DE LA RECHERCHE À L'INDUSTRIE

PICOSEC
Micromegas

université
PARIS-SACLAY

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PHENIICS FEST 2023

Thursday, 11th May 2023

R&D for Picosecond Timing with Novel Micromegas Detectors

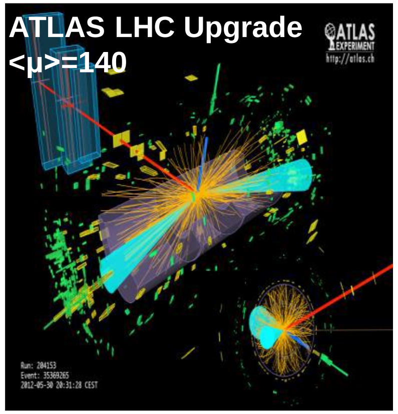
Alexandra Kallitsopoulou
PhD Student
CEA, IRFU, Université Paris – Saclay

Outline

What is our motivation?

Timing with a few 10's of Picosecond

- **High Luminosity LHC**:
- On average 140 p-p interactions per bunch crossing
- Necessary timing resolution ~20ps
- Clean reconstruction of the events
- Reduction of mixing different events due to pile-up
- 3D tracking is not enough for association with the correct vertex
- Timing can be an extra parameter



PID techniques: Alternatives to RICH methods, J. Vavra, accepted in NIMA 876, 2017, https://dx.doi.org/10.1016/j.nima.2017.02.075

BUT

- **Extra detector requirements:**
- Large area coverage
- Resistance to aging effects
- Multi-pad readout tracking

Large area coverage

- **Solid State OR Gaseous Detectors**

Solid state detectors

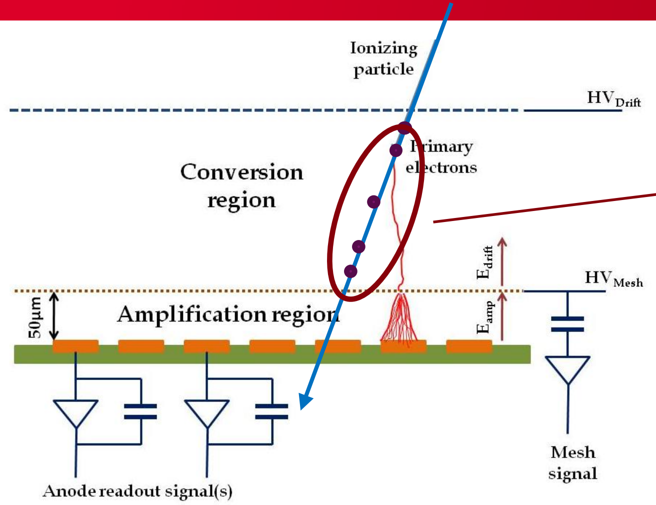
- Avalanche PhotoDiodes: (σ_t ~ 20 ps for single cells)
- Low Gain Avalanche Diodes (σ_t ~ 30 ps)
- HV/HR CMOS (σ_t ~ 80 ps)

Gaseous detectors

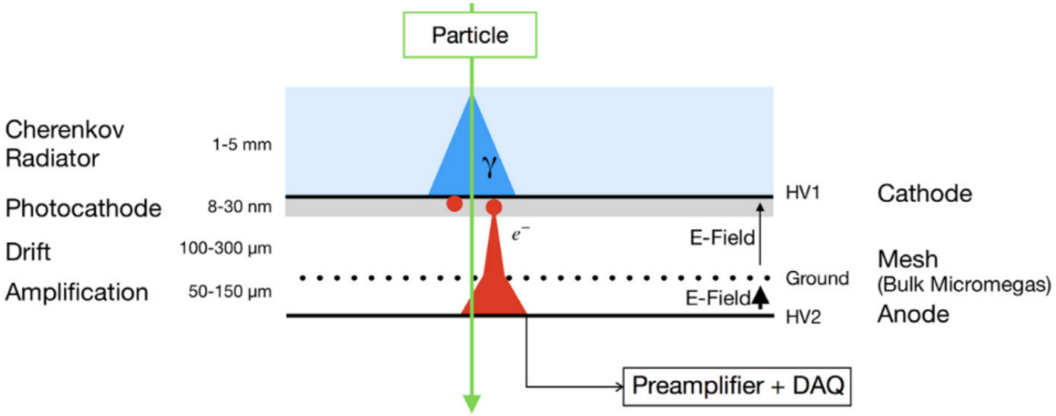
- Resistive Plate Chambers (RPCs): (σ_t ~ 30 ps)
- Micro-Pattern Gaseous Detectors (σ_t ~ 1 ns)

Development of new Instrumentation Technology

Get to know with PICOSEC MM Detector



Y. Giomataris, P. Rebourgeard, J.P. Robert and G. Charpak, *"Micromegas: A high-granularity position sensitive gaseous detector for high particle-flux environments",* Nuc. Instrum. Meth. A 376 (1996) 29



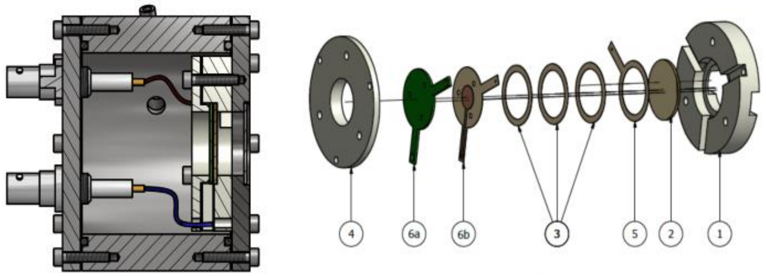
J.Bortfeldt, et al., *"PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector",* https://doi.org/10.1016/j.nima.2018.04.033

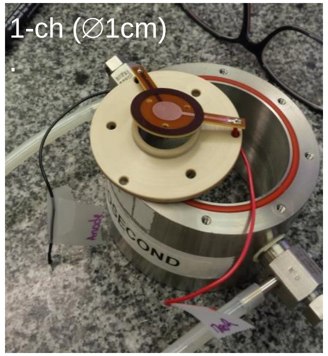
- Limitations of the Micromegas Timing Potential
  - Stochastic nature of ionization
  - Randomness of last ionization
  - Time jitter of a few ns
- The PICOSEC Concept
  - Timing with tens of picosecond precision
- Modifications in MM Geometry
  - Smaller Drift Gap (up to 200µm)
  - Elimination of the stochastic nature of ionization
  - Higher applied Drift Voltage ⟶ Pre-avalanche
- Additional Components in MM geometry
  - Cherenkov radiator +
  - Photocathode (CsI, B4C, Diamond, DLC)

  Prompt photoelectrons

Detector Prototype Evolution

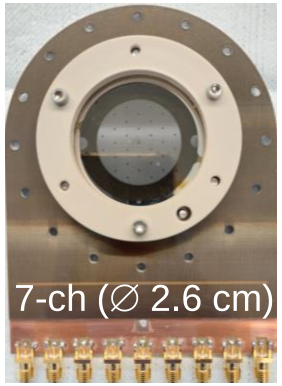
- Single Pad Prototypes (ø 1cm)
  - Proof of concept
  - Resistive and non-resistive prototypes

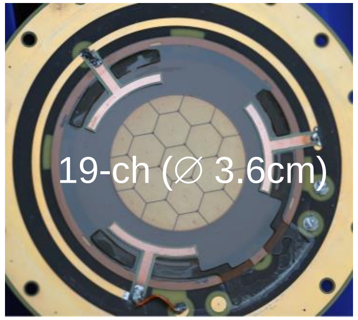


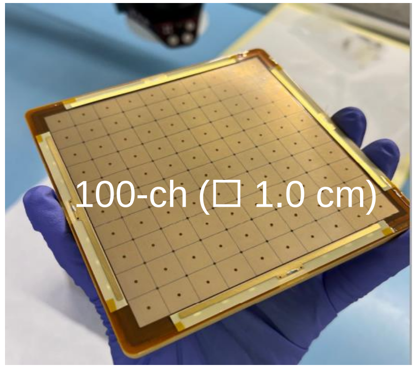


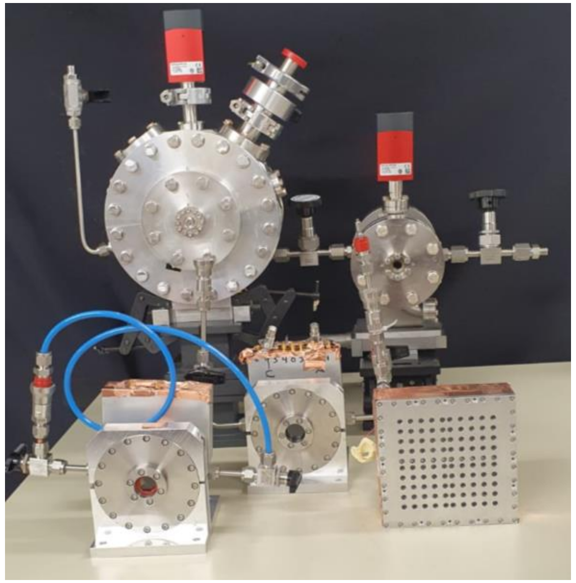
- Photocathodes & Crystals:
  - MgF2 / Sapphire crystal +
  - Metallic (Cr, Al)
  - Metallic substrate + CsI
  - Metallic substrate + polycrystalline diamond
  - DLC
  - B4C, Metallic substrate +B4C
- Gas : 80% Ne – 10% CF_4-10%C_2H_6

- Multi-Pad Prototypes
  - Hexagonal pads ø 1cm
  - Resistive and non resistive prototypes





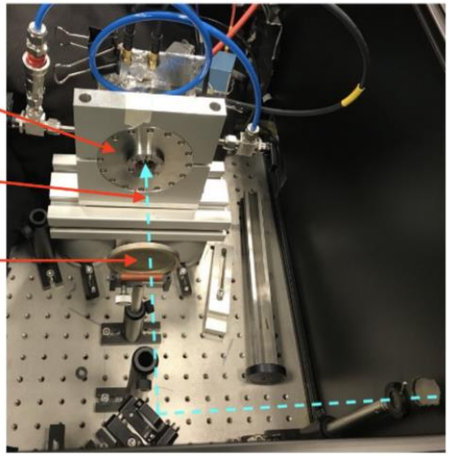


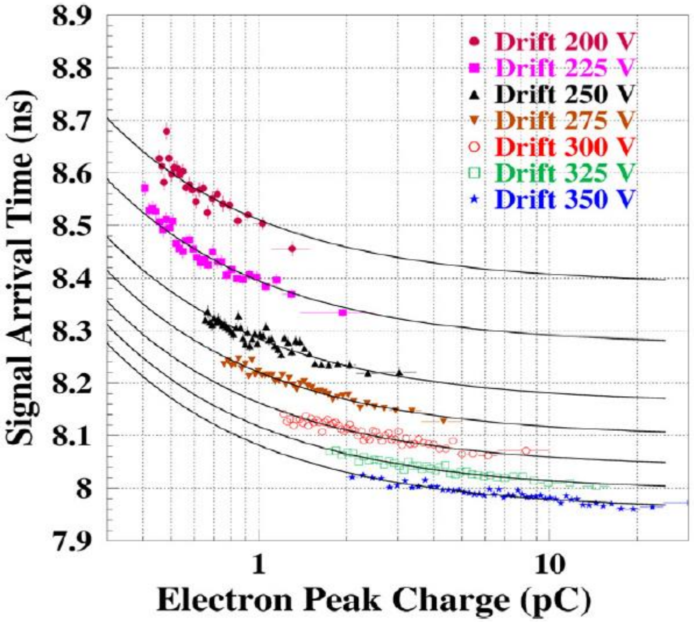


Detector Testing

Detector Testing

- Pulsed 120fs UV Laser (IRAMIS/CEA)
  - Detector response on controllable number of photoelectrons
  - Timing single photoelectrons
  - Understanding the physics dynamics on the detector
  - Independent measurements of the photocathode material



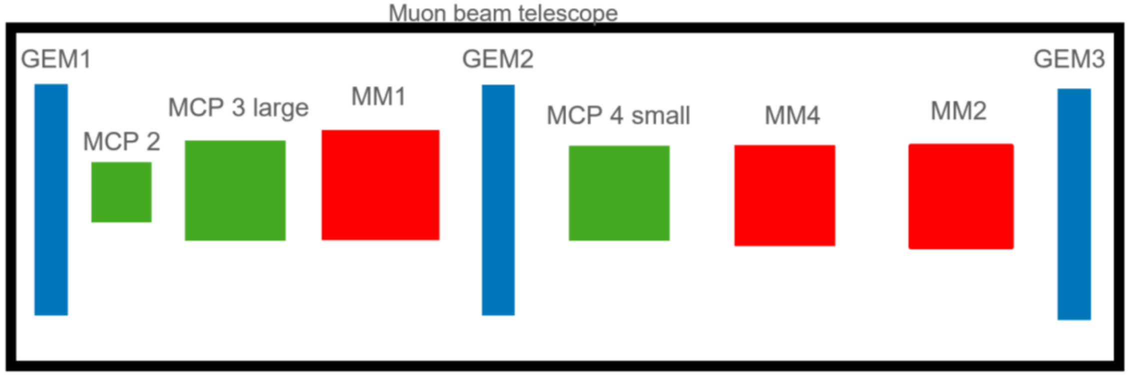


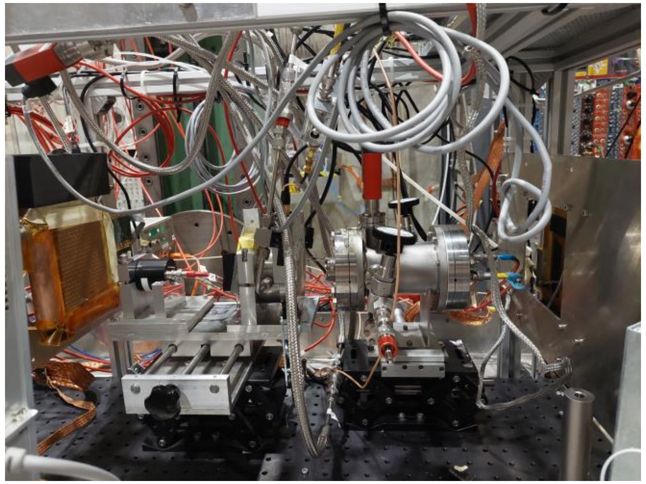
J.Borteldt, et al. "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector", Nuc. Instrum. Meth. A (2021)https://doi.org/10.1016/j.nima.2018.04.033

Timing resolution improves with **higher drift field** & **smaller gap**(**<50ps for 120µm** for single pe)

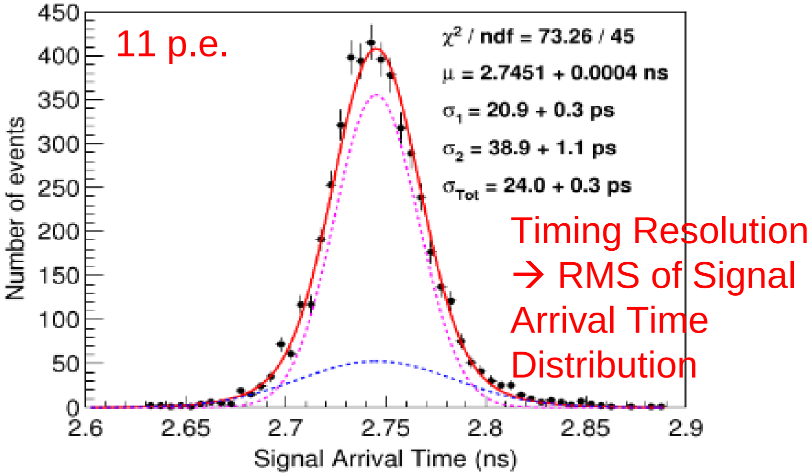
Detector Testing – Particle Beams

- Particle Beams @ CERN SPS H4 Beamline
  - Muons 80-150 GeV
  - Photocathode studies (robustness and efficiency)





- The Setup
  - Use GEMs for tracking
  - Use MCP PMTs as timing reference devices and for triggering
  - Electronics: CIVIDEC preamp. / Customade electronics + LeCroy scopes



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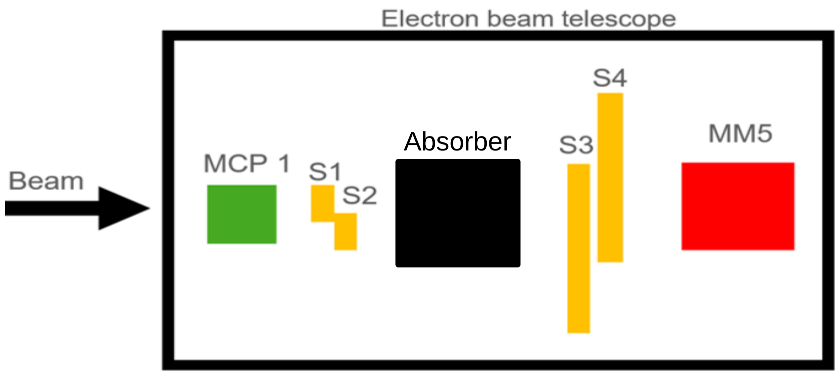
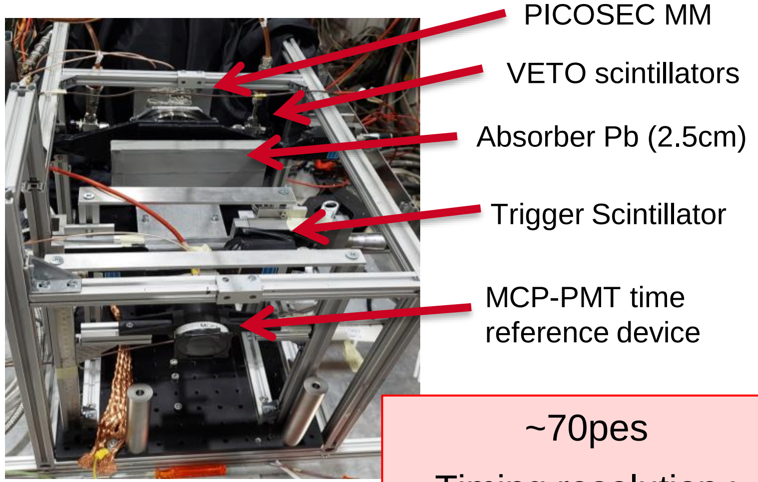
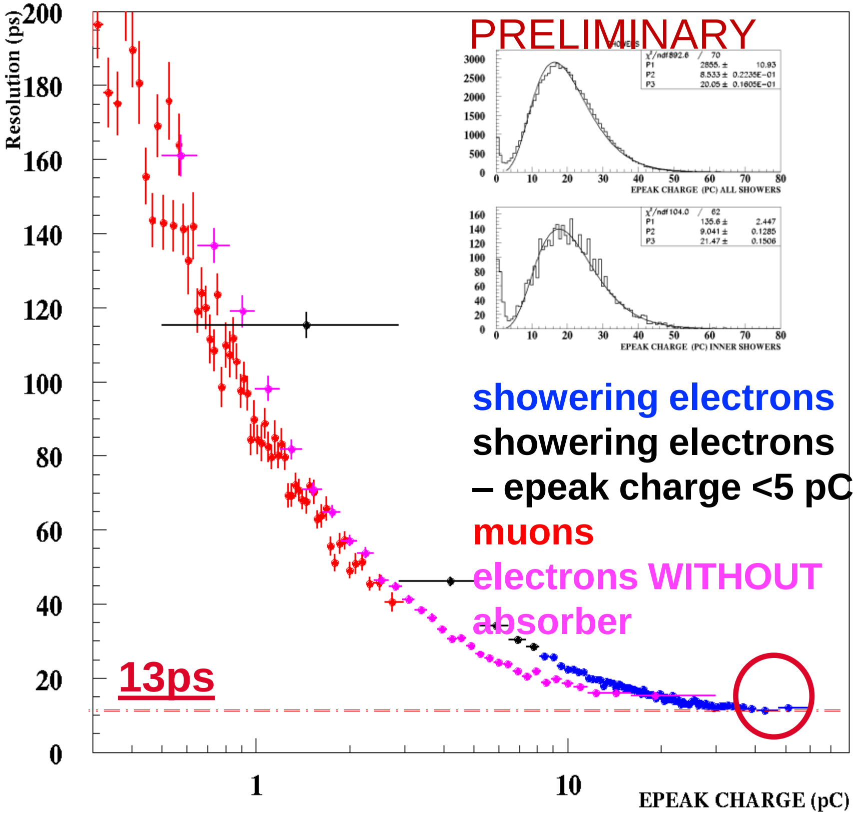
Detector Testing – Particle Beams

- Particle Beams @ CERN SPS H4 Beamline
  - Electrons 30-80 GeV







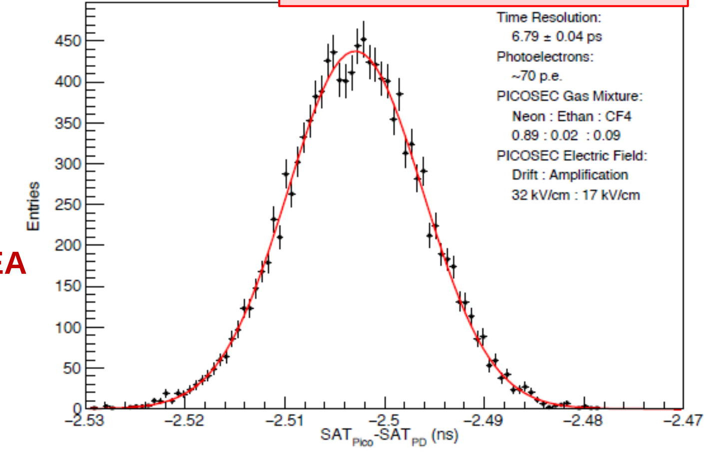
~70pes

Timing resolution :

6.8±0.3 ps

- Application Scenario
  - Embed in Electromagnetic Calorimeter
  - Identify particle showers

First Indications from laser test measurements @ IRAMIS /CEA



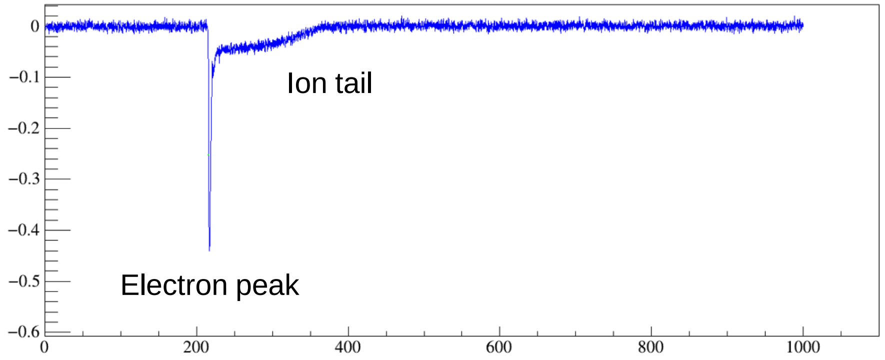
Signal Processing for Timing

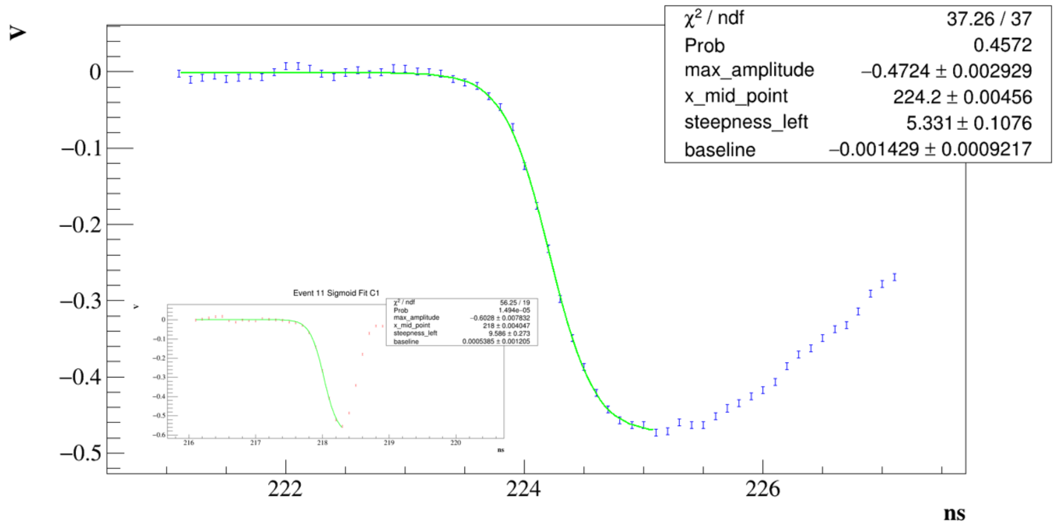
Standard Waveform Analysis

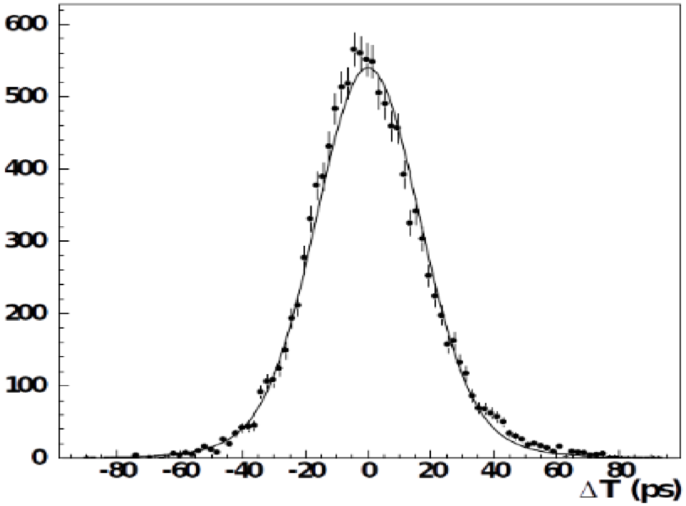
- The Standard CDF Technique
  - Adjust a curve to the experimental data
    - Fitting the leading edge of the waveform with a logistic function

$$f(x; p_0, p_1, p_2, p_3) = V(t) = p_3 + \frac{p_0}{1+e^{-(x-p_1)p_2}}$$

  - Timing at 20% of peak amplitude for all signals (SAT – Signal Arrival Time)
  - Subtract the PICOSEC signal from the reference signal
  - Create calibration curves
  - Correct for dynamical errors
  - Timing resotution ~ RMS of the SAT distribution

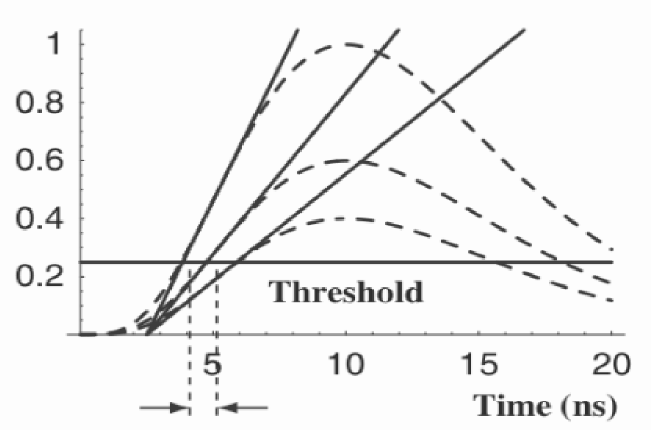




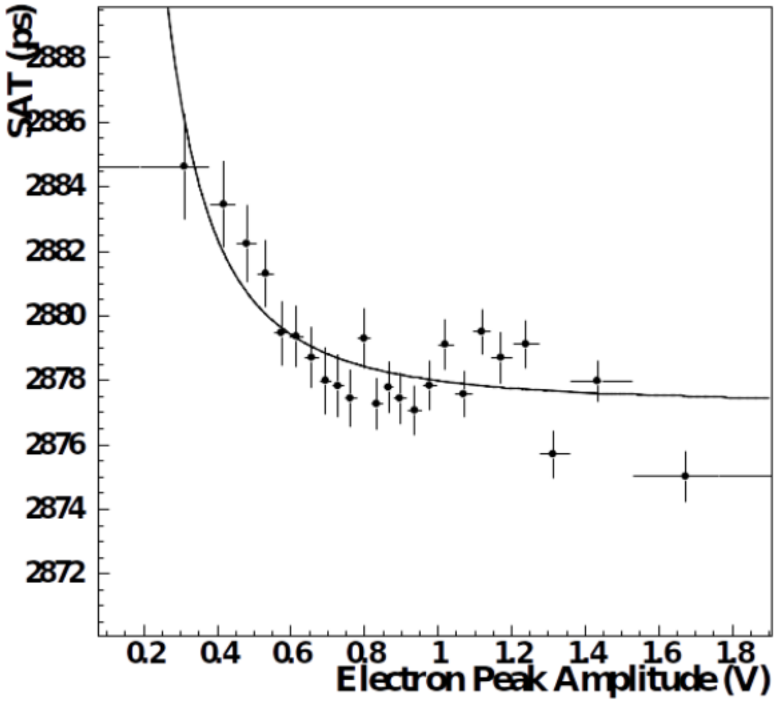


Correcting for Dynamical Errors

- Constant Threshold Timing suffers from Time Walk Effect
  - Realistic case
  - Higher pulses arrive earlier
  - Dependence between timing and amplitude size
  - The effect can be corrected by the offline analysis



Walter Blum, Werner Riegler, and Luigi Rolandi. Particle Detection with Drift Chambers. Springer-Verlag Berlin Heidelberg, 2008



- In principle, CFD method DOES NOT suffer from time walk effects
  - However we observe dependence on signal amplitude
    - Its origin has nothing to do with offline analysis procedure BUT
    - Results from the microscopic behavior of the avalanche
      - Photoelectrons drift with different velocities than the total avalanche
- Calibration curve $g(x; a, b, w) = a + \frac{b}{w}$

$$\text{Corrected } SAT = SAT - \frac{a}{(Pulse\ Amplitude)^b} + c$$

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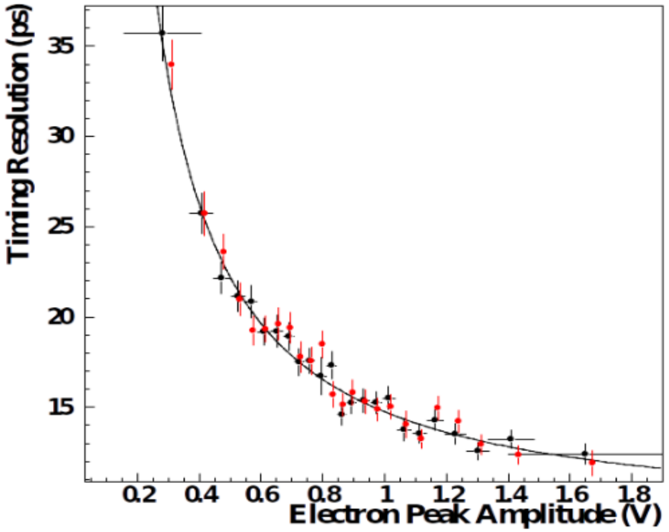
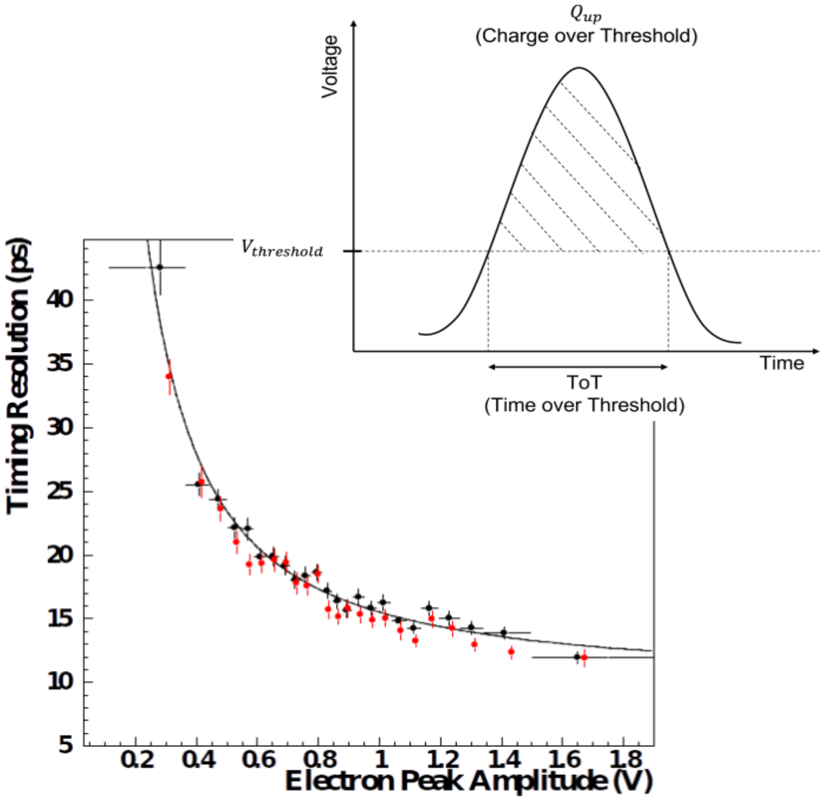
Alternative Timing Techniques

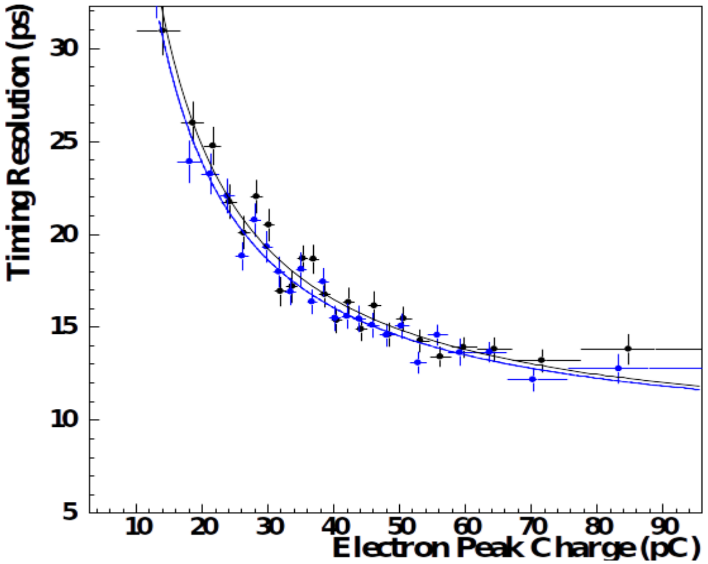
- Constant Threshold
  - SAT defined @ 100mV
  - Parameterization using peak amplitude



- Charge above Threshold
  - Constant threshold+ Using multiple higher thresholds
  - Alternative method of peak size estimation

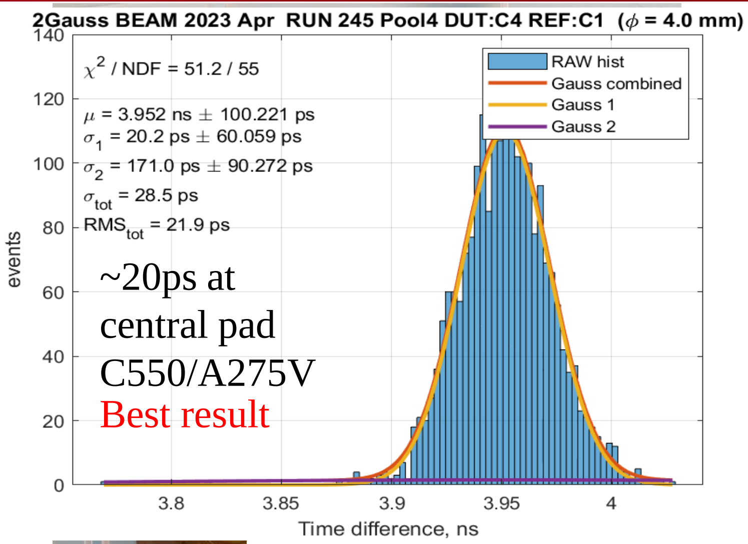


- Artificial Neural Networks
  - SAT defined @ 100mV
  - Using the digitized wavefor to feed an ANN

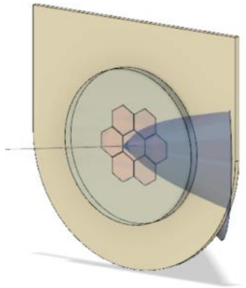


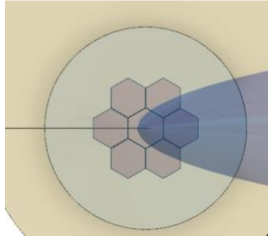
Measurements of Interest and Highlight Preliminary Results

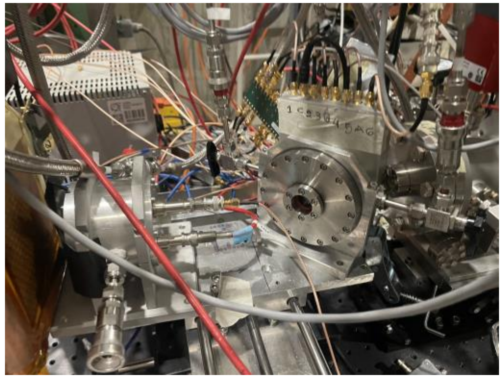
- Robust & Efficient Prototypes ~ put a photo of different detectors tested
  - Different resistivity values (10 MO, 200kO)
  - Different resistivity layer architecture (capacitive sharing)
  - Voltage scans → Stable operation voltage at a high rate
  - Timing runs on individual pads
  - Long scan for uniformity map on amplitude and timing
  - Signal Sharing
  - Tilted detector relative to beam direction in 45 and 35 degrees

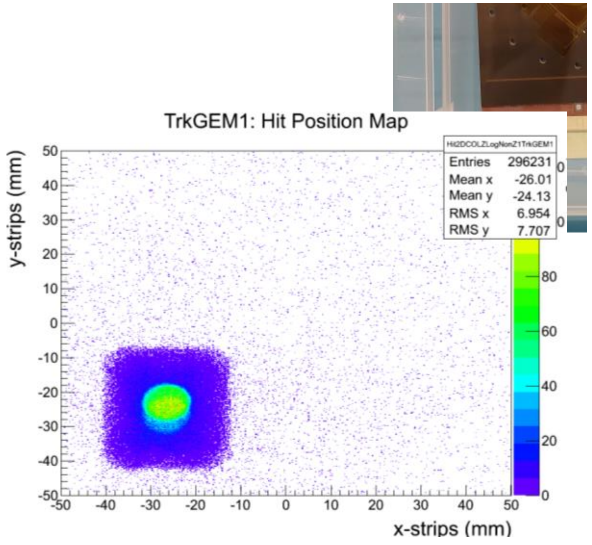


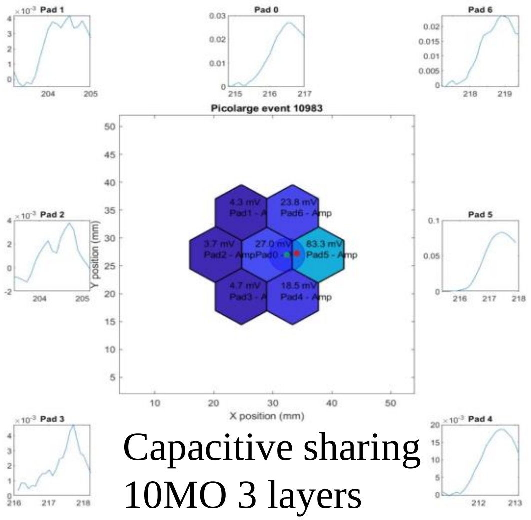
~20ps at central pad C550/A275V
Best result











Capacitive sharing
10MO 3 layers

Concluding Remarks

Ongoing Development

Towards an engineered PICOSEC MM module :
multiple directions in detector development

- **Scalable MM Detector (IRFU/CERN)**
  - 10x10cm2
  - Prove the performance in a multichannel setup
  - Flatness (Planarity < 10μm)

- **Pixelated MM Detector (IJCLab/IRFU/CERN)**
  - Development of front-end & back-end readout electronics for the prototype (~100 channels)

- **Robustness & Efficiency (LIST/USTC/CERN)**
  - Research on various photocathode materials (Replace CsI with B4C, DLC,…)
  - Resistive prototypes

- **Physics Studies (LP2I Bordeaux/ IRFU/ Auth)**
  - T0 tagger and/or embedded in a calorimeter
  - Muon monitoring
  - As a photodetector for T0 tagging at the neutrino detector

In the end it’s all a matter of timing

Thank you!

PICOSEC Micromegas

The RD51 “PICOSEC” Collaboration

universite PARIS-SACLAY

AUTH (Greece) K. Kordas, C. Lampoudis[1], I. Maniatis[6], I. Manthos[5], K. Paraschou, D. Sampsonidis, A. Tsiamis[1], S. E. Tzamarias

CEA - IRFU, LIST, LIDYL (France) S. Aune, D. Desforge, I. Giomataris, T. Gustavsson, F.J. Iguaz, A. Kallitsopoulou, M. Kebbiri, P. Legou, T. Papaevangelou, M. Pomorski, E. Scorsonne, L. Sohl

CERN (Switzerland) J. Bortfeldt[2], F. Brunbauer, C. David, M. Lupberger[2], M. Lisowska, H. Müller[3], E. Oliveri, F. Resnati, L. Ropelewski, L. Scharenberg, T. Schneider, A. Utrobicic, M. van Stenis, R. Veenhof[4], S. White

HIP (Finland) F. García

LIP (Portugal) M. Gallinaro

NCSR Demokritos, (Greece) G. Fanourakis

NTUA (Greece) Y. Tsipolitis

USTC (Hefei, China) J. Liu, B. Qi, X. Wang, Z. Zhang, Y. Zhou

(1) Also Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki 57001, Greece.

(2) Now at University of Bonn, D-53115 Bonn, Germany.

(3) Also University of Bonn, D-53115 Bonn, Germany

(4) Also at National Research Nuclear University MEPhI, Kashirskoe Highway 31, Moscow,Russia; and Department of Physics, Uluda University, 16059 Bursa,Turke

(5) Now at University of Birmingham

(6) Now at CERN

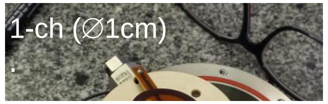
10 institutes from 6 countries

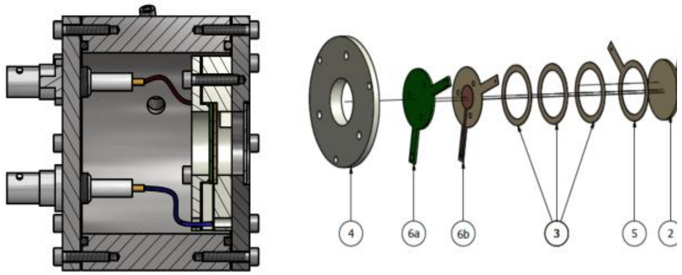
44 collaborators

Backup-slides

Detector Prototype Evolution

- Single Pad Prototypes / Microbulk (ø 1cm)
  - Proof of concept
  - Resistive and non resistive prototy


1-ch (∅1cm)



- Multi-Pad Prototypes
  - Hexagonal pads ø 1cm
  - Resistive and non resistive protot

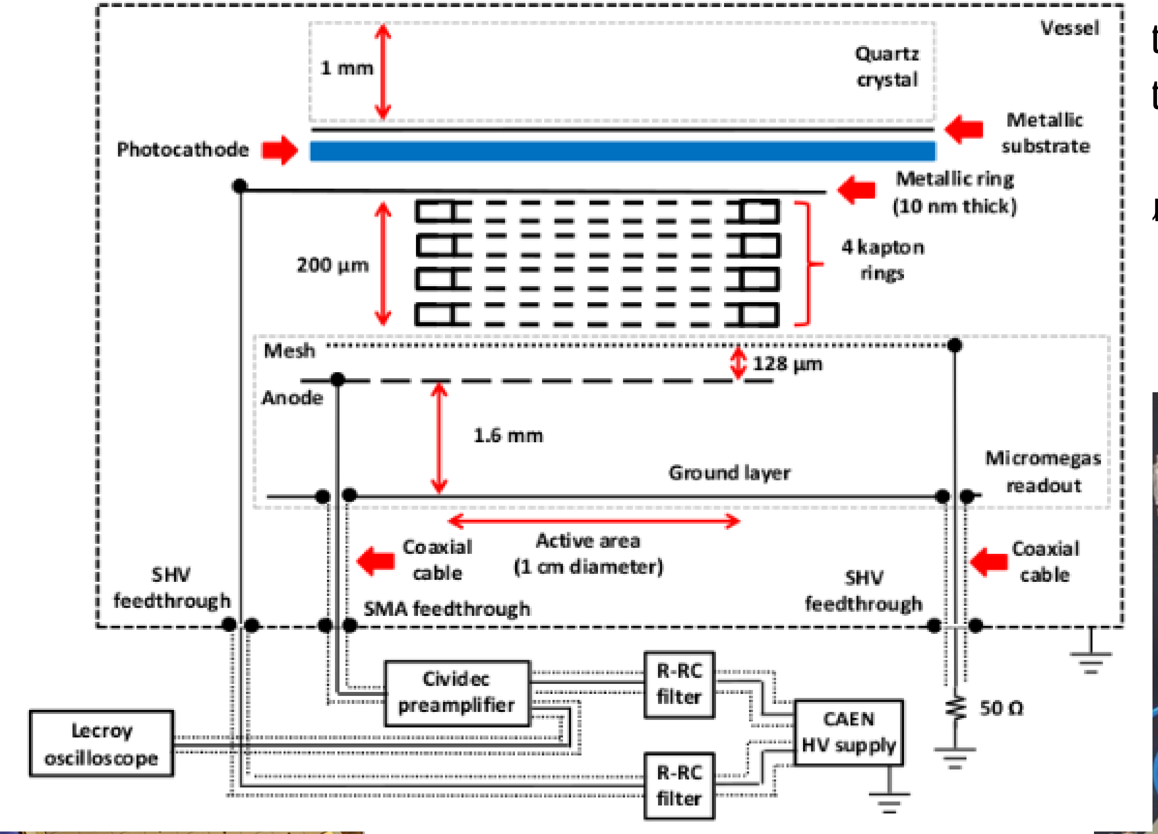
- Photocathodes:
  - MgF2 / Sapphire crystal +

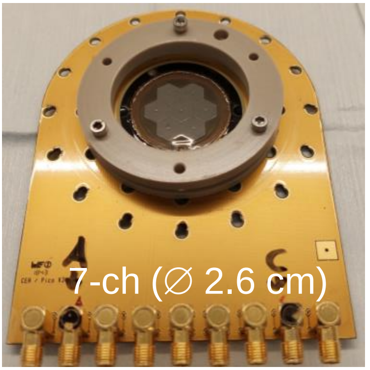
te + CsI

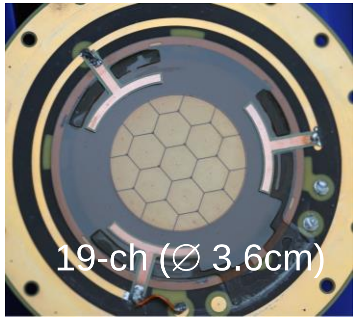
te + polycrystalline diamond

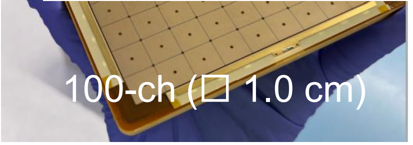
ıbstrate +B4C

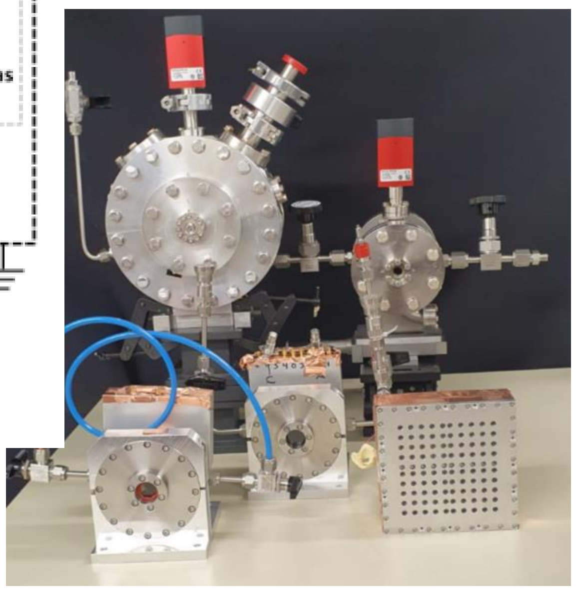
CF_4-10%C_2H_6




7-ch (∅ 2.6 cm)


19-ch (∅ 3.6cm)

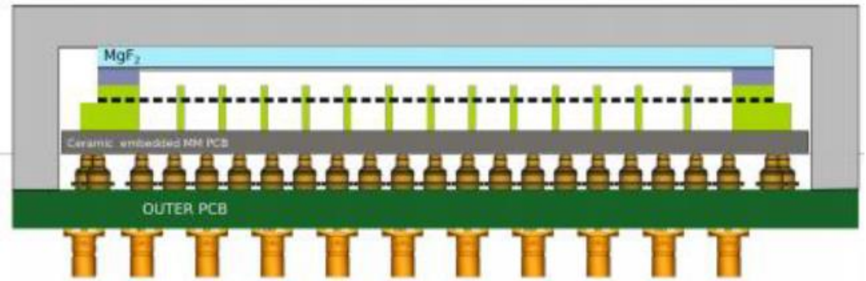

100-ch (☐ 1.0 cm)

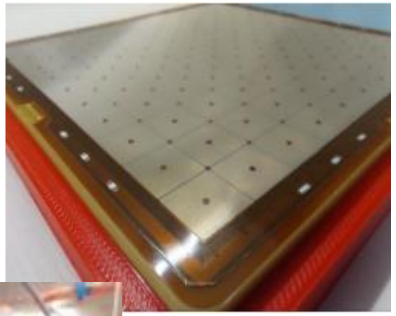


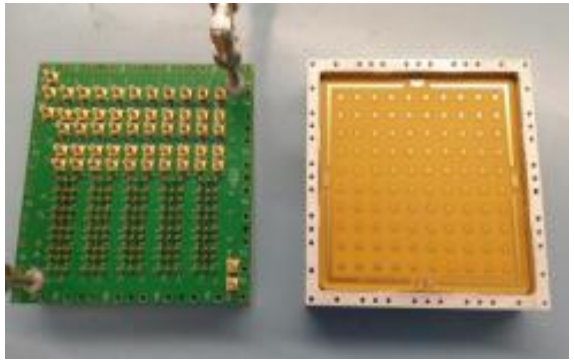
Prototype Scalability

PICOSEC Micromegas

- Tree possible approaches for modular prototypes with 10x10cm^2 active zone :
- **Rigid, ceramic-core PCB for the MM readout**
  - Crystal coupled to the PCB with spacers
  - MgF2 crystal & MM board will be decoupled from the chamber
  - Second PCB will be used for signals towards the amplifiers

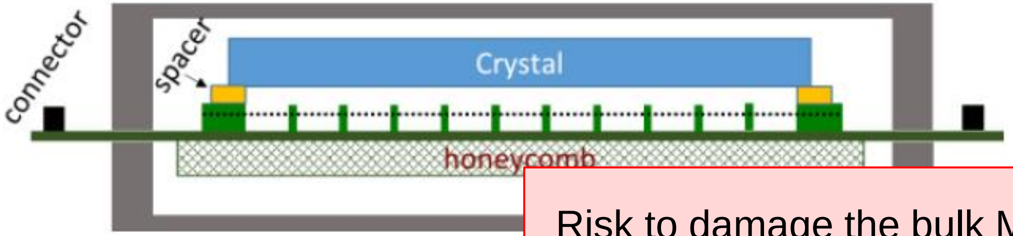






- **Drawback: Increased detector material → timing layers**

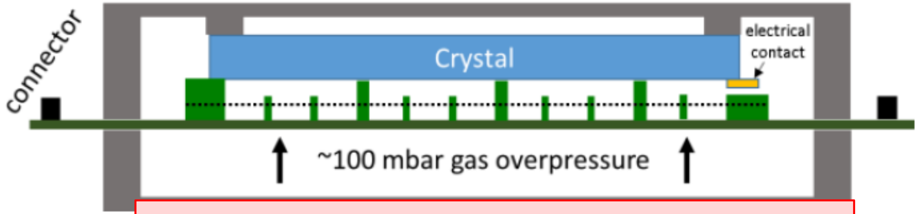
- **The ATLAS NSW Approach:**
  - Pillars on MM bulk readout
  - Pressing against the marble table
  - Backwards with a glued honeycomb layer



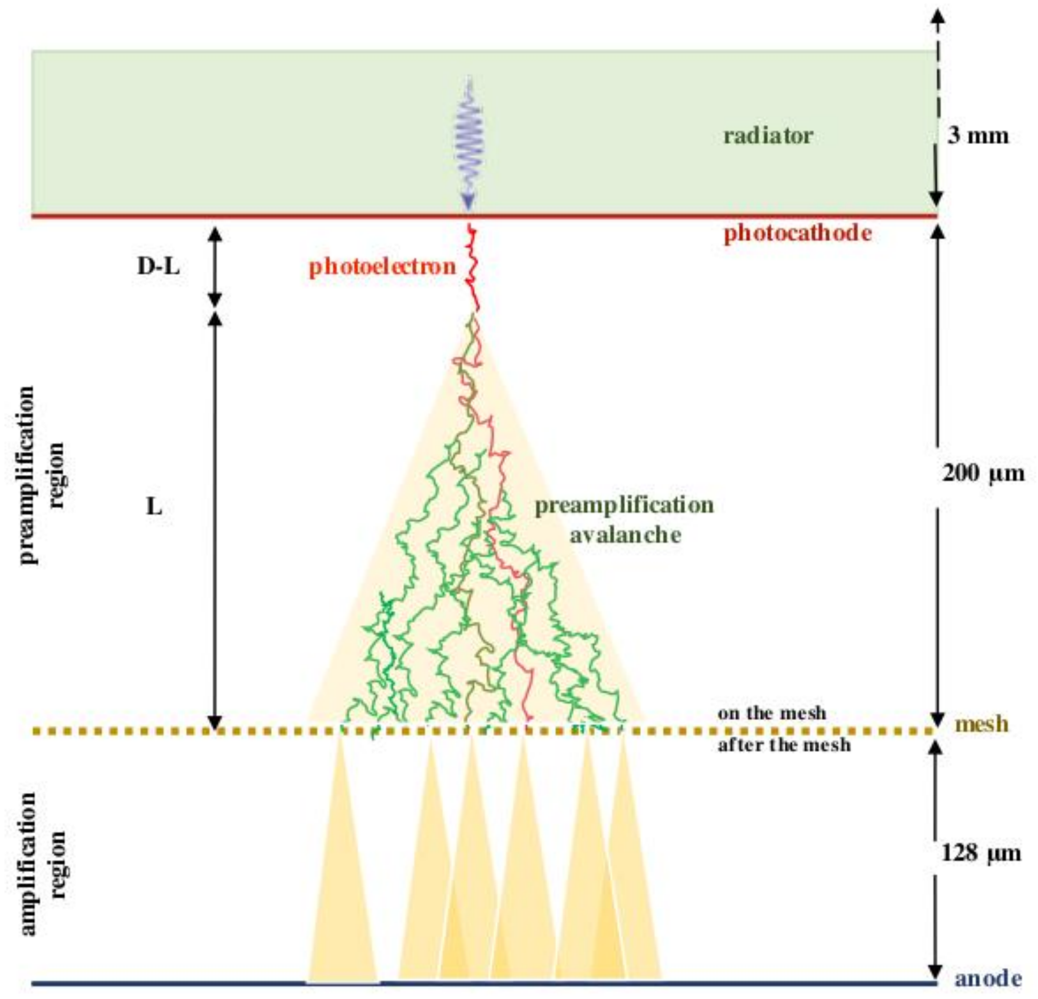
Risk to damage the bulk MM

- **Advantage:**
  - Low material budget on the detector
  - Allow the fabrication of large flat boards

- **Longer pillars MM module:**
  - Pressed against Cherenkov radiator



Risk to damage the photocathode



Physics

- Synchronous Cherenkov photons
- Synchronous Photoelectrons from the photocathode
- Photoelectron conversion(Townset Coeff)
- Preamplification Avalanche
- Transport through the mesh
- Amplification Avalanches

ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
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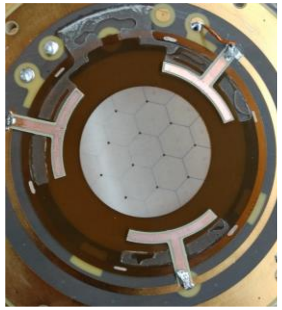
Modeling the timing characteristics of the PICOSEC Micromegas detector

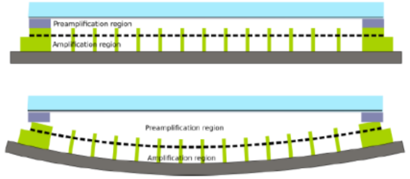
J. Bortfeldt [b, 1], F. Brunbauer [b, 1], C. David [b, 1], D. Desforge [a, 1], G. Fanourakis [e, 1], M. Gallinaro [g, 1], F. García [k, 1], I. Giomataris [a, 1], T. Gustavsson [i, 1], F.J. Iguaz [a, 1], M. Kebbiri [a, 1], K. Kordas [d, 1], C. Lampoudis [d, 1], P. Legou [a, 1], M. Lisowska [b, 1], J. Liu [c, 1], M. Lupberger [b, 1, 2], O. Maillard [a, 1], I. Manthos [d, 1], H. Müller [b, 1], V. Niaouris [d, 1], E. Oliveri [b, 1], T. Papaevangelou [a, 1], K. Paraschou [d, 1], M. Pomorski [j, 1], B. Qi [c, 1], F. Resnati [b, 1], L. Ropelewski [b, 1], D. Sampsonidis [d, 1], L. Scharenberg [b, 1], T. Schneider [b, 1], L. Sohl [a, 1], M. van Stenis [b, 1], Y. Tsipolitis [f, 1], S.E. Tzamarias [d, 1], A. Utrobicic [b, 1], R. Veenhof [h, 1, 3], X. Wang [c, 1], S. White [b, 1], Z. Zhang [c, 1], Y. Zhou [c, 1]

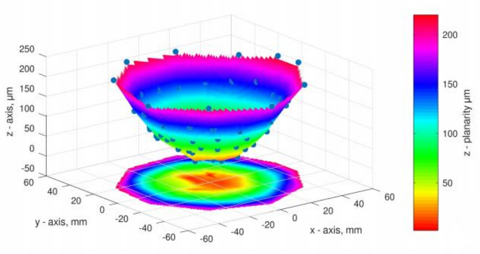
PICOSEC
Micromegas

Robustness and Efficiency

- The importance of planarity
  - 1st multichannel prototype tested
  - 19-hexagonal pad prototype, MgF_2, CsI, 200μm drift gap



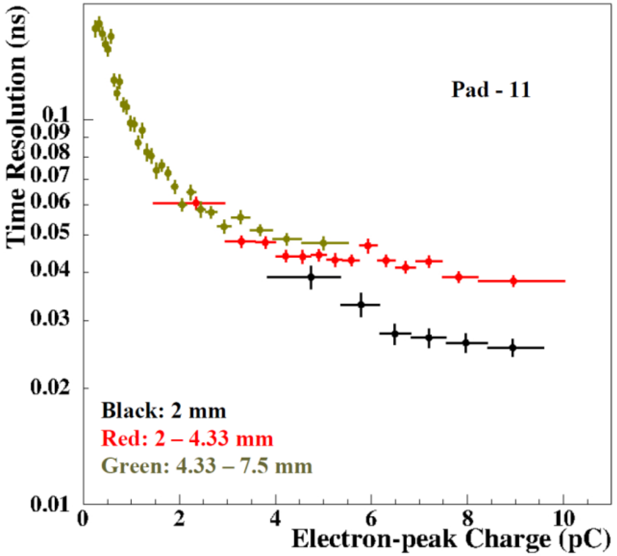


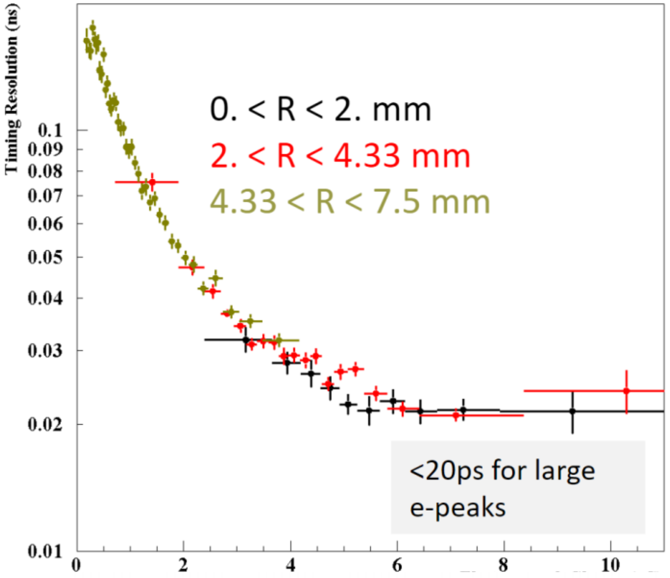


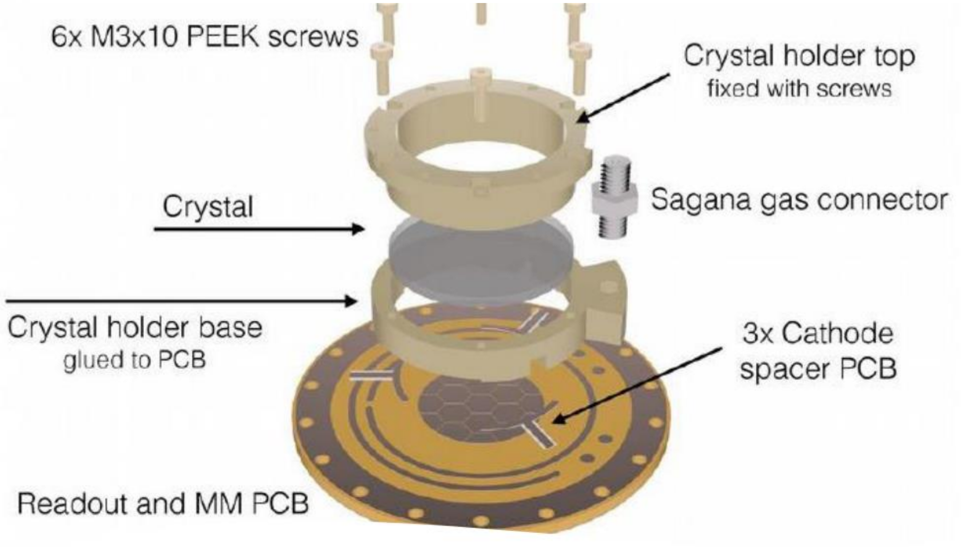
- Variation on timing resolution in different regions on the pad
  - Non uniformity of the drift field gap
  - Different gain in single pad area

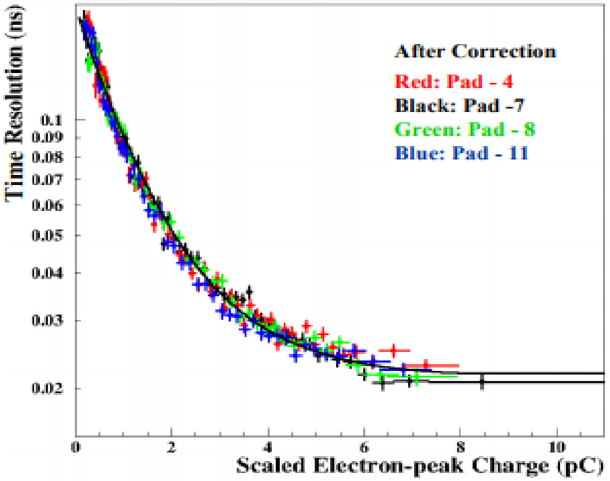
Deformation caused by the

Deformation due to PCB pressure





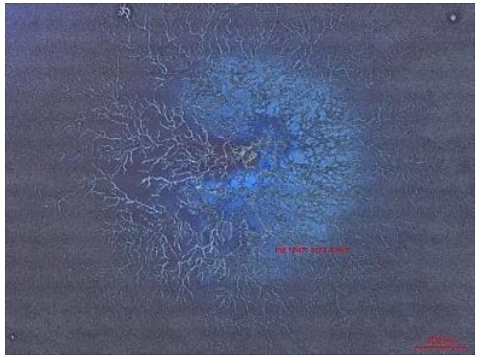


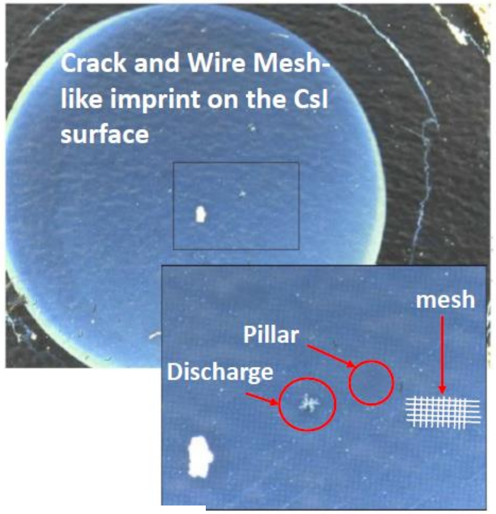


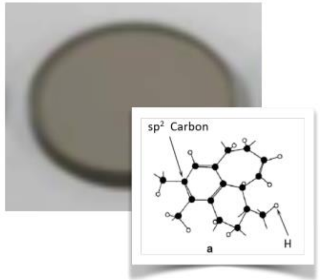
S. Aune et al, "*Timing performance of a multi-pad PICOSEC-Micromegas detector prototype*", Nucl. Instrum. Meth.A 993 (2021) 165076, https://doi.org/10.1016/j.nima.2021.165076

Robustness & Efficiency

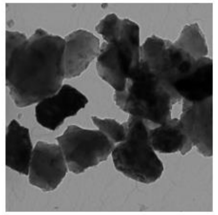
- In the research of photocathode materials
  - Standard photocathode: 18nm CsI +3nm Cr ~ 10pe/mip
  - CsI sensitive to humidity/ion backflow & sparks
  - New materials under test (B4C, DLC, Diamond, Metallic – Al, Cr)

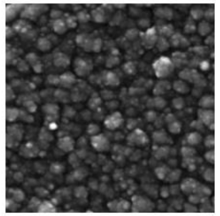




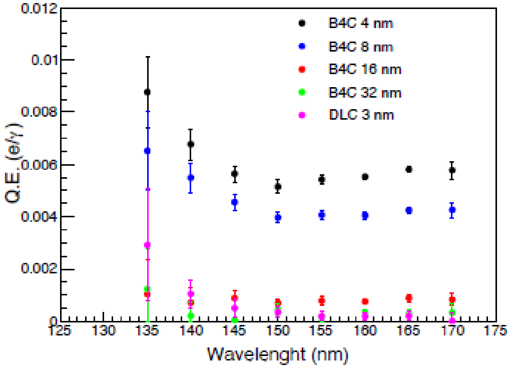


DLC, Y. Zhou et al.


ND, L. Velardi et al.


B_4C, 10.1016/ j.jnucmat.2015.01.015

- Results



B4C 5 times higher q.e. compared to DLC!!

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

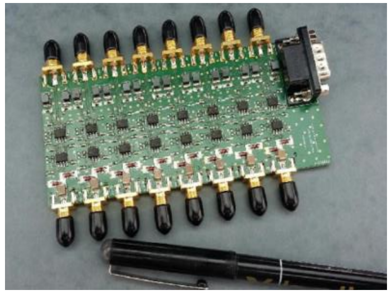
Florian M. Brunbauer on https://indico.cern.ch/event/852331/contributions/4611230/attachments/2367111/4043506/Picosec-TPCSymposium2021.pdf

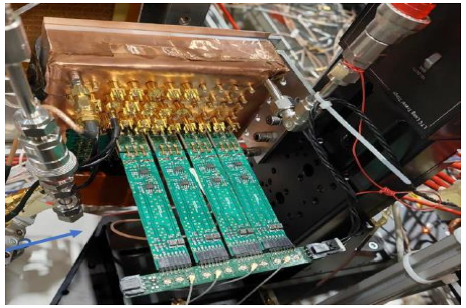
Pixelated PICOSEC Detector

- Towards a large scale detector we need to develop appropriate frond-end & back-end electronics ~ 100channels

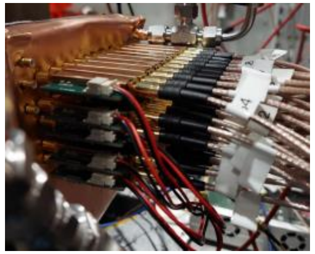
- Discrete current preamplifiers
  - Low noise RMS < 1mV
  - High gain >30dB
  - Bandwidth > 1GHz

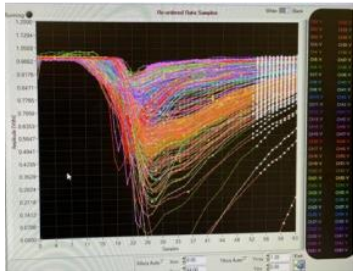
  } Philippe Legou (CEA/Saclay)



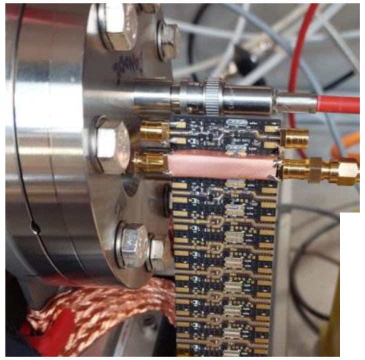


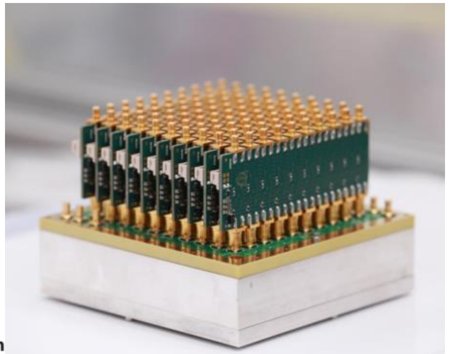
- Research on possible usage of customade charge-sensitive amplifiers (Hans Muller/ CERN)
- Research on different digitization ways → SAMPIC digitizer (IRFU /CEA)

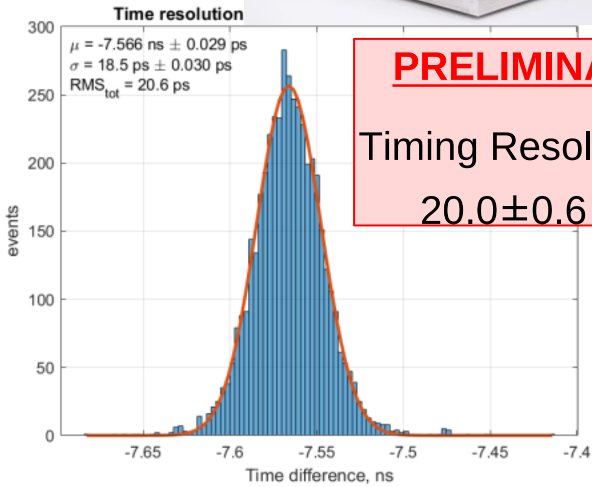




- Recent development @ CERN
  - 10 ch amplifier boards

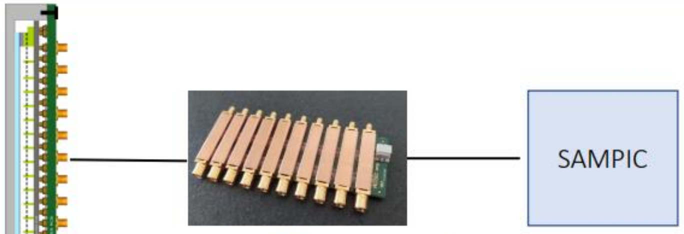






PRELIMINARY

Timing Resolution: 20.0±0.6 ps



More info : A. Utrobičić on RD51 collaboration meeting
https://indico.cern.ch/event/1138814/timetable/#20220614.detailed

PICOSEC Mircomegas production

Anode board production

a) **Production of the ceramic substrate:** embedding ceramics into FR4
   - Polishing to reach planarity below 15 um → Planarity measurements

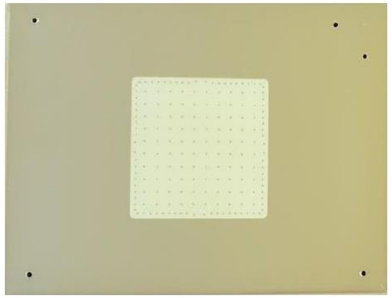
b) **Epoxy coating and copper deposition** (55 µm) on the top and bottom side of the board.
   - Polishing → Planarity measurements.

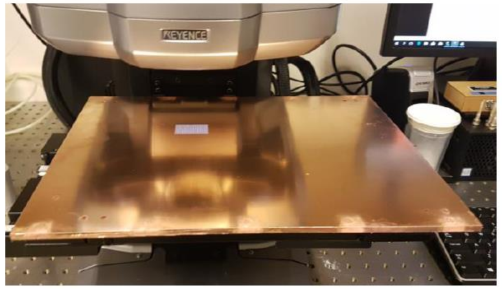
c) **Copper etching.**

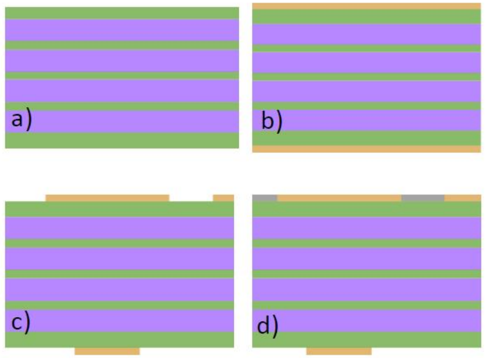
d) **Epoxy fill between the copper** traces/readout pads
   - Polishing → planarity measurements → Mirror polishing → Ni/Au plating

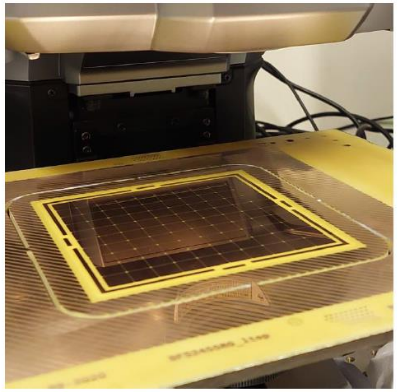
- Additional improvements:
  - **Thicker Cu (70 µm)** to have margin for correction with manual polishing if needed in the later steps.
  - **Residual stress reduction methods** before final polishing to ensure that ceramic is stress free and minimize the possibility of the board wrapping during long time period.
  - **Partial cutting of the board** from the frame just before bulking to reduce the possibility of board deformation during temperature cycling.
  - **Considering using FR4 material with higher T_g** to minimize the possibility of deformations due to heating processes in production

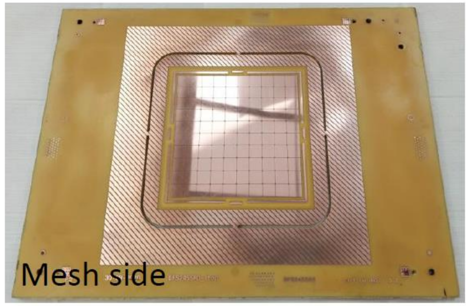
@ CERN MPT workshop

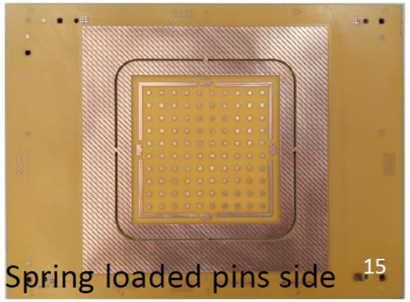












*More info on the contribution by **Antonija Utrobicic** at the VCI2022 conference: https://indico.cern.ch/event/1044975/contributions/4663685/*