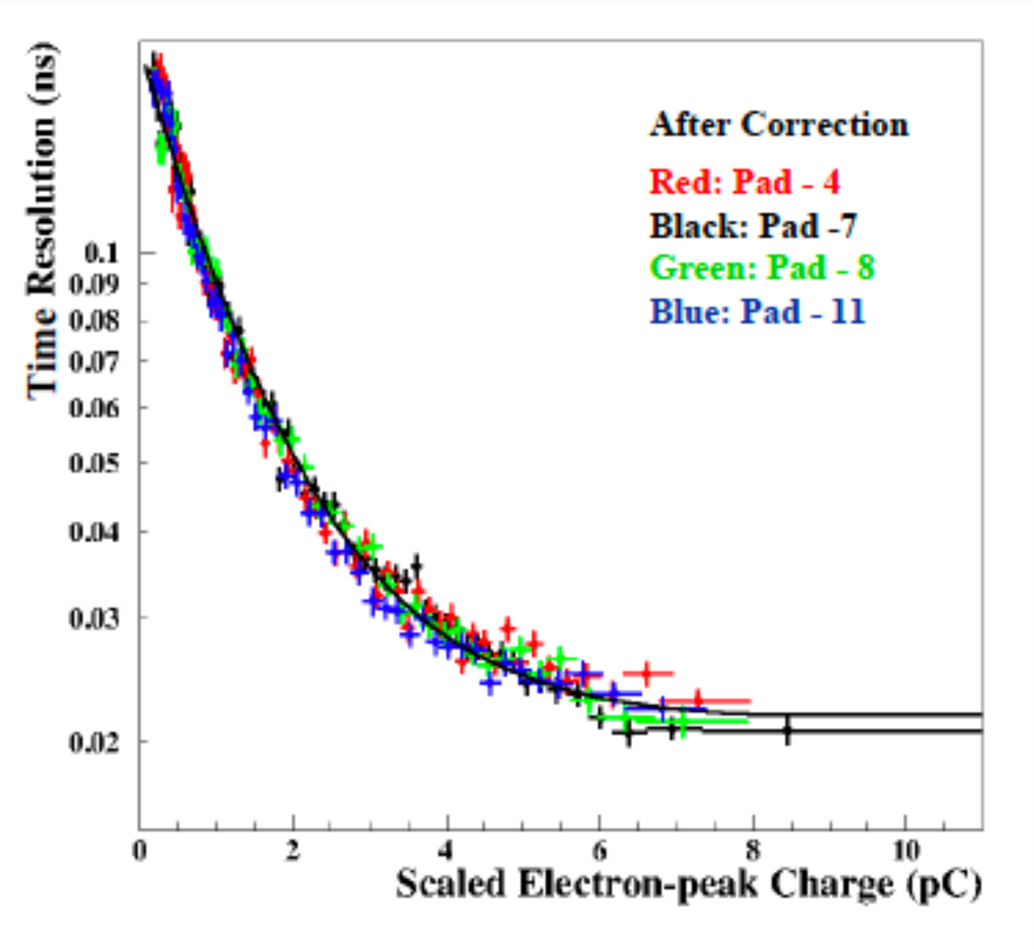
Flatness corrections

- For each peripheral pad parametrized the mean SAT values as a function of cylindical coordinates in the pad frame $S^k(r, \Theta)$
- SAT along the axis with $\Theta = 90^o$ are symmetric
- A correction factor introduced: $\Delta^k(r, \Theta) = S^k(r, \Theta) - S^k(r, \Theta = 90^o)$

$$T^k_{fcorr} = T^k_{SAT}(r, \Theta) - \Delta^k(r, \Theta)$$



MIPs passing within 2 mm all pads center → σ = 25.8 ± 0.6 ps
Method consistency confirmed by the Pull distribution

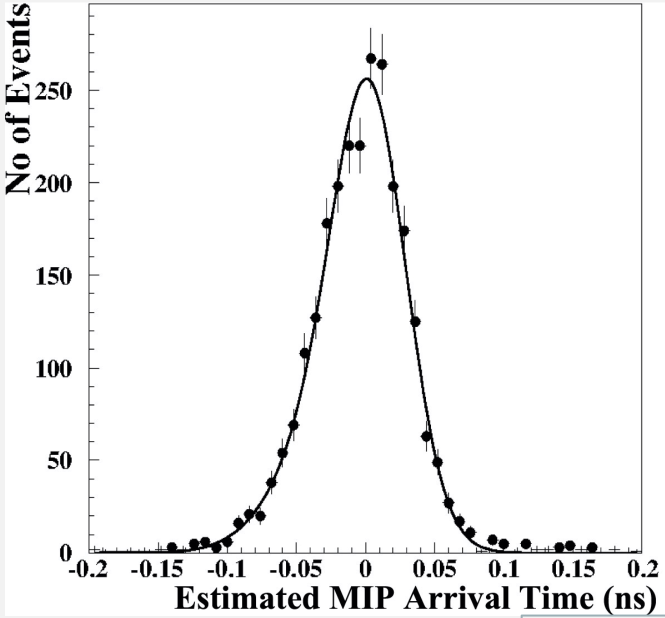


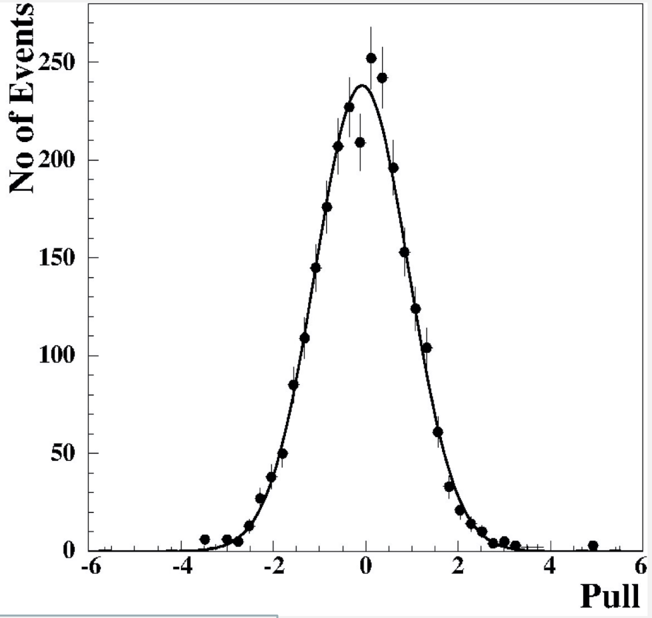
*Charges of peripheral pads scaled down due to the different gain
** The solid curves represent fits of the central pad data.

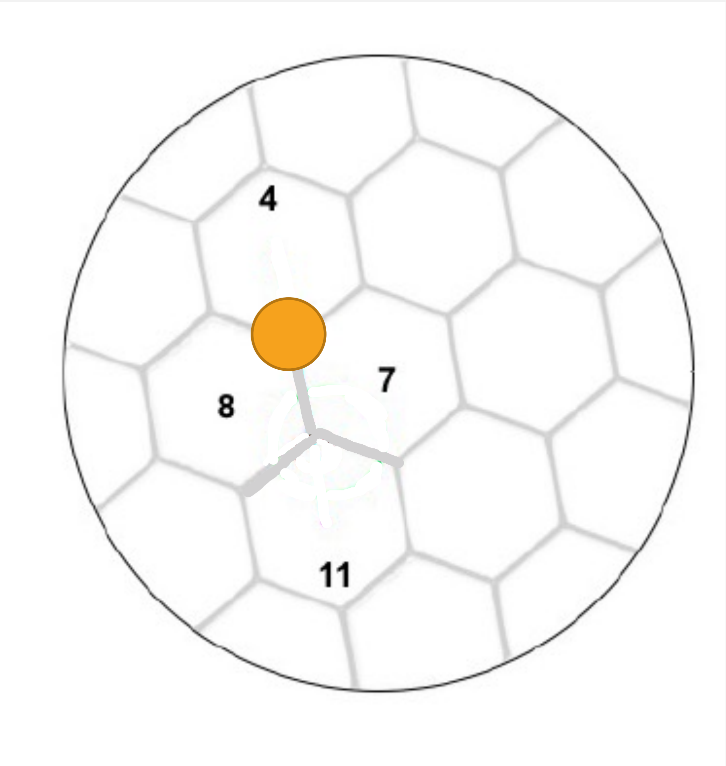
Combining timing information from several pads

The single pad measurements are used to estimate a combined MIP arrival time by the minimization of the χ^2 :

$$\chi^2 = \sum_{m=1,M} \frac{(T_{comb} - [T_{corr}^m - \tau(Q_e^m)])^2}{\sigma^2(Q_e^m)} \rightarrow \hat{T}_{comb} = \frac{\sum_{m=1,M} \frac{(T_{corr} - \tau(Q_e^m))}{\sigma^2(Q_e^m)}}{\sum_{m=1,M} \frac{1}{\sigma^2(Q_e^m)}}$$





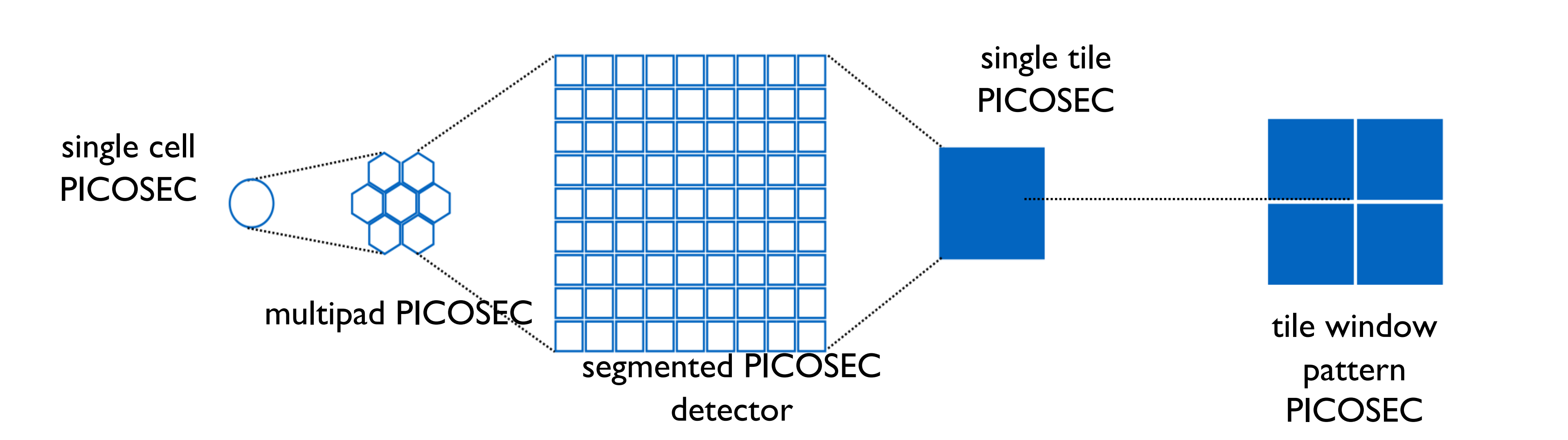


RMS = 32,2 ± 0.5 ps !

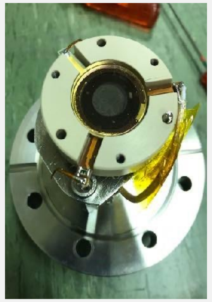
For a better resolution than 20 ps, a tollerance greater than 20 μm is essential !

THE CURRENT PROTOTYPE

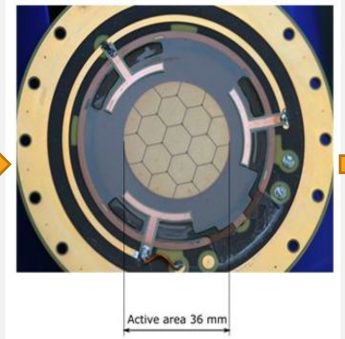
A modular design mult-pad PICOSEC - MicroMegas



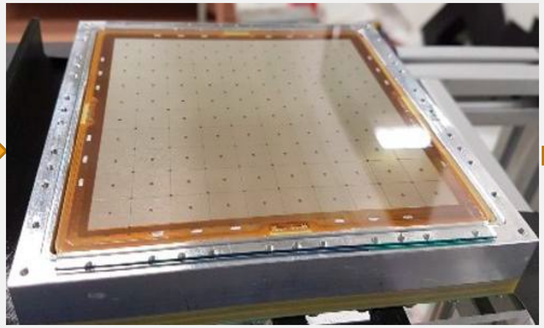
2016

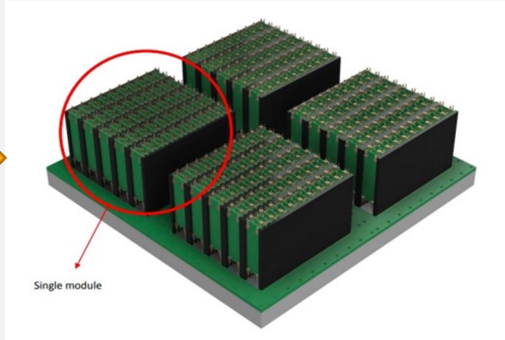


2018



2022



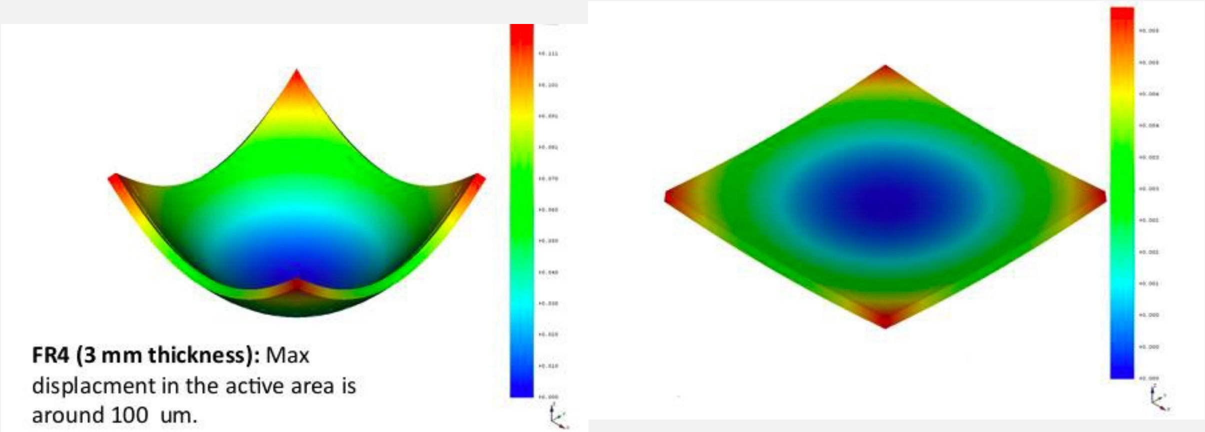


(Florian M. Brunbauer, EP R&D Seminar, May 3, 2021)

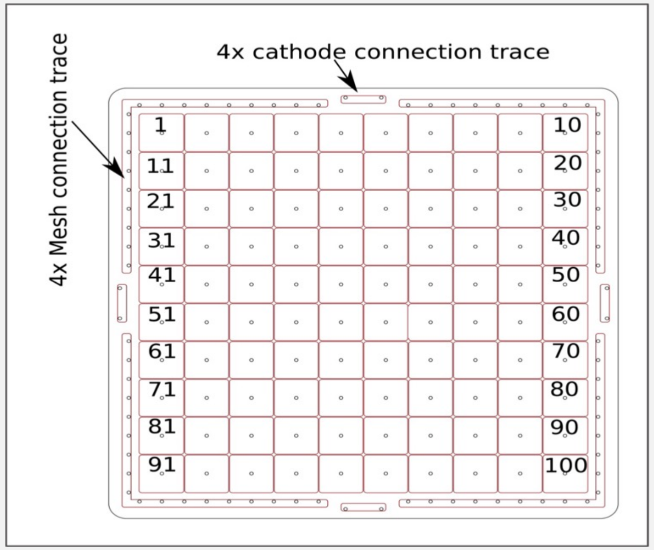
A modular design mult-pad PICOSEC - MicroMegas

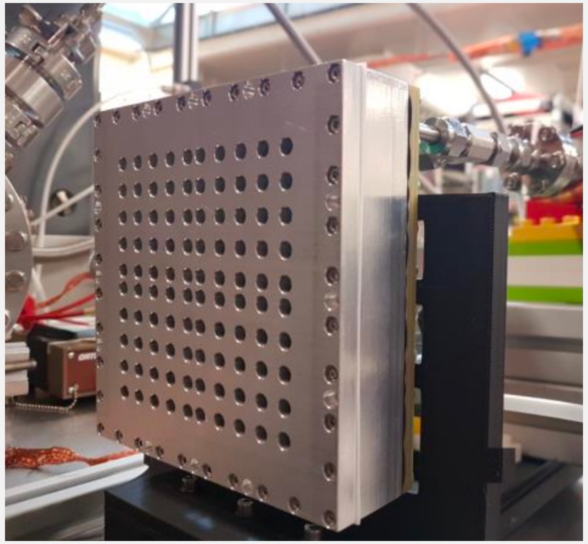
Re-design of the multipad detector:

- Larger surface (x10 times) and the number of channels (x5 times -100 channels-)
- Mosaic-type of 1 cm side pads
- Thick hybrid ceramic PCB for improved rigidity instead of just FR4
- PCB flatness within 10 μm over the active area



❌ FR4 (3mm thickness): 100 μm max displacement in the active area
✅ Ceramic (4 mm thickness): 4 μm max displacement in the active area
(Antonija Utrobicic, RD51 Collaboration Meeting, February 16, 2021)





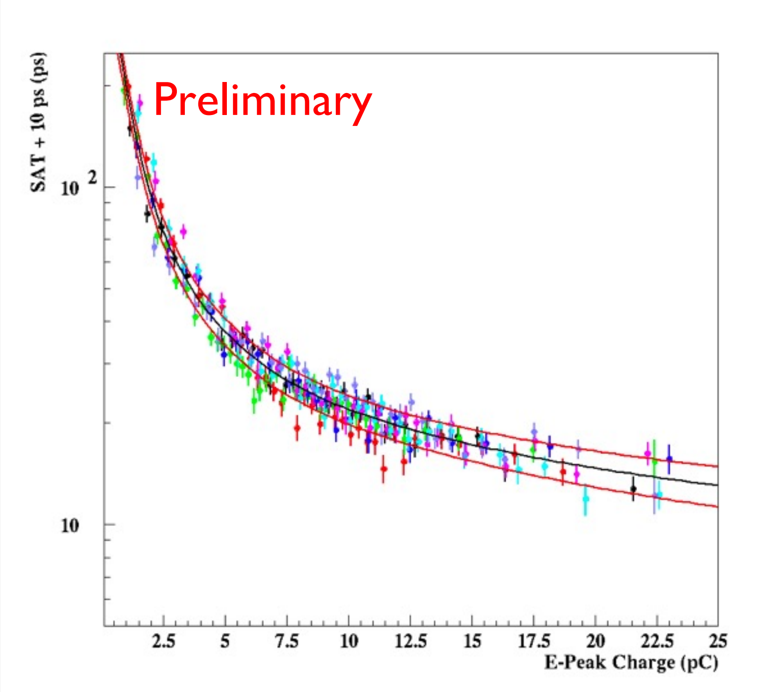
Performance of each pad and global description

- Mean SAT and resolution was calculated for bins of different Signal size (E-Peak charge)

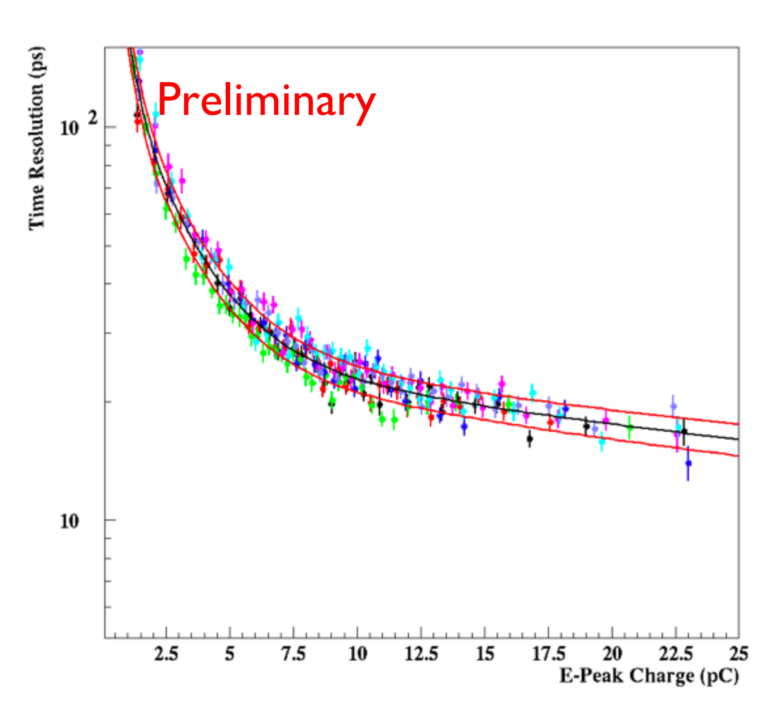
- A uniform drift field across the Pad surface should result to the same, <u>for all Pads</u>, dependence of mean SAT and Resolution on the E-Peak Charge

- All Pads presented the same dependence of mean SAT and Resolution on the E-peak charge
    - Both of these quantities can be described by the same "global" functions

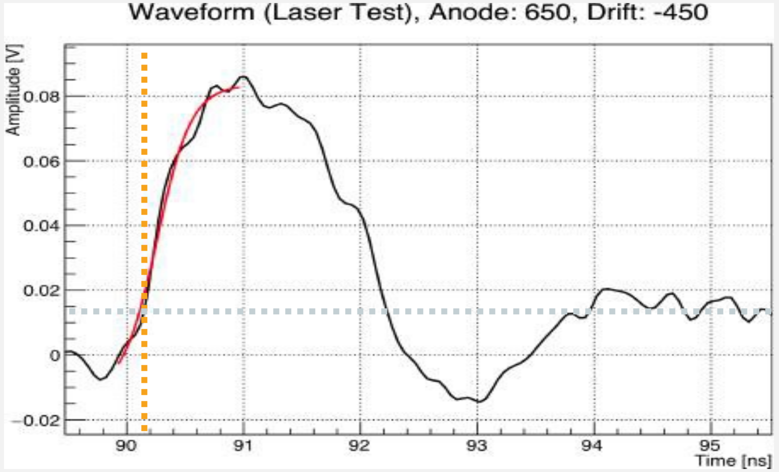
$$f(q) = e^{P_1+P_2\cdot q} + e^{P_3+P_4\cdot q} + e^{P_5+P_6\cdot q} + P_7$$

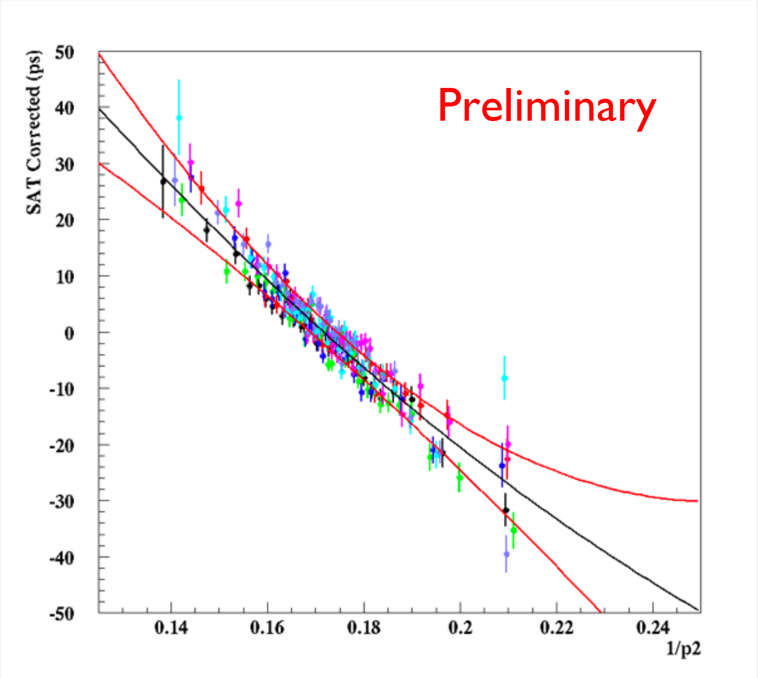


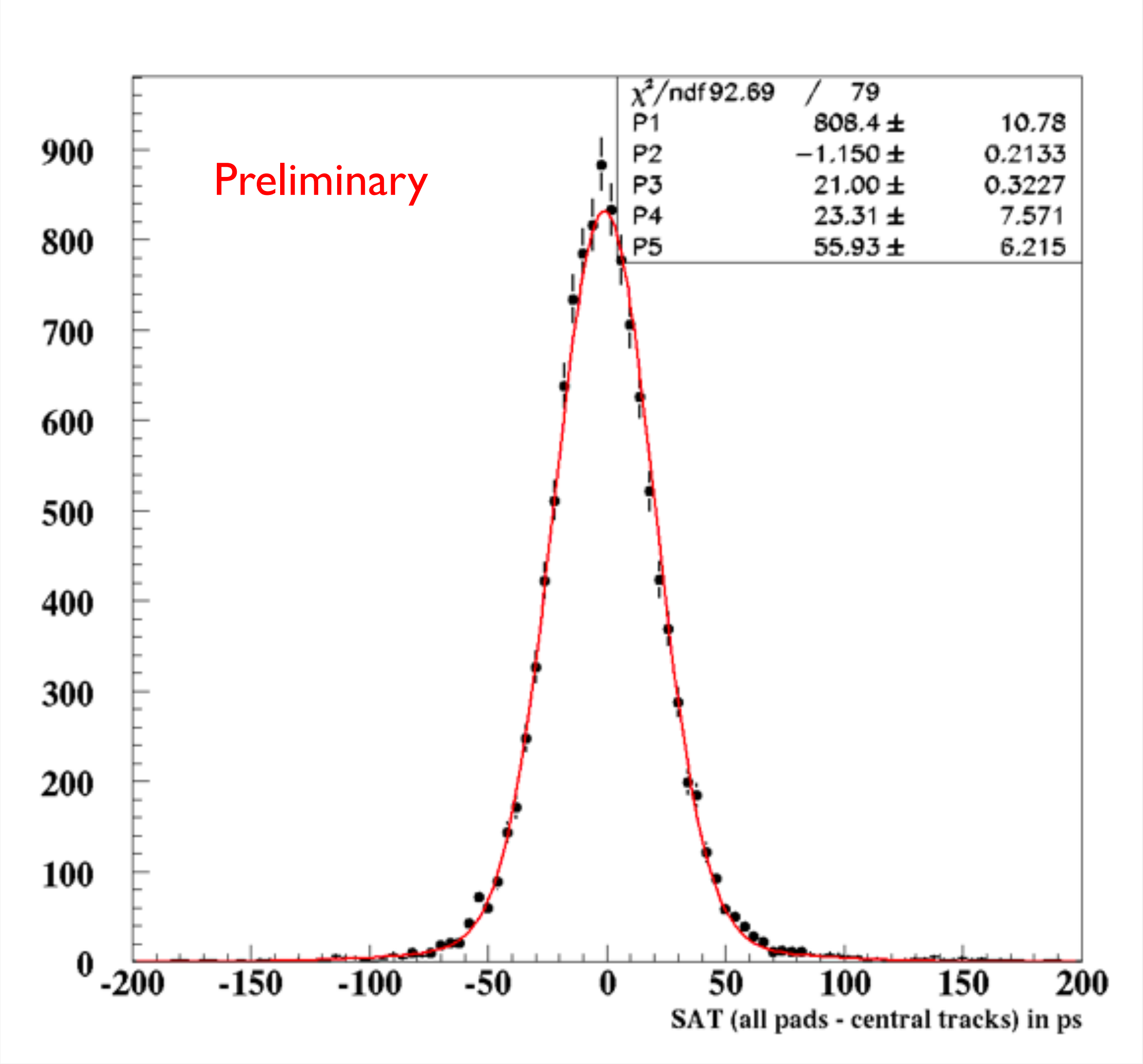
$$f(q) = e^{P_1+P_2\cdot q} + e^{P_3+P_4\cdot q} + P_5$$

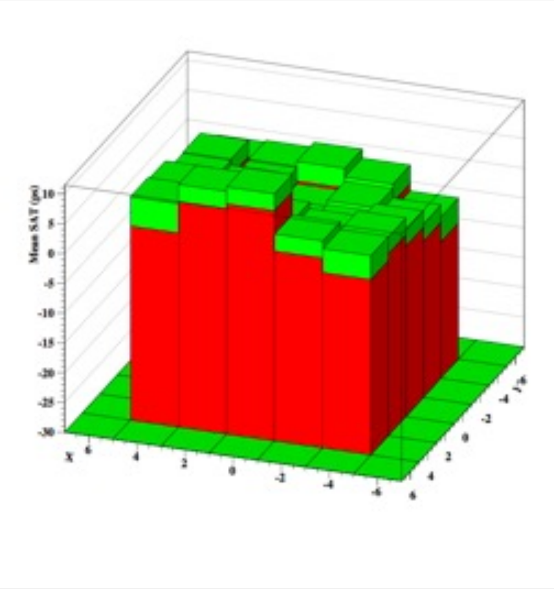


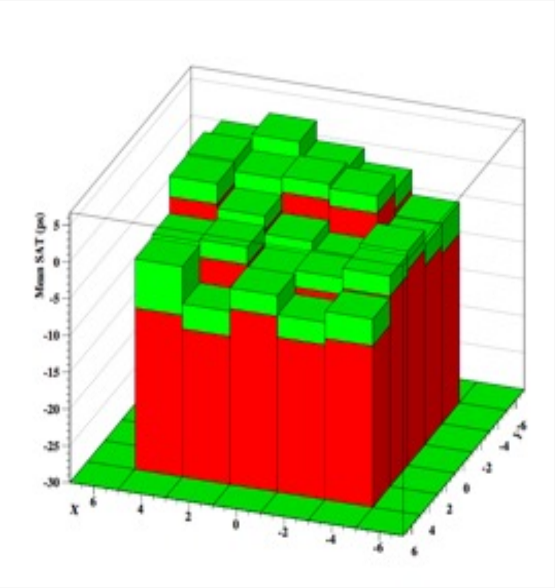
All pads together

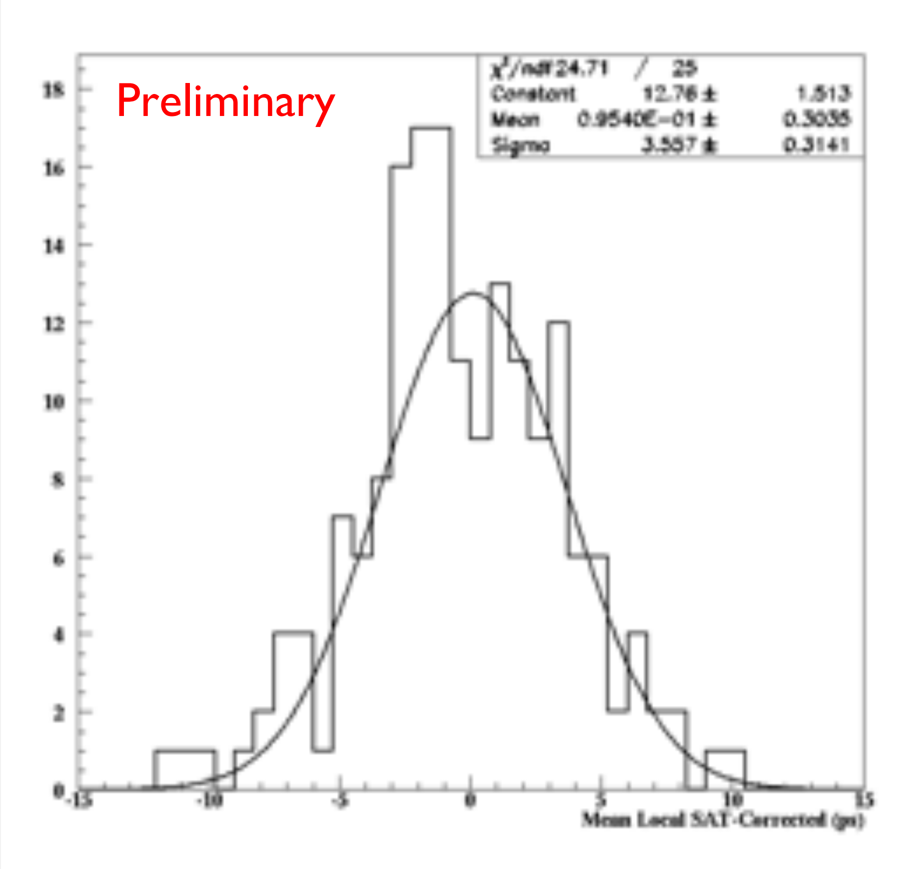


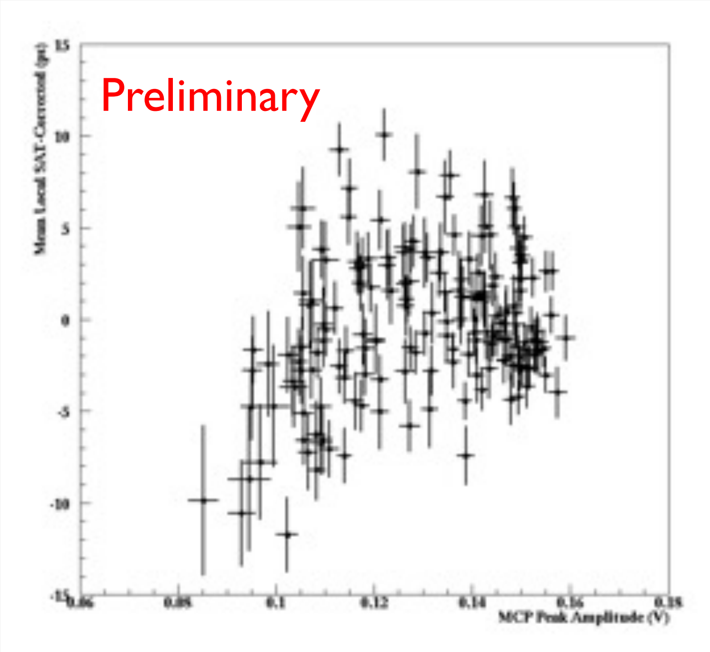


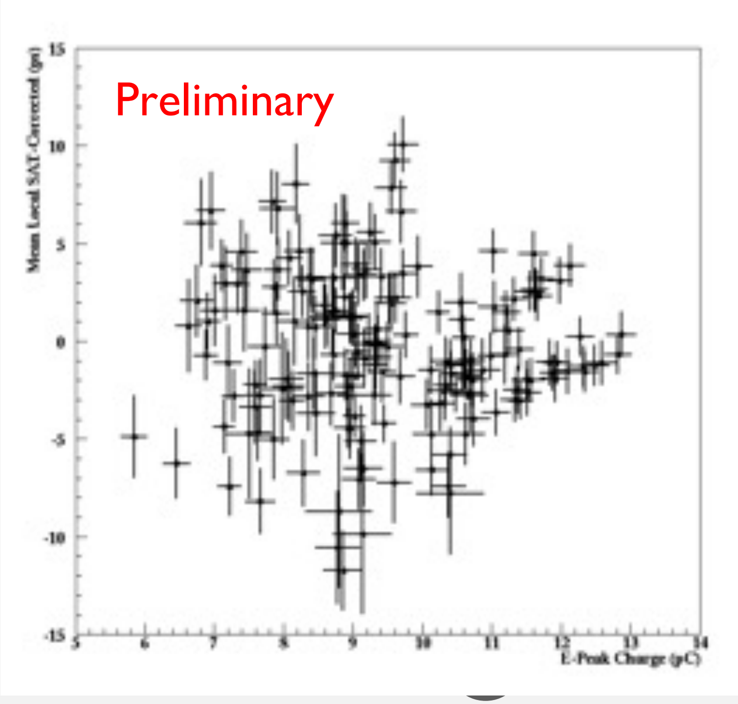










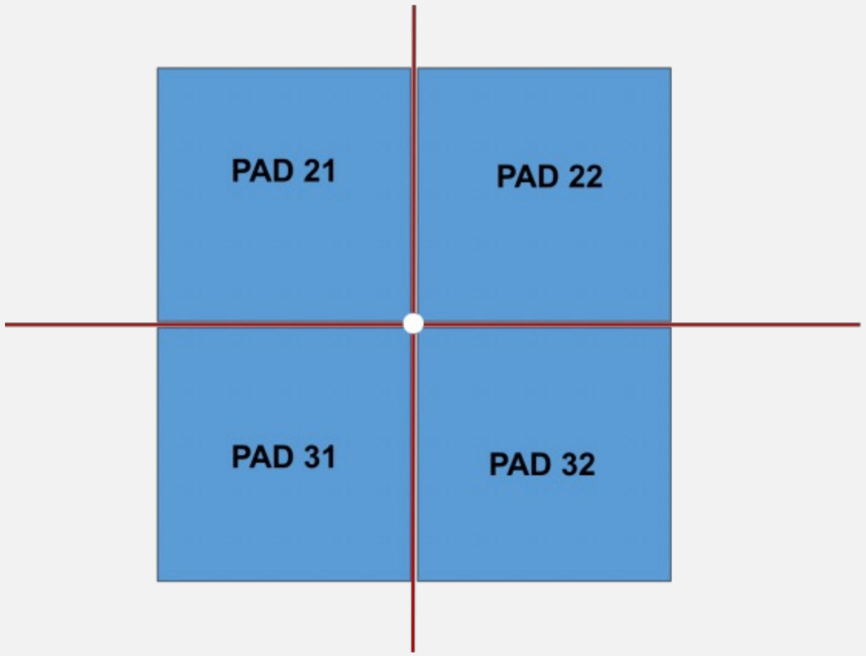


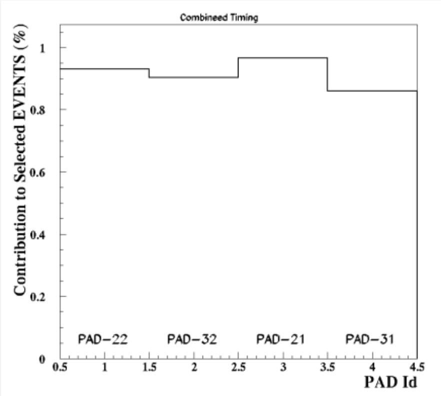
AUTH contribution in the development of the multipad PICOSEC-MicroMegas

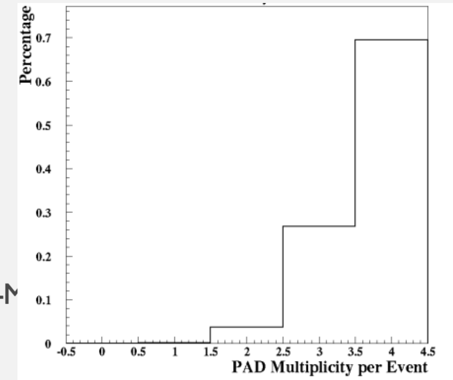
Signal sharing in the common corner

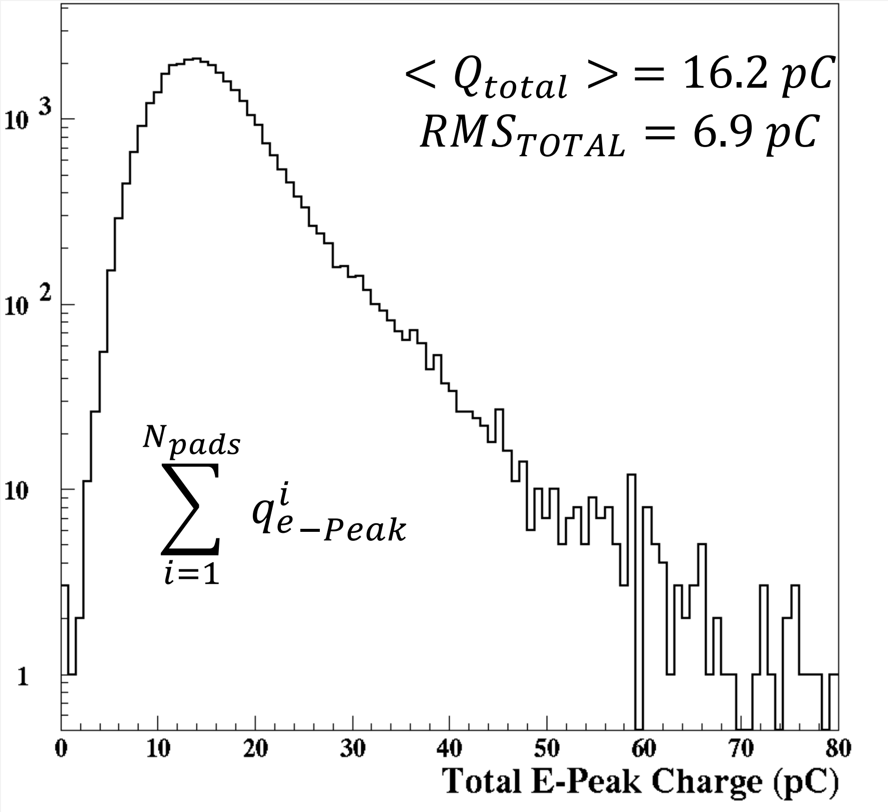
- The signal sharing was studied on the common corner for tracks passing within 3 mm of their common corner
- Only a fraction of the photoelectrons contribute to signal formation on each pad
- It was assumed that each of the pad signals carries an independent information on the MIP arrival time
- The total charge distribution at the common corner is simillar to the distributions on the center of the pads

→ The Cherenkov cone is shared almost equally between pads









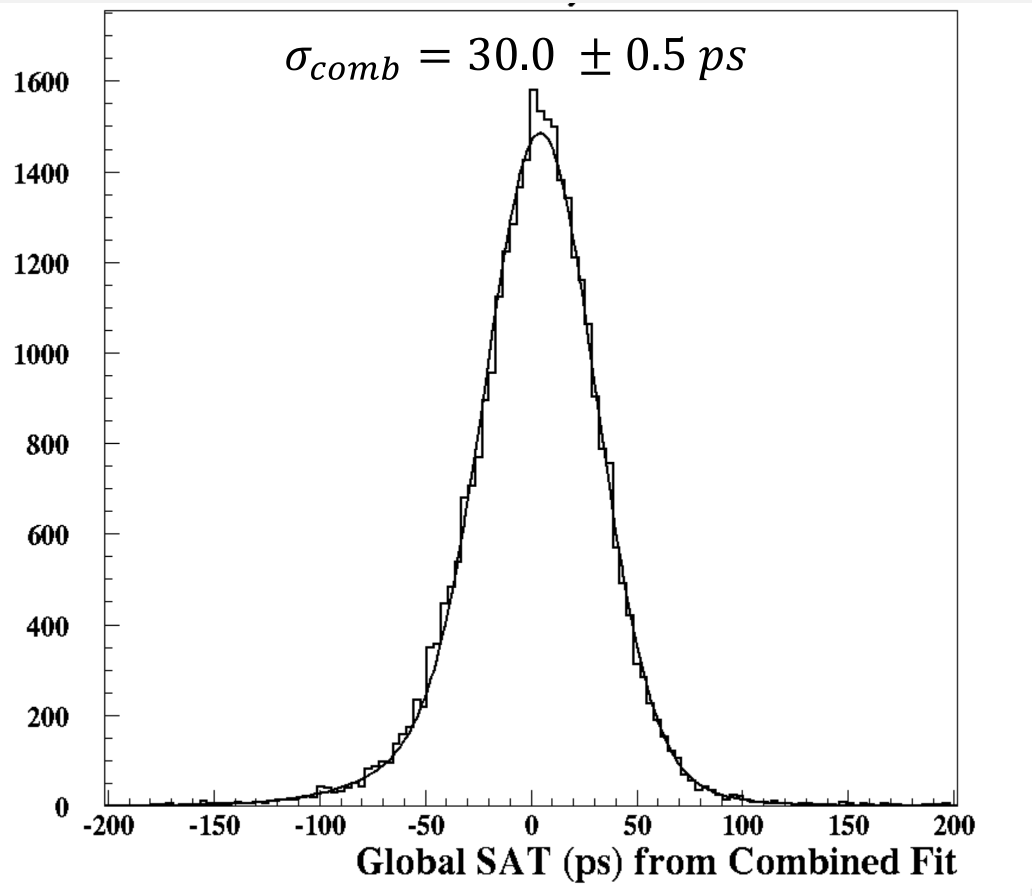
Signal sharing on the common corner

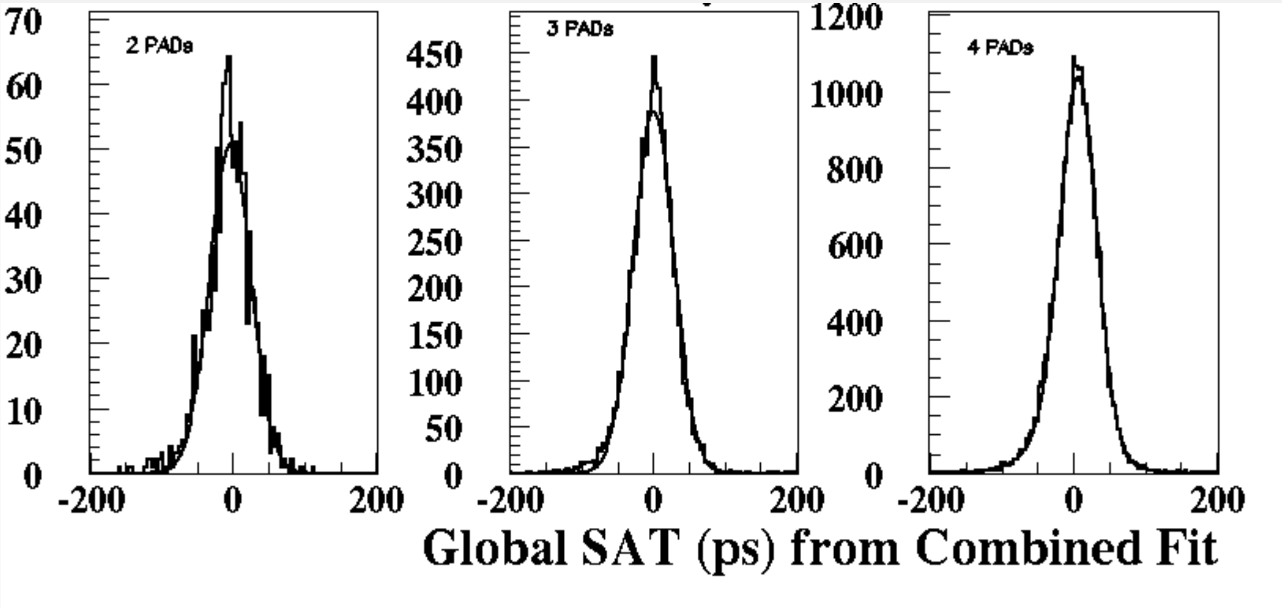
The estimated combined time from the single pads measurements is given as:

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

$W(q_i)$: The SAT vs q parameterization

$R(q_i)$: The resolution vs q parameterization

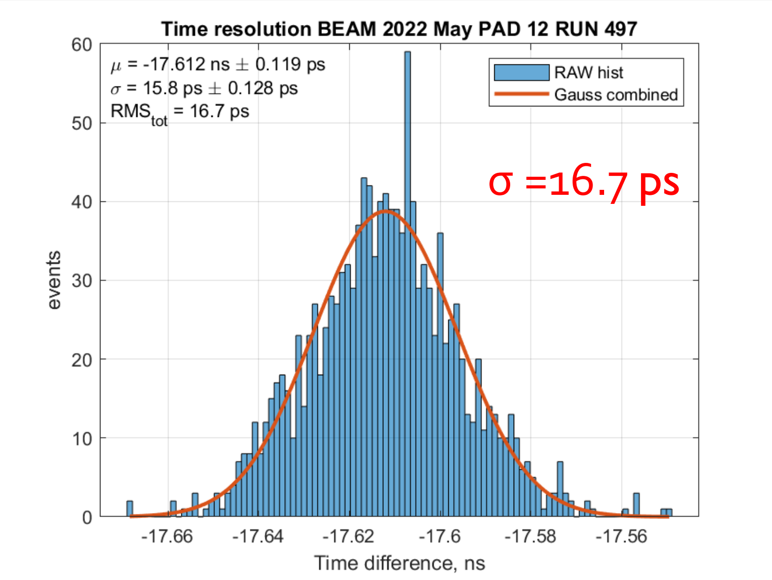




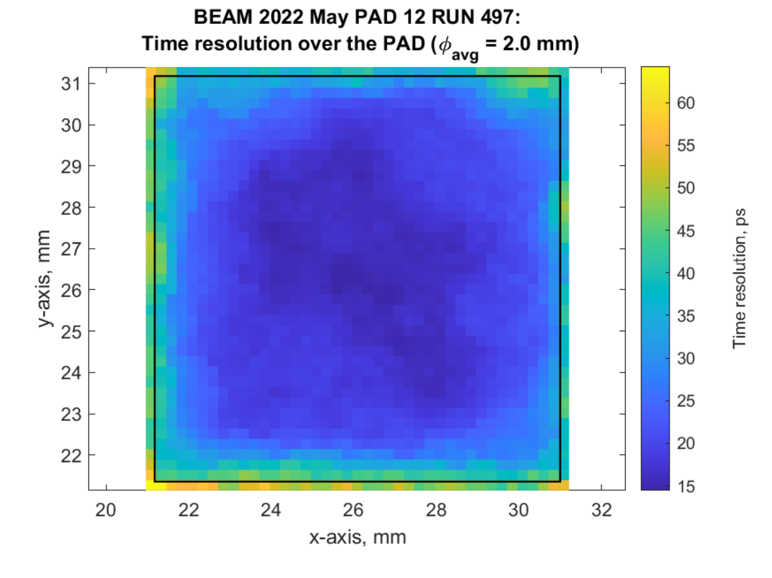
Thin gap PICOSEC

- PICOSEC detector with thinner drift gap devloped in CEA Sacalay
  - Single channel detector
  - Drift gap reduced from 220 μm to 180 μm
  - σ = 17.5 ps with V_c = 475V

- Thin drift gap multipad detector constructed
  - Drift gap: 180 μm
  - σ = down to 16.7 ps! with V_c = 465V

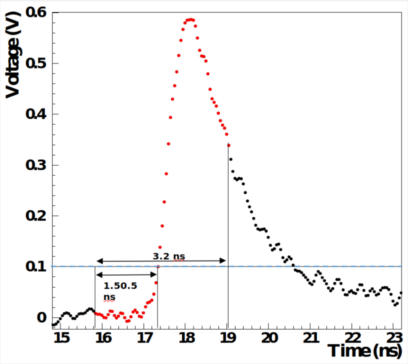


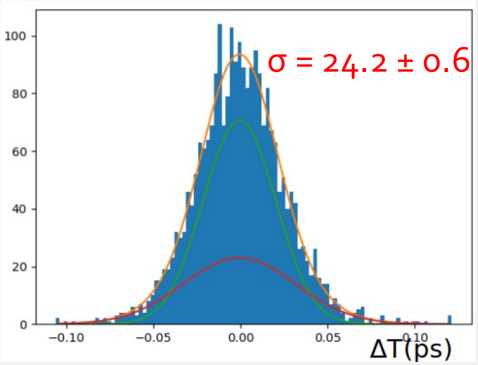
PAD	12	13	22	23	24
RMS (ps)	16.7	16.9	17.9	17.3	17



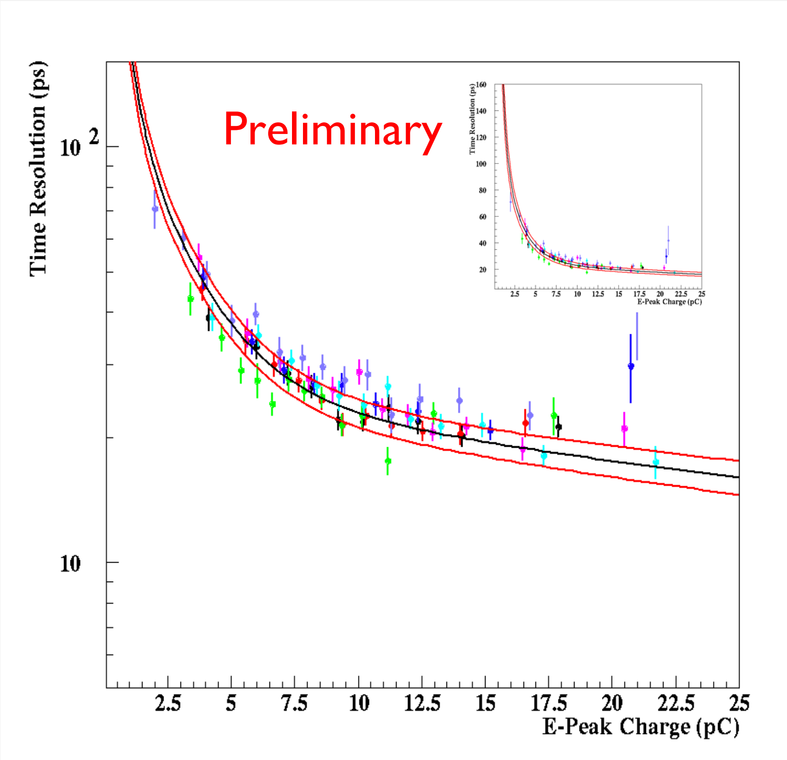
Antonija Utrobicic Advancements in a large area 100 channel PICOSEC Micromegas detector module, RD51 Collaboration Meeting

The neural network implementation

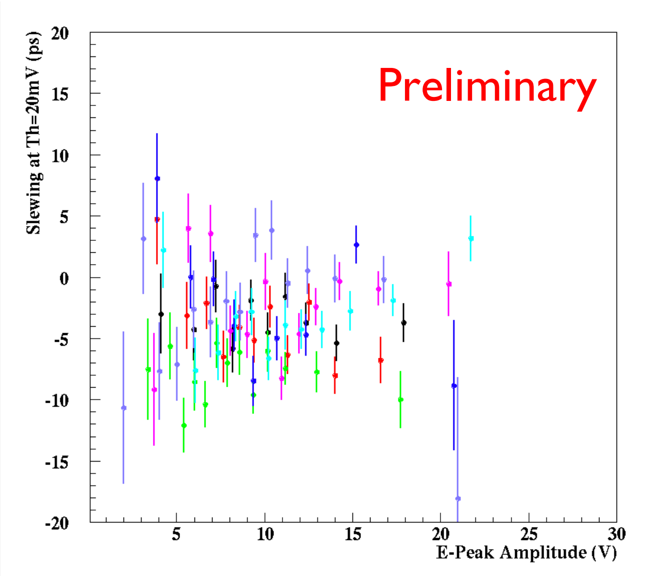




- Pulses with digitization of 200 ps
  - 80% training
  - 20% validation
  - The NN learns not only the timing, but also the relevant delays between pads



- NN slewing consistent to zero ±3 ps
- NN estimated resolution (points) vs our analysis (curves for different pads)
  - Similar results



Conclusions

- The results from the first multipad was not perfect but promising
- Changes on the design of the second multipad was effective
  - Time resolution scans across several pads and inside each pad confirmrd that
  - A global parametrization of the several pads is also an encouraging
- Timing resolution of 30 ps for sharing signals is great
- The thin gap variants can boost the detector to even better results
- The NN reolution calculation is similar to the typical analysis
  - Very promising for fast online signal analysis

THANK YOU FOR YOUR ATTENTION!

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