PICOSEC
Micromegas

Update on the PICOSEC Micromegas R&D

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on behalf of the PICOSEC Collaboration

2nd FCC Italy & France Workshop

Venice, Italy
4-6 November 2024

Motivation

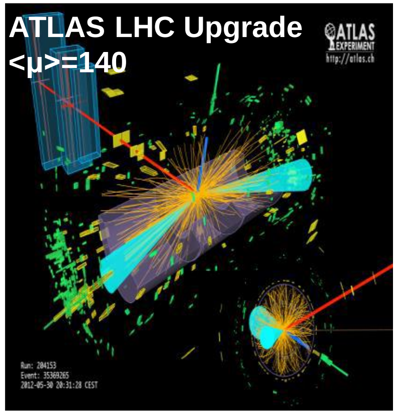
Timing with a few 10’s of Picosecond

- **High Luminosity LHC**:
  - ATLAS/CMS simulations: ~150 vertexes/crossing (RMS 170 ps).
  - Mitigate pile-up background.
  - Clean reconstruction of the events

  ➔ ~20 ps timing + tracking info.

- High demand for precise timing detectors for physics (TOF particle identification), but also for medical and industrial applications

- **Large part the of detector R&D community focuses on timing**



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

Extra detector requirements:
- Large area coverage
- Resistance to aging effects
- Cost efficient

⟷ **MPGDs!**

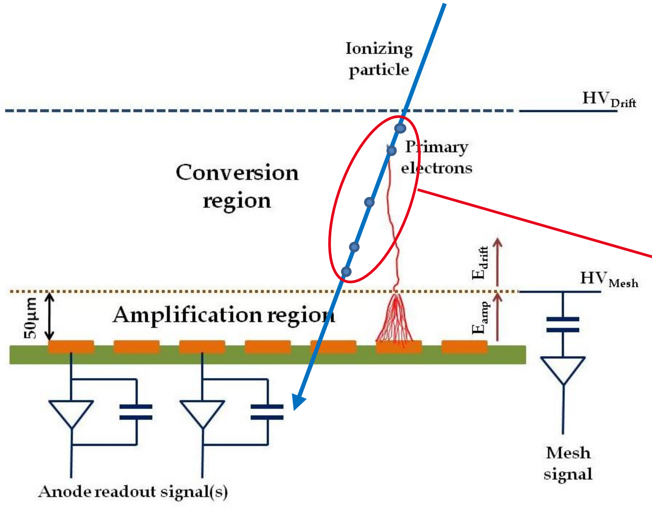
State-of-art

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 ~ 60 ps)

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

Need for improvement >2 orders of magnitude

The PICOSEC Micromegas concept



Can MPGDs reach 𝒪(10ps) resolution for MIPS?

NO !

Timing Limitation factor: *stochastic nature of ionization*

- ~5 mm conversion gap is needed for ~100% efficiency
- Random distribution of ~5 e^- clusters per MIP
- Last cluster position jitter

➔ time jitter of a few ns

Proposal by **Ioannis Giomataris**:

Replace gas ionization by Čerenkov light & use a photocathode to create the primary electrons

➢ *Micromegas had already shown timing resolution <700 ps for single photoelectrons,*

→ possibly limited by deuterium pulsed lamp jitter

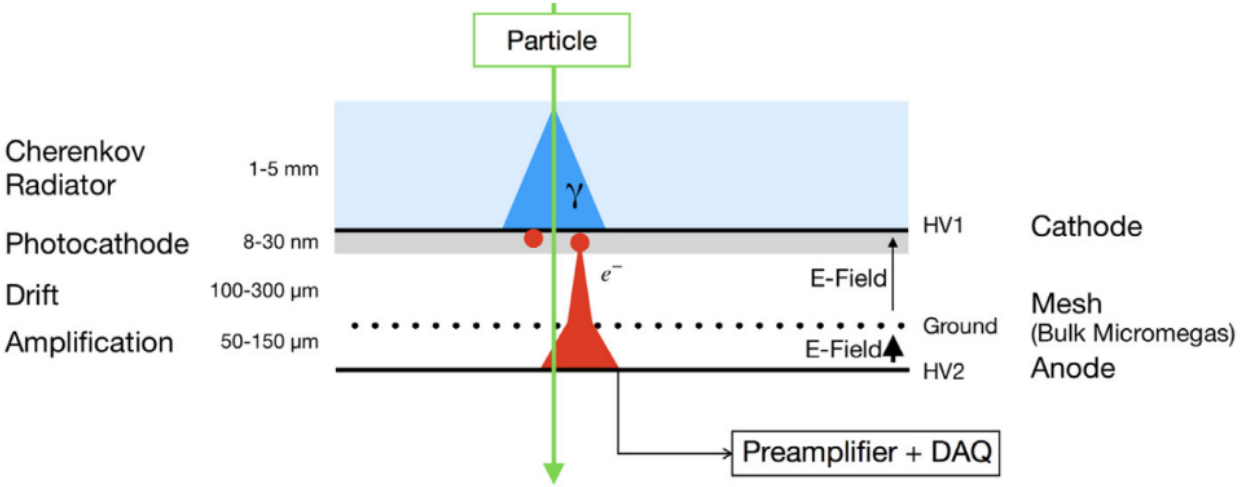
J Derre et al. Fast signals and single photoelectron detection, NIM A 449 (1999) 314

Timing performance could be improved by:

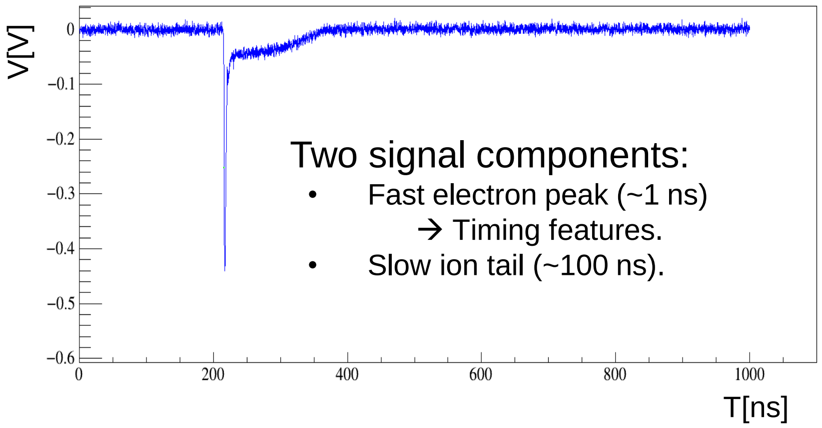
➢ simultaneous creation of primary electrons at the same distance from the mesh

➢ shorten conversion region ➔ limit diffusion, achieve pre-amplification

The PICOSEC Micromegas concept



T. Papaevangelou et al, "Fast Timing for High-Rate Environments with Micromegas", EPJ Web Conf. 174 (2018) 02002, MPGD2015 https://doi.org/10.1051/epjconf/201817402002



- Modification of MM geometry:
  - Smaller Drift Gap → eliminate ionization
  - Higher applied Drift Voltage → pre-avalanche
- Additional Components in MM:
  - Cherenkov radiator
  - Solid converter → Photocathode
    Prompt photoelectrons

- A particle produces Čerenkov light in the crystal.
- Photons extract electrons from the photocathode.
- Electrons multiplied in a two stage Micromegas.

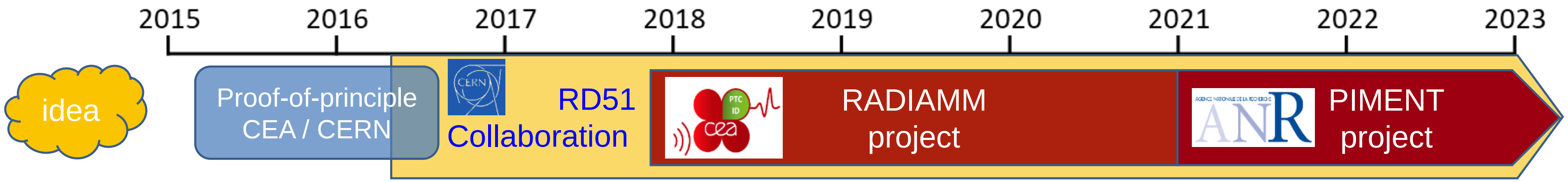
Timing resolution defined by:

☞ **single photoelectron time jitter** (aim < 100 ps)

☞ **Number of photoelectrons** $\left(\sim \frac{1}{\sqrt{N_{p.e.}}}\right)$

→ **efficient photocathode** (aim > 10 p.e. / MIP)

The PICOSEC Micromegas R&D timeline



Project evolution

- 1st phase
  - Conception of first prototypes
  - Proof-of-principle
- 2nd phase
  - Understanding & optimization
  - Photocathodes
  - 1st attempt with multipad detectors
- 3rd phase
  - Large area detectors (10×10 cm^2)
  - Robust photocathodes
  - Resistive anodes
  - FEE & BEE
  - *Towards implementation for physics experiments*

Started as an RD51 common-fund project:

Fast Timing for High-Rate Environments:

A Micromegas Solution

awarded on 03/2015

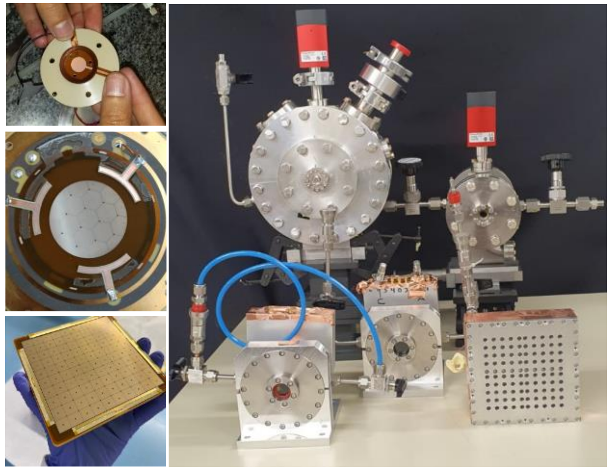
CEA involvement:

RADIAMM: CEA PTC/ID (IRFU - LIST - IRAMIS)

- R&D on the improvement of the PICOSEC Micromegas performance & robustness (*photocathode*)

PIMENT: ANR (IRFU - CENBG - IJCLAB - LIST)

- transfer the well-established detector topology to a larger scale (*electronics, Micromegas etc.*)
- adapt to the specific needs of experiments (ENUBET, EIC, HL-LHC…)



The PICOSEC Micromegas Collaboration

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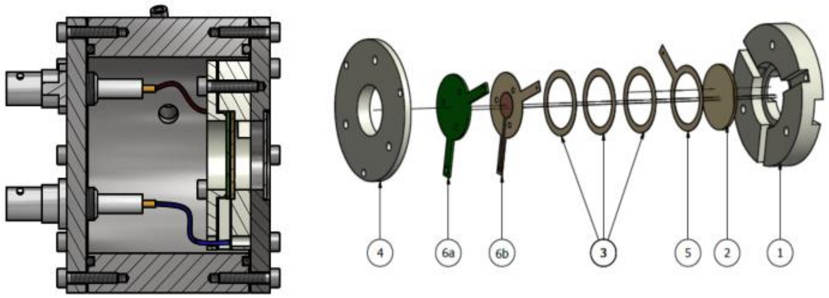
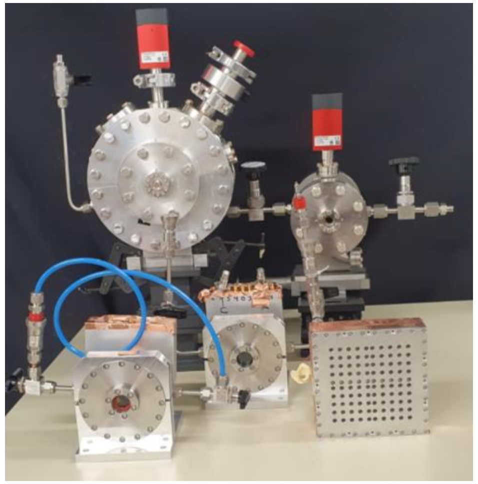
over 50 collaborators

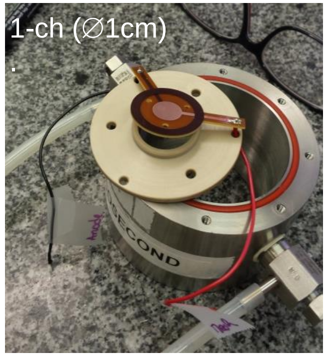
The PICOSEC Micromegas detector

- **Small, single anode prototypes** (~1 cm^2) to:
  - study the PICOSEC concept
  - optimize gas / geometry / voltages
  - test photocathodes with particle beams
- **Large, segmented anode prototypes** (10×10 cm^2) to:
  - prove scalability to large areas
  - study sharing of Čerenkov light among pads
  - study resistive anode technologies
  - develop & test FEE

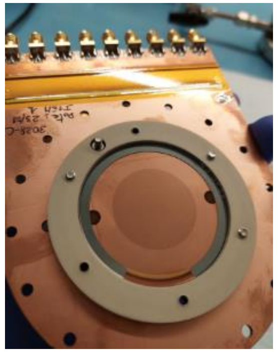




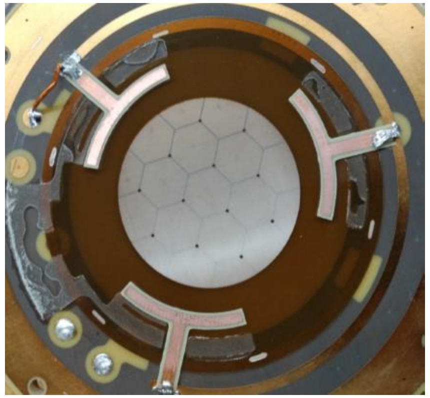
Usual gas mixture: **Ne** + 10% $\mathbf{CF_4}$ + 10% $\mathbf{C_2H_6}$



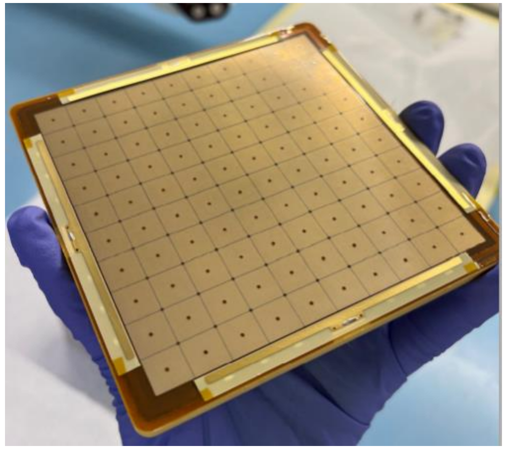
single anode ∅ 1 cm



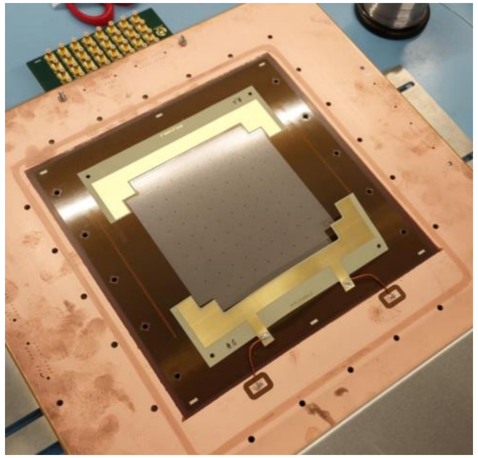
7 channel anode ⬡ 1 cm



19 channel anode ⬡ 1 cm



100 channel anode ☐ 1 cm



96 channel anode ☐ 1 cm

Detector testing: laser beam

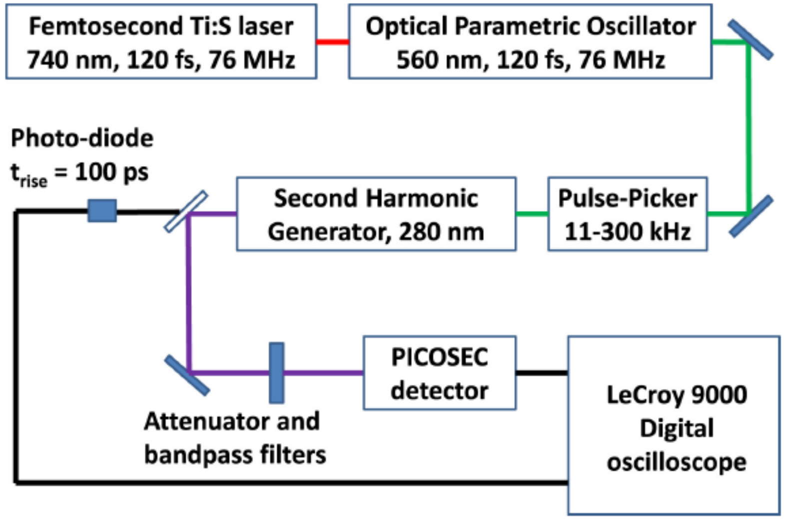
Unique capabilities of the **FLUME** setup at the IRAMIS/LIDYL laser facilities @ CEA Saclay:

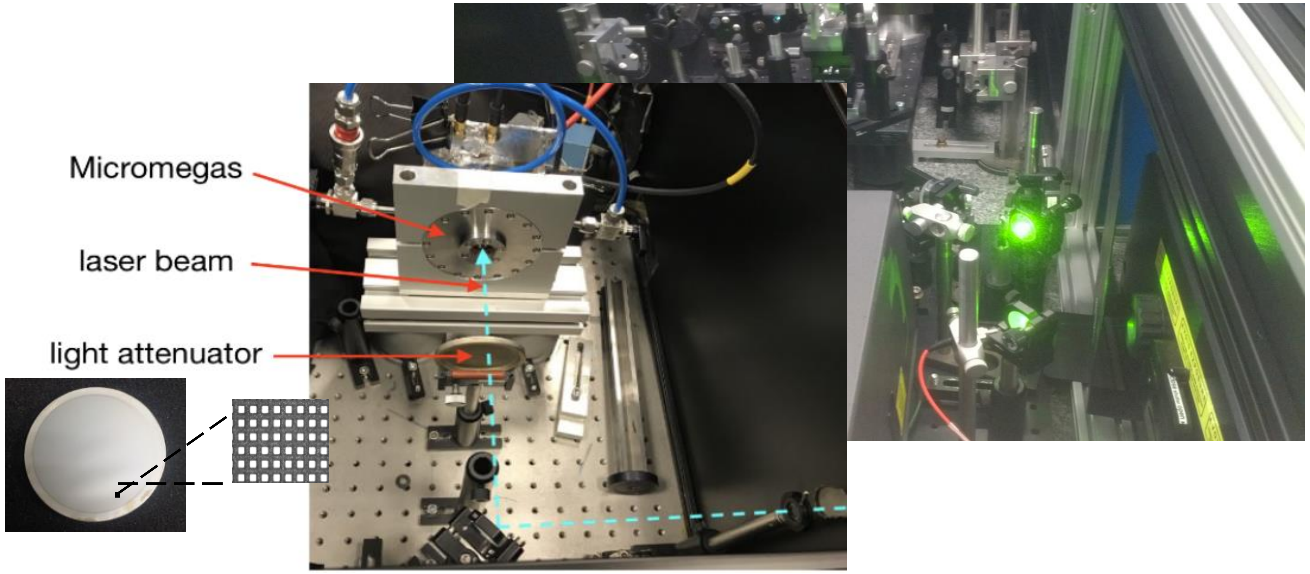
➔ ***Study the single photoelectron timing** performance*

➔ ***Understand** and **optimize** the detector*

FLUME setup:

- IR Ti:S laser with pulse width **120 fs**
- **λ = 267-285 nm** after doubling
- Energy ~ 10 -100 pJoule / poulse
- Spot size: ~1 mm^2
- Repetition 9 kHz – 4.75 MHz
- Light attenuators (fine micro-meshes 10-20% transparent)
- t_0 reference: fast PD (**σ_T~10 ps**)





Detector testing: particle beams

Particle Beams @ CERN SPS H4 Beamline

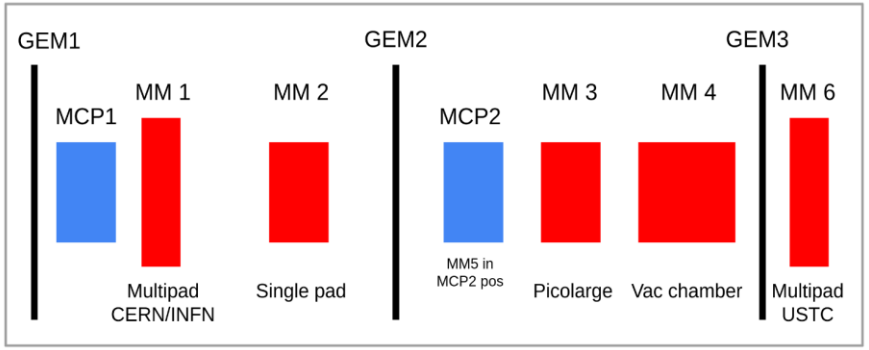
- Muons (80-150GeV)
  - 8cm diameter of beam
  - 10^5muons/spill (measured rate ~kHz/cm^2)
- Pions, electrons (30-80GeV)

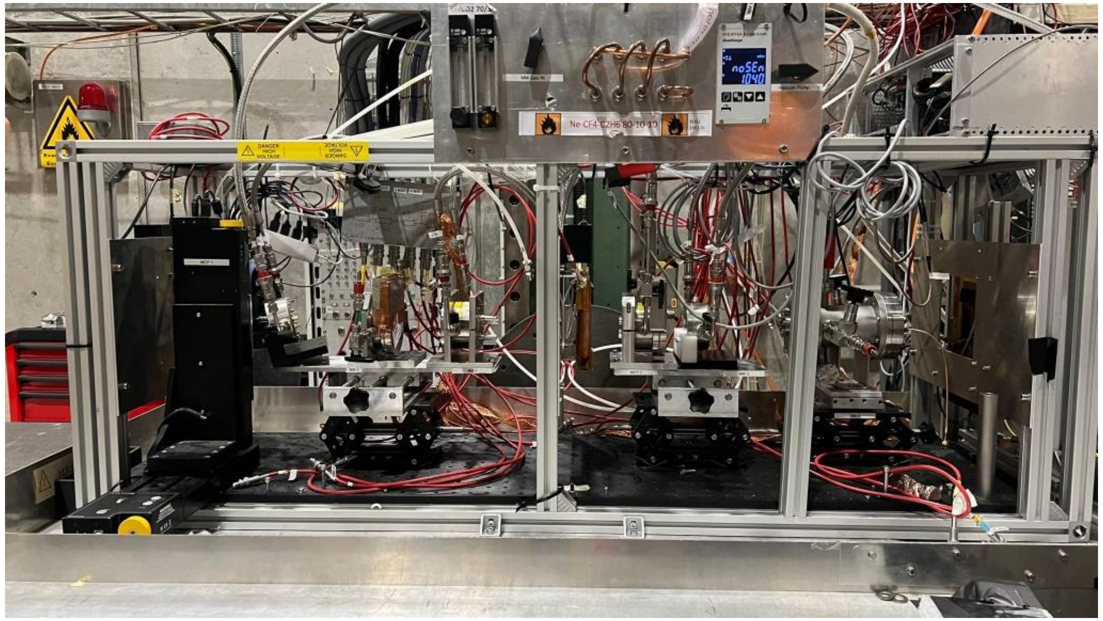
➢ Evaluate prototype performance:
  - Time resolution
  - Detection efficiency

➢ Photocathode efficiency ($\langle N_{p.e.} \rangle$ / MIP)

➢ Test homogeneity / border effects

➢ Light / charge sharing





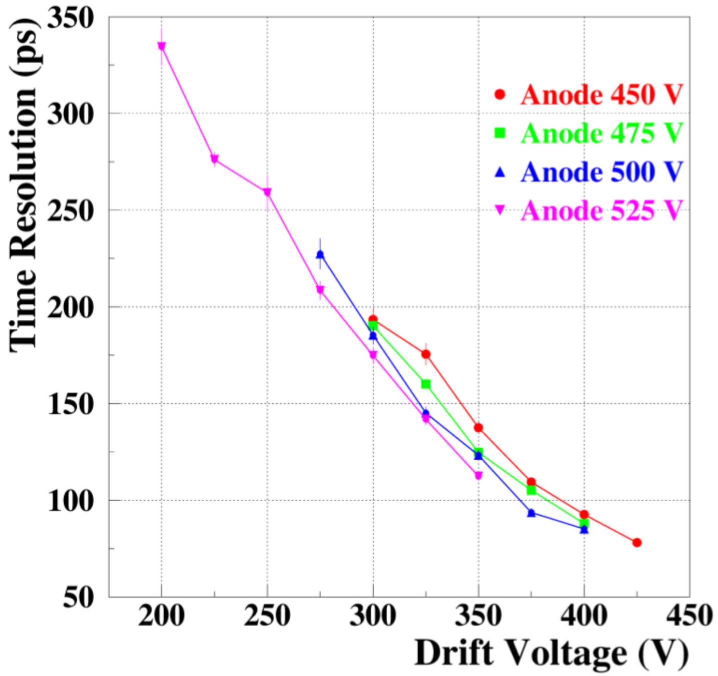
The setup

- Tracking telescope with GEMs
- MCP PMTs as t_0 reference devices & triggering
- Several positions for prototype testing

1st phase: proof-of-principle

2015-2017

Laser

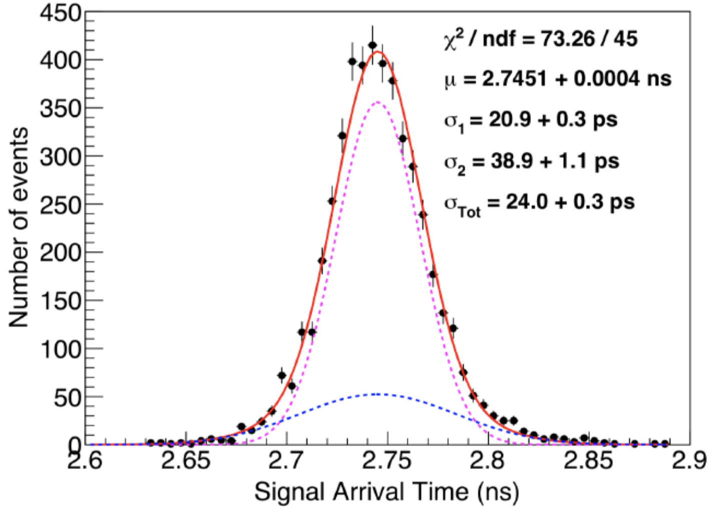


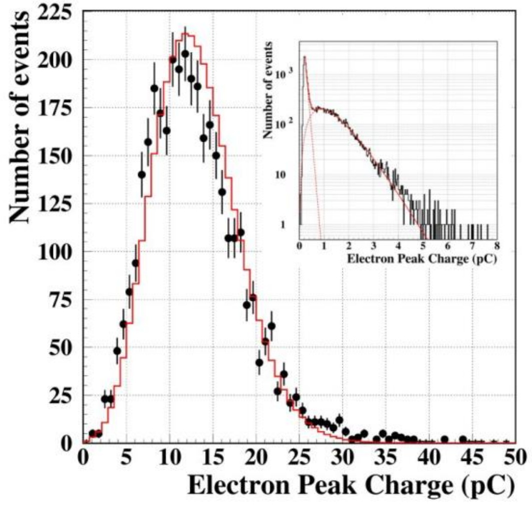
Best time resolution for 1 photo-electron:

76.0 ± 0.4 ps (V_d/V_a = -425V / +450V, 200 μm drift)

➔ *improves strongly with higher drift field,*
less with anode field

Particle beam





Best result: **24 ± 0.3 ps**

$\langle N_{p.e.} \rangle$ = **10.1 ± 0.7**

- Single anode prototype
- MgF_2 radiator 3 mm thick,
- 18 nm CsI on 5.5 nm Cr
- 200 μm drift gap
- Bulk MicroMegas
- “COMPASS gas”
- V_{drift} / V_{anode}: -475V / +275V

J.Bortfeldt, et al., “PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector”, NIM A 903 (2018) 317 https://doi.org/10.1016/j.nima.2018.04.033

2nd phase: understanding the detector

2018-2021

Main findings:

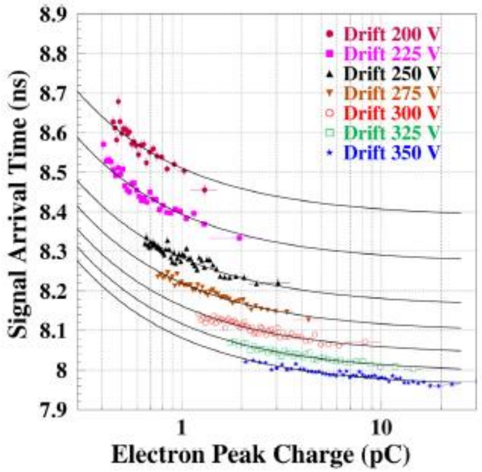
SAT time walk seen in single pe data is explained:

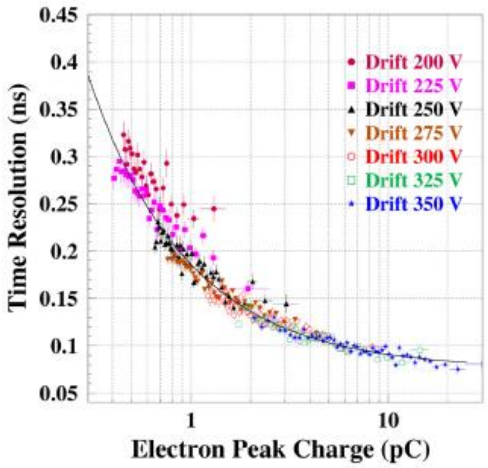
- SAT reduces with avalanche length
- Long avalanches → big e-peak charge
- **SAT reduces with e-peak charge**

SAT & Timing resolution are determined by:

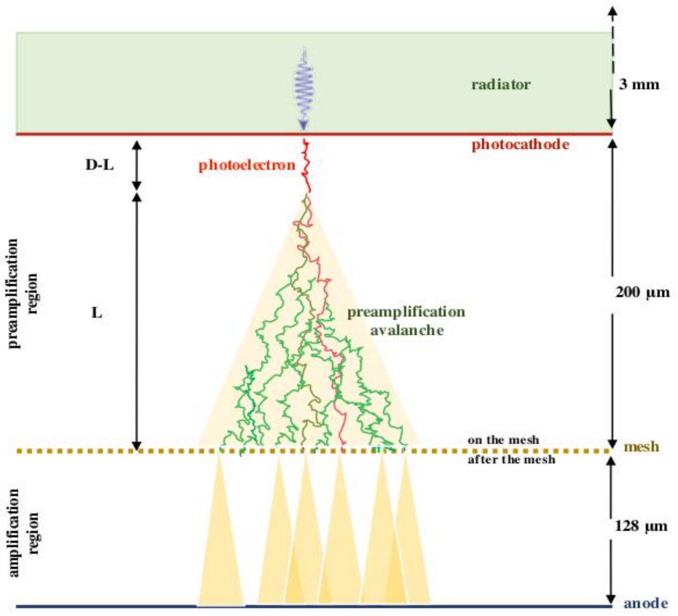
- The drift path of the primary photoelectron

→ number of photoelectrons in avalanche and its length

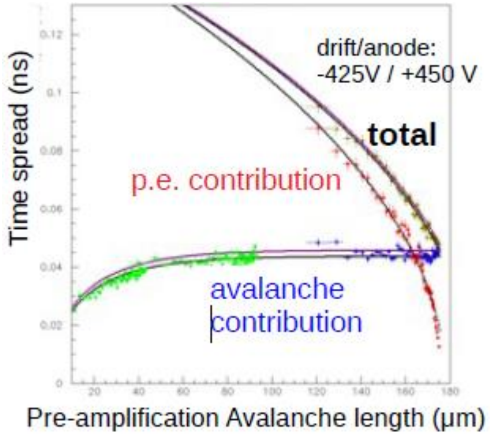


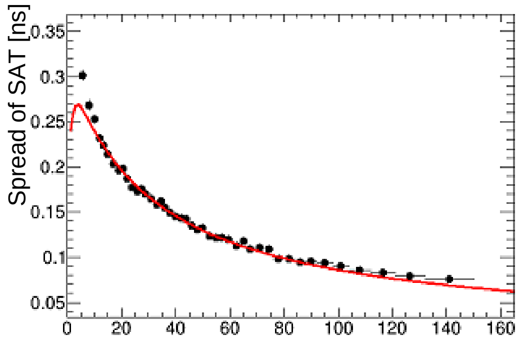


Detector modeling



J.Borteldt, et al. “Modeling the timing characteristics of the PICOSEC Micromegas Detector”, Nuc. Instrum. Meth. A (2021)
https://doi.org/10.1016/j.nima.2021.165049





Time spread of SAT defined by the avalanche length = avalanche size

☞ ideal amplification gap ➔ Optimization of the preamplification avalanche ➔ improve timing

2nd phase: detector optimization

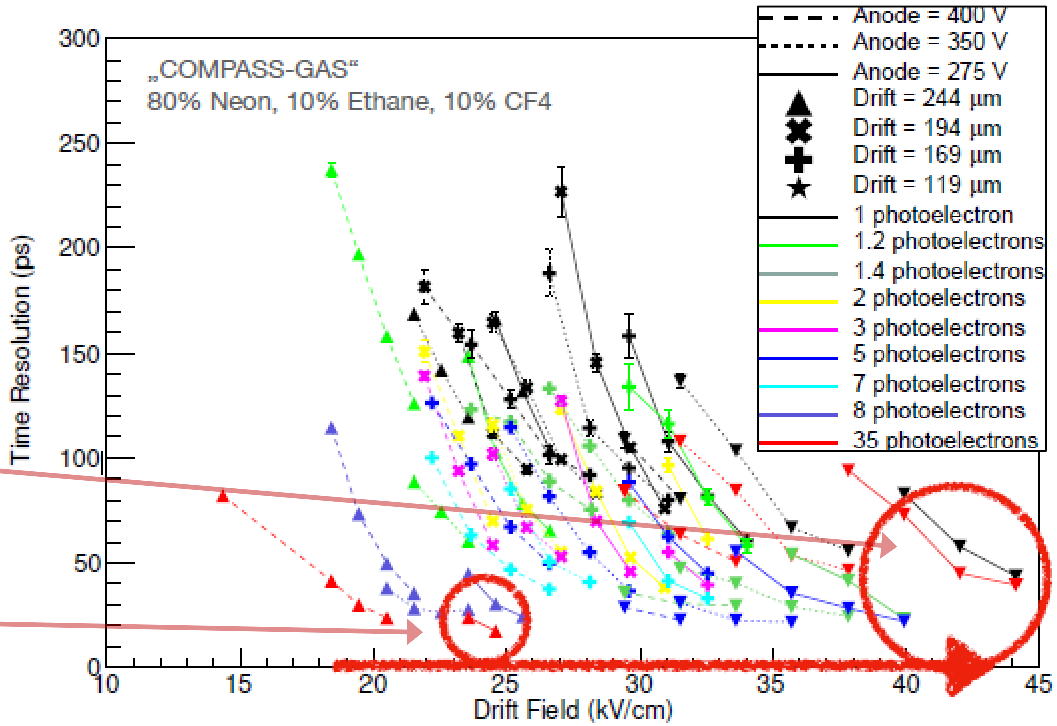
2018-2021

Detector optimization:

- ➢ Field ratio / strength
- ➢ **Drift gap (120 – 250 μm)**
- ➢ Gas composition
  (best performance for Ne + 10%C_2H_6 + 10%CF_4)

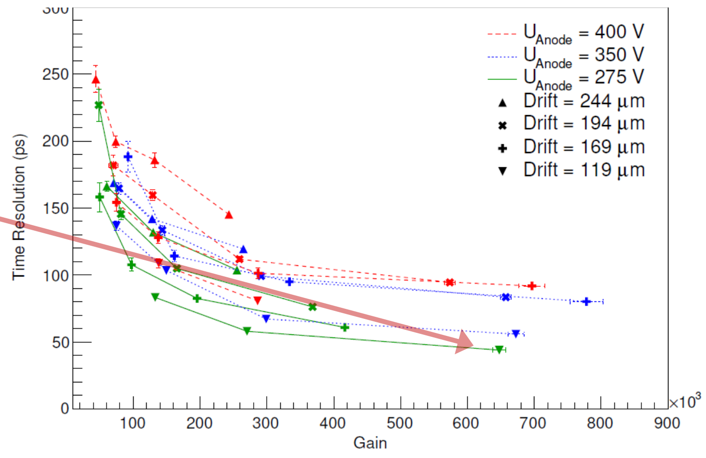
Time resolution < 50 ps is observed
for single photoelectrons !!!

Time resolution ~ 10 ps is possible for high number of photoelectrons in modest field conditions



Best time resolution for 1 photo-electron: 44.0 ± 1.0 ps

@ V_d / V_a = -525V / +275V, 120 μm drift gap

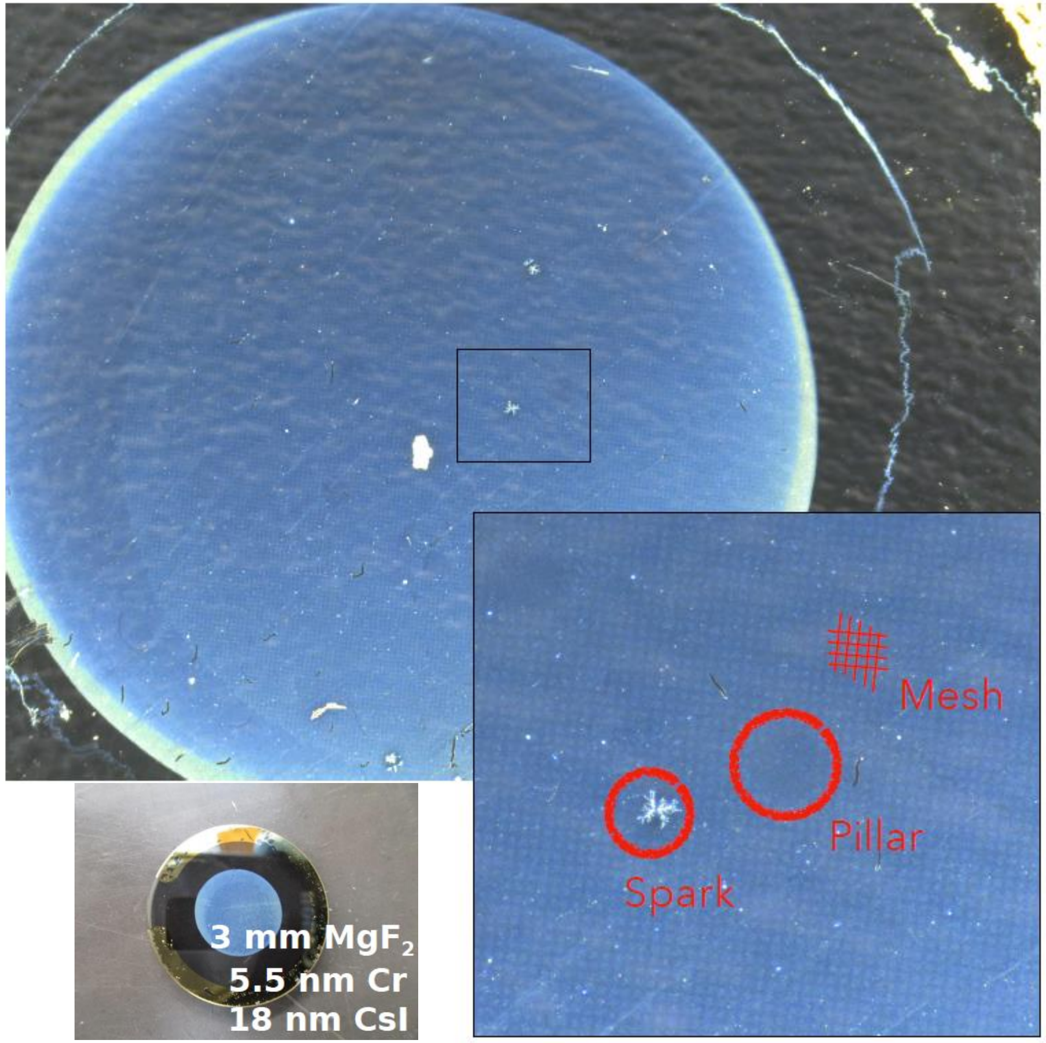


Sohl Lukas, "Development of PICOSEC-Micromegas for fast timing in high rate environments", PhD Thesis, CEA Saclay 17/12/2020, https://www.theses.fr/2020UPASP084

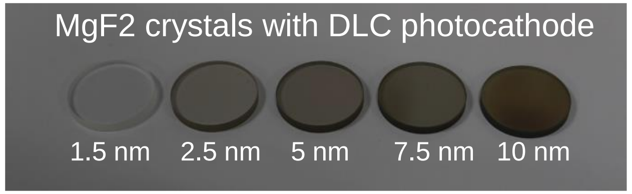
2nd phase: the photocathode issue

2018-2021

A typical CsI photocathode used in a test beam



- Difficult handling & storage due to **high hydrophobicity**
- Photocathode is damaged during intense pion beams: **sparks**, **high ion backflow** (25-75% for high drift fields)



Xu Wang et al, proc MPGD2019

R&D in two directions:

New photocathodes

- Diamond-Like Carbon (DLC) or Boron Carbide (B4C)
- Polycrystalline Diamond or thick diamond films as electron emitters (*M. Pomorski*)
- Pure metallic (Al, Cr, …)

Photocathode protection

- Protection layers (LiF, MgF2,…)
- New detector structure: double mesh Micromegas

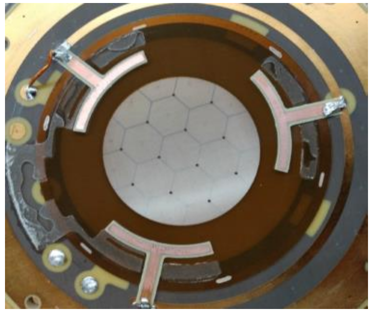
➔ Important: **improve resolution** for **single photoelectrons** through **detector optimization**

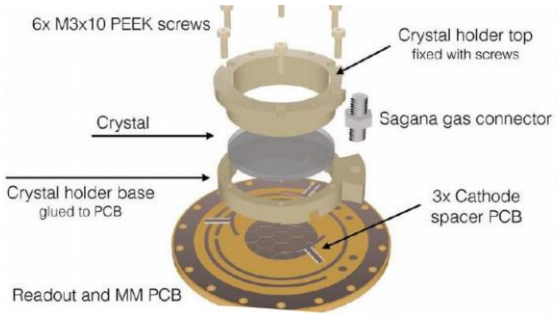
2nd phase: Scalability ↔ planarity

2018-2021

The importance of planarity

- 19-hexagonal pad prototype,
- MgF_2, CsI, 200μm drift gap

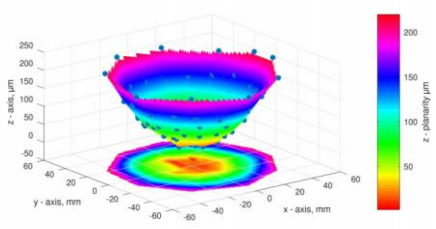


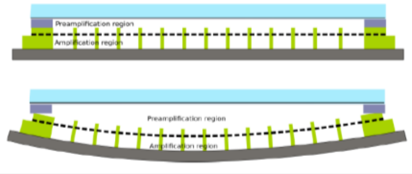


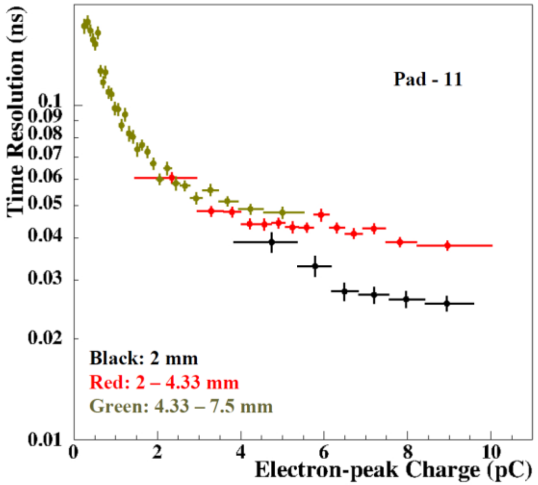
Variation on timing resolution & gain:

- Among different pads
- Along a single pad area

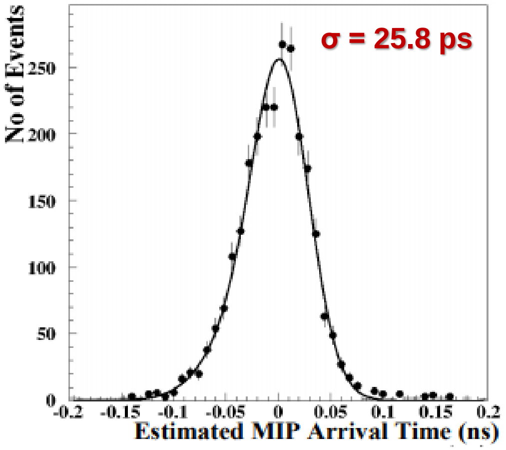
➔ Non uniformity of the drift field gap

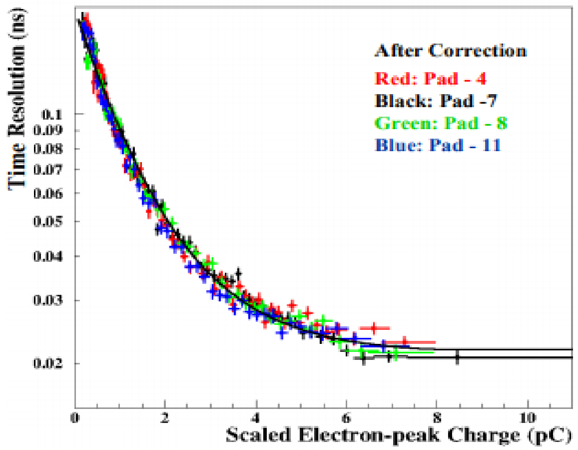


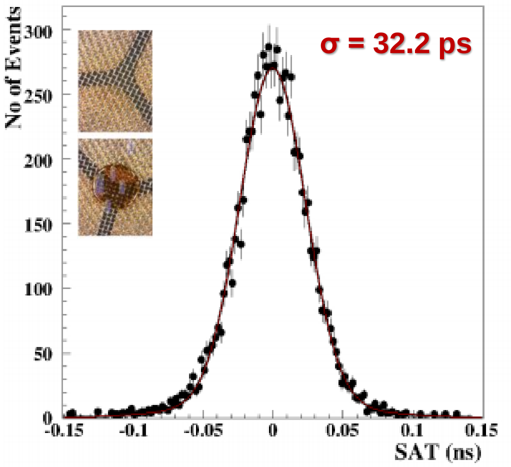




Fully contained tracks
R<2mm from the center of any pad







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

S. Tzamarias, AUTH

Ongoing Development (3rd phase)

2021-2024

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

Scalable MM Detector

- Prove the performance in a multichannel setup
- Flatness (Planarity < 10μm)

Pixelated readout

Development of front-end & back-end readout electronics for the prototypes

Robustness & Efficiency

- Research on various photocathode materials (Replace CsI with B4C, DLC,…)
- Resistive anode technologies

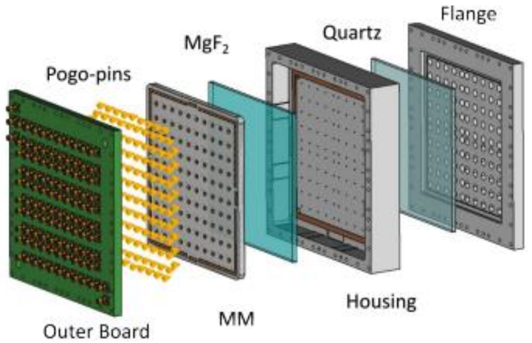
Application in ENUBET (LP2I Bordeaux/ CEA/ Auth)

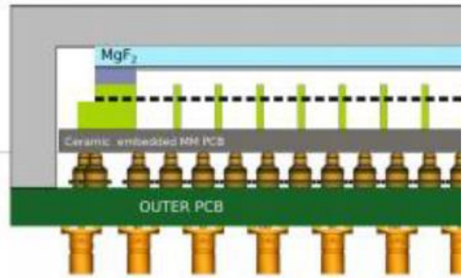
- *T0 tagger and/or embedded in a calorimeter*
- *Muon monitoring at the hadron dump*

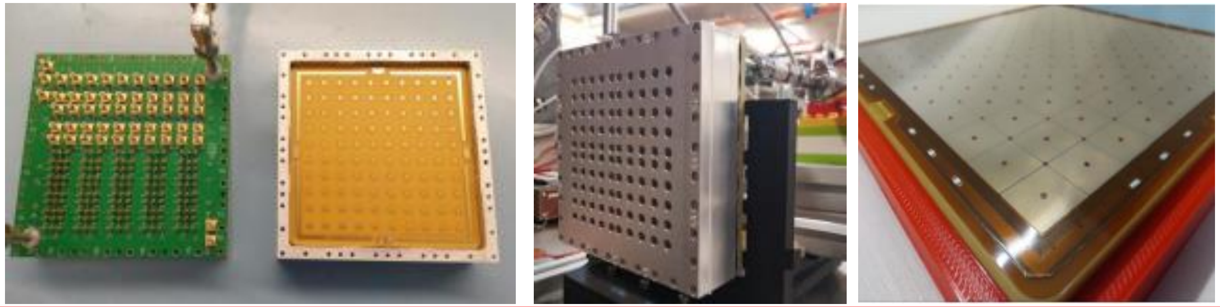
Scalability → importance if planarity

2021-2024

- Three possible approaches for modular prototypes with 10x10 cm^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

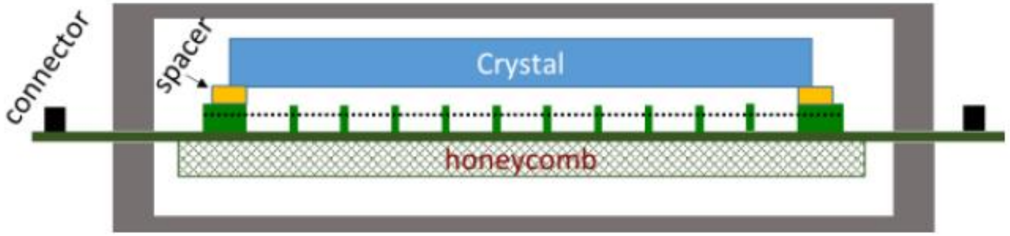






Operational since 2021 (CERN-GDD). Similar approach for:
- **thermal bonding Micromegas** (USTC)
- **micro-Rwell** (Jefferson Lab)

- **The ATLAS NSW Approach**

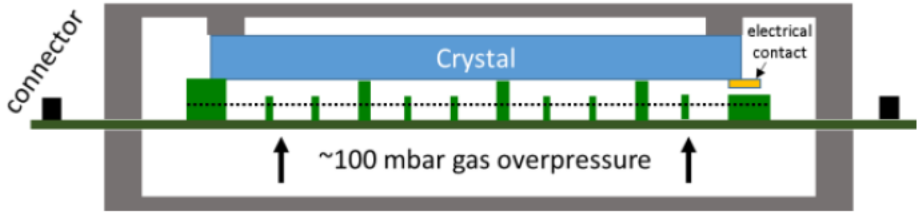


Risk to damage the bulk MM

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

Commissioned July 2024 (CEA)

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

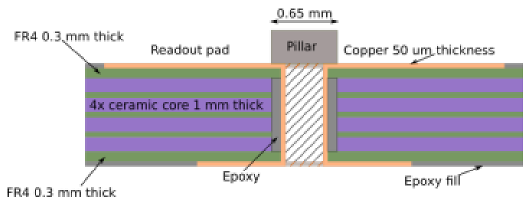


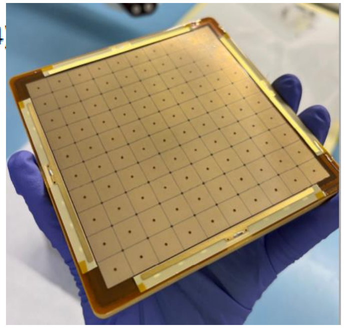
Risk to damage the photocathode

10x10 cm^2 PICOSEC Micromegas (CERN)

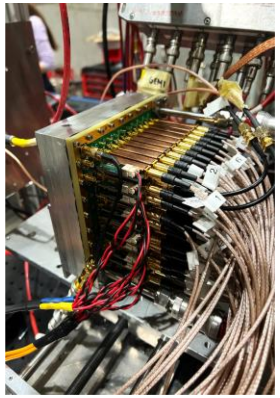
2021-2024

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





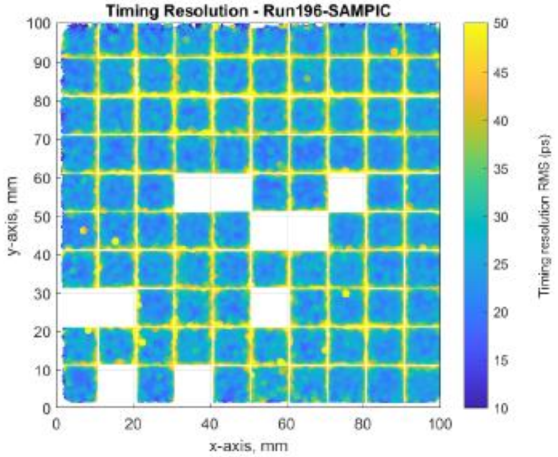
100 channel anode □ 1 cm



Performance:

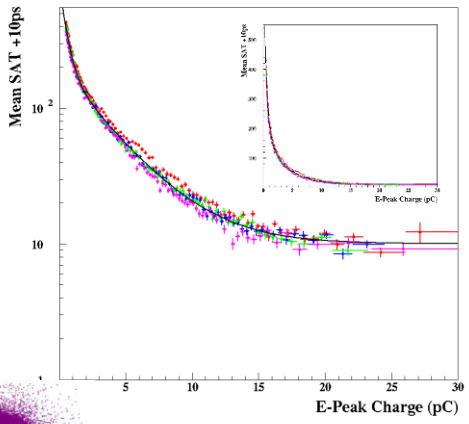
- 180μm drift gap
- CsI photocathode
- **Timing resolution ~17ps**
- Uniform over all area

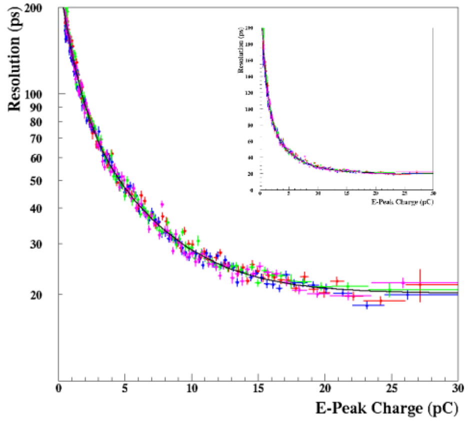
Resolution homogeneity

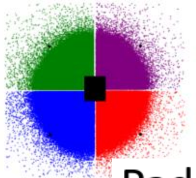


A. Utrobicic et al. "A large area 100-channel PICOSEC Micromegas detector with time resolution at the 20 ps level", *JINST* 18 (2023) 07, C07012, https://doi.org/10.1088/1748-0221/18/07/C07012

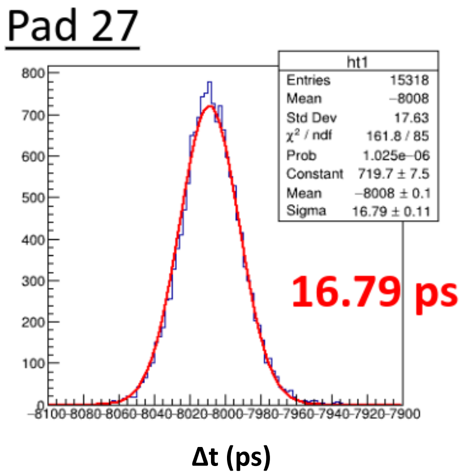
"Global" behavior ➔ excellent homogeneity

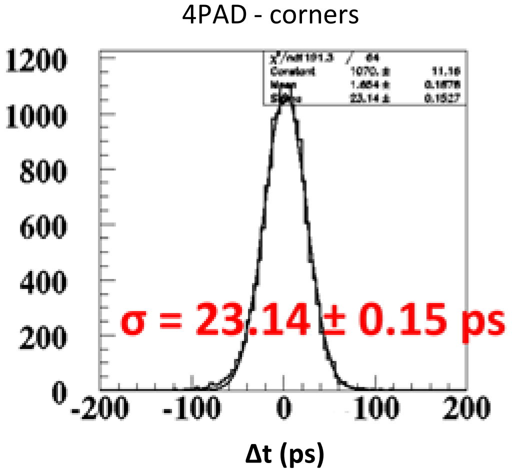






Recovering the resolution in the common corner for signal-sharing events.

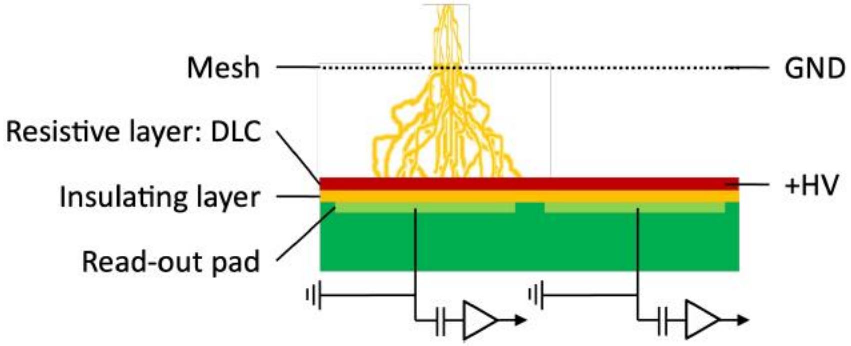


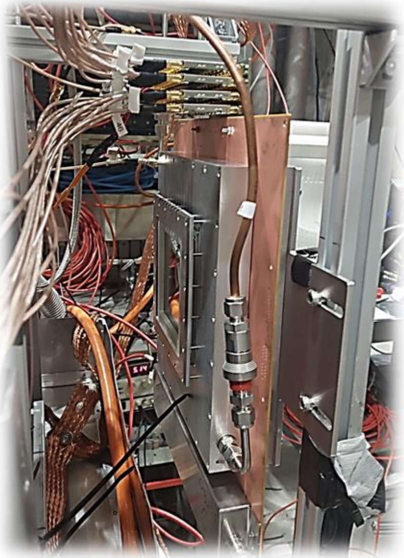


Y. Angelis, E. Chatzianagnostou, I. Maniatis, S. Tzamarias, AUTH

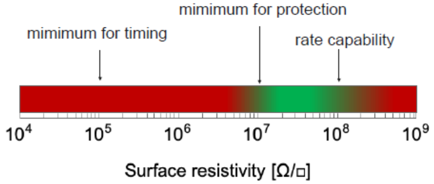
Resistive anodes

- Advantages of the resistive technology
  - ➢ Elimination of destructive effects of discharges
  - ➢ Stable operation in harsh environment (high flux, mixed particle field)
  - ➢ Improve position reconstruction





Optimize resistive anode technology maintaining good timing resolution



- Different prototypes (single pad – 100 pads)
- Different technologies (resistive DLC foils / double DLC layers / capacitive sharing, resistive micro-Well)

➔ Focus on Timing properties

- Testing different resistivity values & architectures
- Ensure the homogeneity of prototype response over the full area
- Spatial resolution studies

*Resolution **<20 ps** with CsI photocathodes has been reached*

M. Lisowska et al. “Towards robust PICOSEC Micromegas precise timing detectors”, JINST 18 (2023) 07, C07018: https://doi.org/10.1088/1748-0221/18/07/C07018

- First tests in 2018 → OK *(L. Sohl thesis)*
- Detailed modeling *(D. Janssens thesis)*
- Optimization of resistivity (*M. Lisowska thesis*)
- Testing different resistivity values & architectures
  - Ensure the homogeneity of response
  - Spatial resolution studies *(A. Kallitsopoulou ongoing)*
- **Implementation on 100-pad prototypes**
  - CERN
  - CEA (thin PCB)
  - USTC (thermal bonding MM)
  - JLAB (μRwell)

Large area, resistive anode detectors

Several pads of the 100-channel module (CERN) were characterised during particle beam measurements

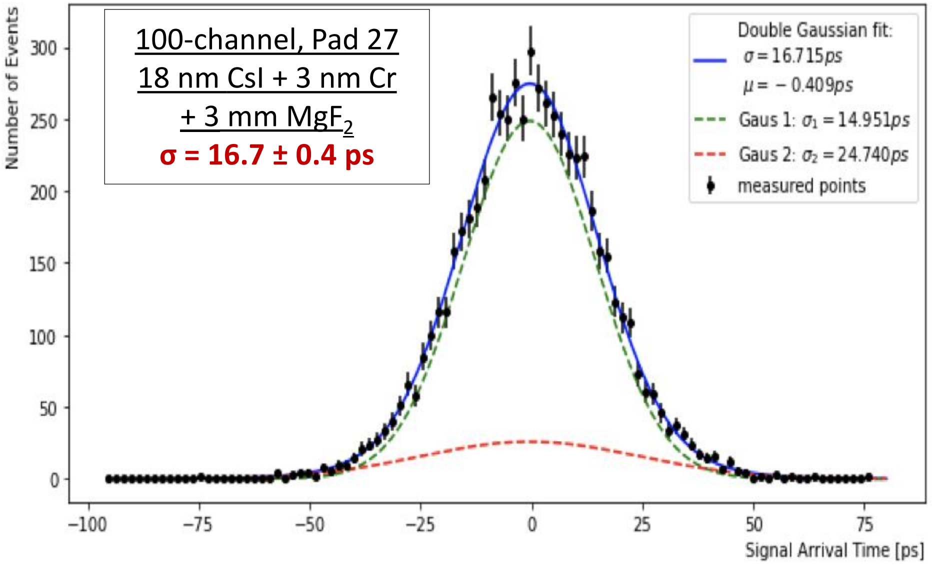
Prototype equipped with

- **CsI photocathode** achieved time **resolution** of **σ < 18 ps**
- **DLC photocathode** achieved time **resolution** of **σ < 35 ps**

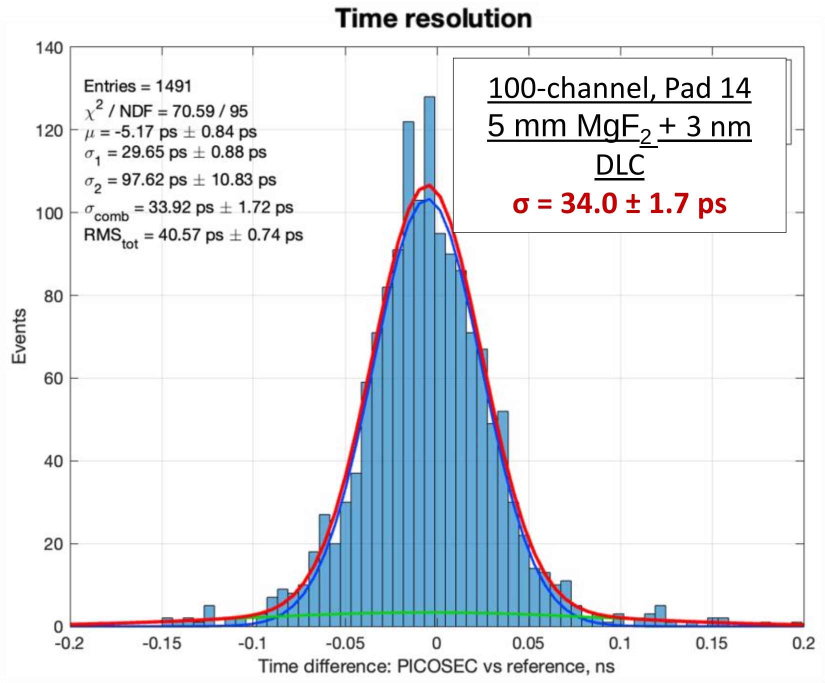
for individual pads and fully contained events

Spatial resolution testg:

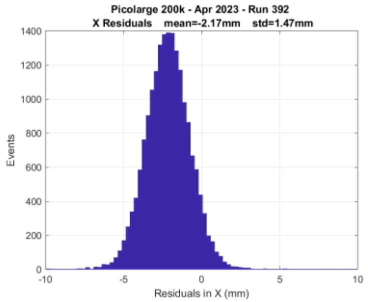
- *7-pad prototype*
- *with hexagonal pads*
- *200kΩ/◻*
- *B4C photocathode*



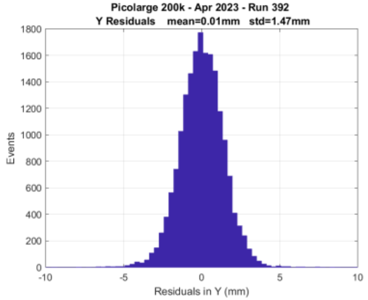
E. Chatzianagnostou, MsC Thesis, 2022



M. Lisowska, PhD thesis dissertation, 2024



σx = 1.47mm

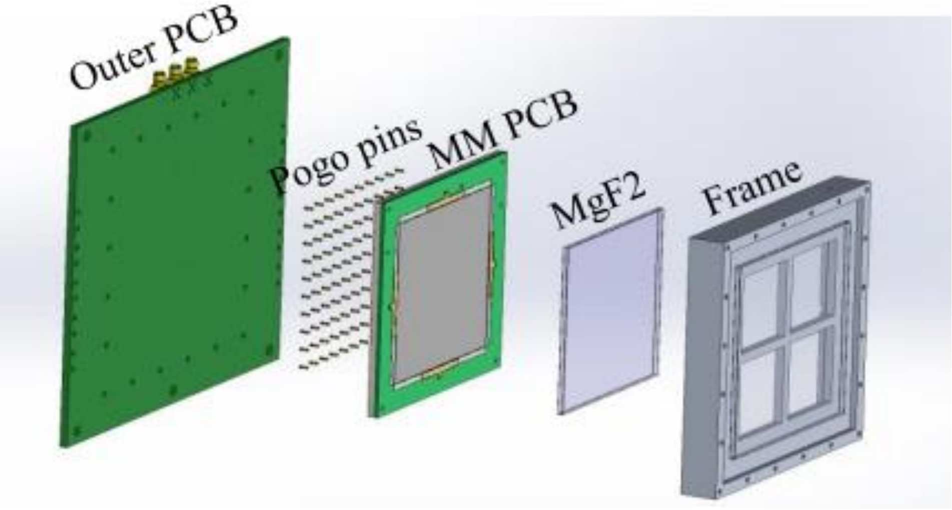


σy = 1.47mm

A. Kallitsopoulou, preliminary

Thermal bonding Micromegas (USTC)

Design Scheme of the 10×10 PICOSEC MM (USTC)

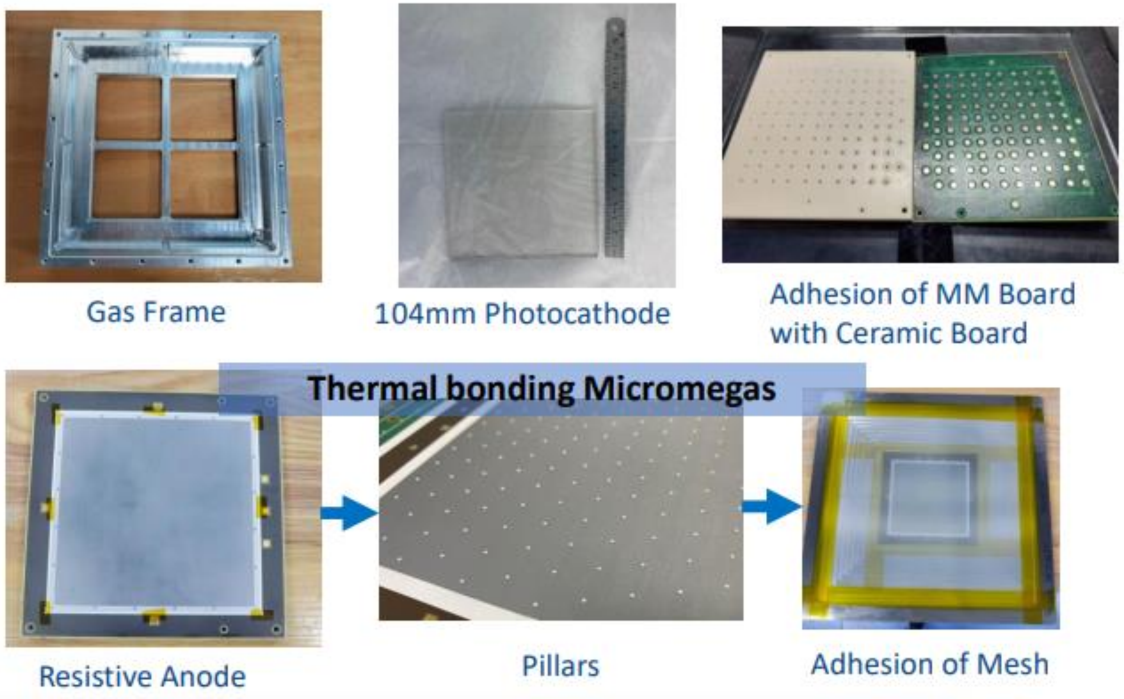


- 100 channels of 1cm*1cm pads
- 104×104 mm^2 MgF_2 crystal as photocathode
- Resistive Micromegas with **germanium coating**

Y. Meng *“PICOSEC Micromegas Precise-timing Detectors Towards Large-scale Application and Optimization”*, *MPGD 2024*, https://indico.cern.ch/event/1453371/contributions/6146437/

Manufacturing the 10×10 PICOSEC MM (USTC)

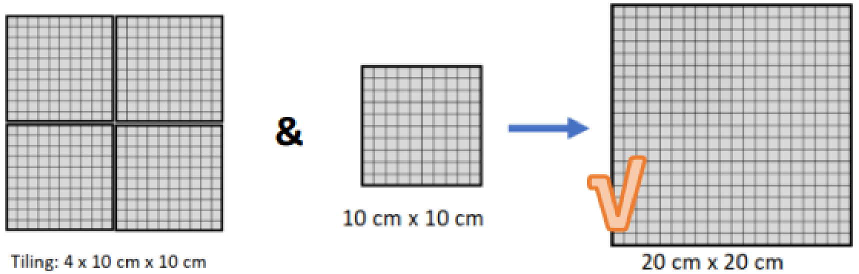
- Magnetron sputtering technology to coat DLC
- Thermal bonding Method for making resistive Micromegas (Resistivity~ 50 MΩ/sq)
- Adhesion of MM Board with Ceramic Board to ensure mechanic strength



Thermal bonding Micromegas → 20×20 cm^2

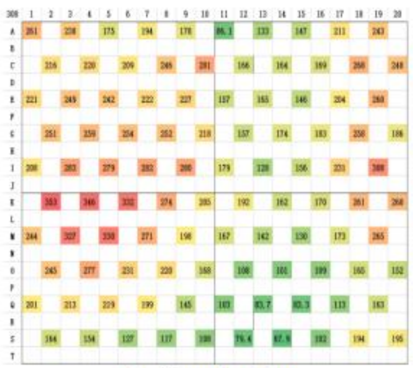
2 approaches towards 20×20cm^2:

- Tile of 10×10 cm^2 modules
- Tile of 10×10 cm^2 crystals on large MM board.

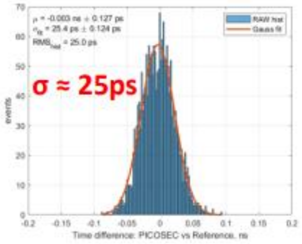


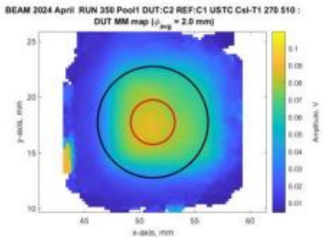
Tested at SPS H4, Sep. 2024. Preliminary performance:

- Gain **>10^6**
- Uniformity of **σ = 32.3%** (assembling of crystals in the detector)
- Time resolution with **CsI** photocathode: **σ ≈ 25ps** (pad's center)
- Tested with DLC/B4C photocathodes, analysis ongoing

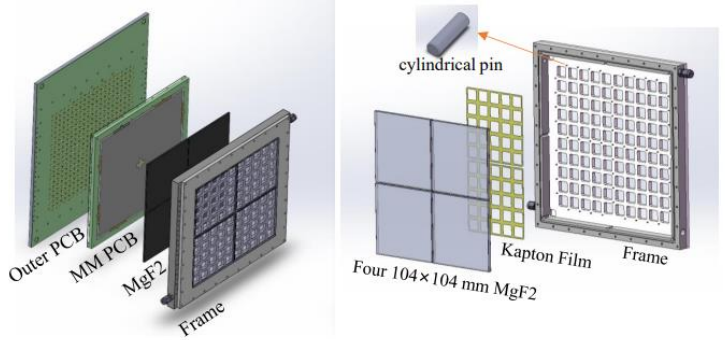


Uniformity Map

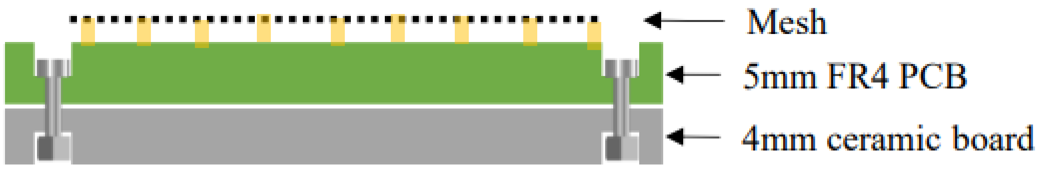




Design of the 20×20 PICOSEC MM (USTC)



- Structure similar to that of the 10×10 PICOSEC MM
- Assembling of 4 104×104×3 mm^3 MgF_2 as radiator
  - MgF2 crystals placed directly on the frame with cylindrical pins (Φ1.5) for positioning
  - Kapton films (12.5μm) to compensate for thickness variation
- FR4 board bonded with a ceramic plate, and screws added on the edge to further strengthen

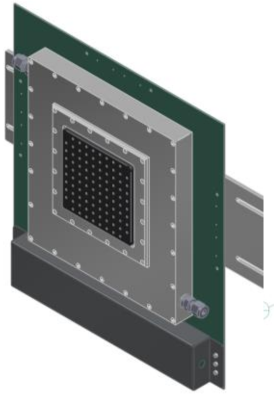


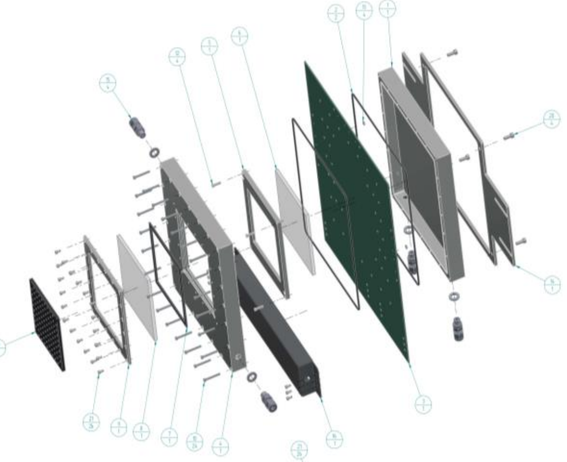
Y. Meng *"PICOSEC Micromegas Precise-timing Detectors Towards Large-scale Application and Optimization"*, *MPGD 2024*, https://indico.cern.ch/event/1453371/contributions/6146437/

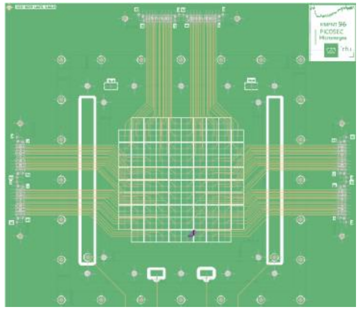
Micromegas on thin PCB + stiffener

Advantage:

- Low material budget on the detector
- Allow the fabrication of **large flat boards** with a **mosaic of 10×10 cm^2 crystals**

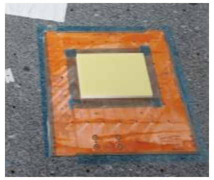


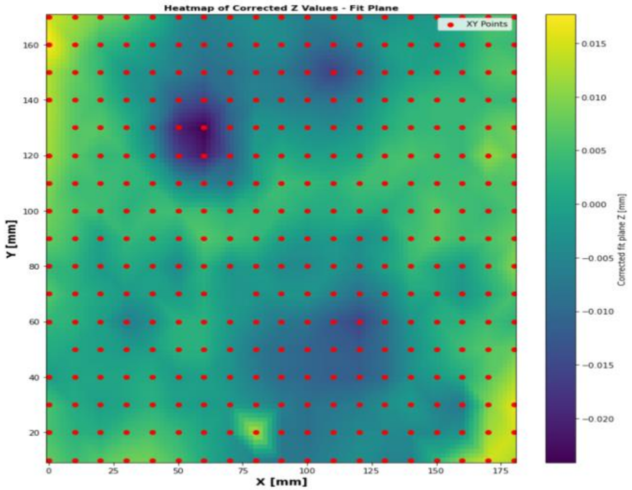




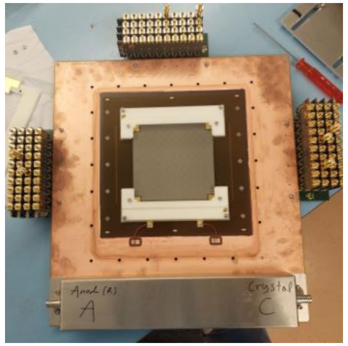
1st prototypes tested July / Sep 2024

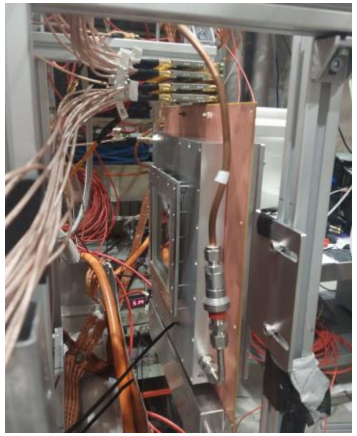
- 10MO/☐ Resistive prototypes
- PCB thickness: 0.8 / 1.6 mm
- Detector flatness using stiffener (Roisel)
- Square pads 1cm
- MgF_2 crystal + DLC photocathode
- Amplifier cards deported using long lines and multipin connectors





planarity measurements
after the stiffener ➔ 9 µm





1st look on the data:

- Homogeneous gain / timing (~10%)
- Small degradation of performance due to signal lines & connectors

➢ Improved version in progress

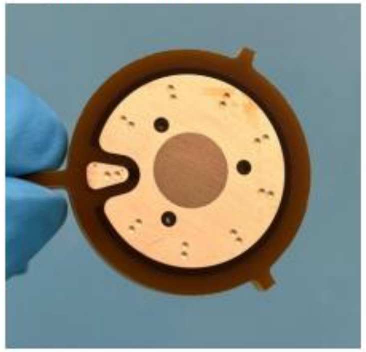
A. Kallitsopoulou. PhD thesis, ongoing

μRwell PICOSEC

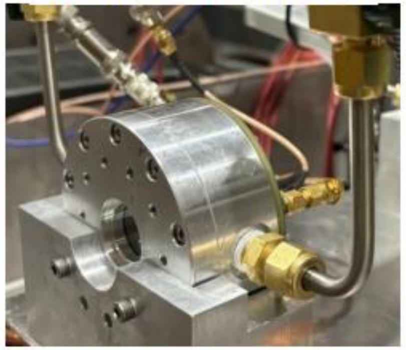
Single anode - μRWELL PICOSEC structure

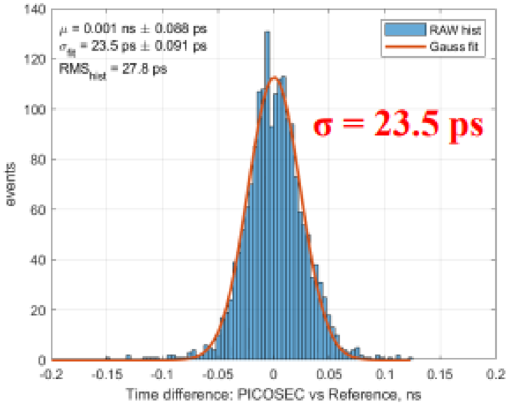
- Best performance for a pattern of 120 μm pitch, 100 μm outer diameter, 80 μm inner diameter holes
- **σ_t = 23.5 ps** for CsI photocathode
- **σ_t = 37 ps** for DLC photocathode

μRWELL -PICOSEC PCB

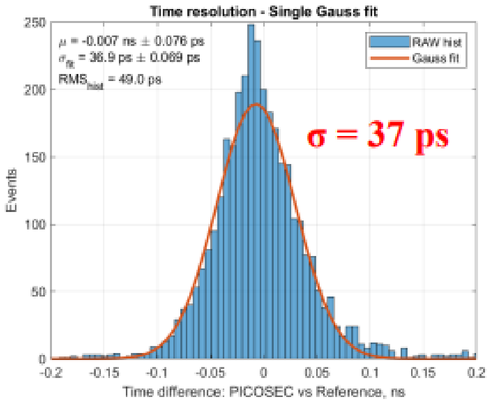


Prototype tested in LED setup





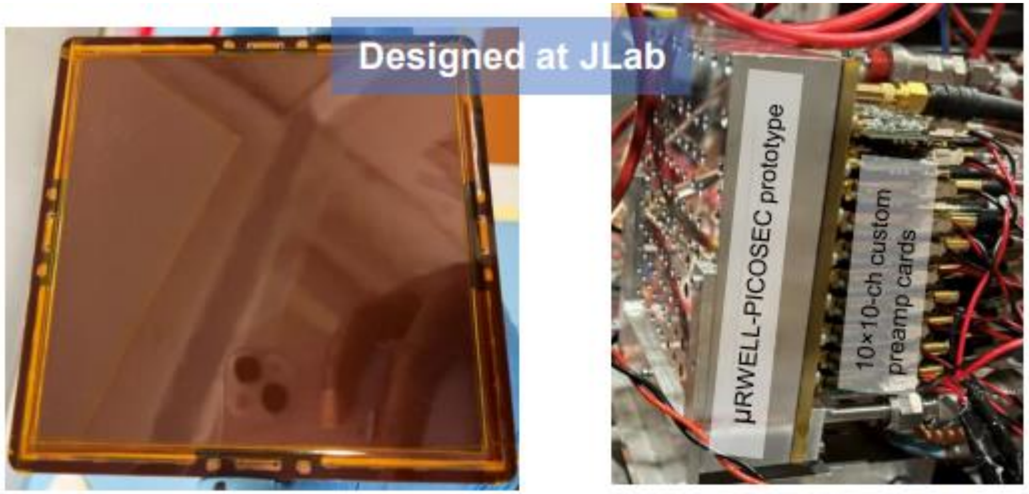
Time resolution with CsI photocathode



Time resolution with DLC photocathode

10×10 μRWELL-PICOSEC Prototype

- μRWELL-PICOSEC with the optimal pattern: 120 μm pitch, 100 μm outer diameter, 80 μm inner diameter holes
- Preliminary time resolution with CsI photocathode: **σ_t ~50 ps** (@CERN SPS H4 Beam Test, July 2024) ➔ partially due to drift gap non uniformity and poor photocathode quality
- *Analysis is ongoing*

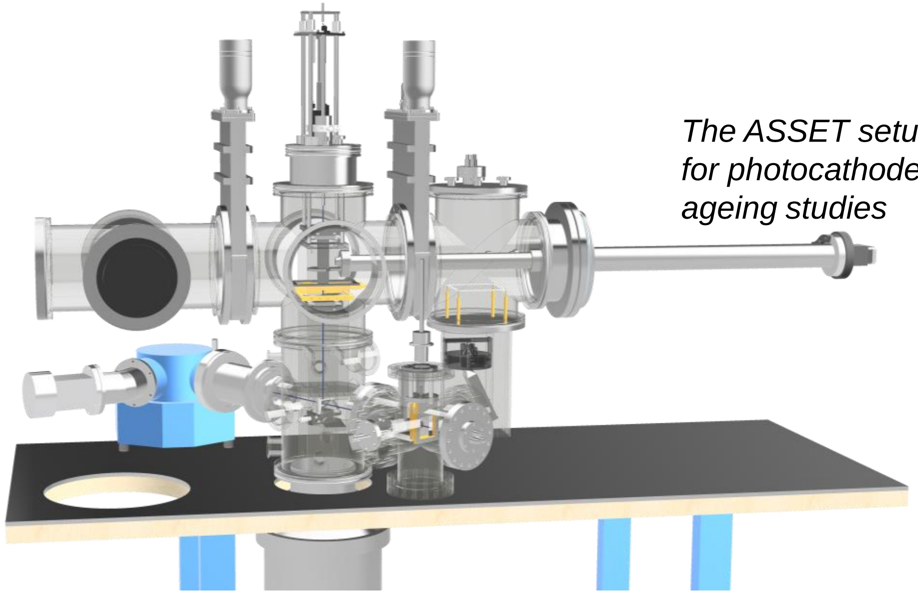


100-pads μRWELL-PICOSEC PCB   Large μRWELL-PICOSEC in beam at CERN

Y. Meng *"PICOSEC Micromegas Precise-timing Detectors Towards Large-scale Application and Optimization"*, *MPGD 2024*, https://indico.cern.ch/event/1453371/contributions/6146437/

Robust & efficient photocathodes

- Systematic study of carbon based photocathodes
  - DLC direct deposition on MgF2 crystls (CERN / USTC)
  - B_4C with Cr substrate (CEA / CERN / USTC)
  - Systematic characterization in monochromators (CERN/USTC)
  - Ageing studies
  - Particle beam tests in 2024 (April, July, now)

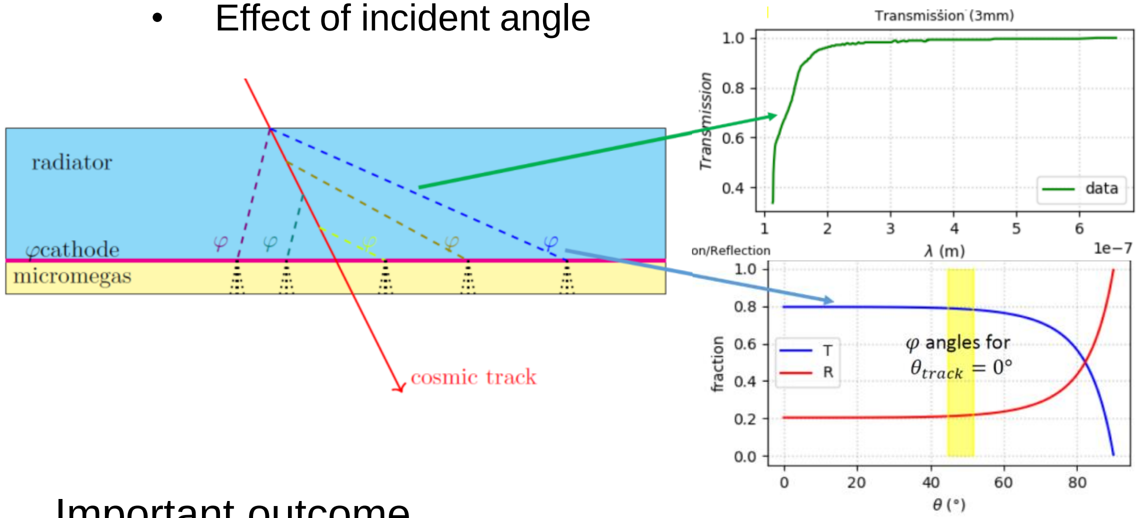


The ASSET setup @ CERN for photocathode Q.E. and ageing studies

X. Wang et al. “A novel diamond-like carbon based photocathode for PICOSEC Micromegas detectors”, e-Print: 2406.08712 [physics.ins-det]

M. Lisowska et al. “Photocathode characterisation for robust PICOSEC Micromegas precise-timing detectors”, e-Print: 2407.09953 [physics.ins-det]

- Detailed modeling of optical properties & experimental studies (R. Aleksan / A. Kallitsopoulou)
  - Optimization of the light transmission / p.e. yield
  - Effect of incident angle



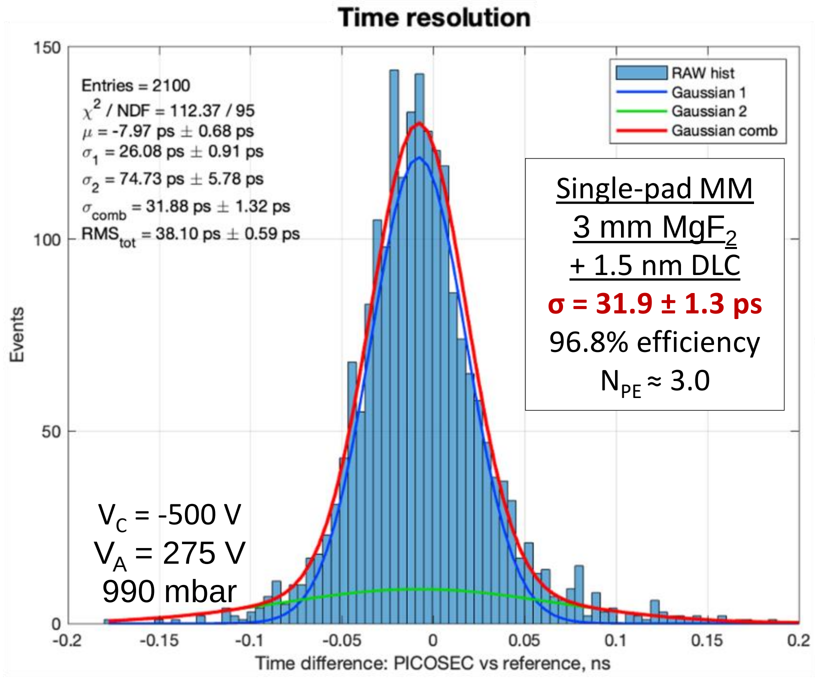
<u>Important outcome</u>

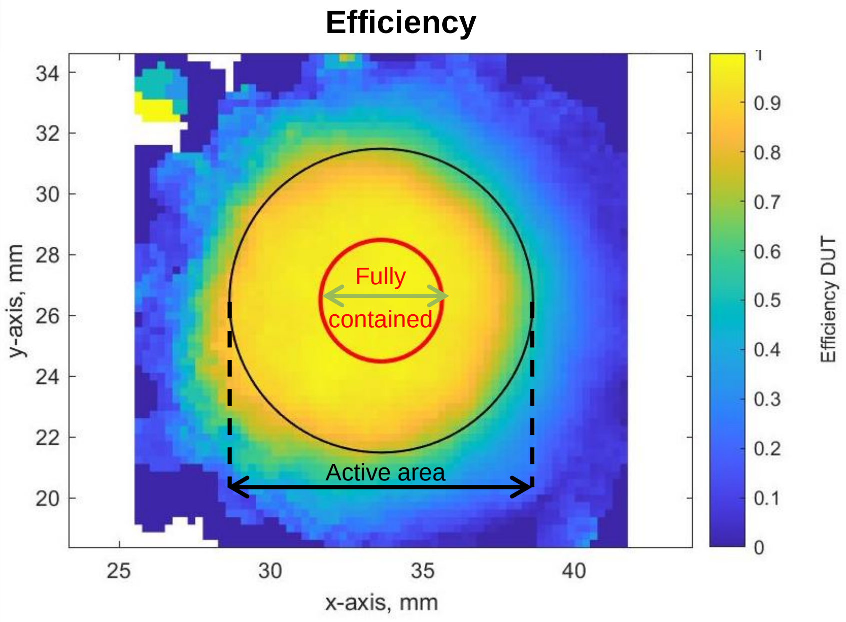
- For 3 mm thick MgF_2 and CsI (Q.E. from a Hamamatsu commercial PMT) expected yield **~36 p.e.**
- Experiment: **10-11 p.e.** (for optimized CsI thickness)
  - ➔ reflections due to large impact angle
  - ➔ optimization of metallic substrate matching the refractive index (**Cr → Ti**). First tests July 2024, more systematic in Sep 2024. Expected p.e. **factor of ~2 more –** analysis ongoing

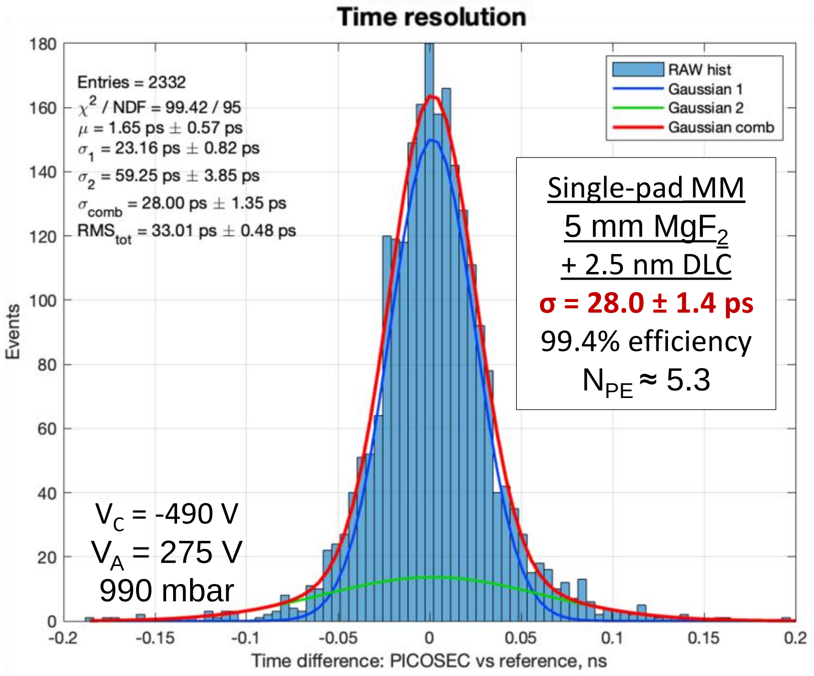
Robust photocathodes

Diamond-Like Carbon

- DLC photocathodes, thickness 1.5 - 3.5 nm, were characterised during particle beam measurements
- **Detector with a 1.5 nm DLC** deposited directly on the radiator, **exhibited σ = 31.9 ± 1.3 ps**;
- To enhance UV photon production, a **5 mm MgF_2 radiator** with a 2.5 nm DLC was tested





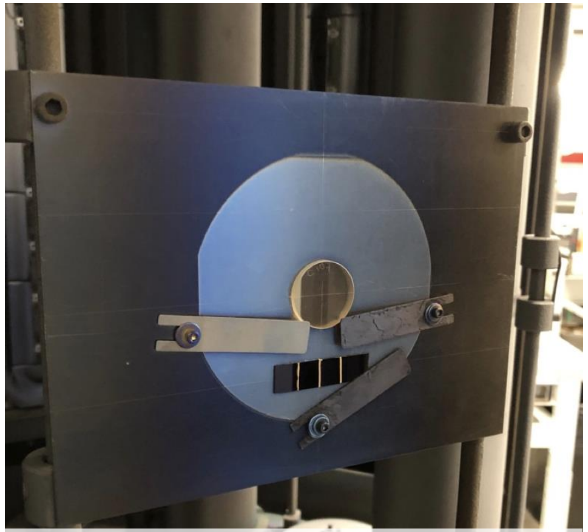


M. Lisowska. PhD thesis *dissertation*, 2024

Robust photocathodes

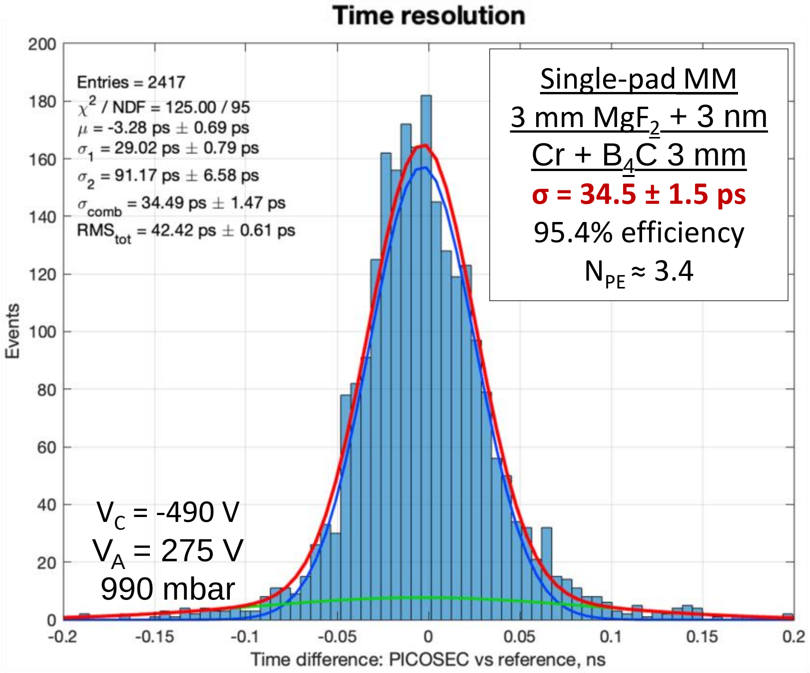
Boron Carbide

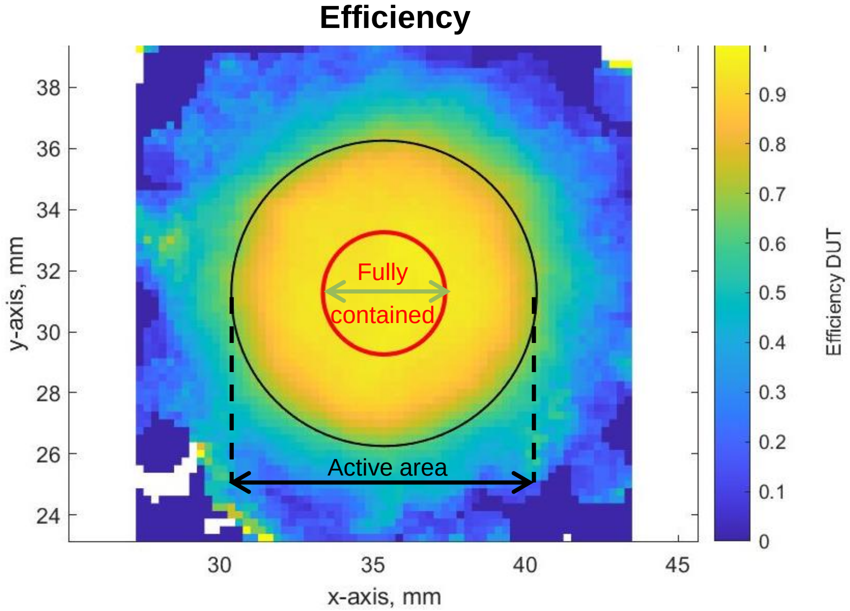
- B_4C photocathodes deposited at CEA-Saclay and ESS showed promising results
- Samples of **3 mm MgF_2** + **3 nm Cr** + **B_4C** (7.5 - 15 nm)
- **Detector with a 9 nm B_4C** and a 3 nm Cr interfacial layer **exhibited σ = 34.5 ± 1.5 ps**;



B_4C sample in the sputtering machine

C.-C. Lai, ESS





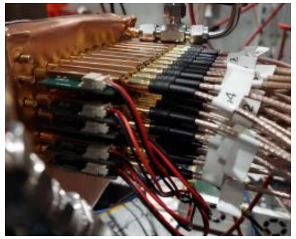
M. Lisowska. PhD thesis *dissertation*, 2024

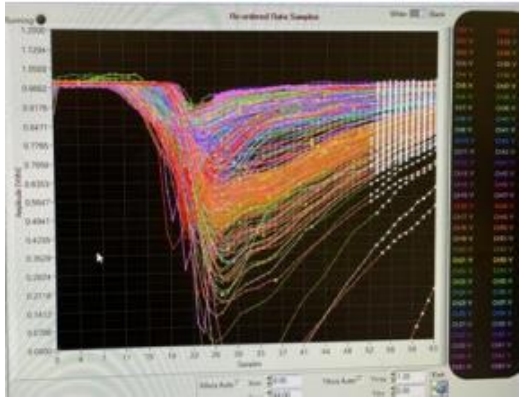
Pixelated PICOSEC Detector: FEE & BEE

➔ Development if frond-end & back-end electronics (~ 100 channels) for detector testing

Signal digitization → SAMPIC digitizers (IJCLab, IRFU)

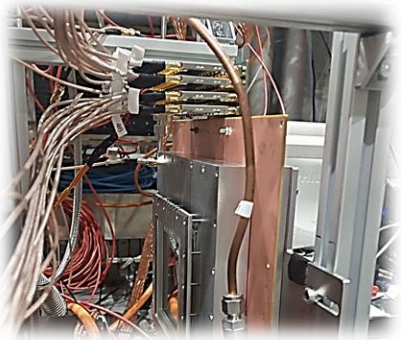
- Development of a 256-channel system





RF-amplifiers (CERN / Zagreb University)

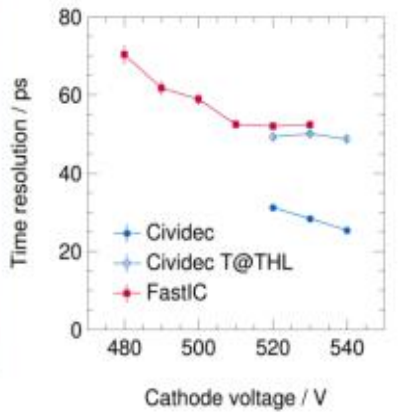
- 10 ch amplifierboards (M.Kovacic, A. Utrobicic)



A. Utrtobicic et al. "Single channel PICOSEC Micromegas detector with improved time resolution", e-Print: 2406.05657 [physics.ins-det]

FastIC ASIC (CERN)

- Positive or negative input with intrinsic amplification
- 8 readout channels
- ~ 2 MHz per channel (time & energy)
- ~ 50 MHz per channel (time only)
- Tested with PICOSEC detector @CERN SPS H4, Sep. 2024



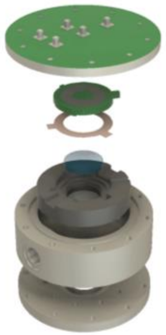
L. Scharenberg *"Fast-timing and high-granularity readout of MPGDs: FastIC and Timepix4"*, *MPGD 2024*, https://indico.cern.ch/event/1453371/contributions/6146454/

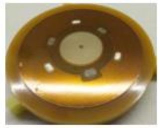
Lucian Scharenberg

Detector & electronics optimization

Improvement of the timing performance by reducing external component limitations:

- *thinner pre-amplification gap*
- *enhanced HV stability*
- *reduced noise level*
- *improved signal integrity*
- *dedicated amplifiers*

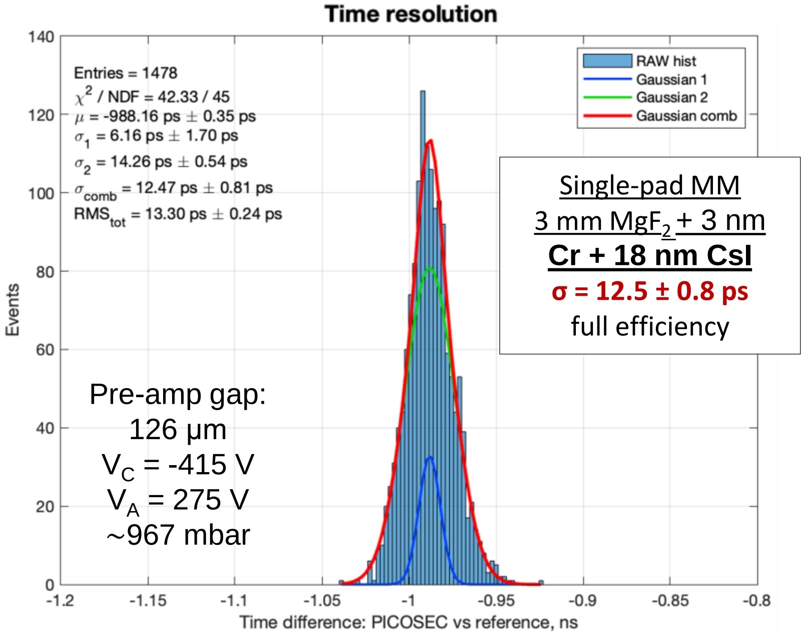




Φ10 mm

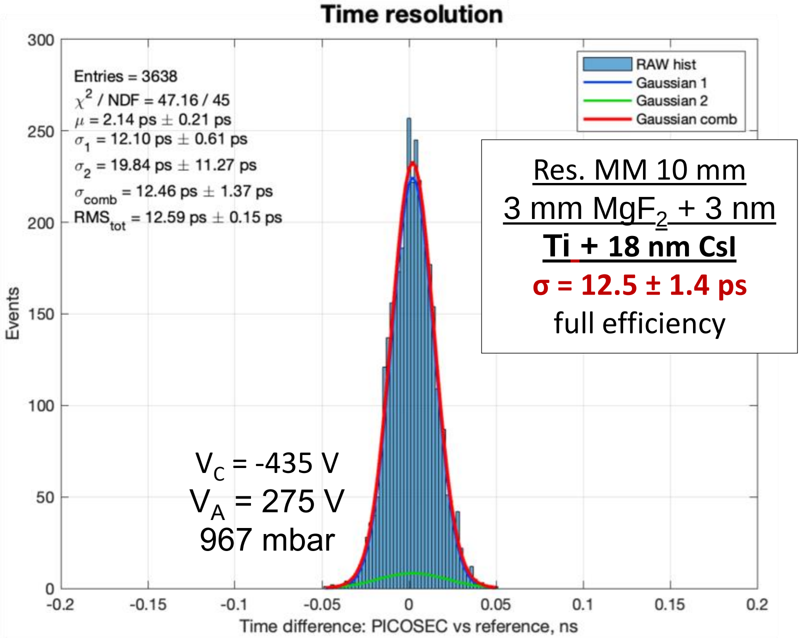
Metallic anode, 10 mm Ø

time resolution of **σ = 12.5 ± 0.8 ps!**



Resistive anode, 10 mm Ø

time resolution of **σ = 12.5 ± 1.4 ps!**



A. Utrtobicic et al. "Single channel PICOSEC Micromegas detector with improved time resolution", e-Print: 2406.05657 [physics.ins-det]

PICOSEC Micomegas summary

- *PICOSEC Micromegas R&D activity ➔ an exciting quest, aiming at a huge improvement of timing precision of MPGDs* (> 2 orders of magnitude)
- Ongoing R&D aiming at the development of robust & performant scalable detectors
  - **Several technologies for 10×10 cm^2 detectors**
  - First implementation of 20×20 cm^2 prototype
  - Robust photocathodes with good efficiency
  - Detector optimization / alternative gasses

Major results (CsI photocathode - records)
- $\langle N_{p.e.} \rangle$ / MIP ≈ **10 – 11**
- **σ_t ~ 13 ps** , with single anodeprototypes (∅=1cm)
- **σ_t < 24 ps 10×10 cm^2** , prototypes (100 channels)

Major results (robust detectors)
- **10×10 cm^2** prototypes - resistive anode (100 channels)
- **σ_t ~ 30 - 35 ps** for 150 GeV muons, with **robust B_4C or DLC** photocathode,
- $\langle N_{p.e.} \rangle$ / MIP ≈ **3 – 4**

- A significant number of publications and conferences over the last few years including 6 PhD theses completed or ongoing – more to follow
- *Towards **implementation** of the technology to **physics experiments** ?*

Prospects: Picosec MM on ENUBET?

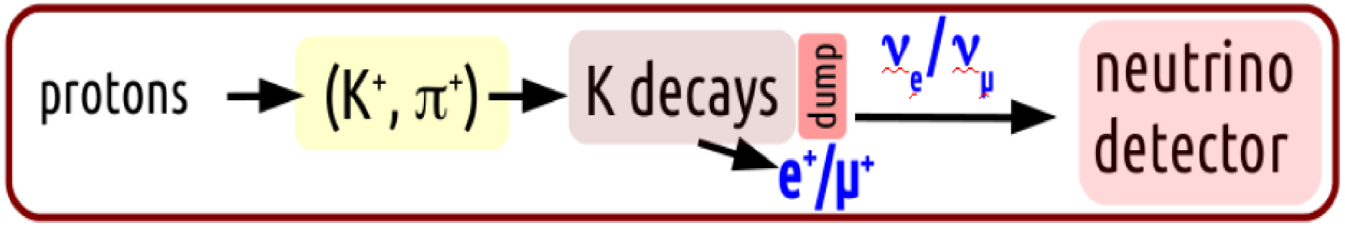
Follow up on ν Cross-section measurements

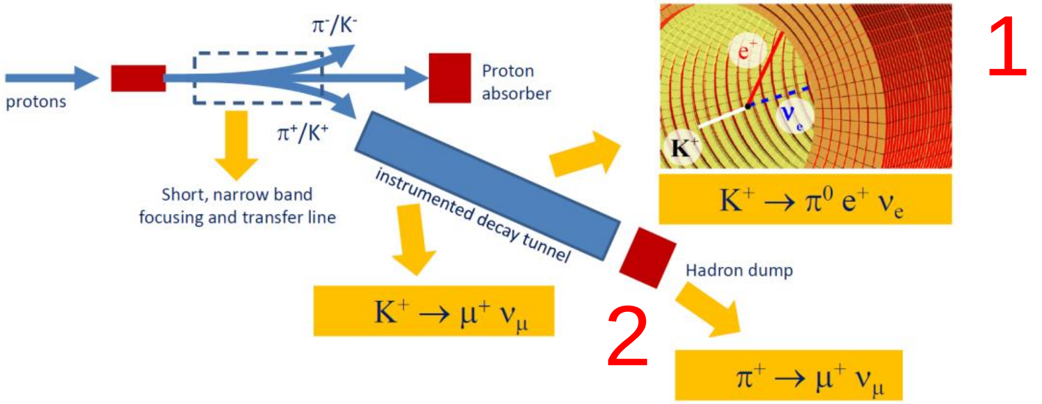
CERN NP06/ENUBET(**E**nhanced **NeU**trino **BE**ams from kaon **T**agging)

- ENUBET is aimed:
  - At designing a narrow-band beam @ GeV scale
  - Having control of the neutrino flux & energy
- ENUBET characteristics facility
  - Monitored neutrino beam
    with no one-to-one correlation
    between **leptons** tagged in beamline and **neutrinos**
    in the far detector
- **Sub-ns sampling would offer this correlation (~100ps)**
  - On an event-by-event basis
  - Determine the flavor of neutrino

Possible use of PICOSEC Micromegas:

1. t_0 tagger and/or embedded in the EM calorimeter
2. **Muon monitoring at the hadron dump**





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

Thank you for your attention!

backup

The Micromegas concept

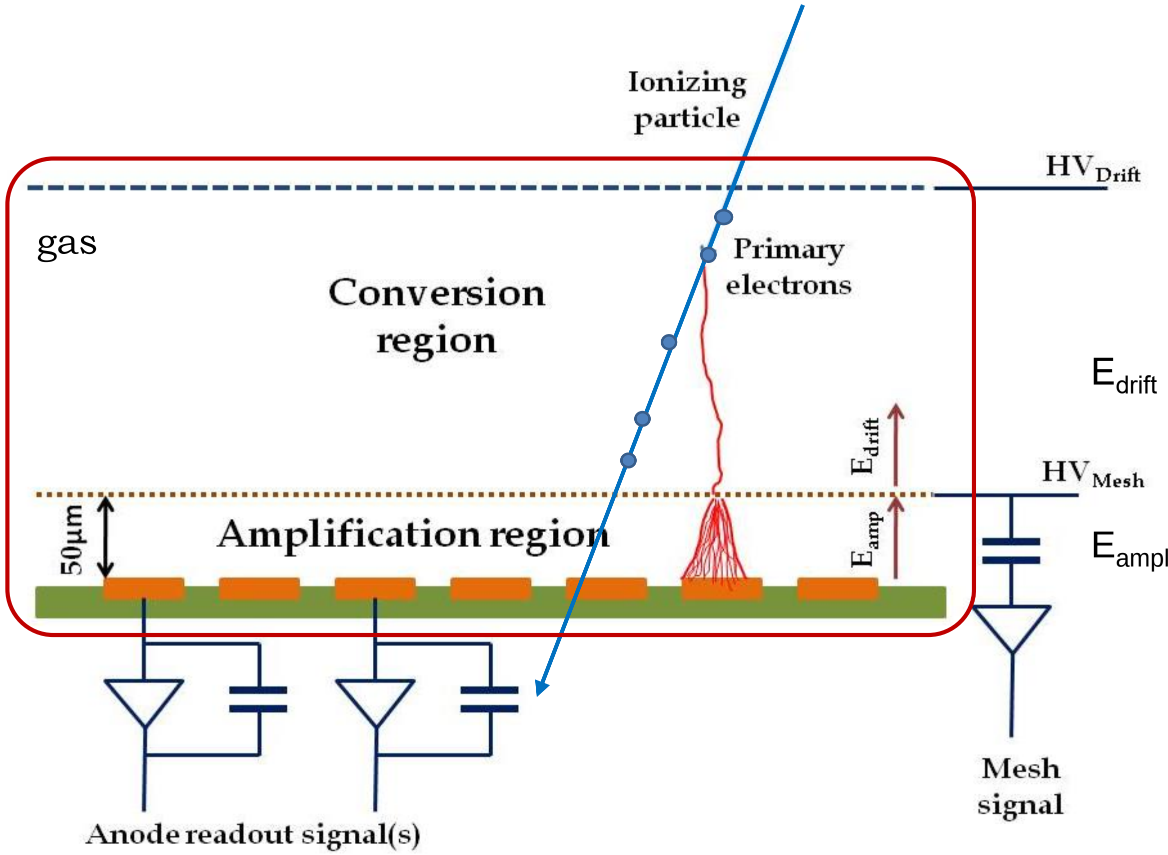
A *two-region* parallel plate gaseous detector separated by a ***micromesh*** :

- Conversion region
  - Primary ionization
  - Charge drift towards A.R.
- Amplification region
  - Charge multiplication
  - Readout layout
    - Strips (1/2 D)
    - Pixels

➔ metallic micromesh (typical pitch ~50 μm)

➔ sustained by 50-150 μm pillars

Amplification gap: 50-150 µm



E_{drift} ~ $10^{2\text{-}3}$ V/cm

E_{ampl} ~ $10^{4\text{-}5}$ V/cm

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

The Micromegas concept

The virtue of the small gap

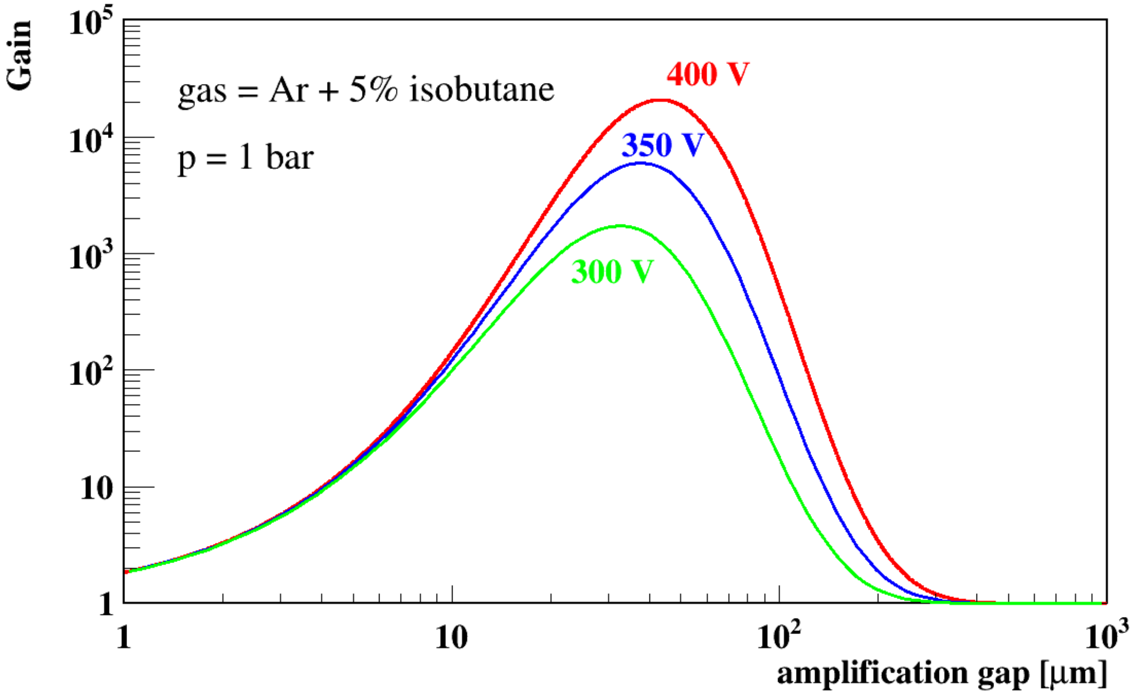
Parallel plate detector gain: $G = e^{\alpha d}$

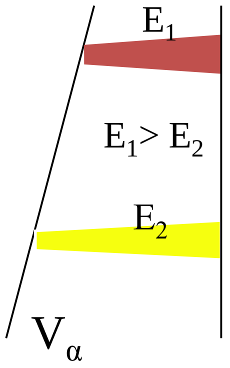
Townsend coefficient α: $a = \frac{p}{\lambda} e^{-\frac{I_e}{\lambda}\frac{pd}{V_a}}$

Gain variation: $$\frac{\delta G}{G} = G\left(1 - \frac{I_e}{\lambda}\frac{pd}{V_a}\right)\frac{\delta d}{d}$$

The gain variation is reaching a minimum for :

$$d = \frac{V_a}{p}\frac{\lambda}{I_e}$$





Optimum amplification gap: 30 – 100 μm

Stable gain – *less sensitive to flatness defects or temperature and pressure variation*

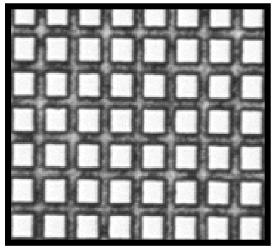
➔ **gain homogeneity over large areas**

➔ **good energy resolution**

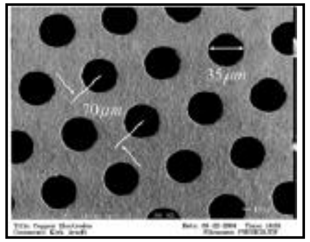
Building a Micromegas

Micromesh

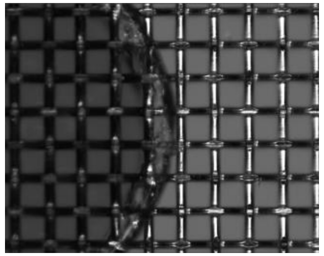
- Many different technologies have been developped for making meshes (Back-buymers, CERN, 3M-Purdue, Gantois, Twente…)
- Exist in many metals: nickel, copper, stainless steel, Al,… also gold, titanium, nanocristalline copper are possible.



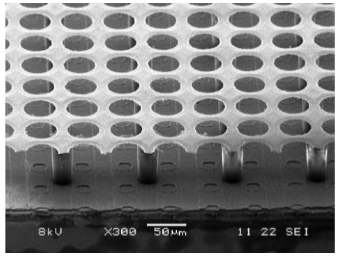
Electroformed



Chemically etched



Wowen



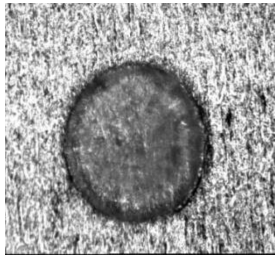
Si wafer (GridPix)

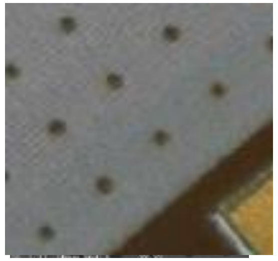
Laser etching, Plasma etching, Deposited by vaporization…

Pillars

- Can be on the mesh (chemical etching) or on the anode (PCB with a photoimageable coverlay).
- Diameter 40 - 500 µm every few mm

200 mm





+ Anode (readout)

Micro-mesh type → Micromegas family

- **"Conventional"**: a micromesh stretched on a frame is placed on a readout board with the help of spacers ("pillars")
- **Bulk Micromegas**: Process to encapsulate the mesh on a readout board
- **Resistive Anode**
- **Microbulk:** Photolithography & chemical etching of Kapton foils with Cu layers on both sides ("GEM technology").
- **Hybrid**: Micromesh placed on top of a silicon readout chip (i.e. InGrid, GridPix)
- **Piggyback**: A resistive bulk Micromegas on top of a dielectric. Decoupled readout
- **XY-Microbulk**: A Microbulk with segmented anode and mesh. Real XY-structure
- **Hybrid / double stage:** Micromegas with pre-amplification from at the drift space or by a GEM foil
- ***Micro r-well (µRwell)****: a resistive Microbulk (DLC layer)*
- **Optical readout**: Micromegas build on a transparent anode and read by an optical camera
- **Thermal bonding**: Mesh stretched under high tension, supported by pillars formed with thermal bonding
- ***PICOSEC Micromegas***

PICOSEC
Micromegas

Micromegas for precise timing

Exploring Alternative Gas

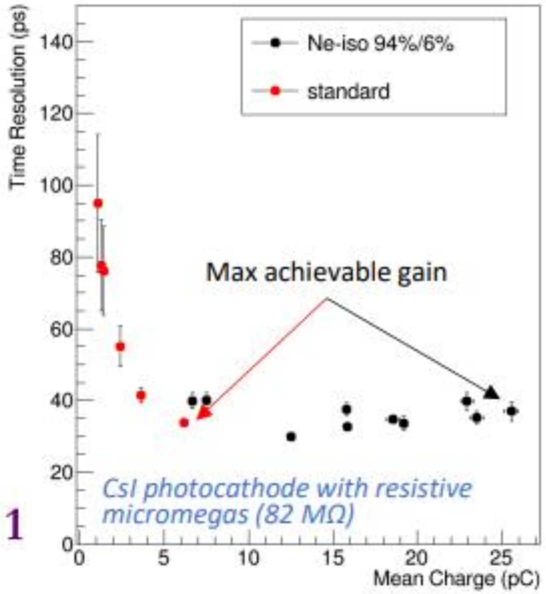
Standard mixture:

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

- Expensive
- Flammable
- High GWP (~ 740)

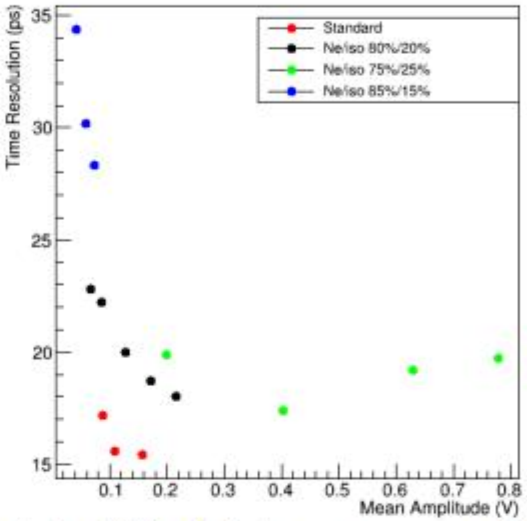
New mixtures:

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



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

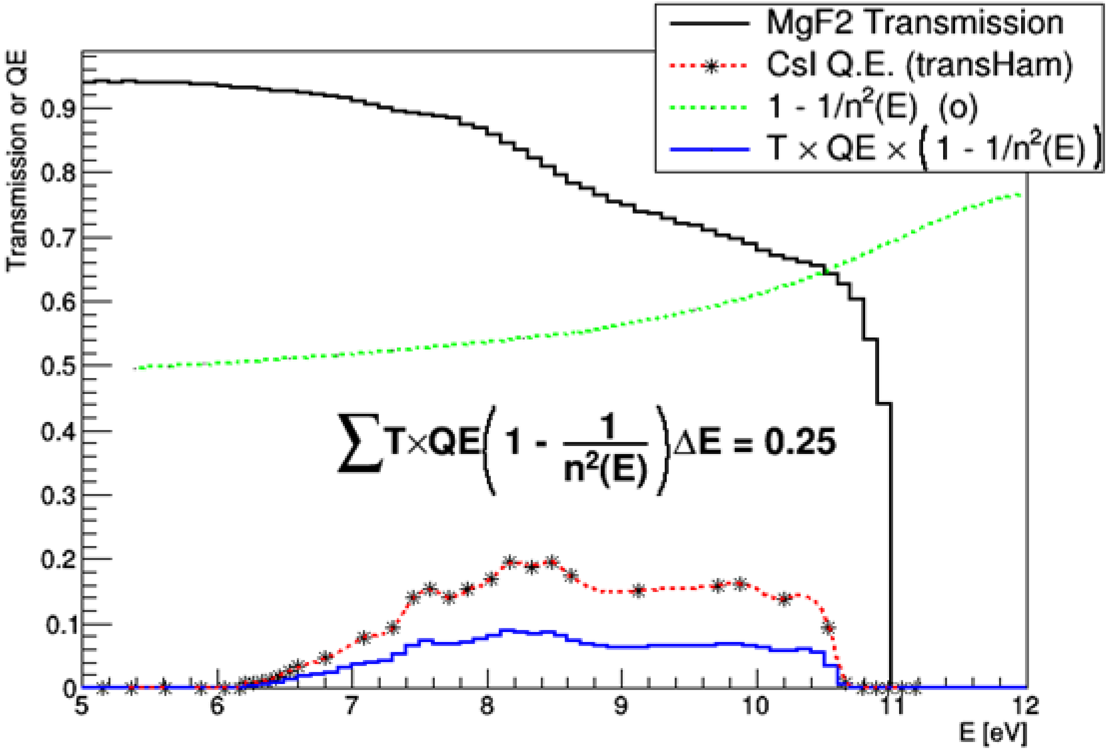
GWP

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.

Expected number of p.e. per MIP

A MIP passing through a crystal will emit:

$$N_{p.e.} \approx 370L \int T(E)QE(E)\left(1 - \frac{1}{n^2(E)}\right) dE$$



For a MgF2 crystal and a CsI photocathode with typical bibliography values for *QE*(*E*), *T*(*E*) and *n*(*E*) as seen, we expect:

370 × 0.25 = 92 p.e./cm

for a **3 mm MgF2** crystal we would expect **~28 p.e.**

Single photoelectron calibration runs have been taken using a cigarette ***lighter's flame*** for all detector settings. Analysis pending. For the time being matching the amplitude spectra with poisson distributions we estimate **~10 p.e. per MIP**

Margin for improvement!!

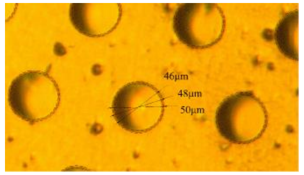
UV photon detection

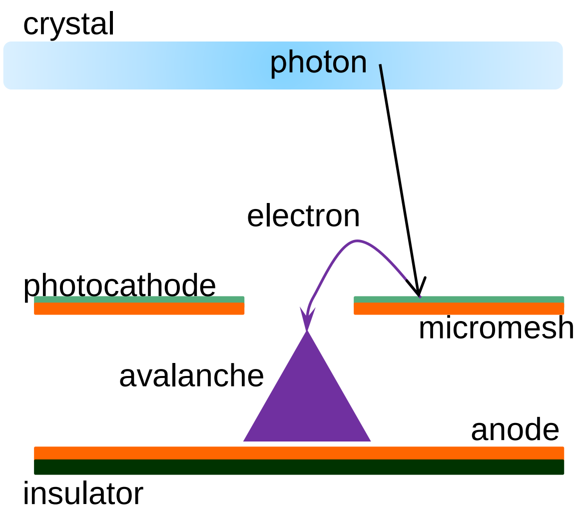
Reflective photocathode:

Photosensitive material is deposited on the top surface of the micromesh.

Photoelectrons extracted by photons will follow the field lines to the amplification region

- ✓ *Smaller ion backflow* ➔ radiation hardness
- ✓ The photocathode does not "see" the avalanche ➔ *no photon feedback* ➔ higher gain in single stage (~ 10^5)
- ✓ Higher electron extraction efficiency
- × Reflection on the crystal
- × e^- path variation
- × Limitation to Microbulk / opaque meshes

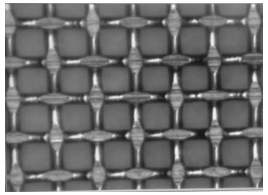


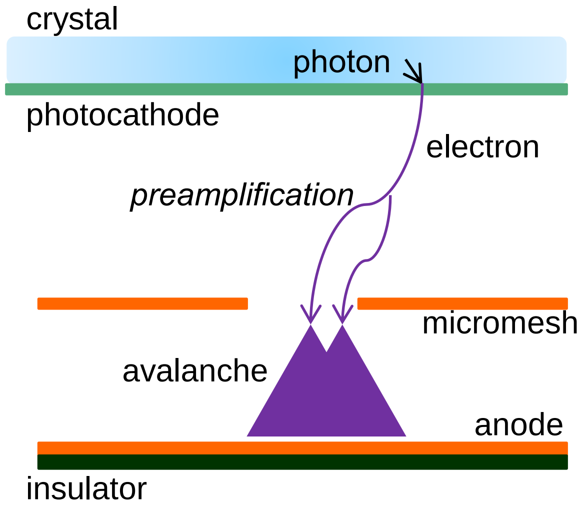


Semi-transparent photocathode:

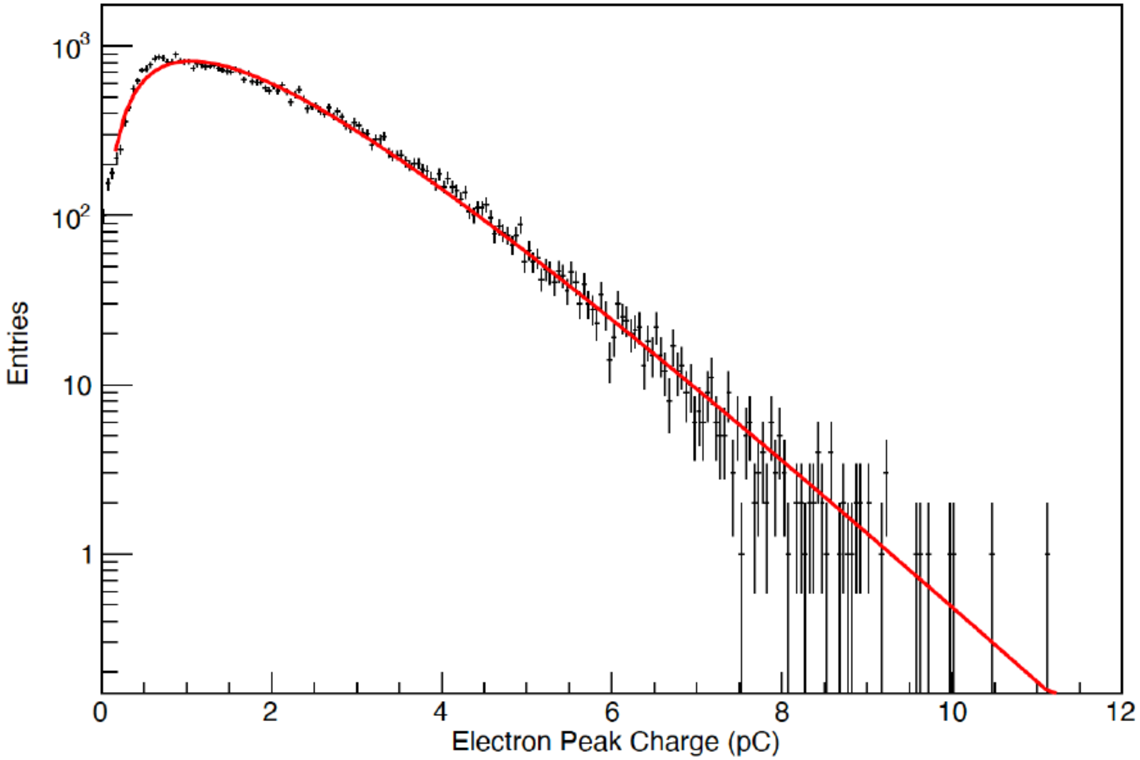
Photosensitive material is deposited on an aluminized MgF_2 window (drift electrode)

- ✓ Extra preamplification stage ➔ better long-term stability
- ✓ higher total gain
- ✓ Various MM technologies & gas mixtures possible
- ✓ Decoupling of sensor - photocathode
- × Lower photon extraction efficiency
- × Photocathode exposure to sparks
- × Ion backflow ➔ radiation hardness (?)





Electron-peak distribution and Polya fit



- The integral of the electron peak is giving the induced charge
- Charge distribution is fitted by Polya function

$$P(Q;c;\Theta;\bar{Q}) = \frac{c}{Q}\frac{(\Theta+1)^{\Theta+1}(Q/\bar{Q})^{\Theta}}{\Gamma(\Theta+1)}e^{-(\Theta+1)Q/\bar{Q}}$$

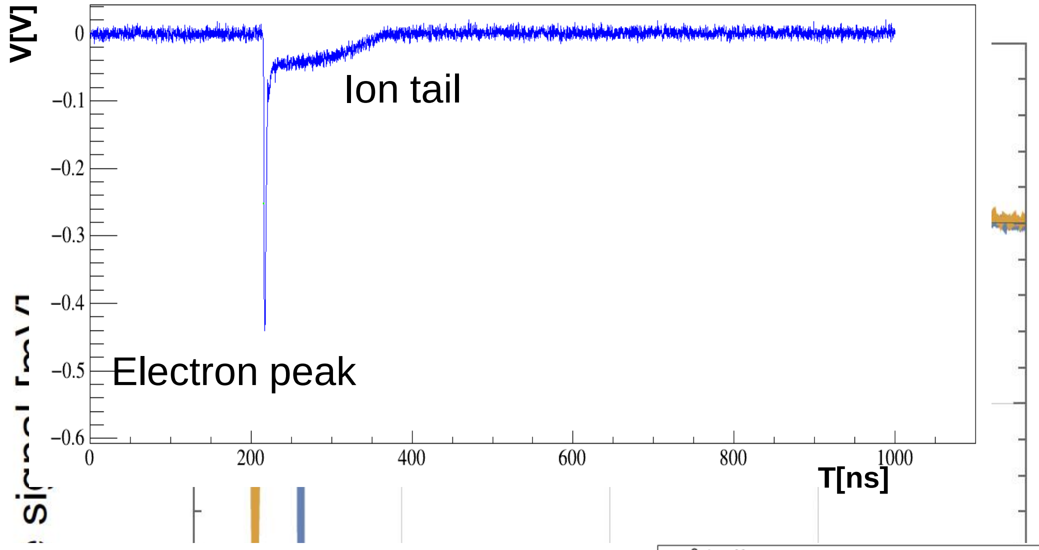
- Fit is giving information of mean signal charge
- Needed for calculating the photocathode efficiency

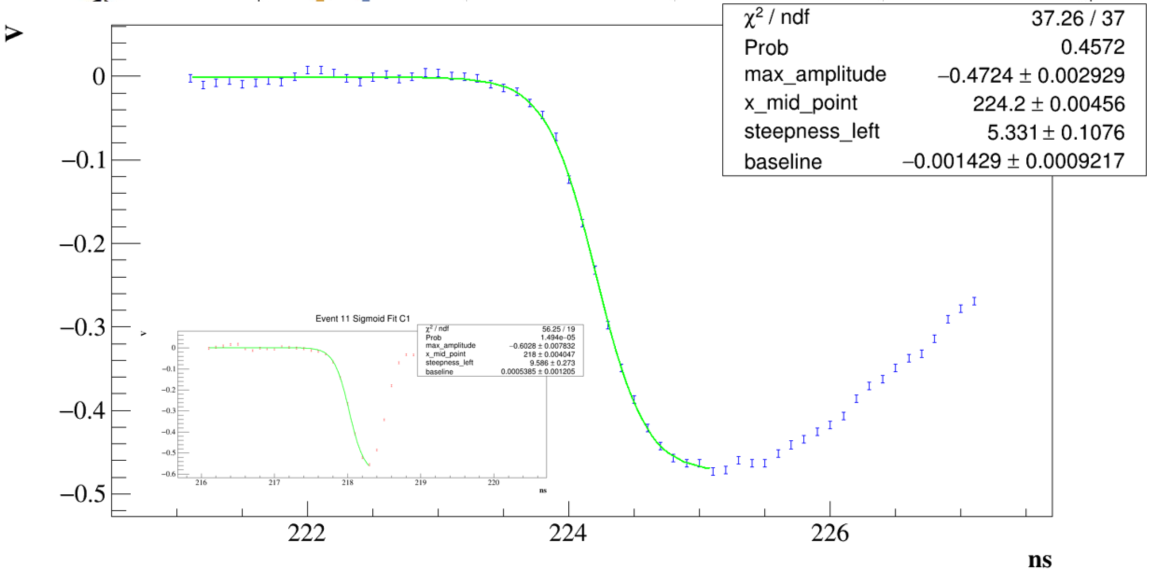
Signal Processing for Precise Timing

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

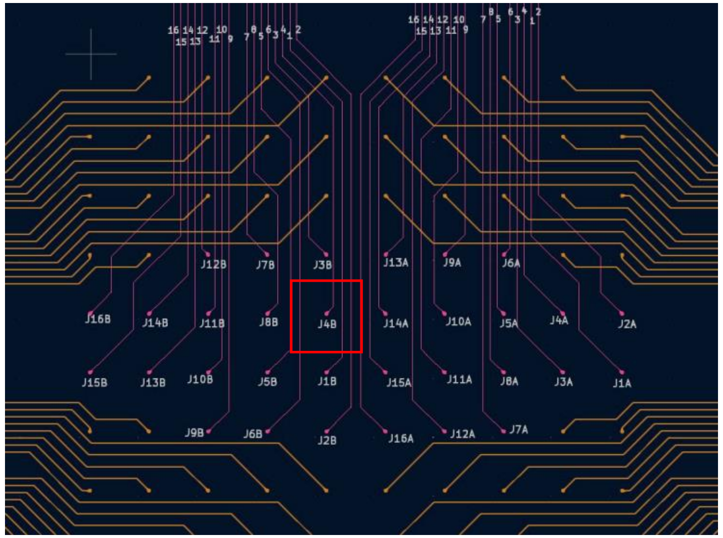
$$f(x; p_0, p_1, p_2, p_3) = V(t) = p_3 + \frac{p_0}{1+e^{-(x-p_1)p_2}}$$

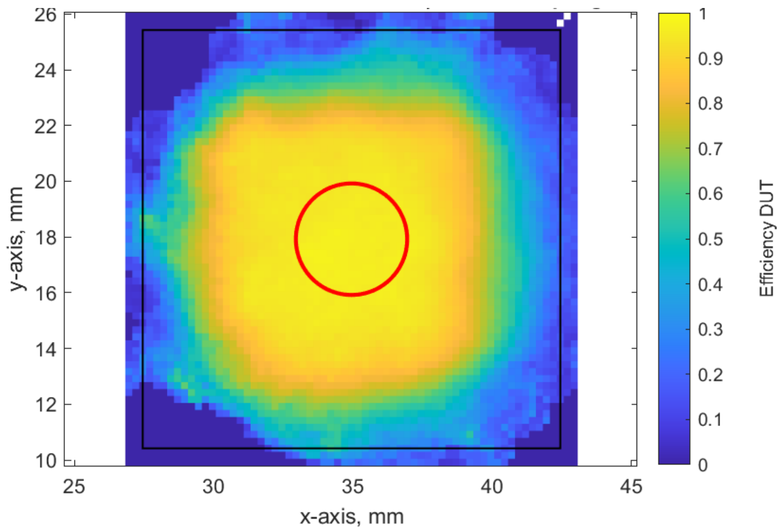
- Timing at 20% of peak amplitude for all signals (SAT – Signal Arrival Time)

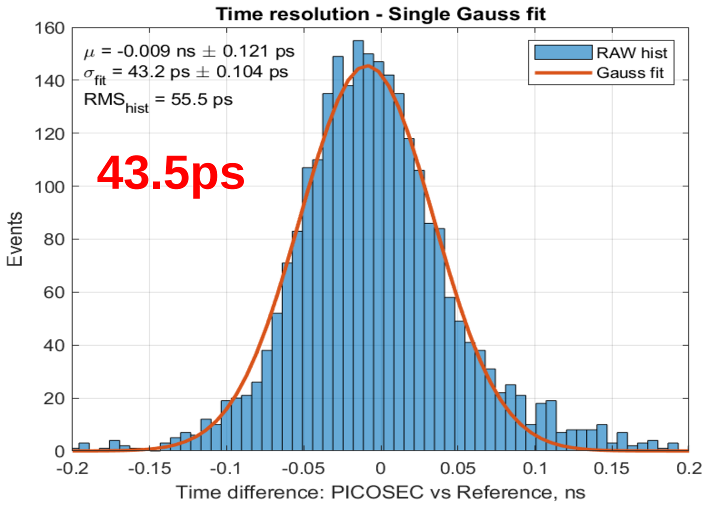


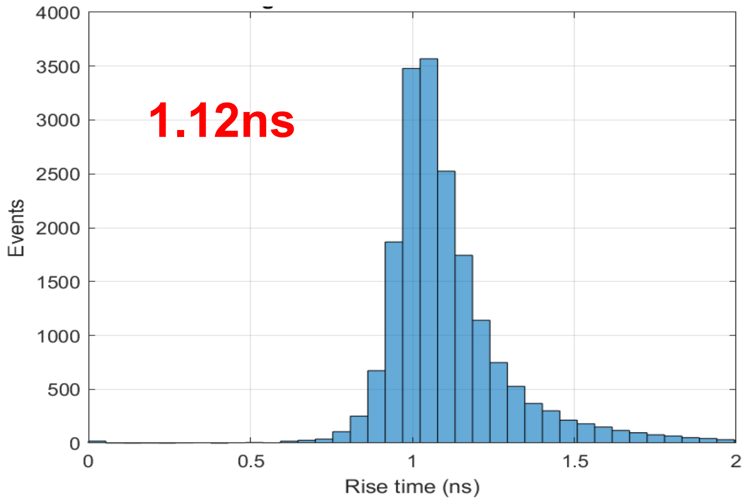


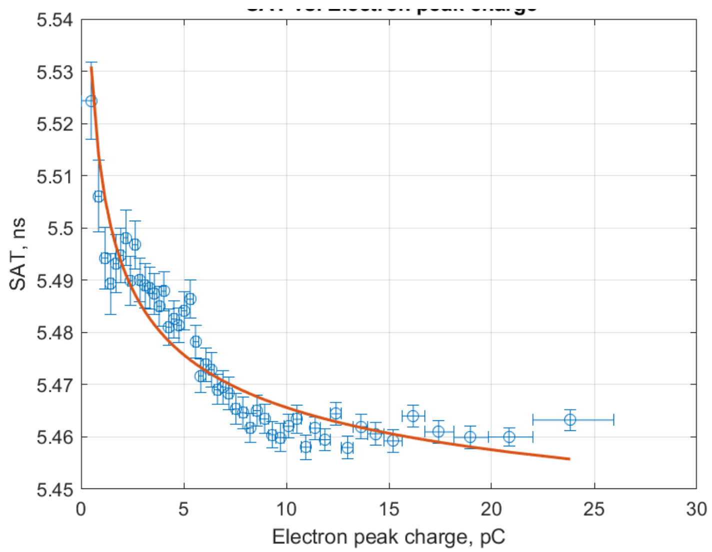
Best Timing Performance per single cell



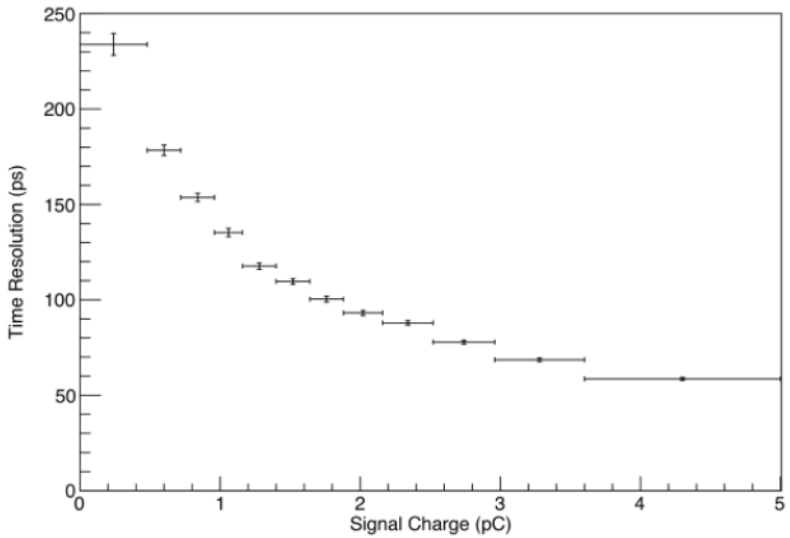




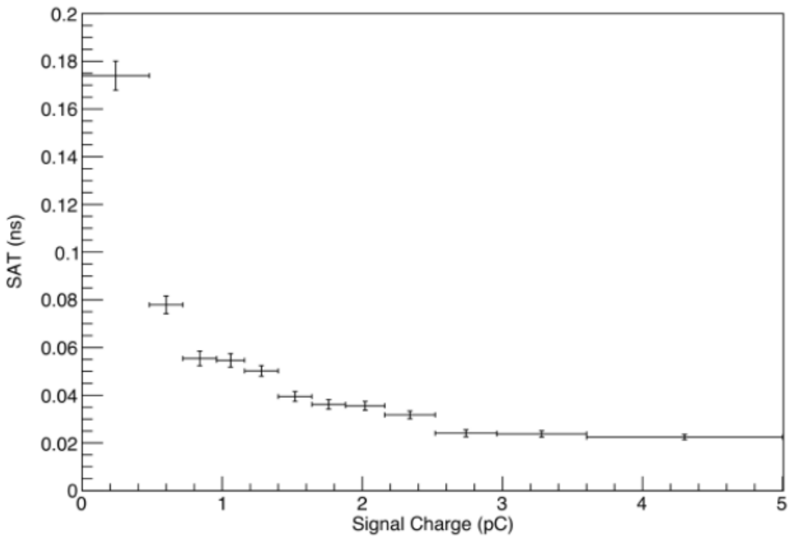




Time resolution vs. Signal Charge

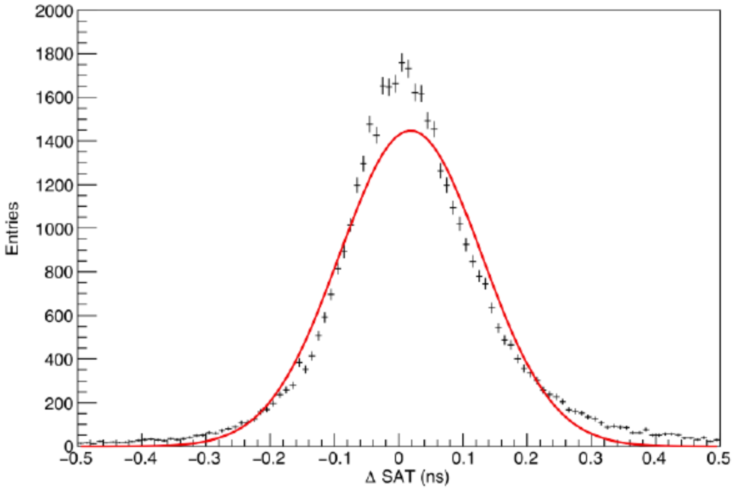


Mean SAT vs. Signal Charge

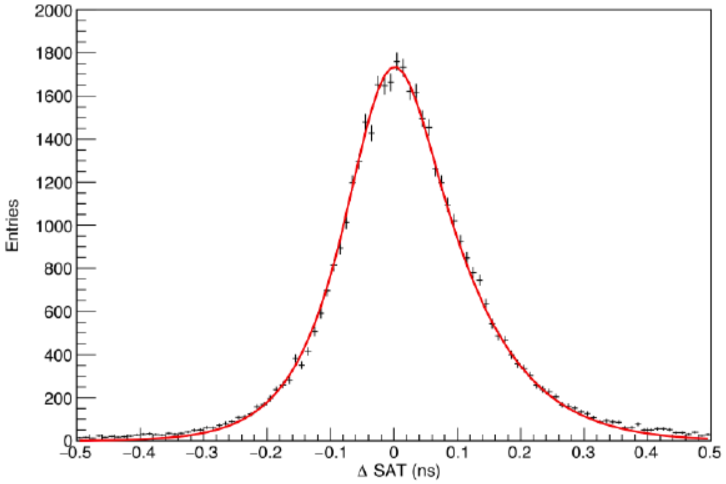


- Time resolution improves and mean SAT moves at higher signal charge
- Binning is selected according to the Polya fit
- Total time resolution is calculated by the convolution of the individual time resolutions

Single Gauß fit



Superposition of several Gauß curves



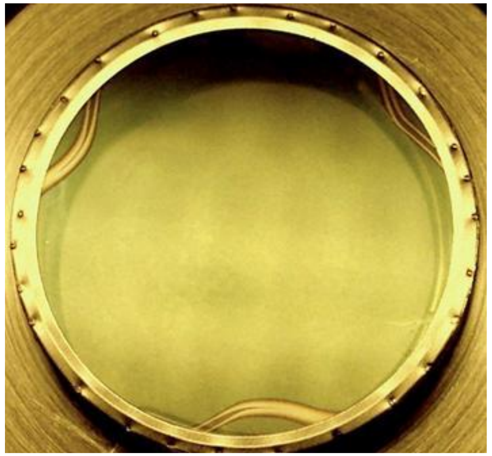
- Time resolution is determined by the sigma of the SAT difference between the DUT and a t0 reference
- Correction of the slewing effect improves the fit of the distribution

$$\sigma^2 = \sum_{i=1}^{n} a_i \sigma_i^2 + \sum_{i=1}^{n} \sum_{j=i+1}^{n} a_i \times a_j \times \left(\sigma_i^2 + \sigma_j^2 + (\mu_i - \mu_j)^2\right)$$

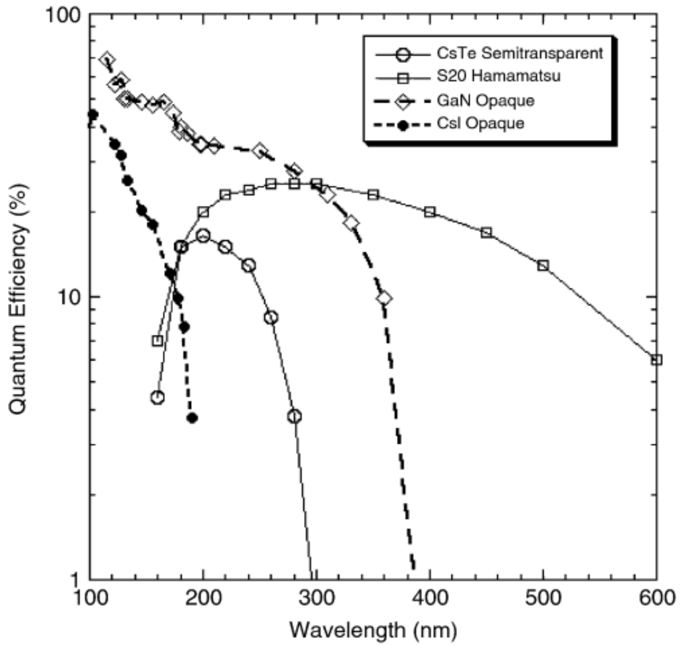
GaN can be an alternative photocathode material?

GaN:

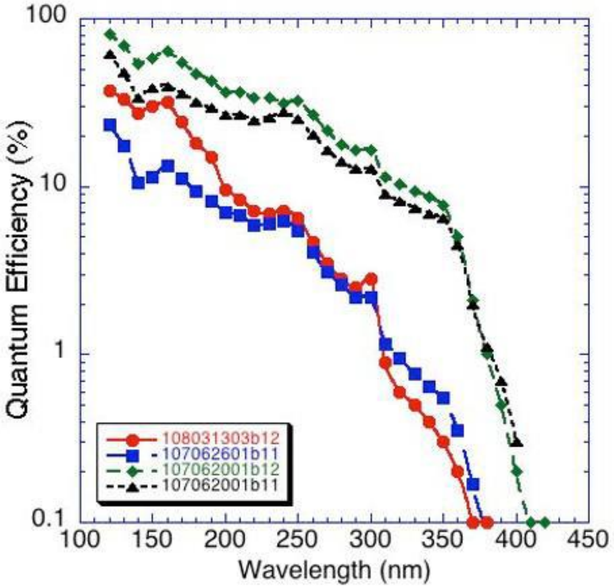
- Higher quantum efficiency than CsI
- Broader bandwidth towards higher wavelengths ➔ Quartz instead of MgF_2 ?
- Aging & Stability in the gas?
  - → *A GaN sputtering target already acquired!*



GaN 0.15 µm cathode on a sapphire substrate



O. Siegmund, et al, "Development of GaN photocathodes for UV detectors" *Nucl. Instr. and Meth. A,* vol. 567, 1, 89-92, 2006, https://doi.org/10.1016/j.nima.2006.05.117



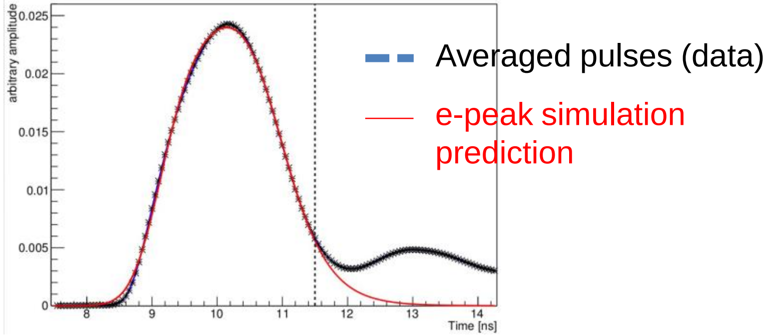
QE measurements for **opaque** GaN samples:
on sapphire (**black**/**green**),
on an alumina substrate (**blue**)
and on fused silica (**red**)

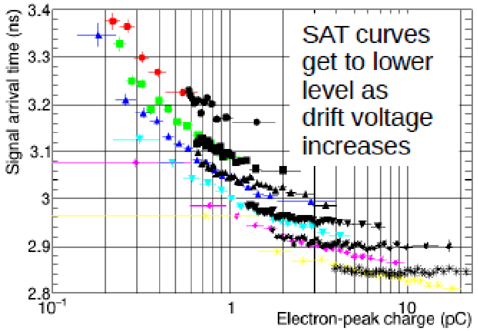
Could be ideal for a photodetector for cross-section measurements for water!!!

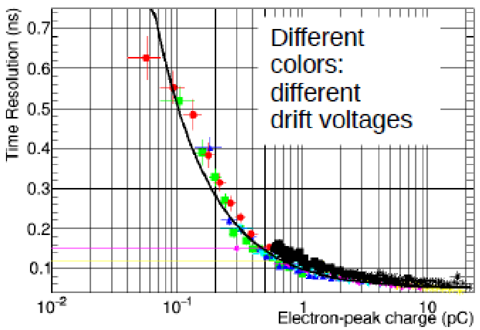
Detailed simulations

electron

Garfield++ and *electronics response*

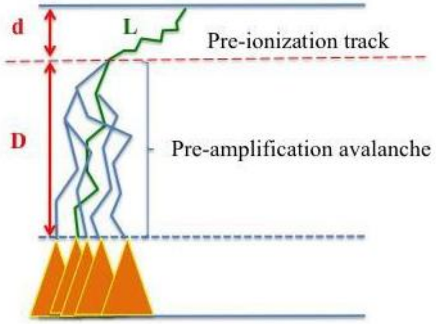




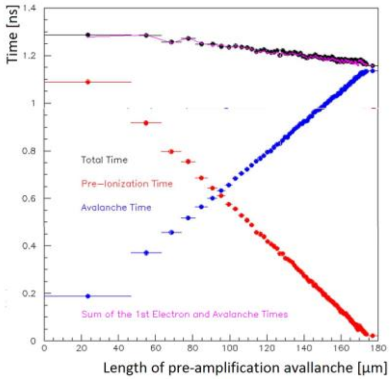


All behaviors seen in single p.e. laser data are also seen in these detailed Garfield++ simulations.

Phenomenological model describing stochastically the dynamics of the signal formation

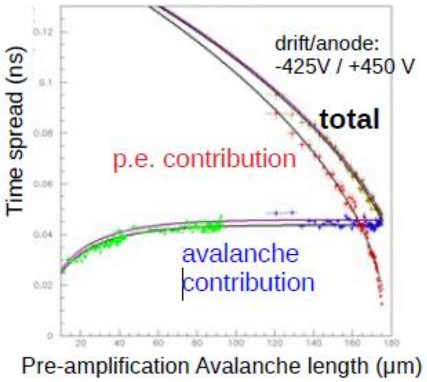


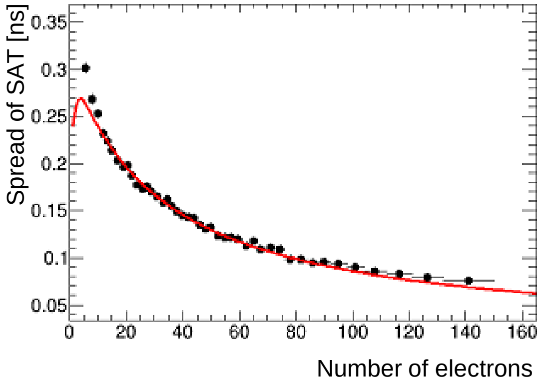
The model describes **SAT** and **Resolution** vs. **avalanche length** & vs. **number of electrons** in avalanche (i.e, e-peak charge)



Avalanche speed = 154 μm/ns

Electron speed = 134 μm/ns

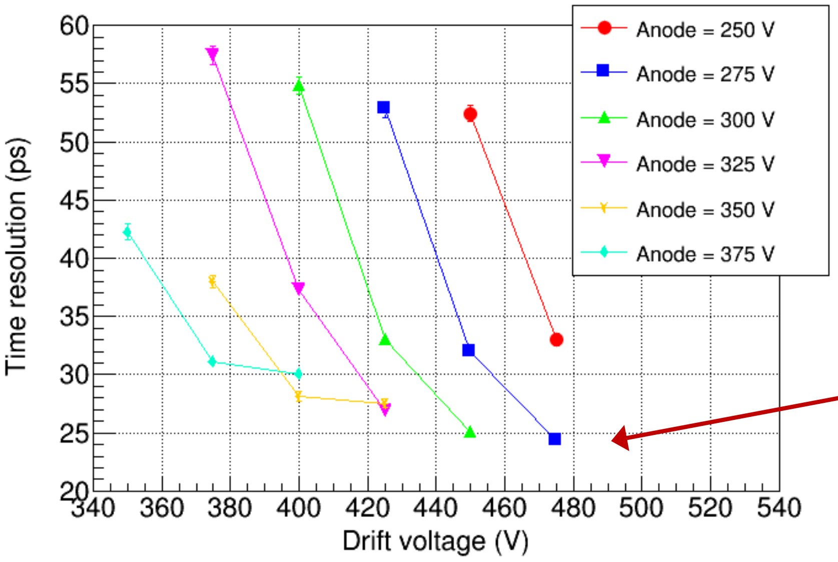




Time spread of SAT defined by the avalanche length = avalanche size

arXiv:1901.10779v1 [physics.ins-det]

Results from beam tests (2017)



Same detector as for Laser tests:

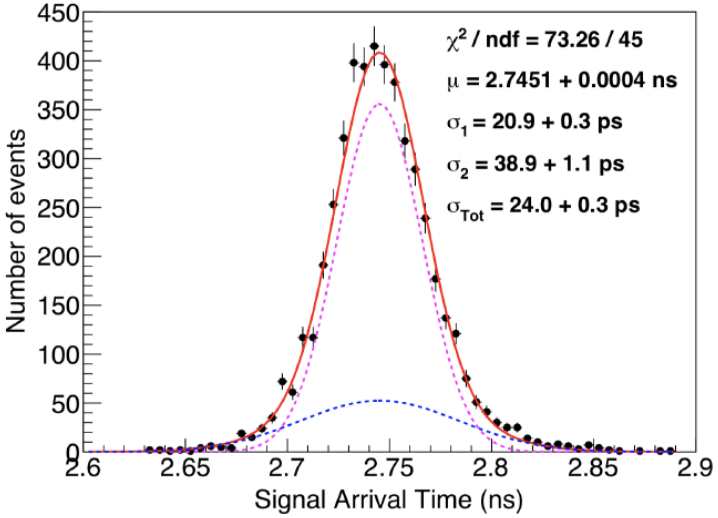
- MgF2 radiator 3 mm thick,
- 18 nm CsI on 5.5 nm Cr
- Bulk MicroMegas
- "COMPASS gas"

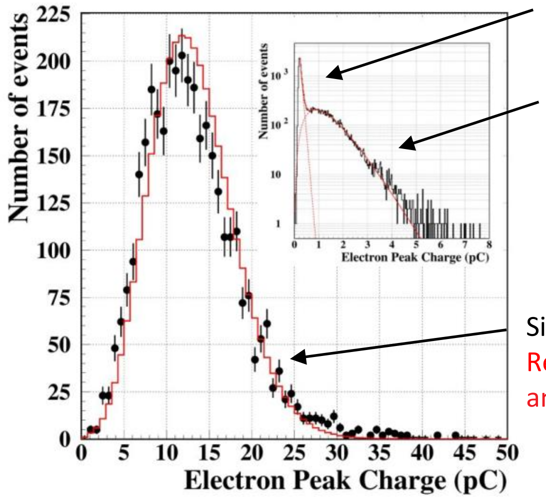
Optimum operation point: $\mathbf{V_{drift}/V_{anode}}$**: -475V/+275V**

Best result: **24 ± 0.3 ps**

$N_{p.e.}$ = **10.1 ± 0.7**

- *Result repeated in two different beam campaigns.*





Noise component

Signal for single p.e from UV-lamp tests: "Polya" (Gamma distribution)

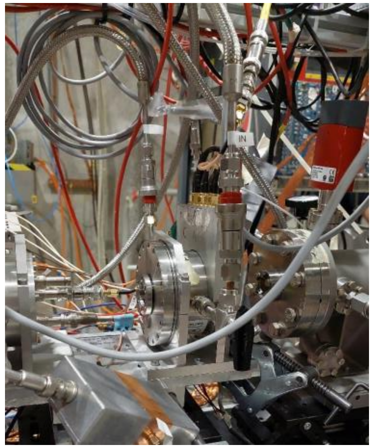
Signal of MIPs

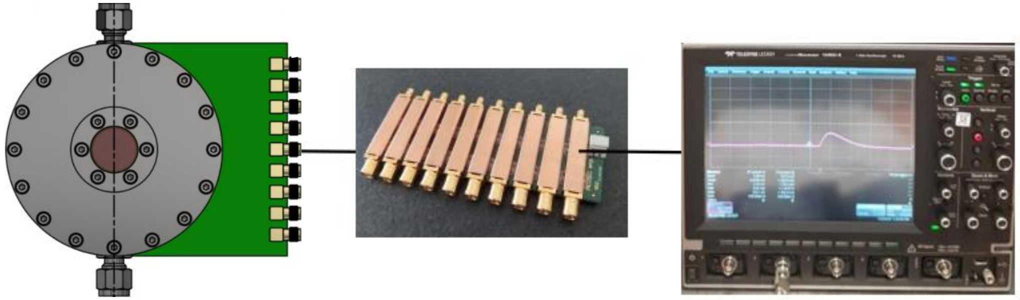
Red curve: convolution of Poison and single p.e response (Polya)

J. Bortfeldt, et al., "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector", Nucl. Instrum. Meth. A903 (2018) 317-325, doi:10.1016/j.nima.2018.04.033

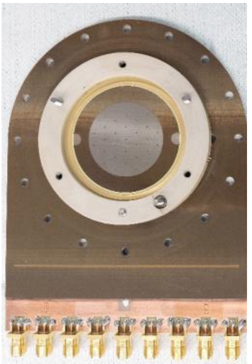
Resistive technology tests

- Multi-Pad Prototypes (7-pad)
  - Hexagonal pads ø 1cm
  - MgF_2 crystal
  - CsI & B4C photocathodes

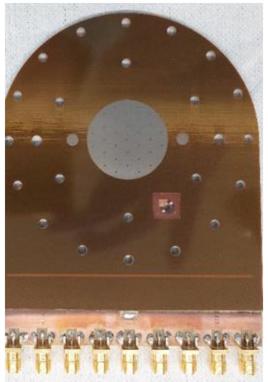




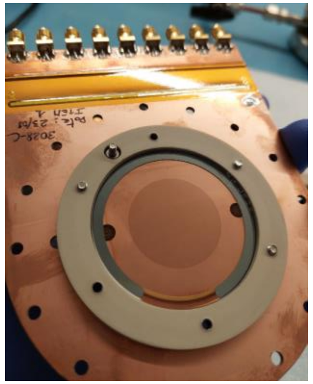
Resistive layer



Capacitive sharing

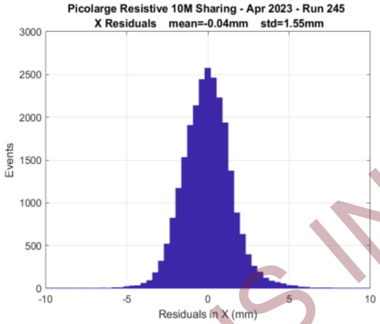


μRwell

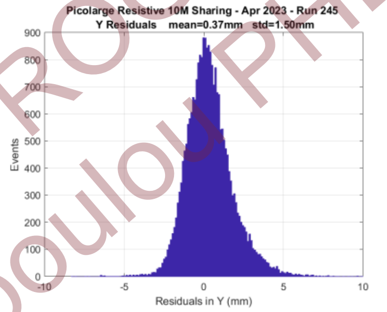


1st time spatial resolution measurements for the 10MO/☐ resistive detector

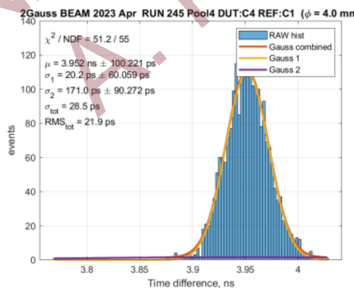
σx= 1.5 mm



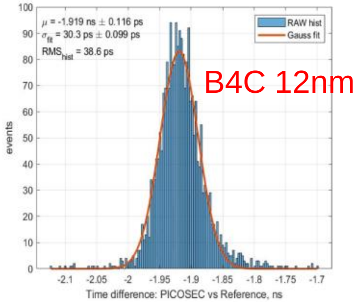
σy = 1.55 mm



RMS→20 ps central region



RMS→30 ps central region

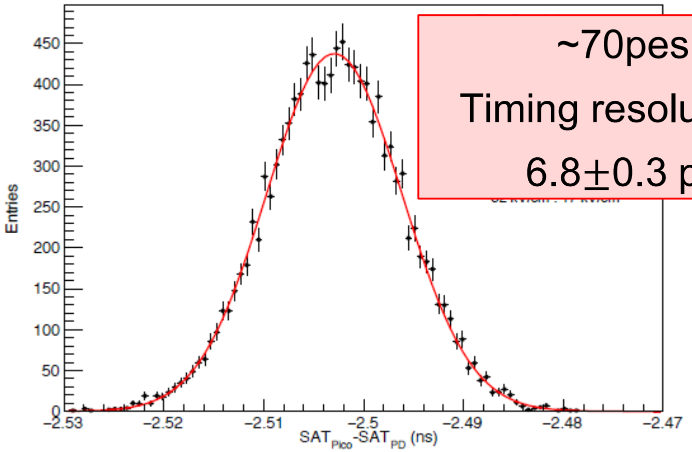


B4C 12nm

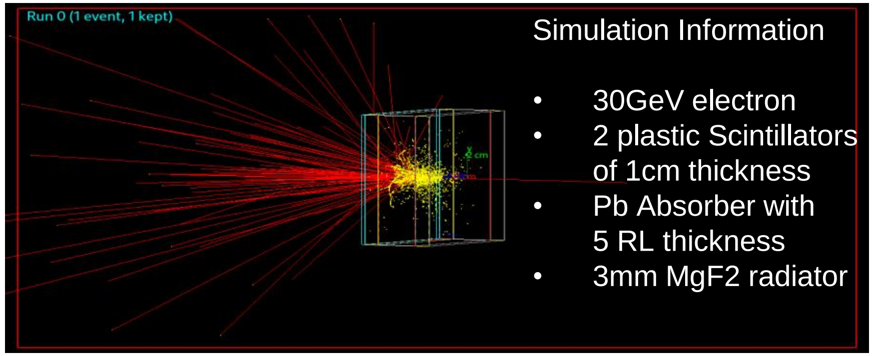
Timing e/m showers: from Simulation to Reality

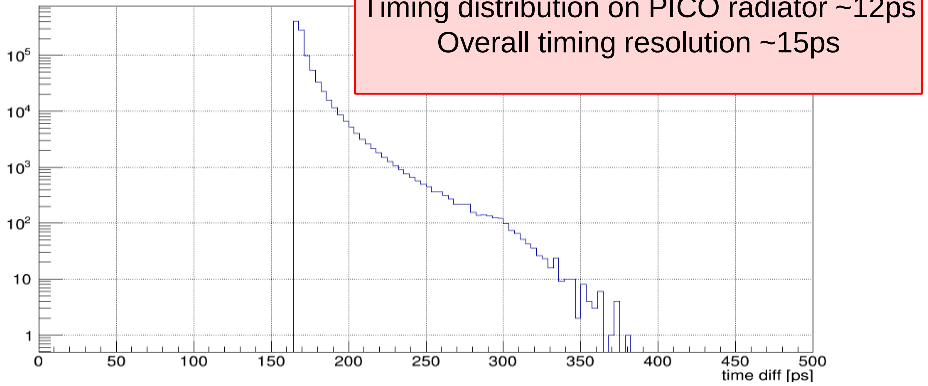
Embed a PICOSEC-Micromegas layer inside a calorimeter after a few radiation lengths and/or inside the instrumented hadron damp

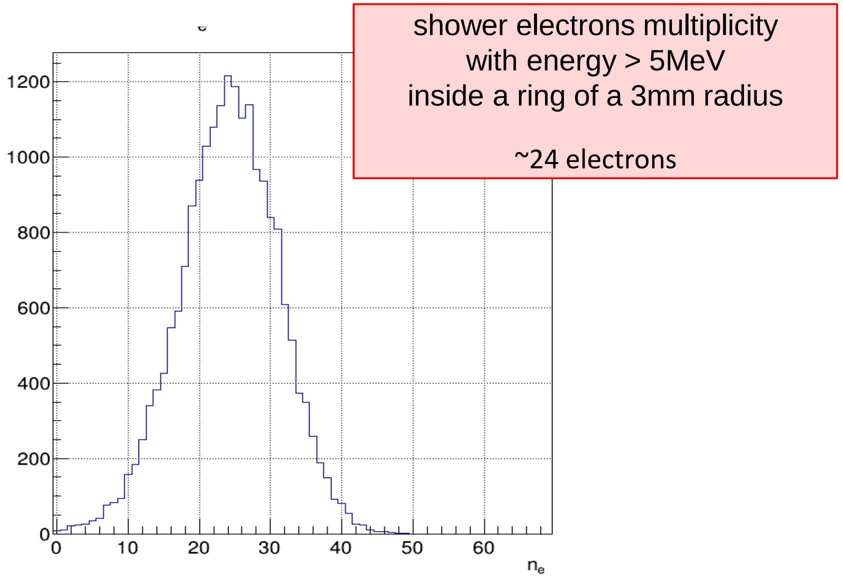
First Indications from laser test measurements @ IRAMIS /CEA-Saclay



First Simulation Studies with Geant4





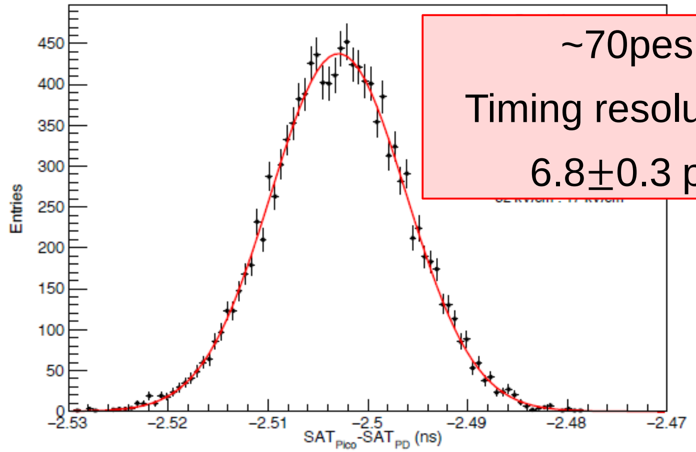


For more info see the presentation by **A. Kallitsopoulou** *the RD51 Mini Week, CERN (7-10 Feb 2022)*
https://indico.cern.ch/event/1110129/contributions/4733737/attachments/2388605/4082733/PICOSEC_in_electron_beam.pdf

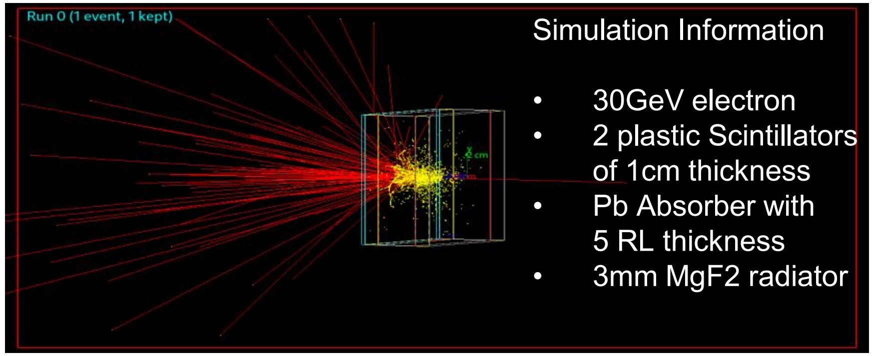
Timing e/m showers: from Simulation to Reality

Embed a PICOSEC-Micromegas layer inside a calorimeter after a few radiation lengths and/or inside the instrumented hadron damp

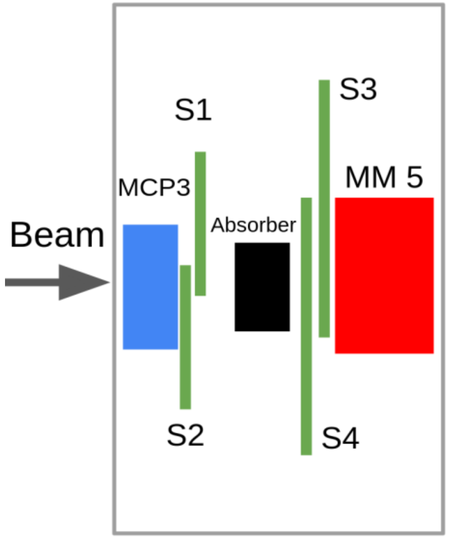
First Indications from laser test measurements @ IRAMIS /CEA-Saclay

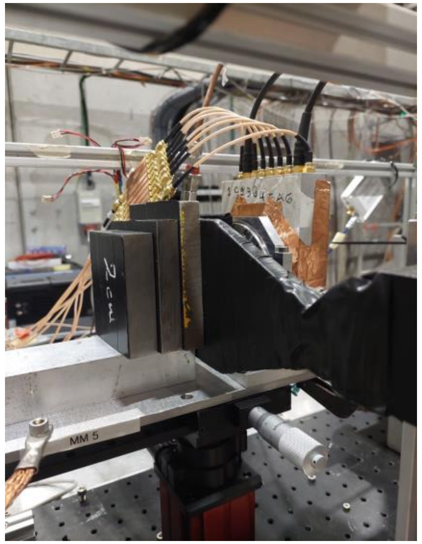


First Simulation Studies with Geant4



- Particle Beams @ CERN SPS H4 Beamline
  - Electrons 30GeV
  - ~1MH/cm2

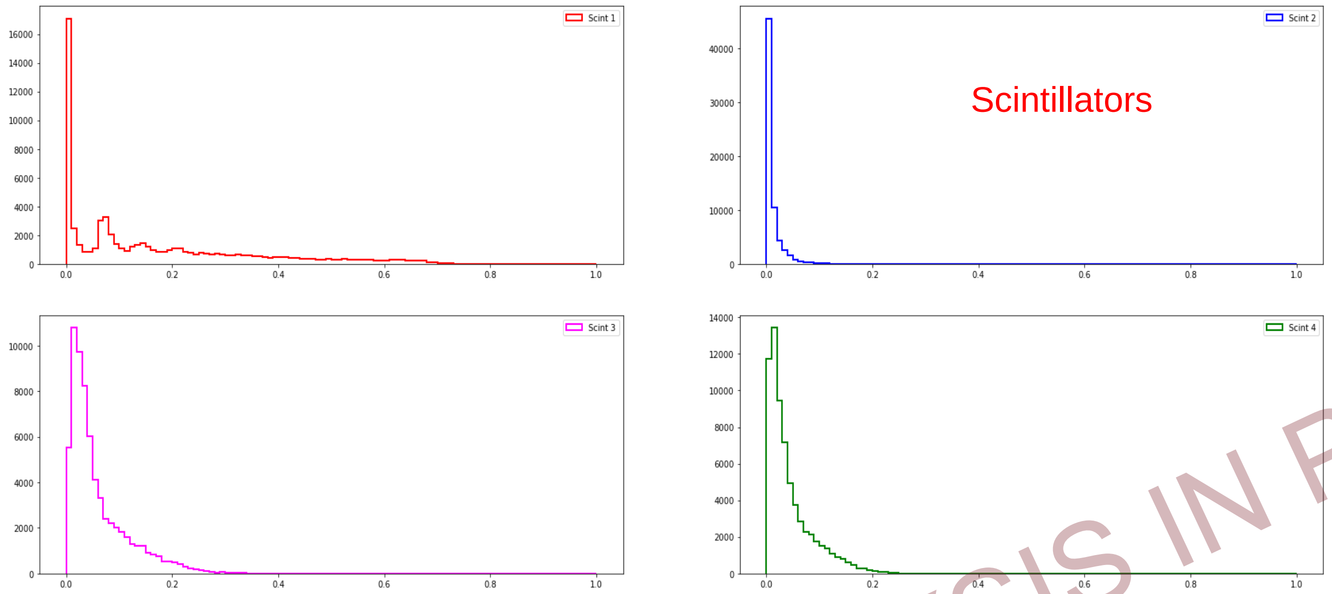


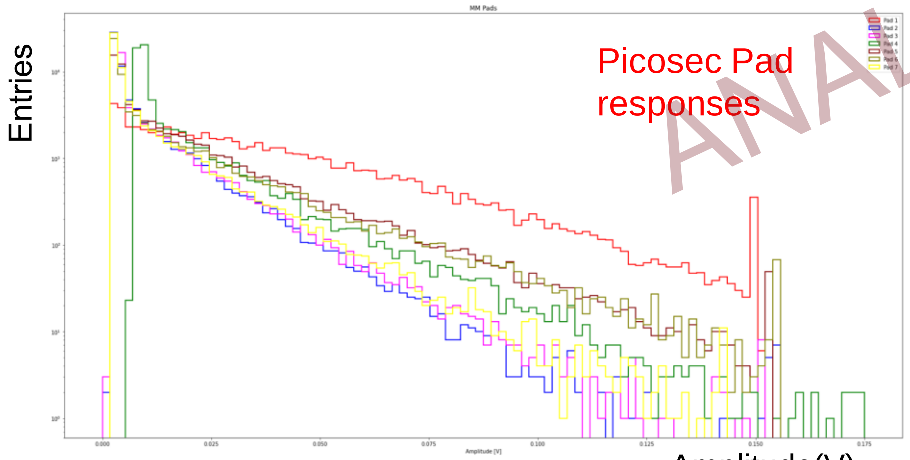


- Multi-Pad Prototype (7-pad)
  - Resistive prototype
  - Hexagonal pads ø 1cm
  - MgF2 crystal
  - B4C (12min) photocathode

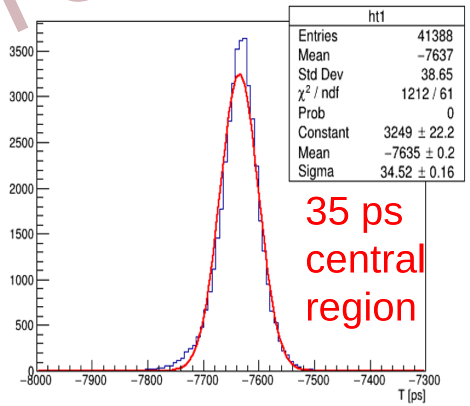
Detector response to electrons - 10MO/□ & B4C photocathode

30GeV electrons without absorber





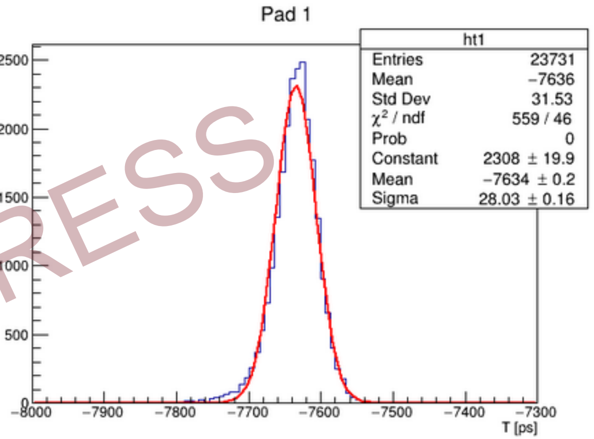
Amplitude(V)



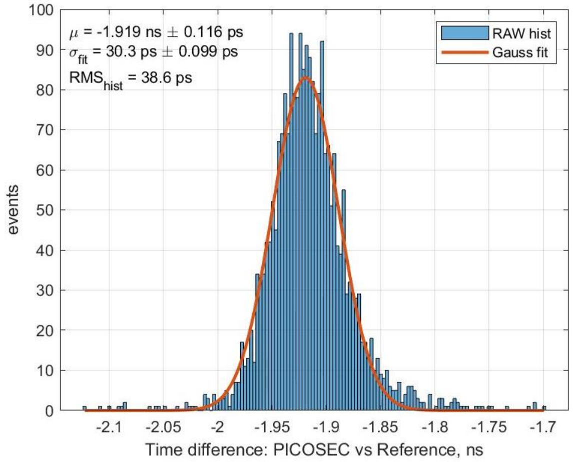
Max Amplitude value ~ 150mV

ANALYSIS IN PROGRESS

Comparison of response to MIPS
(high gain)



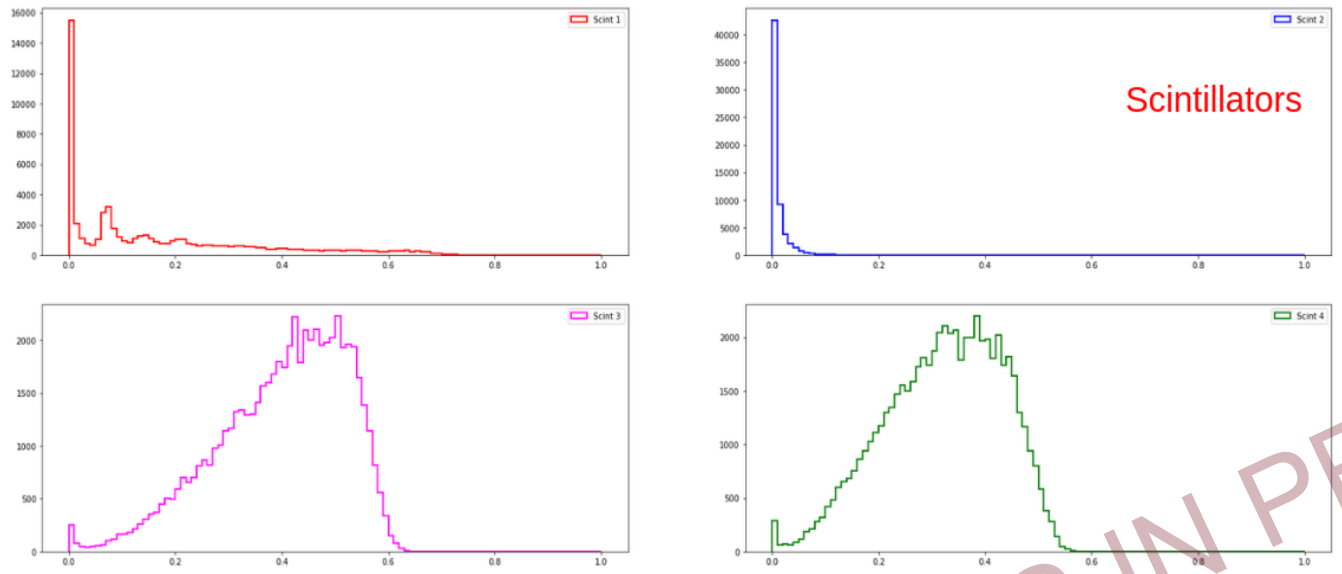
Electrons as MIPs **~ 28ps** for the central pad

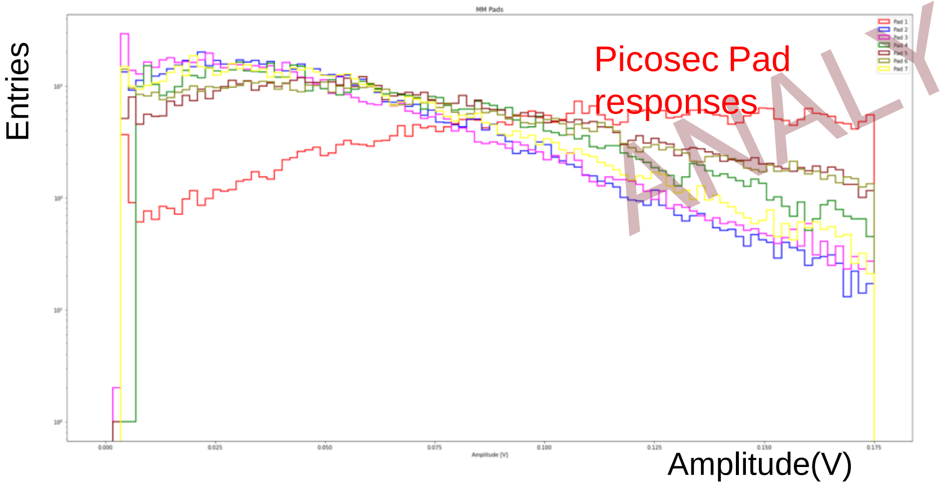


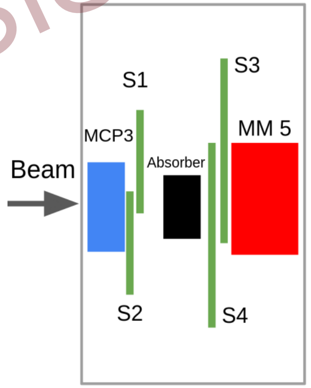
Muons as MIPs **~ 30ps** for the central pad

Detector response to showers by 30 GeV electrons

30GeV electrons with 5cm Fe absorber

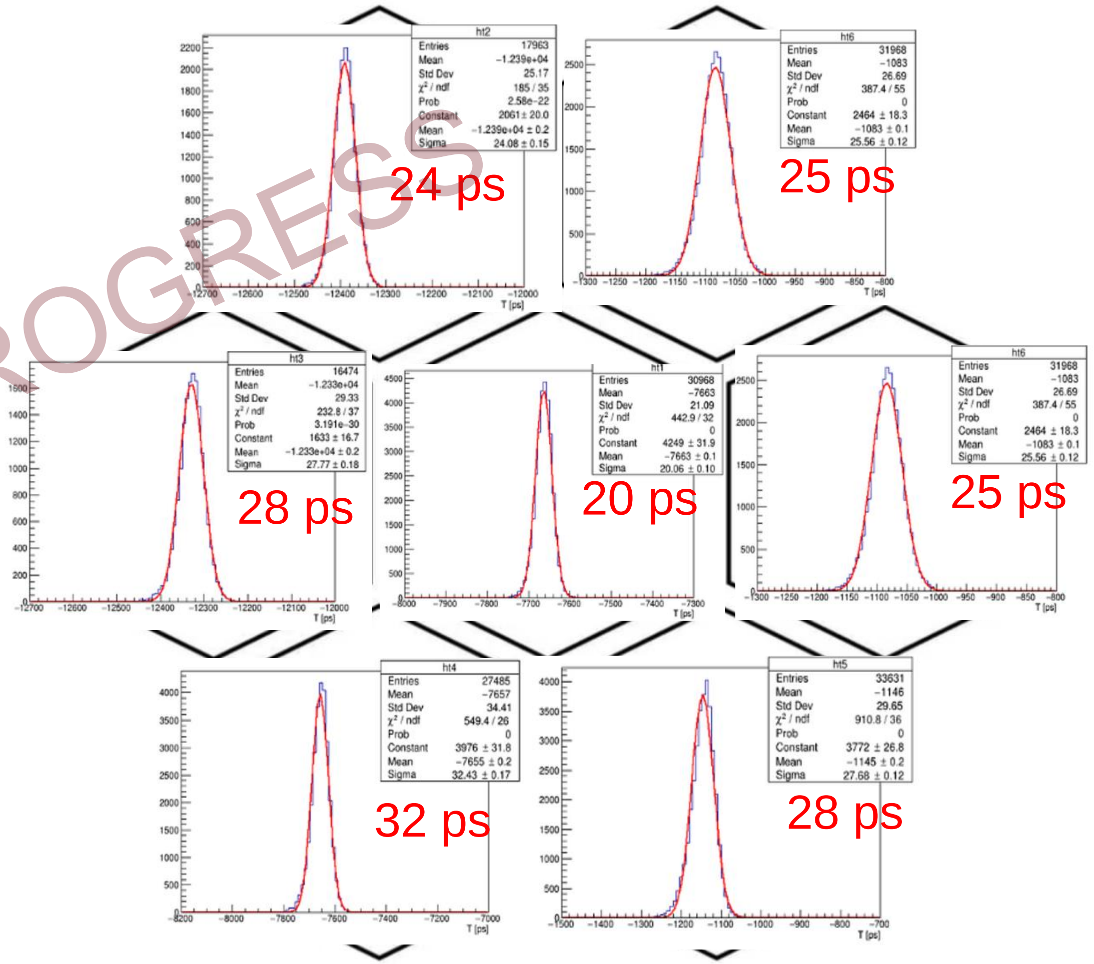






Max Amplitude value ~ 175mV

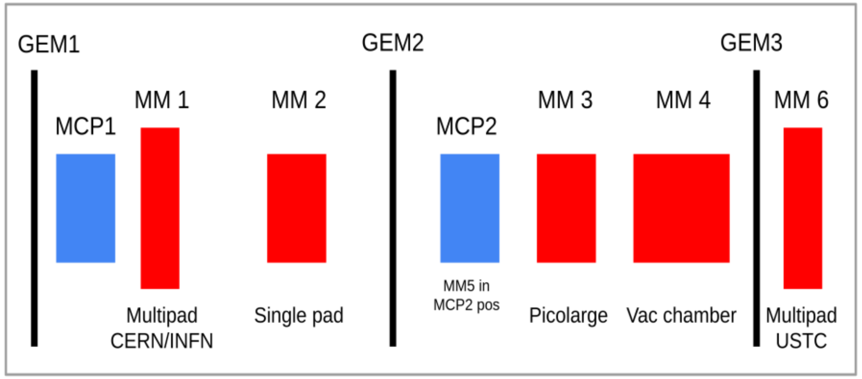
Overall timing response to showers below 30 ps



First Results on Detector response to high rate Pions

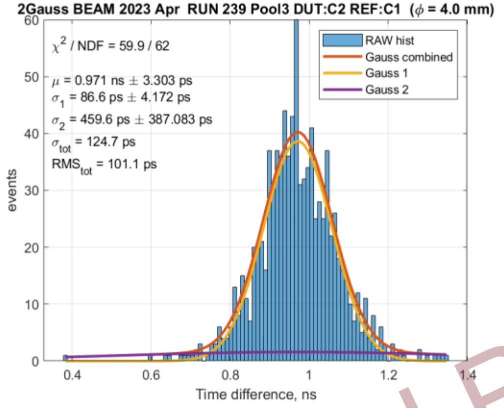
- Pions of 80GeV Energy
- Beam size 2.3x1.6cm
- **Rate ~MH/$\mathbf{cm^2}$**

- The Set Up
  - MCP-PMT for time reference and comparison with muon runs
  - Single pad 82MO/□ resistive - 6nm B4C photocathode used as reference timing device
  - Detector Under Test
    - Single pad non resistive - 1 cm - 7nm B4C

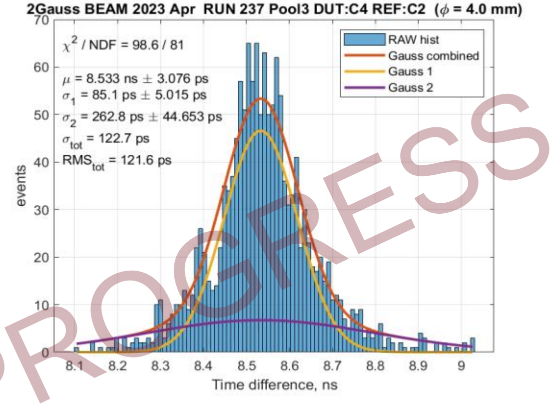


➔ New test planned for 2024 in common with ENUBET using the large area resistive detectors (SPS or PS)

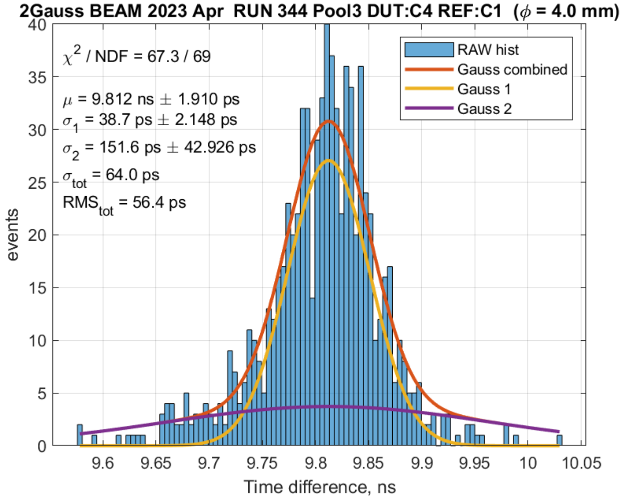
Using MCP reference
DUT @ 275/430V



Using picosec as reference
DUT @ 300/420V



Best detector's response in muons ~56 ps



Picosec publications

PhD Thesis:

Sohl L., “*Development of PICOSEC-Micromegas for fast timing in high rate environments*”, CEA Saclay 17/12/2020, https://www.theses.fr/2020UPASP084

Maniatis I. “*Research and Development of MicroMegas Detectors for New Physics Searches*”, AUTh. Greece 25/02/2022, http://ikee.lib.auth.gr/record/339482/files/GRI-2022-35238.pdf

Master Thesis:

Paraschou K. “ *Study of the PICOSEC Micromegas Detector with Test Beam Data and Phenomenological Modeling of its Response*”, AUTh. Greece, 14/03/2018 GRI-2018-21474.pdf (auth.gr)

Kallitsopoulou A. “*Development of a Simulation Model and Precise Timing Techniques for PICOSEC Micromeas Detectors”, AUTh. Greece, 15/10/2021,* [2112.14113] Development of a Simulation Model and Precise Timing Techniques for PICOSEC-Micromegas Detectors (arxiv.org)

Published papers:

1. J. Bortfeldt et al. (PICOSEC Collaboration), “*PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector*”, Nucl. Instrum. Meth. A903 (2018) 317-325. https://doi.org/10.1016/j.nima.2018.04.033
2. J. Bortfelt et al. (PICOSEC Collaboration), "*Timing Performance of a Micro-Channel-Plate Photomultiplier Tube*", Nucl. Instrum. Meth. A960 (2020) 163592, https://doi.org/10.1016/j.nima.2020.163592
3. J. Bortfeldt et al. (PICOSEC collaboration), "*Modeling the Timing Characteristics of the PICOSEC Micromegas Detector*", Nucl. Instrum. Meth. A993 (2021) 165049, https://doi.org/10.1016/j.nima.2021.165049
4. S. Aune et al. (PICOSEC collaboration), "*Timing performance of a multi-pad PICOSEC-Micromegas detector prototype*", Nucl. Instrum. Meth. A993 (2021) 165076, https://doi.org/10.1016/j.nima.2021.165076

Selected Conference proceedings:

1. T. Papaevangelou et al., “*Fast Timing for High-Rate Environments with Micromegas*“ , EPJ Web Conf. 174 (2018) 02002, https://doi.org/10.1051/epjconf/201817402002
2. F.J. Iguaz et al. (PICOSEC collaboration), “*Charged particle timing at sub-25 picosecond precision: The PICOSEC detection concept*”, Proceeding of Pisa 2018 conference, accepted in Nucl. Inst. Meth. A, https://doi.org/10.1016/j.nima.2018.08.070
3. L. sohl et al. (PICOSEC collaboration), “*Progress of the Picosec Micromegas concept towards a robust particle detector with segmented readout*”, 9th international symposium on Large TPCs for low-energy rare event detection, 2018, https://doi.org/10.1088/1742-6596/1312/1/012012
4. L. Sohl et al. (PICOSEC collaboration), “*Single photoelectron time resolution studies of the PICOSEC-Micromegas detector*”, JINST 15 (2020) 04, C04053, Contribution to: IPRD1, https://doi.org/10.1088/1748-0221/15/04/C04053
5. J Manthos et al. (PICOSEC Collaboration), “*Recent Developments on Precise Timing with the PICOSEC Micromegas Detector*“, J.Phys.Conf.Ser. 1498 (2020) 1, 012014, https://doi.org/10.1088/1742-6596/1498/1/012014

What is needed for a new generation cross-section facility?

- Measure the neutrino flux of a xsect-dedicated short baseline beam with a precision <1% in ν_e and ν_μ . **Flux** is the dominant systematics. Generally known at 10% level with a few notable exceptions
  - Combine hadroproduction data + ν-e scattering (5-10%). World record: L. Zazueta [Minerva Coll.] PRD 107 (2022) 012001 (3.3-4.7% for ν_μ)
  - Monitored neutrino beam (**this seminar**) 0.5-1 %
  - Muon storage ring (nuSTORM) <1%
- Measure the **energy** of the neutrino without relying on the final state to get rid of all biases coming from nuclear reinteractions
  - Narrow band beams combined with movable detectors (rough approximation of a "monocromatic beam")
  - Monitored neutrino beam "Narrow band- off-axis technique" (**this seminar**)
  - Tagged neutrino beams (ENUBET+NuTAG – Physics Beyond Collider)
- Use the same **target** as DUNE and HyperK + low Z target (existing or new experiments)
  - Some information available from near detectors (but, then, issues with flux × cross-section deconvolution)
  - New experiments with existing or novel detectors along a short-baseline beam (following the success of dedicated experiments like Minerva)

ENUBET: the first monitored neutrino beam*F. Terranova*
https://indico.cern.ch/event/1353517/attachments/2772398/4831052/terranova_cern_enubet_15dec2023.pdf