PICOSEC Micromegas Precise-timing Detectors Towards Large-scale Application and Optimization

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USTC HEFEI 2024

MPGD2024 - The 8th International Conference on Micro Pattern Gaseous Detectors
Oct.14th - Oct.18th 2024 USTC·Hefei, China

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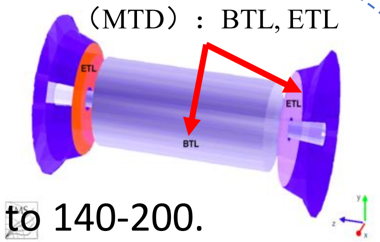
Outline

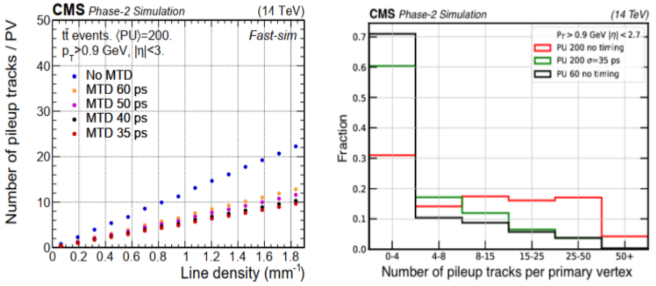
- Motivation
- Optimization
  - Enhanced Timing Performance
  - Resistivity & Robustness
  - Alternative Gas
  - Exploration of Detector Geometry
- Large-area Development
  - Detector prototype: from single channel to 20x20
  - Integrated Readout Electronics
- Summary and Prospect

Motivation

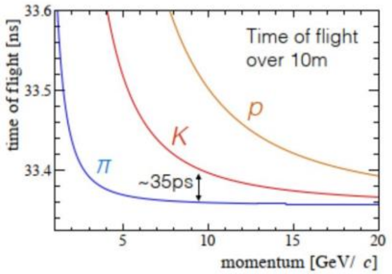


High Luminosity Upgrade of LHC:

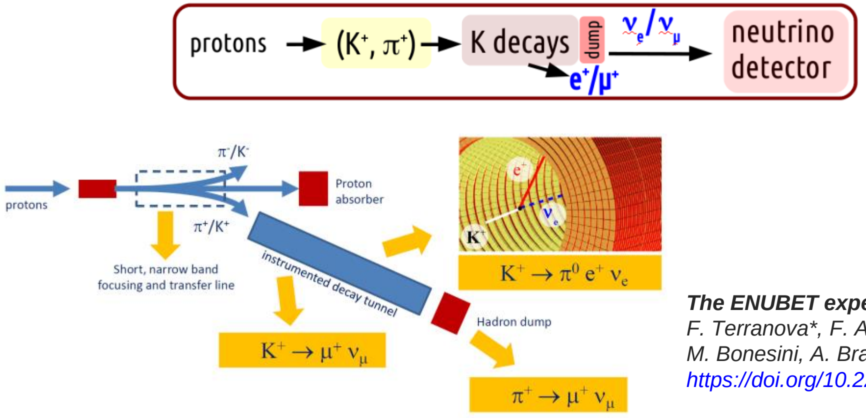
- Instantaneous Luminosity ~ $5 - 7.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, Pile-up effects increase to 140-200.
- **Precise timing (~30 ps)** detectors in need to connect the tracks with the primary vertex.
- For wider momentum range particle Identification, TOF detector with better **time resolution (~10 ps)** needed.



Cms C. A MIP timing detector for the CMS phase-2 upgrade[R]. 2019.



https://indico.cern.ch/event/999817/contributions/4253048/attachments/2240084/3797788/TOF%20technologies.pdf



The ENUBET experiment-
F. Terranova, F. Acerbi, G. Ballerini, M. Bonesini, A. Branca, C. Brizzolari*
https://doi.org/10.22323/1.390.0182

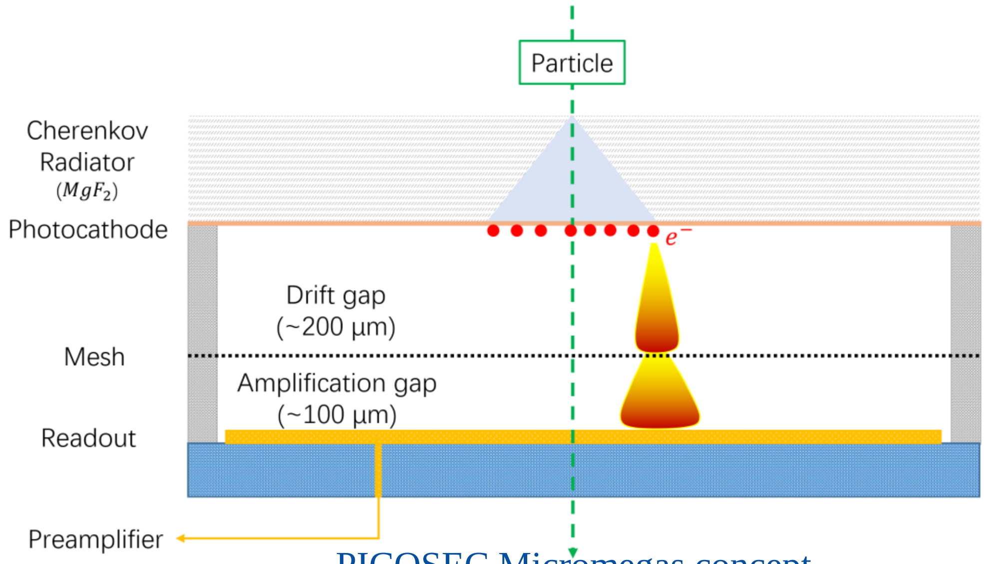
Event Triggering and Tagging Context:

- **ENUBET** (**E**nhanced **N**e**U**trino **BE**ams from kaon **T**agging)
- neutrino beam with no one-to-one correlation between p+ and neutrino
- **Sub-ns sampling** would offer this correlation on an event-by-event basis and determine the flavor of neutrino

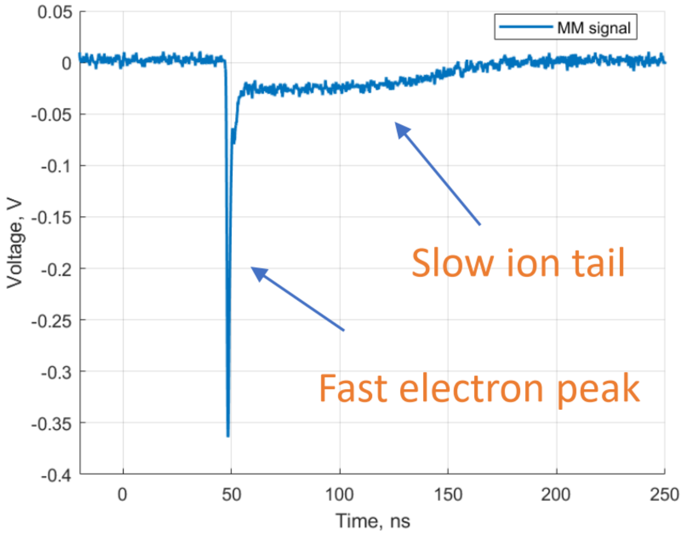
Aims at :

MPGD Timing with a few 10's of Picosecond

PICOSEC MM Concept



PICOSEC Micromegas concept

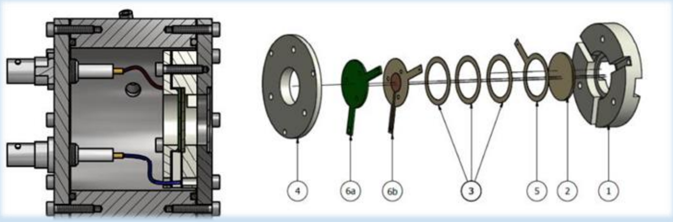


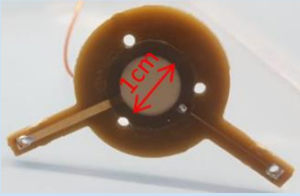
- **PICOSEC Micromegas (MM):** precise timing gaseous detector based on a Cherenkov radiator coupled to a semitransparent photocathode and a MM amplifying structure
- Cherenkov radiator and photocathode converting charged particles into photoelectrons.
- Micromegas structure enables electron avalanche amplification.
- Narrow gap and high electric field (E≈20-40 kV/cm) applied to drift region, facilitating pre-amplification.
- Timing resolution: order of tens ps.

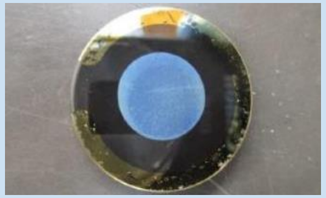
J.Borteldt, et al. "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector", Nuc. Instrum. Meth. A (2021)https://doi.org/10.1016/j.nima.2018.04.033

First Prototype: Proof of Concept

Single Channel PICOSEC MM Prototype:

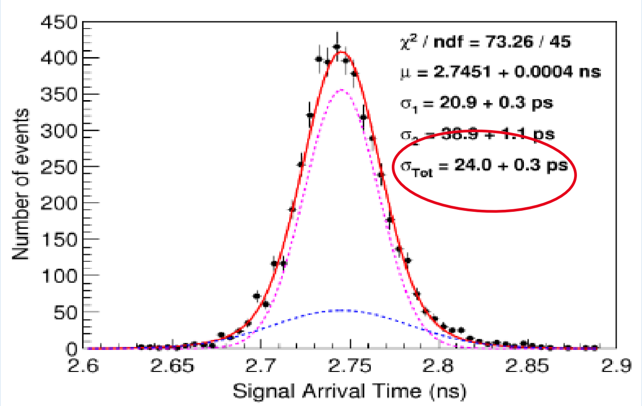




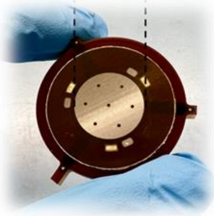


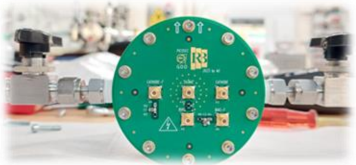
- 1 cm diameter active area
- 3 mm MgF2, CsI photocathode
- Drift/preamplification region of 200 μm
- Operating gas: Ne:C2H6:CF4 (80-10-10)

- First timing measurement: 150 GeV muons @CERN SPS H4 (2017) **<25ps**



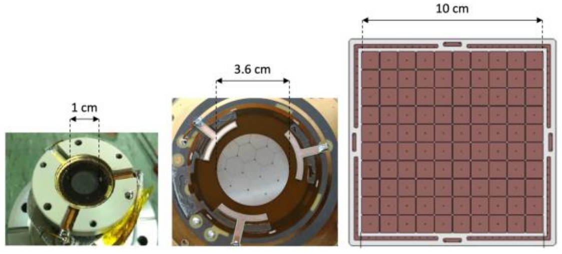
J.Borteldt, et al. "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector", Nuc. Instrum. Meth. A (2021)https://doi.org/10.1016/j.nima.2018.04.033





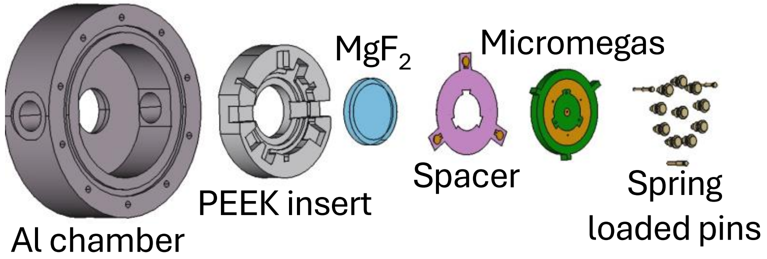
Next steps: Multiple directions in detector development

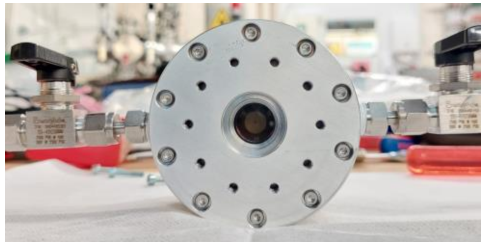
- Detector optimization
  - Timing Performance
  - Resistivity & Robustness
  - Alternative Gas
  - New Geometry
- Large area coverage
  - Large area prototypes
  - Readout Electronics

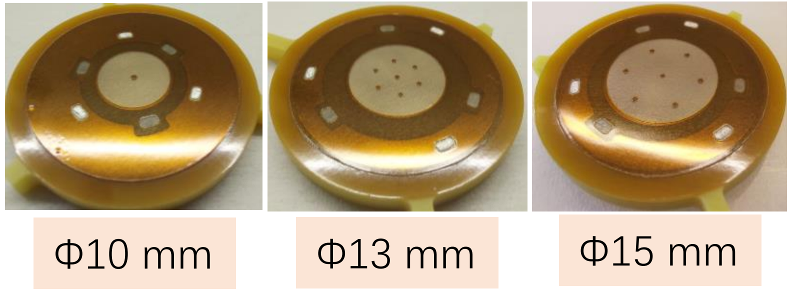


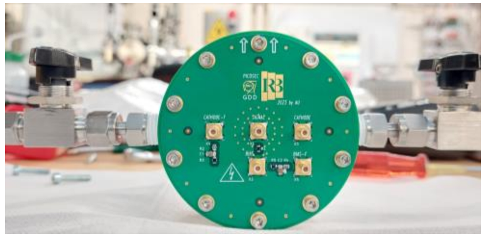
Enhanced Timing Performance

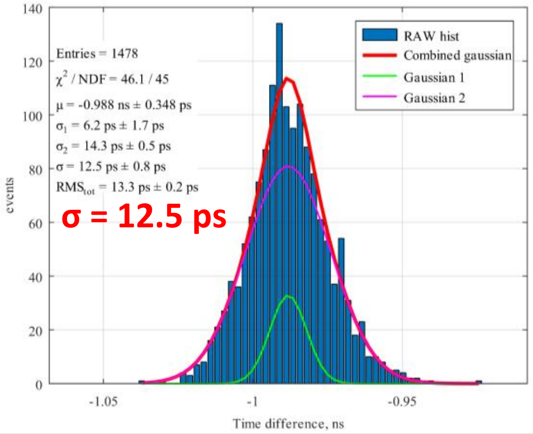
- **Designing of a new single-channel PICOSEC MM detector:**
  - Focus on **improving HV stability, preserving or enhancing signal integrity** and **time response uniformity** over the entire active area.
  - **Simple and fast reassembly procedure** for easy replacement of detector elements to simplify research (studies of different photocathode materials, detector geometry or amplification structures).
  - The new detector housing and three different size of MM boards with 10 mm, 13 mm and 15 mm diameter active area that are compatible with same housing were designed and produced
  - The 10 mm detector achieved excellent time resolution of **σ ≈ 12.5 ps** within pad central region Φ 4 mm (drift gap 120 ± 10 μm)@150 GeV/c muons at CERN SPS H4 beamline
  - Test beam results showed that all three prototypes can operate stable with very uniform time response.

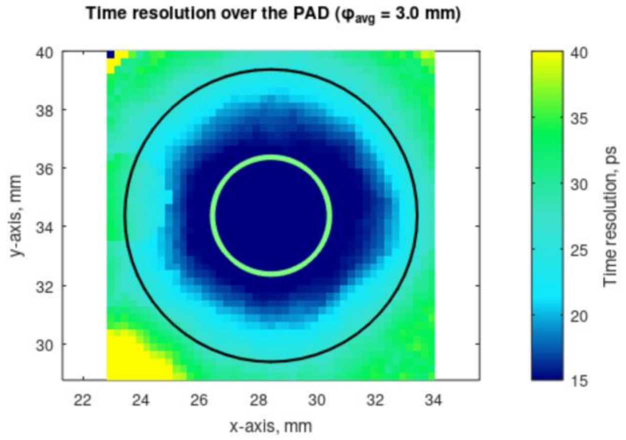












Utrobicic, A., et al. "Single channel PICOSEC Micromegas detector with improved time resolution." arXiv preprint arXiv:2406.05657 (2024).
https://doi.org/10.48550/arXiv.2406.05657

Robust Photocathodes

- First single-pad prototype: **Cr + CsI**
  - √ high QE with NPE exceeding 12 per MIP, excellent time resolution
  - × can be damaged by ion back flow, sensitive to humidity (assembly)

➢ **Search for Robust Photocathodes：**

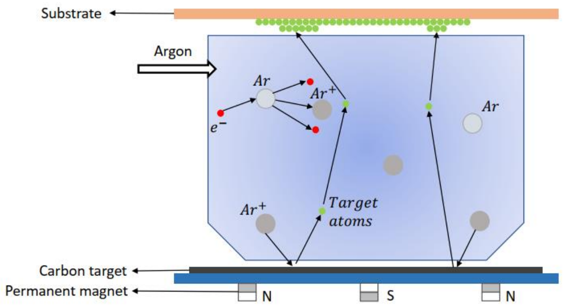
→ Diamond Like Carbon (DLC)

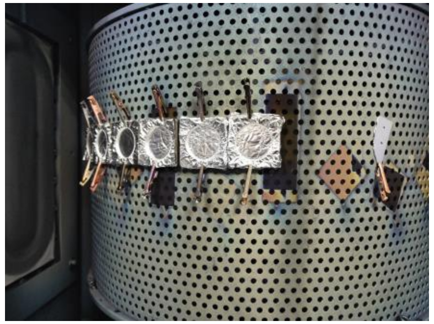
→ Boron Carbide (B4C)

→ Nanodiamonds

→ Carbon nano-structures

- Depositions of DLC photocathodes with magnetron sputtering technique in China: capable of coating Φ1 small crystals and larger area ones



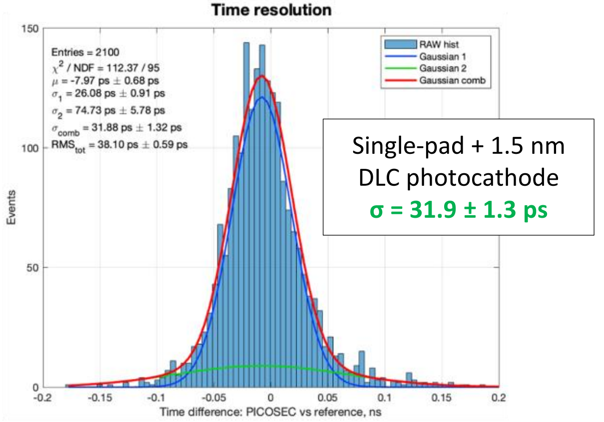


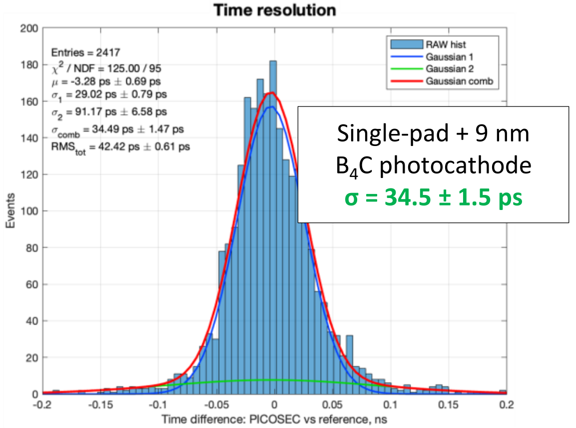
Wang, X., et al. "A Novel Diamond-like Carbon based photocathode for PICOSEC Micromegas detectors." arXiv preprint arXiv:2406.08712 (2024). https://doi.org/10.48550/arXiv.2406.08712

Thanks to Lanzhou Institute of Chemical Physics

- Depositions of DLC photocathodes carried out at the CERN MPT workshop.
- The best results achieved with a **1.5 nm DLC** photocathode, yielding a time resolution of **σ ≈ 32 ps.**
- Measurements conducted with **B_4C** photocathodes exhibited the best time resolution of **σ ≈ 34.5 ps** for the 9 nm layer.

Pulsed DC magnetron vacuum deposition machine





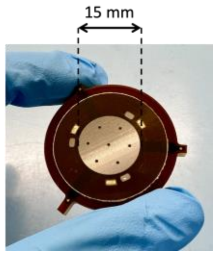
Lisowska, M., et al. "Photocathode characterisation for robust PICOSEC Micromegas precise-timing detectors." arXiv preprint arXiv:2407.09953 (2024). https://doi.org/10.48550/arXiv.2407.09953

PICOSEC with Resistive Micromegas

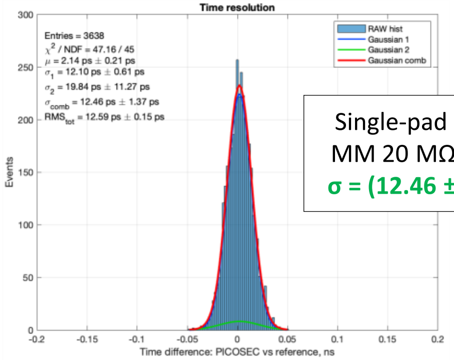
- **Resistive Micromegas:**

- **Advantages:**
- ✓ protecting detector from highly ionizing events
- ✓ ensuring stable operation under intense particle beams
- ✓ achieving better position reconstruction by signal sharing

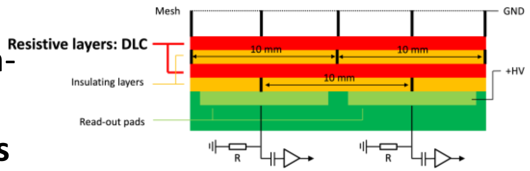
Resistive bulk Micromegas



Resistive single-pad prototype



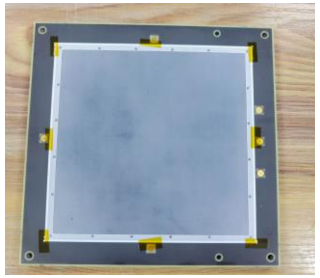
Single-pad resistive MM 20 MΩ/sq + CsI
σ = (12.46 ± 1.37) ps



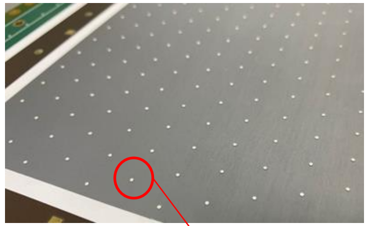
- Single-pad resistive MM of 20 MΩ/sq equipped with a CsI photocathode obtained equivalent precision to a non-resistive prototype, exhibiting an excellent time resolution of **σ ≈ 12.5 ps**
- double-layer DLC for vertical charge evacuation and evaluation of rate capability

See next talk by Djunes Janssens

Thermal bonding Method to fabricate Micromegas

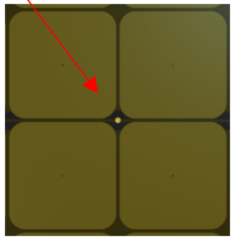


Coating of Germanium for Resistive Anode



Pillar on Micromegas

- Coating of Germanium on PCB to form resistive anode (resistivity ~ 50 MΩ/sq)
- Grounding points placed under each pillar for fast grounding, achieving high rate capability



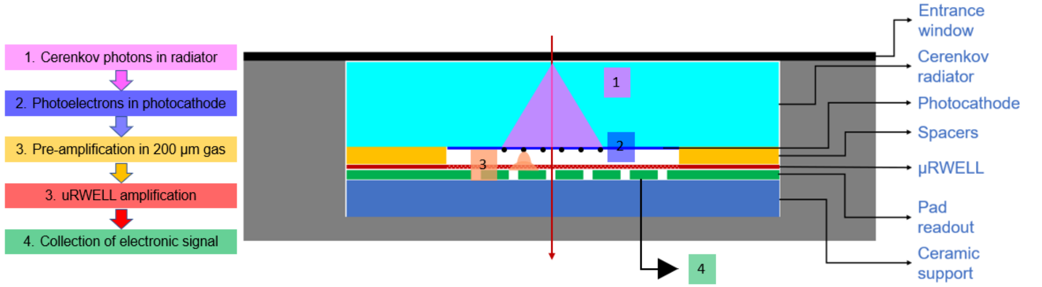
Grounding points

By USTC

μRWELL PICOSEC

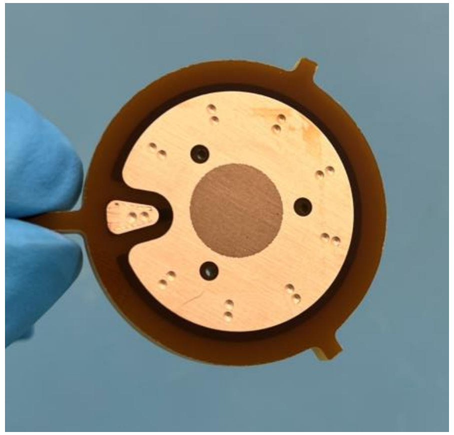
➢ Development of PICOSEC based on μRWELL technology:

- μRWELL structure with high E field **(>40 kV/cm)** to facilitate electron amplification
- Several single-channel prototypes tested with various holes pitch and geometry and gap between μRWELL amplification and pad readout
- **23.5 ps** was obtained with CsI and **37 ps** for DLC with 120 μm pitch, 100 μm outer diameter and 80 μm inner diameter μRWELL-PICOSEC
- There is still room to improve ultimate performances with geometry optimization

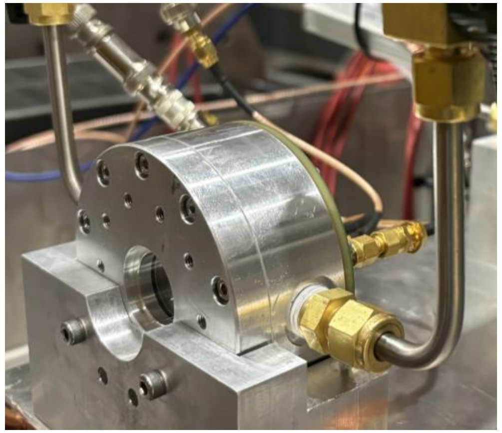


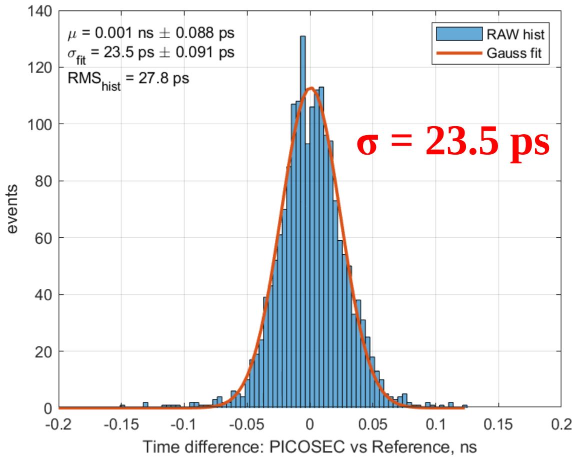
Weisenberger, Andrew, et al. μRWELL-PICOSEC: The Development of Fast Timing Resistive Micro-WELL Detector Technology. No. JLAB-PHY-23-3979; DOE/OR/23177-7316. Thomas Jefferson National Accelerator Facility (TJNAF), Newport News, VA (United States), 2023.

μRWELL -PICOSEC PCB

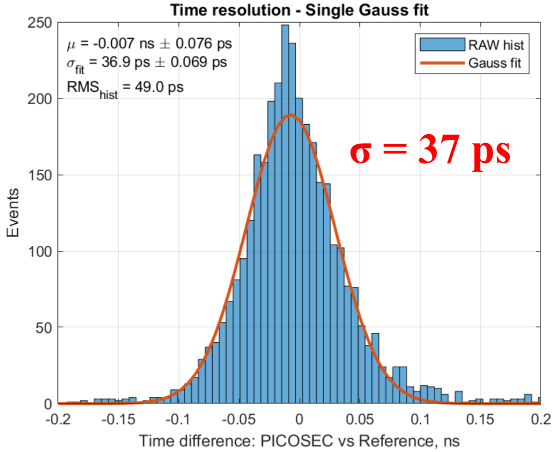


Prototype tested in LED setup





Time resolution with CsI photocathode



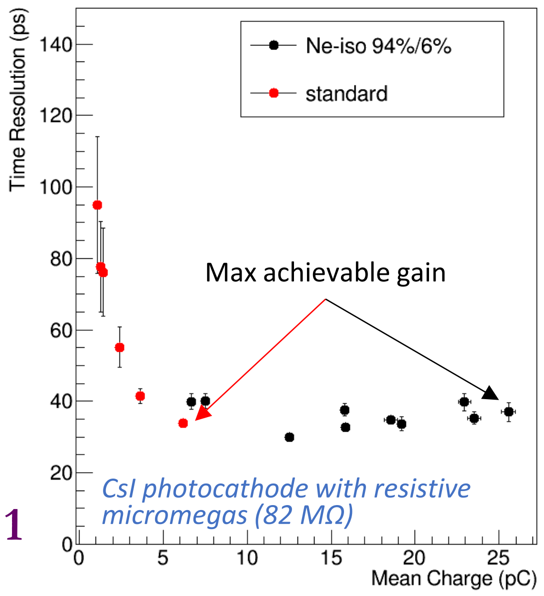
Time resolution with DLC photocathode

Exploring Alternative Gas

Standard mixture:

Neon / C_2H_6 / CF_4: 80% /10% /10%

- Expensive
- Flammable
- High GWP (~ 740)



New mixtures:

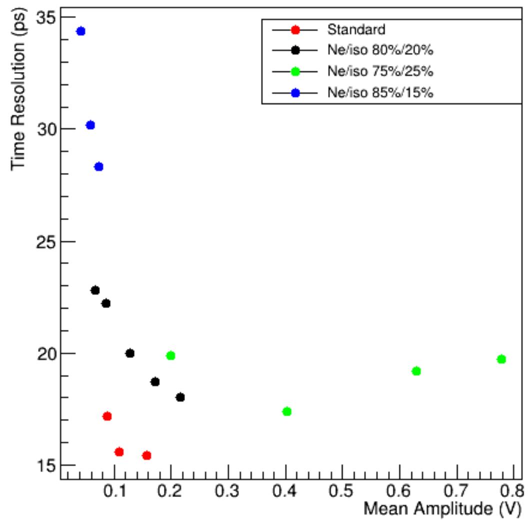
Ne/iC_4H_{10} 94/6 GWP less than 1

GWP

The **Global Warming Potential (GWP)** is the ratio between the greenhouse effect of a substance over 100 years and that of CO_2. Therefore, if a compound has a GWP of ≈740, the greenhouse effect produced by that compound is 740 times greater than that of CO_2.

Different concentrations of Ne and iC_4H_{10}

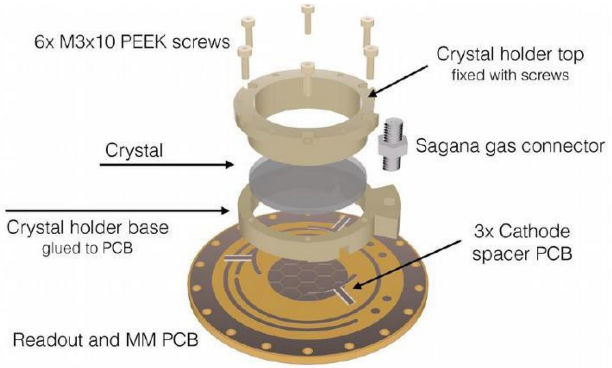
- Reached **~17ps** with the **75/25** mixture and **~19ps** with the **80/20** (~15ps with the standard mixture).
- Need to determine precisely the concentration inside the detector due to problems with the gas mixing system.
- Ne/iso mixture good candidates to achieve good time resolution with low GWP (order of 1).

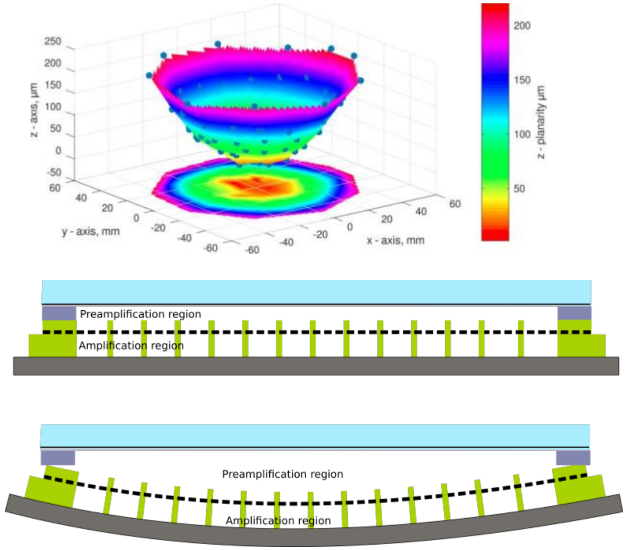


Aimè, C., et al. "Simulation and R&D studies for the muon spectrometer at a 10 TeV Muon Collider." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment (2024): 169903. https://doi.org/10.1016/j.nima.2024.169903

Multi-channel PICOSEC MM

- **First 19 ch. prototype of ϕ=3.6 cm active area:**
  - Observed decrease in timing performance depending on the position of MIP passing.
  - Source of error → non-uniformity of the drift field gap ->due to non flatness of the board itself.



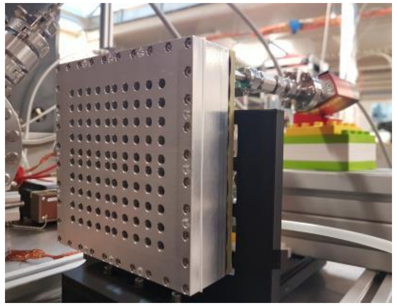


Aune, S., et al. "Timing performance of a multi-pad PICOSEC-Micromegas detector prototype." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 993 (2021): 165076.

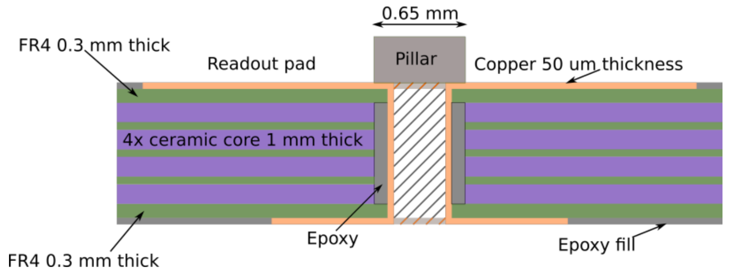
MAIN CHALLENGE: Make detector with uniform drift gaps over active area.

- **100 channel prototype:**

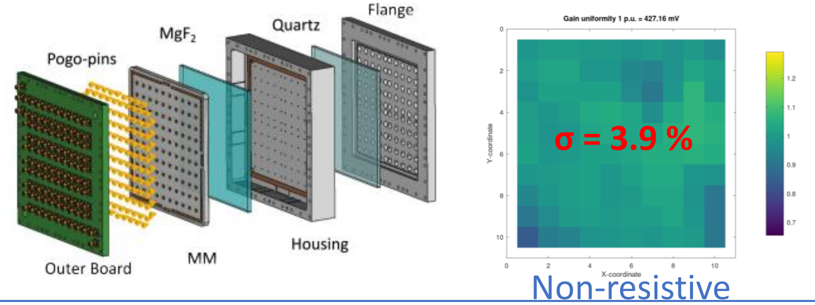
  can be tiled, 100 channels,
  10 cm x 10 cm active area,
  10μm flatness over entire area.



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



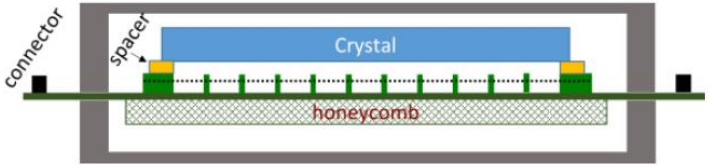
CHAMBER: mechanically decouple MM board and MgF_2 crystal to avoid deformations due to the attachment.



Utrobicic, A., et al. "A large area 100 channel Picosec Micromegas detector with sub 20 ps time resolution." MPGD 2022-7th International Conference on Micro Pattern Gaseous Detectors. 2022.

Multi-channel PICOSEC MM

➢ **Search on Low Material Budget Approaches**
-The ATLAS NSW-like approach

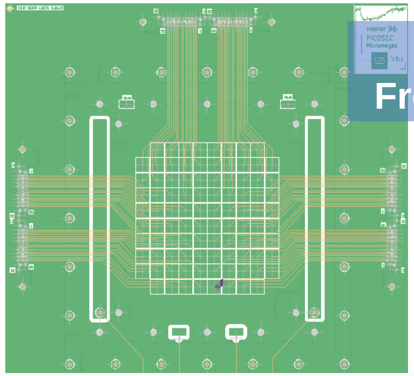


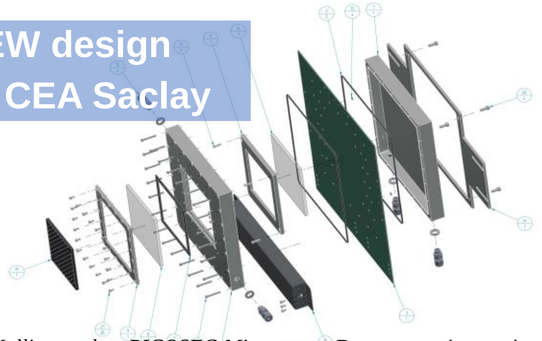
Advantage:

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

96-pad prototype

- 1cm single cell size
- Extended R&D on the PCB design as well as QA/QC to ensure low material budget X/X0 < 10%

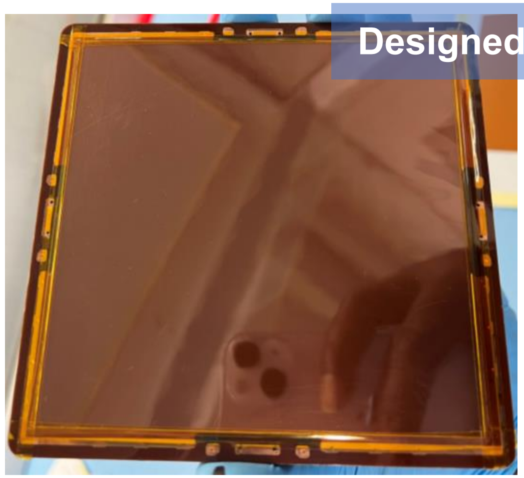




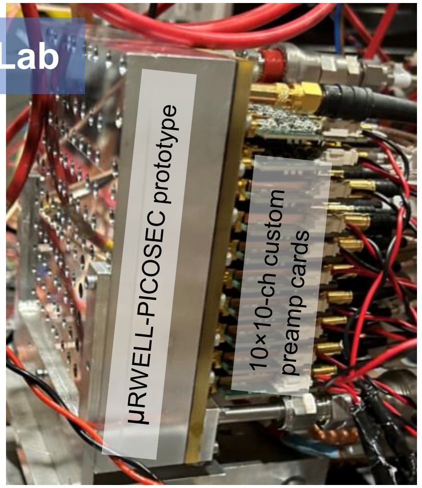
A. Kallitsopoulou. PICOSEC-Micromegas Detector, an innovative solution for Lepton Time Tagging [Oral session]. 16th Pisa Meeting on Advanced Detectors. Isola d'Elba, Italy

➢ **10×10 µRWELL-PICOSEC Prototype :**

- µRWELL-PICOSEC with **120** µm pitch, **100** µm outer diameter and **80** µm inner diameter assembled
- Preliminary time resolution results with CsI photocathode ~50 ps (@CERN SPS H4 Beam Test, July 2024)➔ partially due to drift gap non uniformity and poor photocathode quality
- Full analysis of the test beam data is ongoing



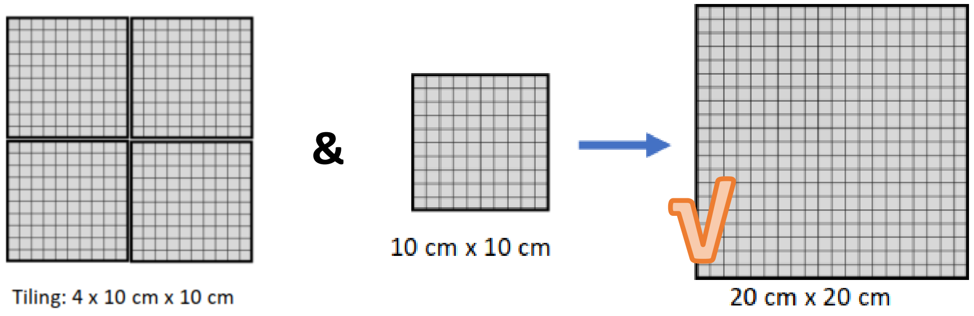
100-pads µRWELL-PICOSEC PCB



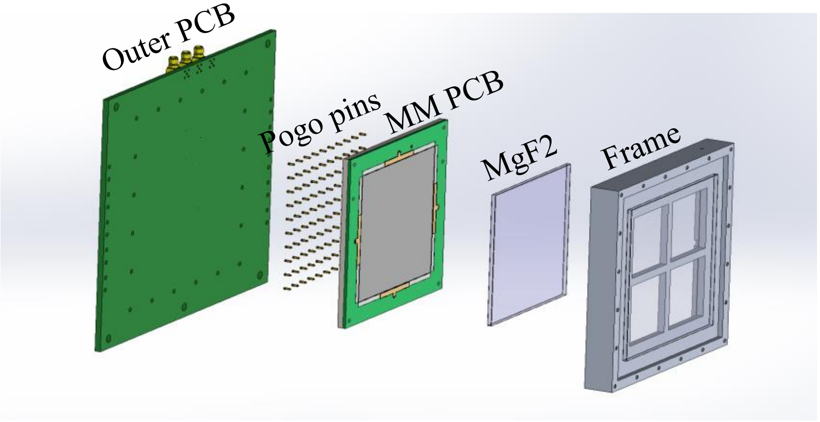
Large µRWELL-PICOSEC in beam at CERN

Towards Larger Area: From 10×10 PICOSEC

Two approaches for scaling to larger area:



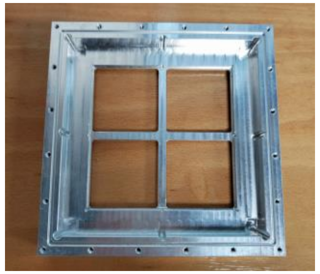
➢ Design Scheme of the USTC 10×10 PICOSEC MM



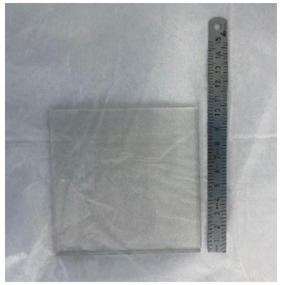
- 100 channels of 1cm*1cm pads
- A whole 104×104 mm MgF_2 crystal as photocathode
- Resistive Micromegas with coating germanium

➢ Manufacturing the USTC 10×10 PICOSEC MM

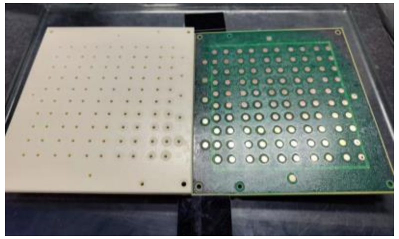
- Magnetron sputtering technology to coat DLC
- **Thermal bonding Method** for making resistive Micromegas (Resistivity~ 50 MΩ/sq)
- Adhesion of MM Board with Ceramic Board to ensure mechanic strength



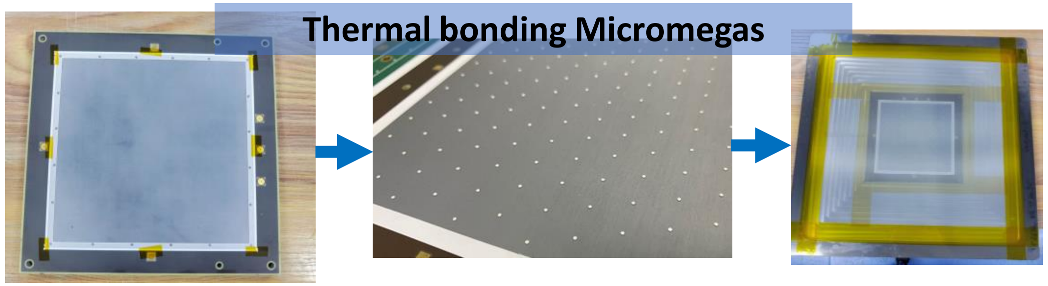
Gas Frame



104mm Photocathode



Adhesion of MM Board with Ceramic Board



Resistive Anode

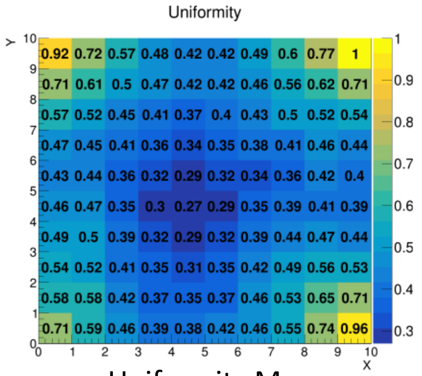
Pillars

Adhesion of Mesh

Towards Larger Area: From 10×10 PICOSEC

➢ **Basic Performance:**

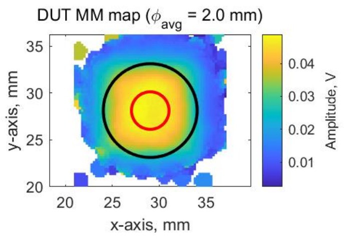
- Gain reach to 4×10^6
- Uniformity shows σ = 29.61% (caused by MM board deformation induced by mesh tension)

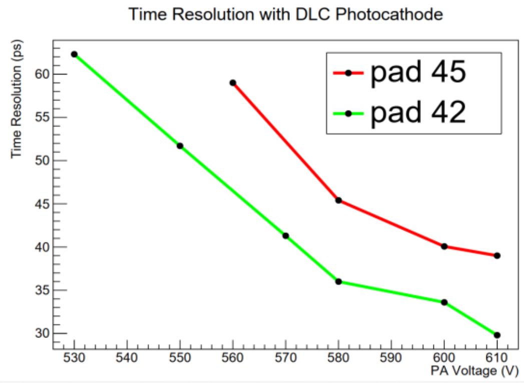


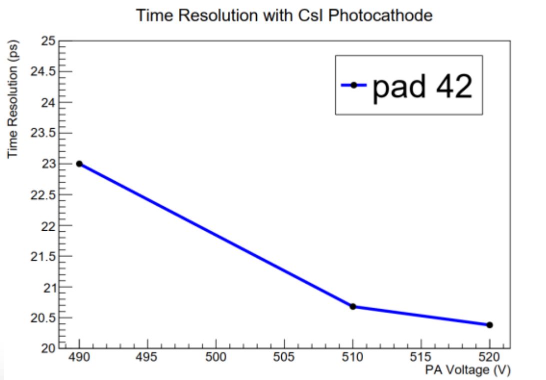
Uniformity Map

➢ **Time Resolution for single pad:**

- @CERN SPS H4 Beam Test, 2023 July
- CsI photocathode **σ ≈ 20ps** at the pad's central area (240/520)
- DLC photocathode **σ ≈ 29ps** at the pad's central area (260/610)

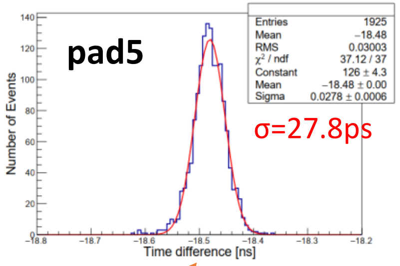


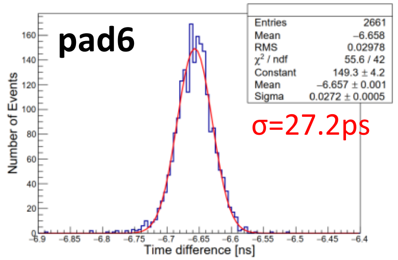


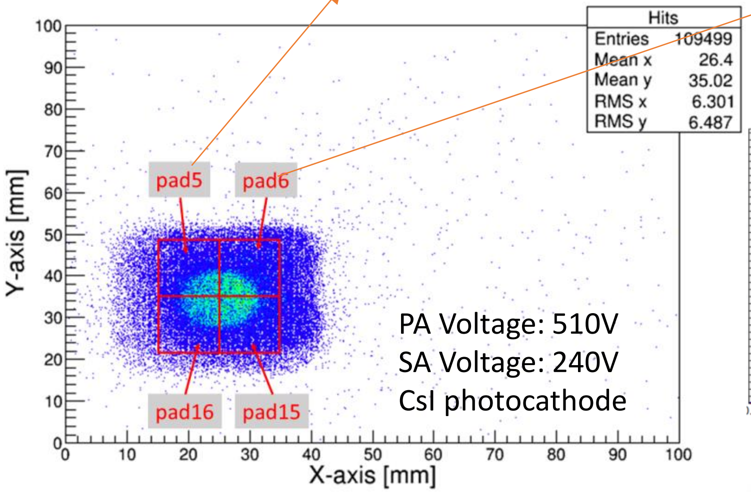


Time resolution for Signal sharing:

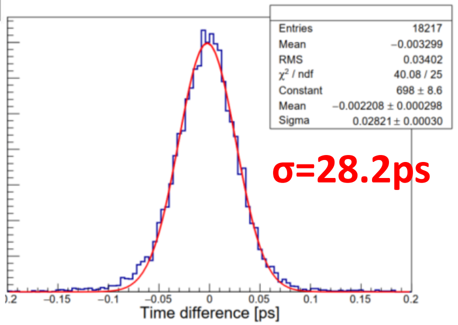
$$\text{Combined Time Resolution} = \frac{1}{\sum_{i=1}^{M}\frac{1}{(\delta(signal\ size))^2}}\sum_{i=1}^{M}\frac{SAT_{true}^{i} - SAT_{corr}^{i}(signal\ size)}{(\delta(signal\ size))^2}$$





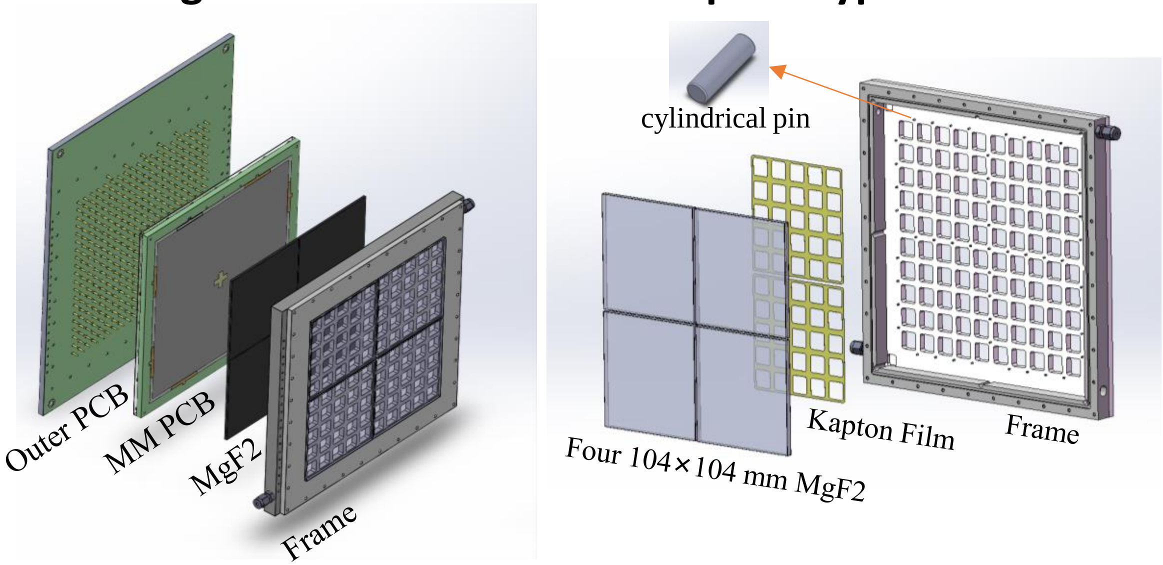


All Events



20×20 PICOSEC MM

Design of 20×20 PICOSEC MM prototype

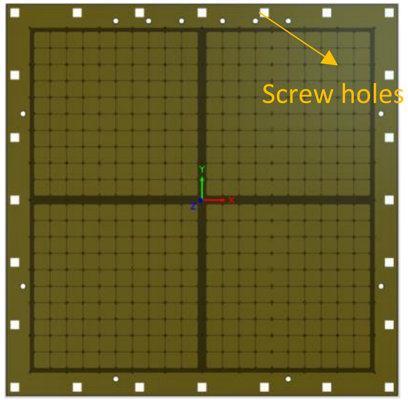


20×20 Resistive PICOSEC MM from USTC

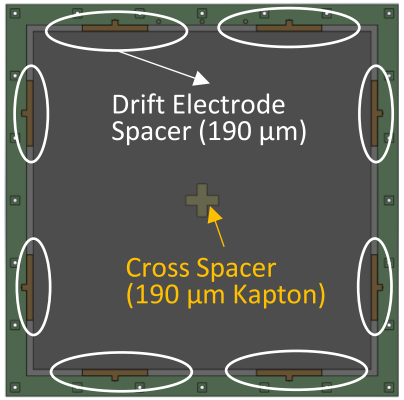
- Assembly structure similar to that of the 10×10 PICOSEC MM
- Assembling of the four 104×104×3 mm MgF2 as photocathode
  - MgF2 crystals placed directly on the frame with cylindrical pins (Φ1.5) for positioning
  - Kapton films (12.5μm) underneath to compensate for thickness variation between crystals
- Pogo pins soldered onto the Outer PCB to extract signals

Micromegas board

- Featuring a whole 20cm×20cm Micromegas
- 400 pads arranged on the 2×2 area, aligned with the crystals
- FR4 board bonded with a ceramic plate, and screws added on the edge to further strengthen



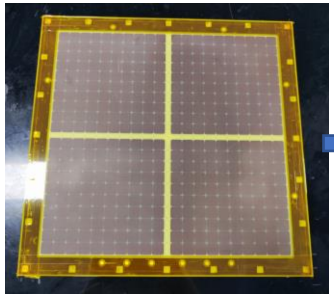
MM PCB



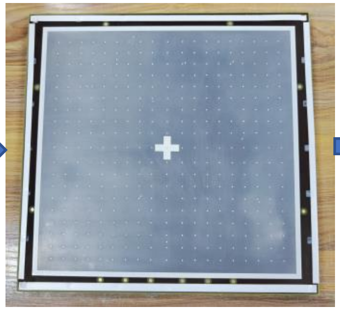
After made into Micromegas

20×20 PICOSEC MM

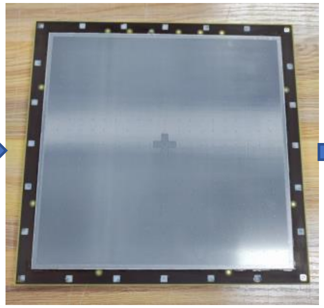
- **Manufacturing the USTC 20×20 PICOSEC MM**
  - Thermal Bonding Method to make Micromegas



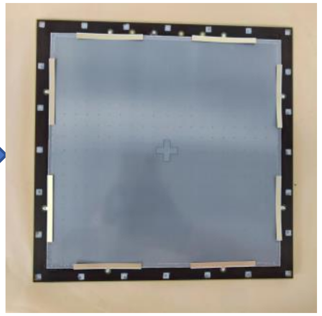
FR4 board after bonding ceramic board



Resistive Electrode

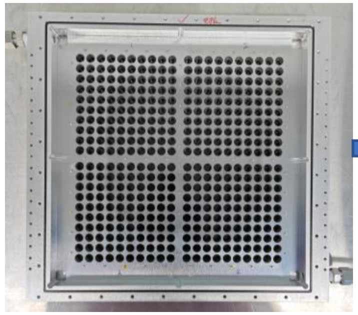


Adhesion of the mesh

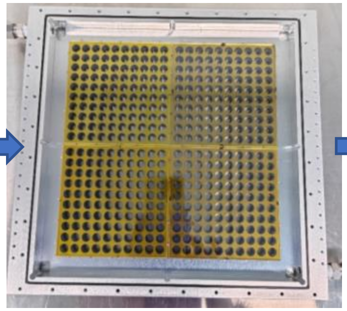


Putting on the Spacers

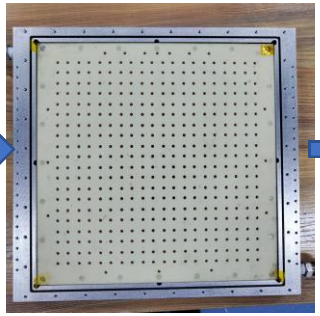
  - Assembling into PICOSEC mode



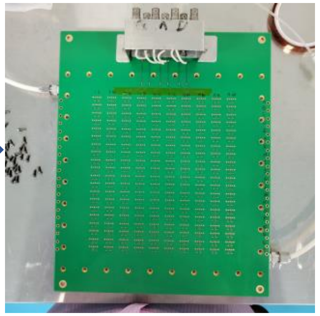
Gas Frame



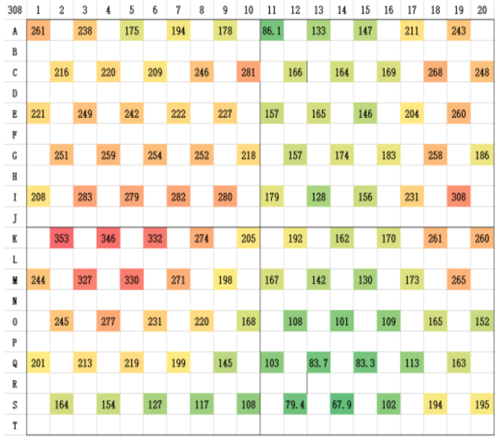
Kapton film & Photocathodes



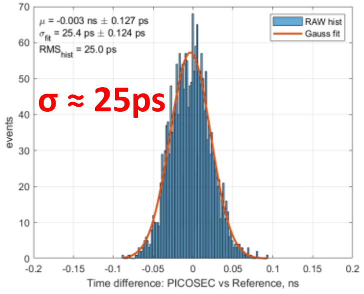
MM board

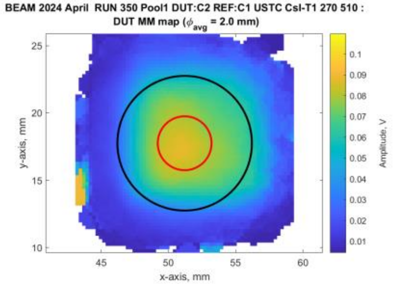


Outer PCB



Uniformity Map

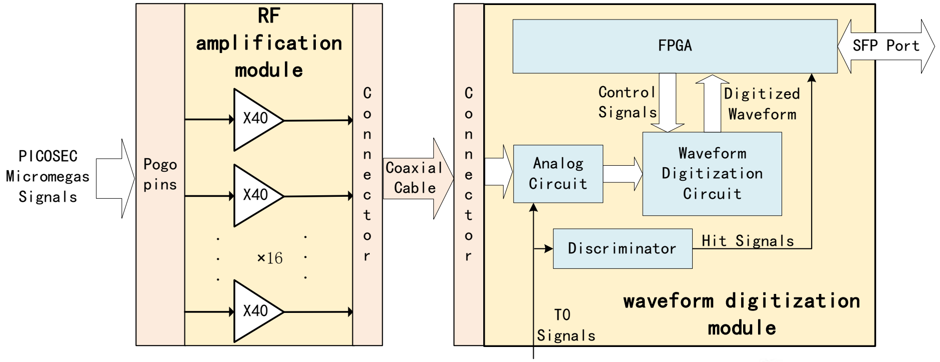




- **Preliminary Test Results:**
  - Gain reach to >10^6
  - Uniformity of σ = 32.3% (shows related to the assembling of crystals in the detector)
  - (@CERN SPS H4 Beam Test, 2024 Apr/Sep) Time resolution with CsI photocathode achieve **σ ≈ 25ps** at the pad's central area
  - Tested with DLC/B4C photocathodes, more analysis of the data is still ongoing

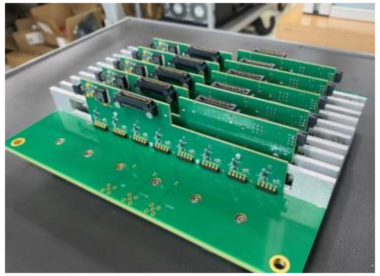
Readout Electronics

➢ Readout Electronics for large-area PICOSEC MM：



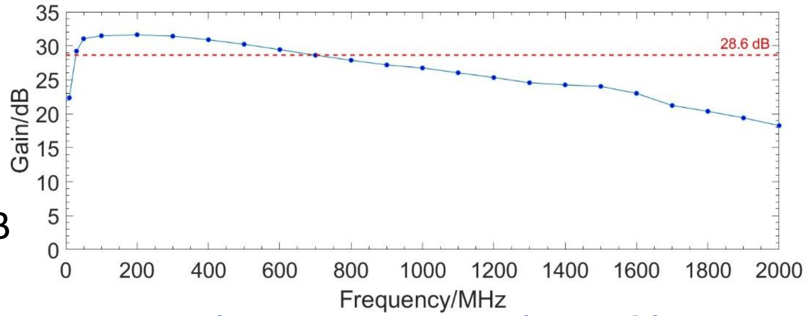
Structure of the prototype readout electronics


RF Amplifier board

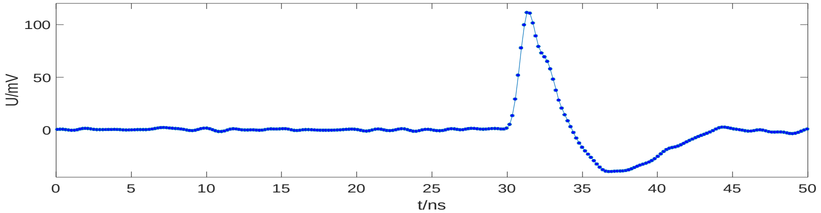

Amplifier connected to PICOSEC


DRS4 based WDM

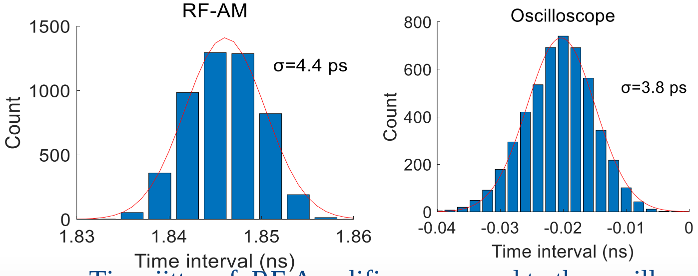
- Custom made **RF Amplifier + DRS4 based Waveform Digitization Module (WDM)**
- 16 channel RF Amplifier on a board, HF -3dB cut-off 700 MHz, LF -3dB cut-off 25 MHz
- DRS4 based WDM with 5.12 GS/s sampling frequency, 950MHz bandwidth
- RF Amplifier connected to the detector with pogo pins, SAMTEC cable to drs4
- Time jitter of the entire electronic ~4.8ps



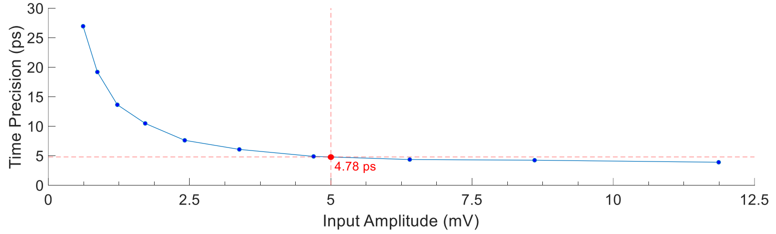
Gain frequency response curve of RF Amplifier



Waveform Sampled by the DRS4



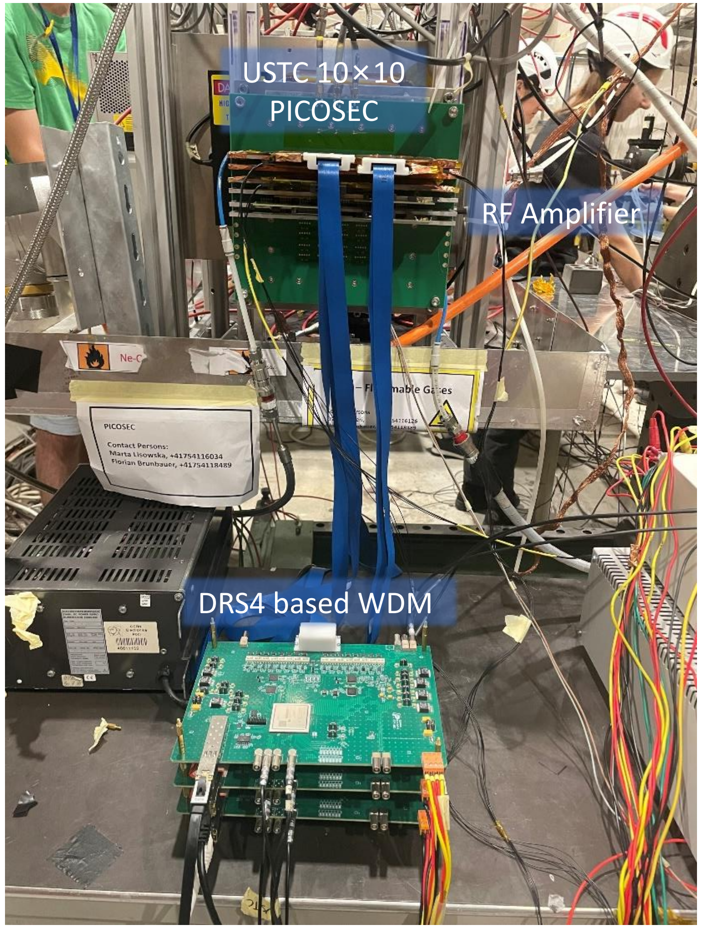
Time jitter of RF Amplifier compared to the oscilloscope



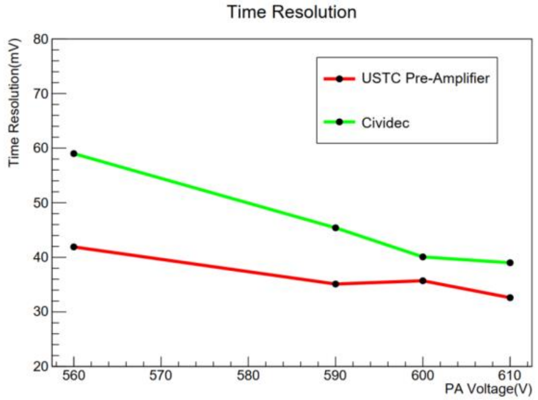
Time jitter of the entire electronic

Readout Electronics

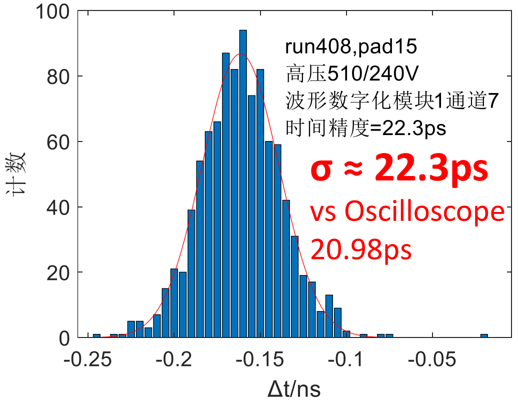
➢ **Results on Beam Tests** (@CERN SPS H4 Beam Test, 2023Jul & 2024Apr)：



- RF Amplifier achieved better time resolution compared to Cividec (due to higher SNR)
- The 10×10 PICOSEC equipped with CsI tested with the entire electronic achieved a time resolution of **22.3ps**, compared to the 21ps obtained by oscilloscope
- The 20×20 PICOSEC equipped with DLC was scanned with 13 pads using the entire electronic at a single run



Test beam results for RF Amplifier vs Cividec



Test beam results for RF Amplifier + drs4 WDM

Pad num.	3	4	5	6	7	8	9
C	40.95	44.29	44.00	48.99	49.77	52.23	50.30
D		36.71	39.50	41.94	49.97	51.86	46.36

Time Resolution scan for 20×20 PICOSEC with DLC photocathode

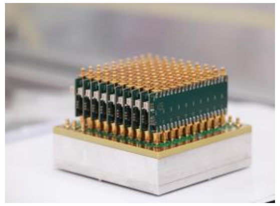
Readout Electronics

➢ Alternative Readout Electronics for large-area PICOSEC MM:

RF Pulse Amplifier + SAMPIC based digitizer

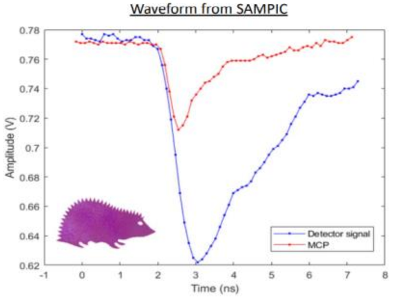
RF Pulse Amplifier

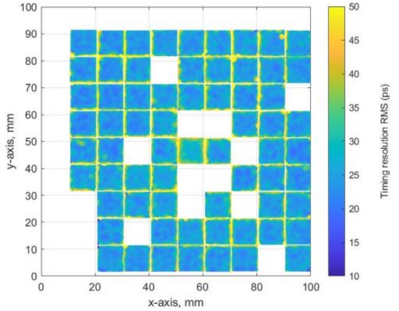
- 10 channel on a board
- Gain 38.5dB @100MHz
- HF -3dB cut-off 650 MHz, LF -3dB cut-off 4 MHz



SAMPIC based digitizer

- 8.5 GS/s sampling frequency
- stacking 16-channel mezzanine modules
- bandwidth 1.6 GHz
- Internal FPGA –algorithms for signal processing

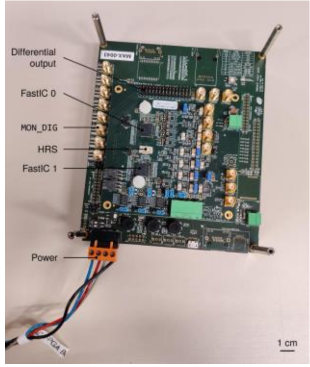


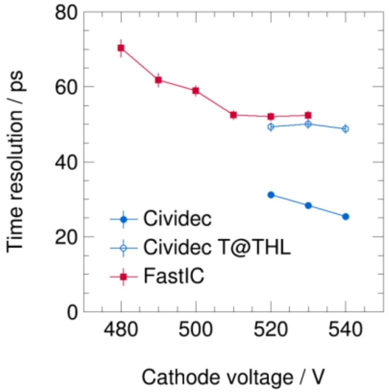


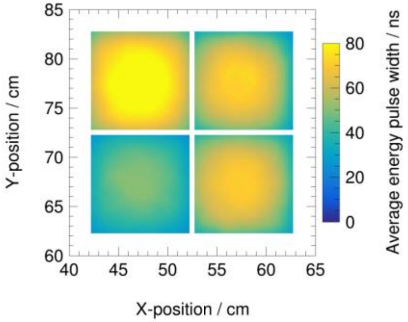
https://indico.cern.ch/event/1219224/contributions/5130512/attachments/2565710/4423222/Marta%20Lisowska%20-%20PICOSEC%20Micromegas%20-%20MPGD2022.pdf

FastIC ASIC

- Positive or negative input polarity sensors with intrinsic amplification
- 8 readout channels
- ~ 2 MHz rate capability per channel with time and energy information
- ~ 50 MHz rate capability per channel with time information only
- Tested with PICOSEC detector @CERN SPS H4







https://indico.cern.ch/event/1327482/contributions/5692915/attachments/2766180/4819415/fastic-and-timepix4_2023-12-06_lucian.pdf

Conclusion

➢ Performance Optimization

- A new single-channel PICOSEC MM detector to achieve **σ ≈ 12.5** ps time resolution.
- Search for Robust Photocathodes: deposition of DLC with magnetron sputtering technique; 1.5 nm **DLC photocathode** yields a time resolution of σ ≈ 32 ps; **B4C photocathodes** exhibited a time resolution of σ ≈ 34.5 ps.
- **Resistive Micromegas:** bulk-MM with 20 $\mathrm{M\Omega/cm^2}$ resistivity and thermal bonding method to fabricate MM.
- Development of PICOSEC based on **μRWELL** technology: obtained 23.5 ps with CsI.
- **Ne/iC4H10** 72:25 (GWP < 1) measured with ~17 ps as alternative gas.

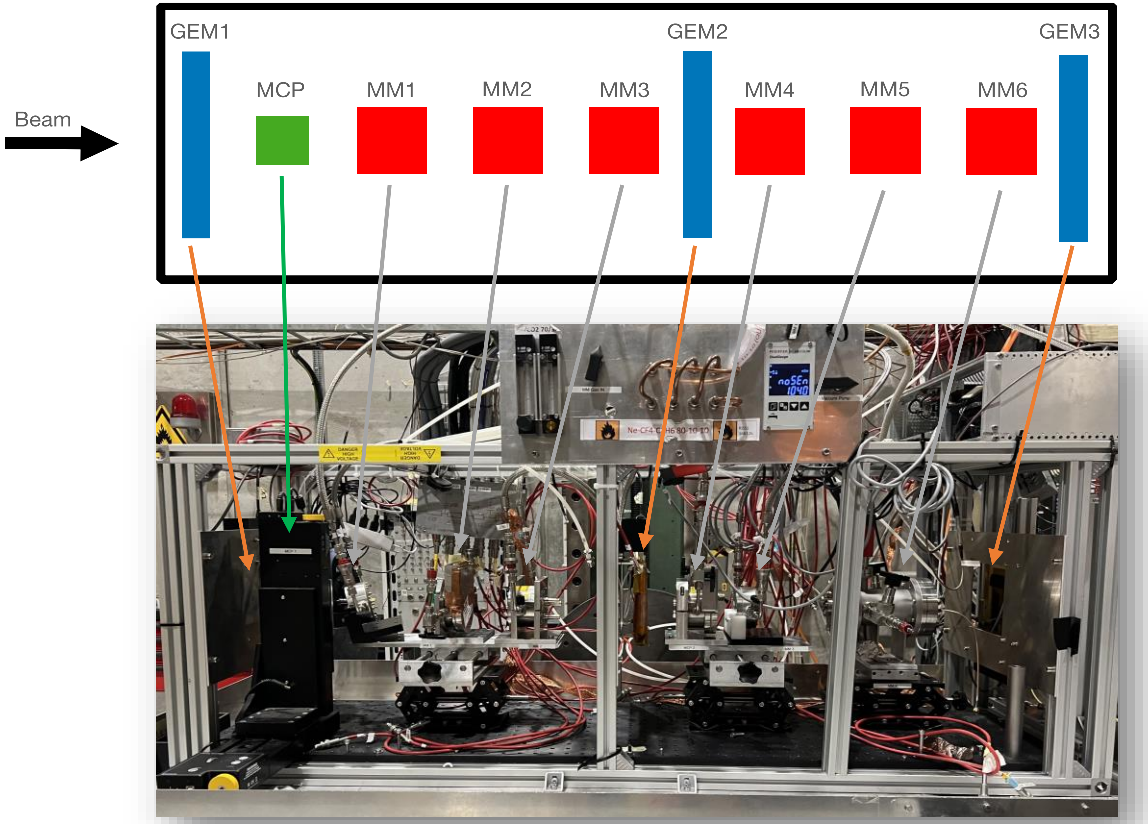
➢ Large-area Development

- Intensive developments on the **10×10 PICOSEC prototype**
- From 10×10 PICOSEC to **20×20 PICOSEC prototype**: design, production, successfully tested with MIP at SPS H4 beamline, yields a time resolution of σ ≈ 25ps on the pad of highest gain with CsI.
- **Readout Electronics:** successfully developed and operated with multi-channel PICOSEC MM, demonstrating good performance.

➢ **R&D still ongoing:** towards large-area application and further optimization……

Thank you for your attention!

Beam Setup



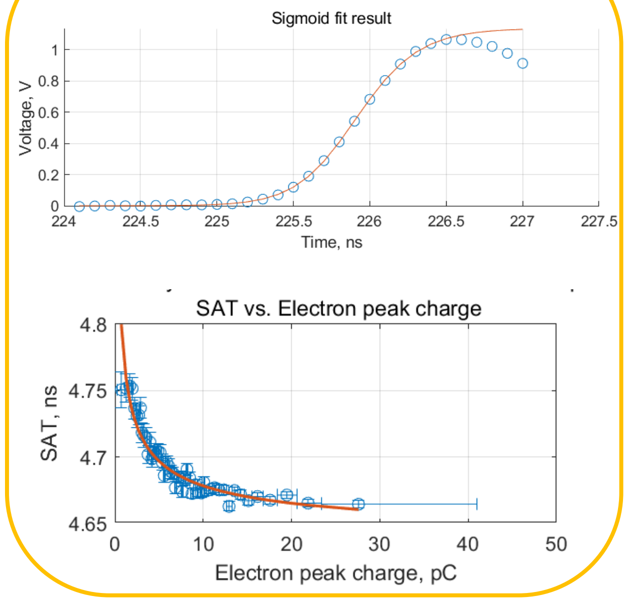
Particle Beams @ CERN SPS H4 Beamline

Timing measurements:

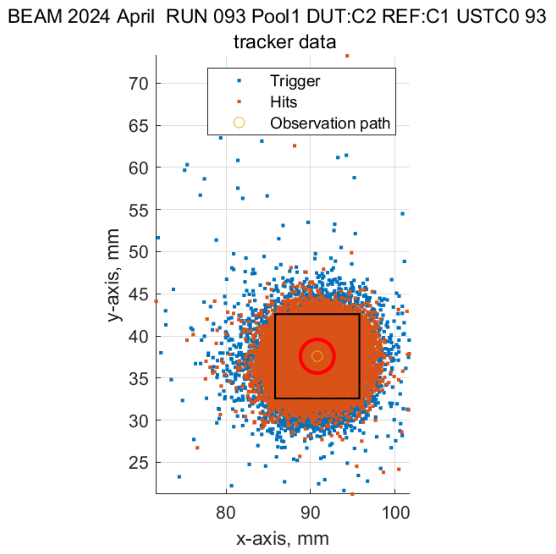
- Muon beam **(80-150 GeV):** 8cm diameter of beam - muons/spill (measured rate ~kHz/)
- 3 triple- GEMs for the tracking
- MCP-PMT as the trigger and **time reference**

Data Analysis

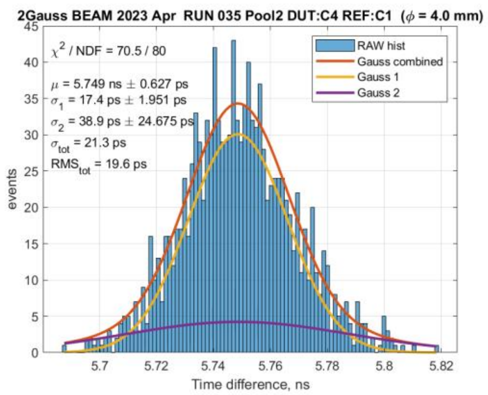
Signal Processing



Position reconstruction



Time Difference



- Reconstruction code from Spyros Tzamarias et al. (AUTh)
- Ported to Matlab (A. Utrobicic et al.) for immediate analysis of acquired data during beam periods

- **Signal Timing**: The PICOSEC detector signal undergoes leading-edge fitting, 20% constant ratio timing, and Time-walk correction.
- **Track Selection**: Selection of events where the Cherenkov ring produced by incident particles is completely within the measurement area of the detector.
- The MCP1 signal serves as a reference time to statistically analyze the time difference distribution between the PICOSEC detector and the MCP1 signal.