PIMENT – Development of a PICOSEC Micromegas detector for ENUBET

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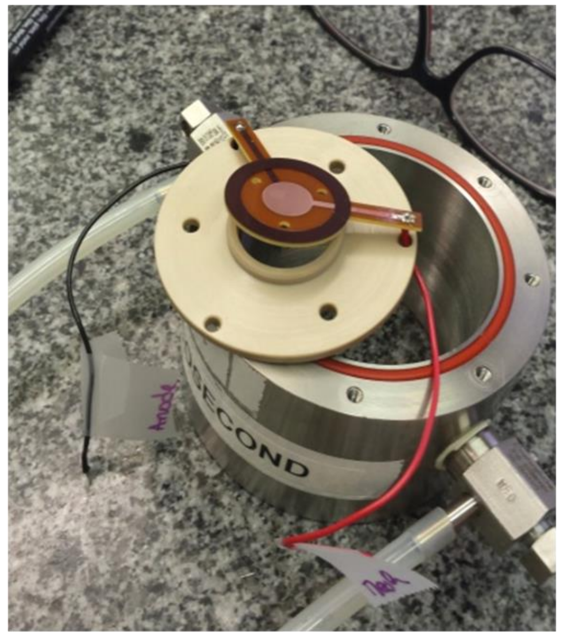
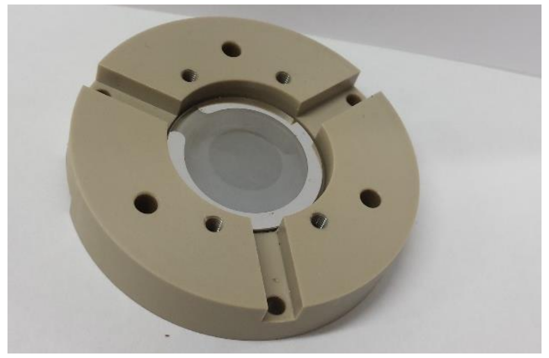
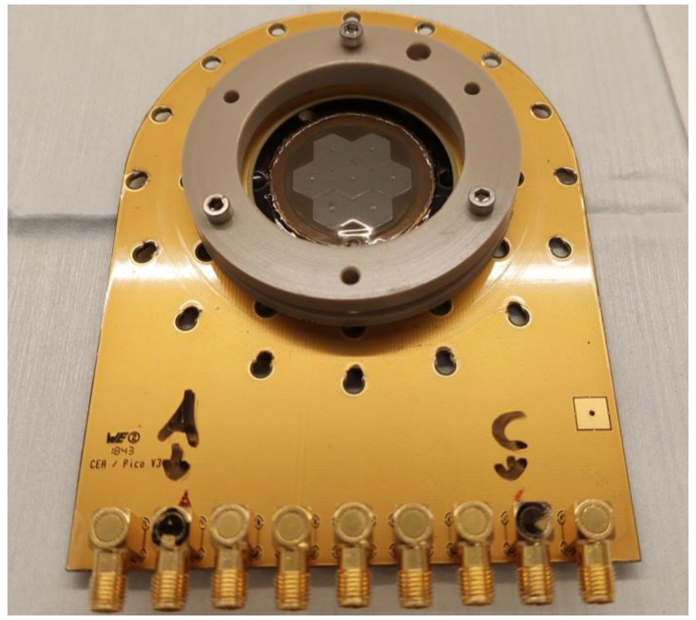
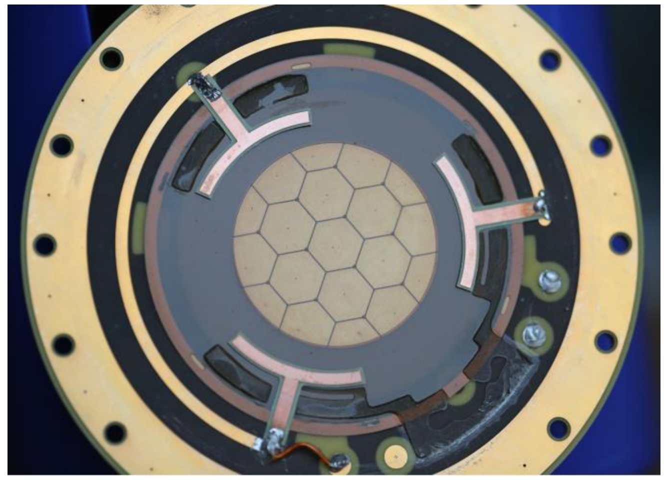
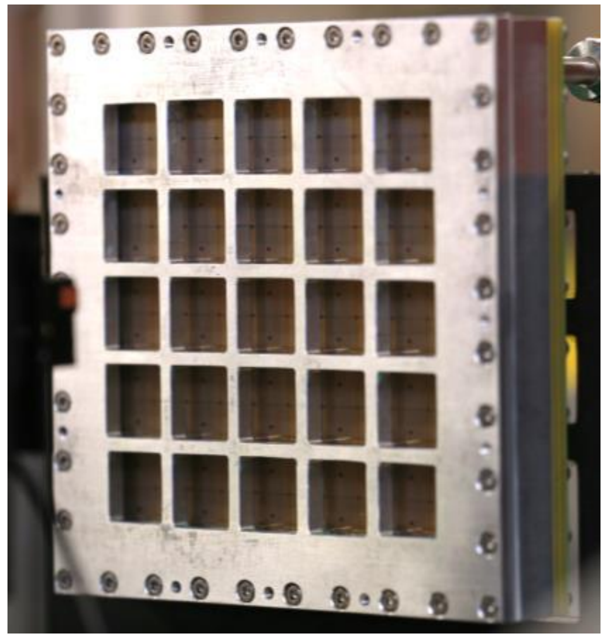
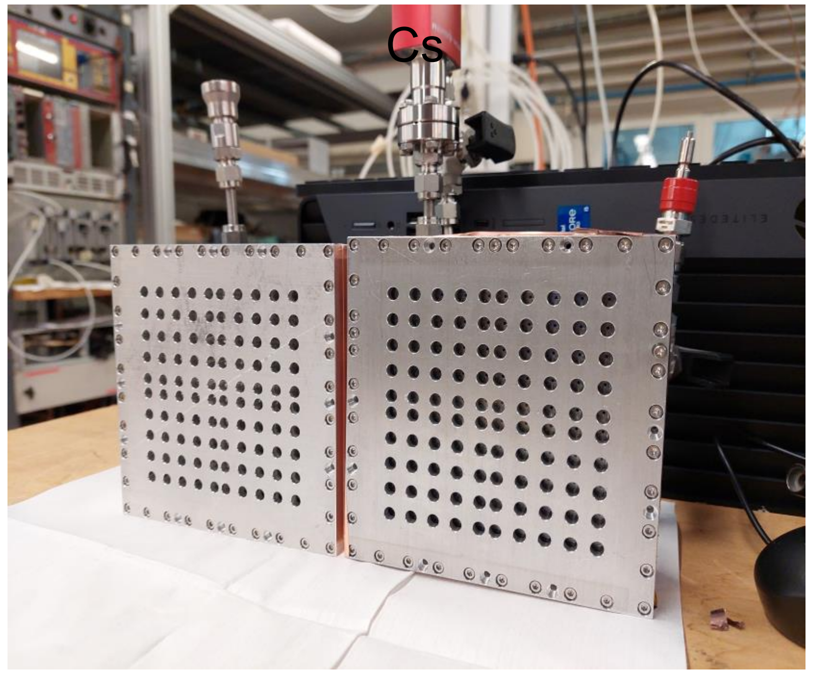
LAPP Annecy

OUTLINE

- Objectives & Research hypothesis
- PICOSEC-Micromegas Detector Concept
- Project State of the Art - Plans
- Detector's Performance & Latest Results

Project Collaboration

- Partners:
  - Thomas Papaevangelou (**CEA/DRF/IRFU**)
  - Anselmo Meregaglia(**CNRS/IP2I Bordeaux**)
  - Dominique Breton (**IN2P3/IJCLab**)
  - Michal Pomorski (**CEA/DRT/LIST**)
- Duration: 36 months started from Jan 2022

- External Partners:
  - **CERN** (L. Ropelewski, E. Oliveri, F. Brunbauer, Rui d'Oliveira, A. Utrobičić, M.Lisowska)
  - **University of Thessaloniki**(S.Tzamarias, I.Angelis, D.Sampsonidis, K.Kordas, Ch.Lampoudis, A.Tsiamis)
  - **USTC Hefei China** (Zhou Yi)
  - **ENUBET Collaboration** (A.Longhin)

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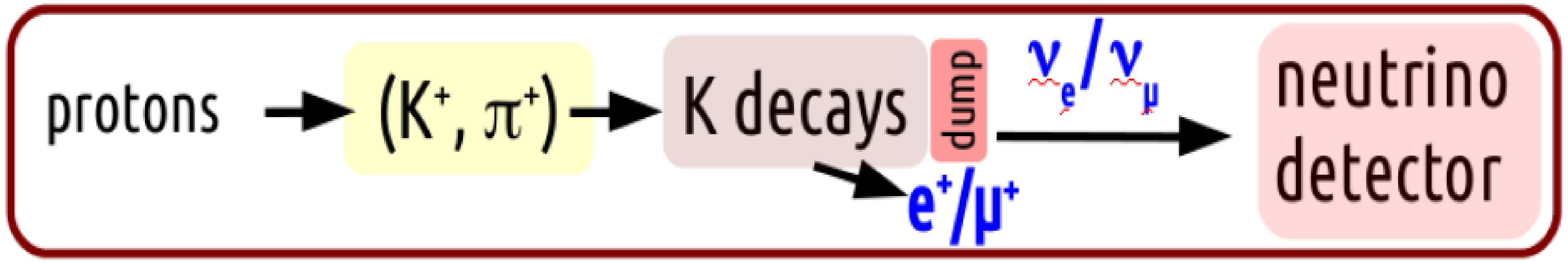
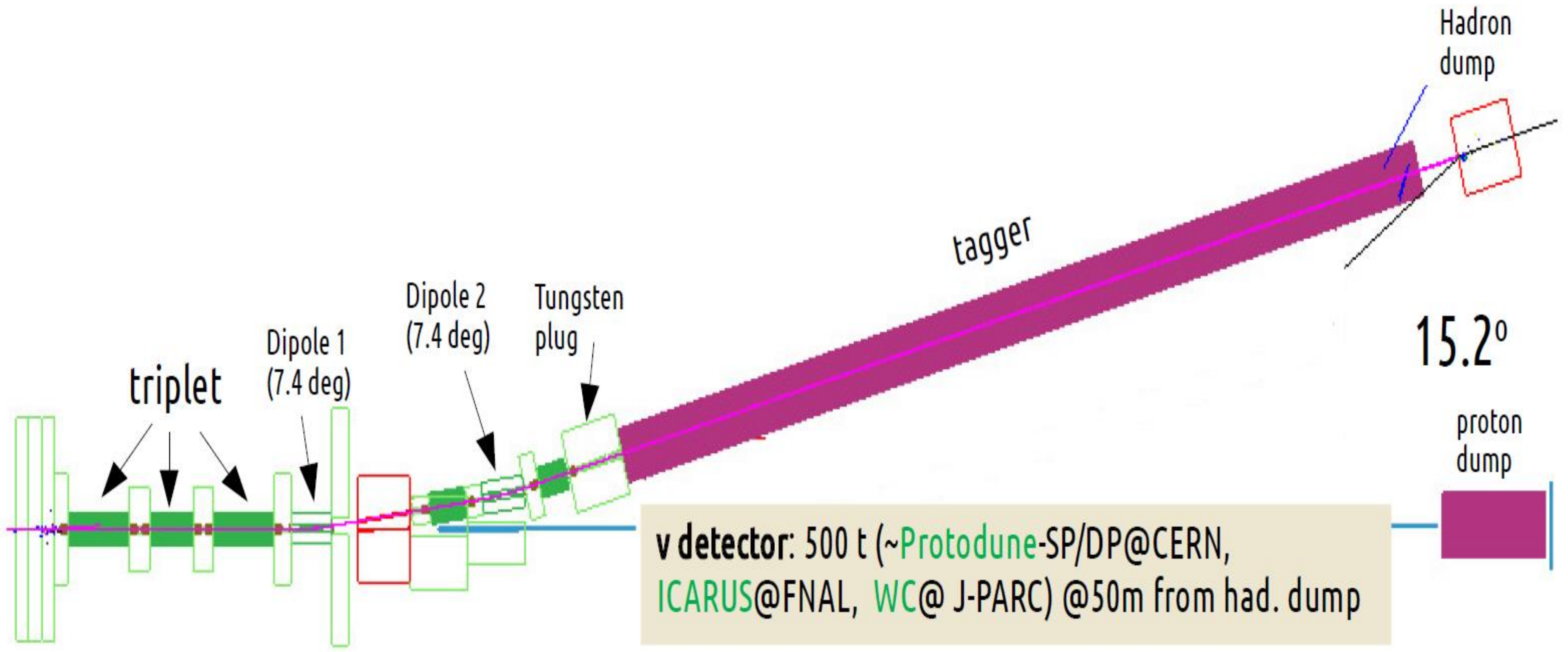
Context of ENUBET



- Need of precise timing resolution critical for :
  - Clean reconstruction of the events &
  - Reduction of mixing different events due to pile-up
- ENUBET characteristics facility (*more on Francesco Teranova presentation*)
  - Monitored neutrino beam **with no one-to-one correlation** between positrons tagged in beamline and neutrinos tagged in the far detector
- Sub-ns sampling would offer this correlation
  - On an event-by-event basis
  - Determine the flavor of neutrino



Development of new instrumentation based on PICOSEC Micromegas Detectors

Need of PIMENT Context

- 3-year R&D Project aiming to:
  - Develop novel instrumentation based on PICOSEC-MM detector concept
  - Demonstrate the impact of such detectors on New Physics searches
  - Investigate the possibility of a real tagged neutrino beam

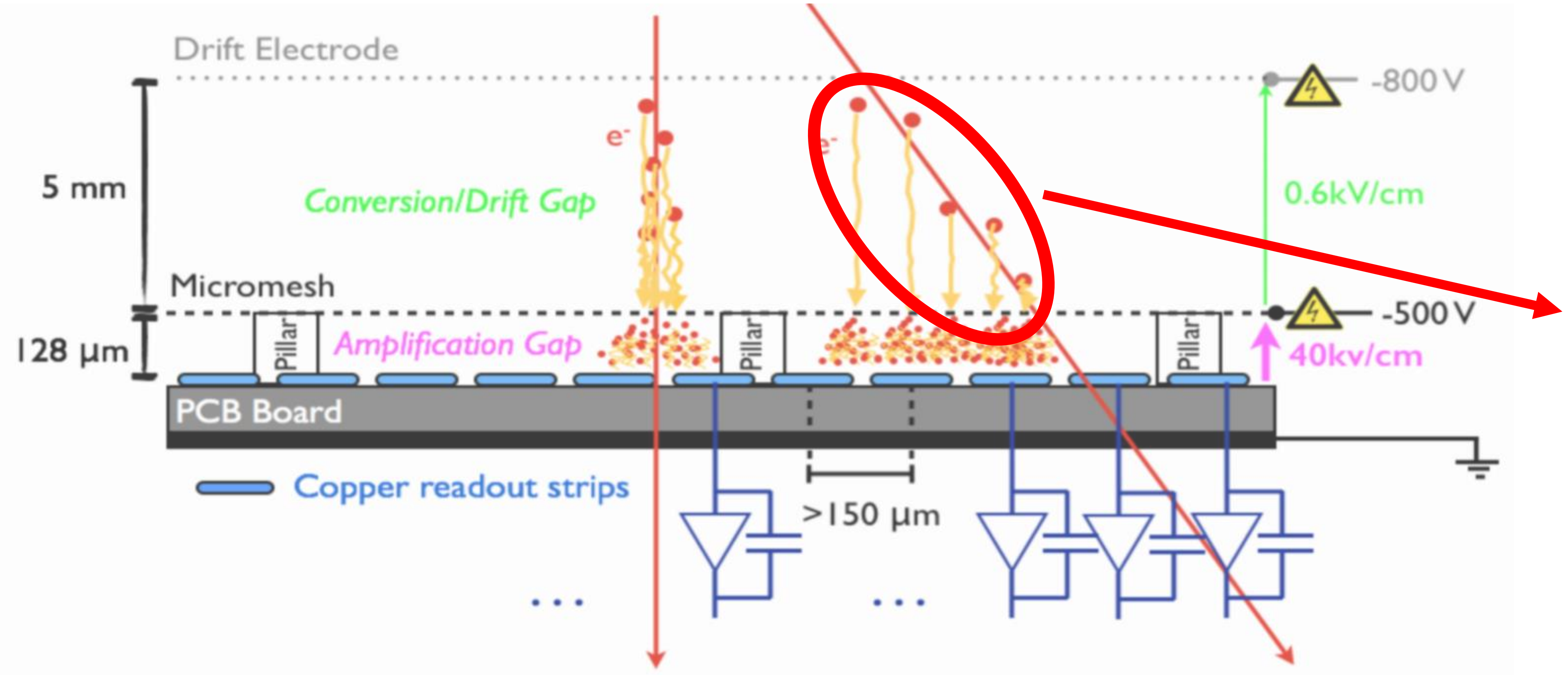
Possible exploitation Scenarios:

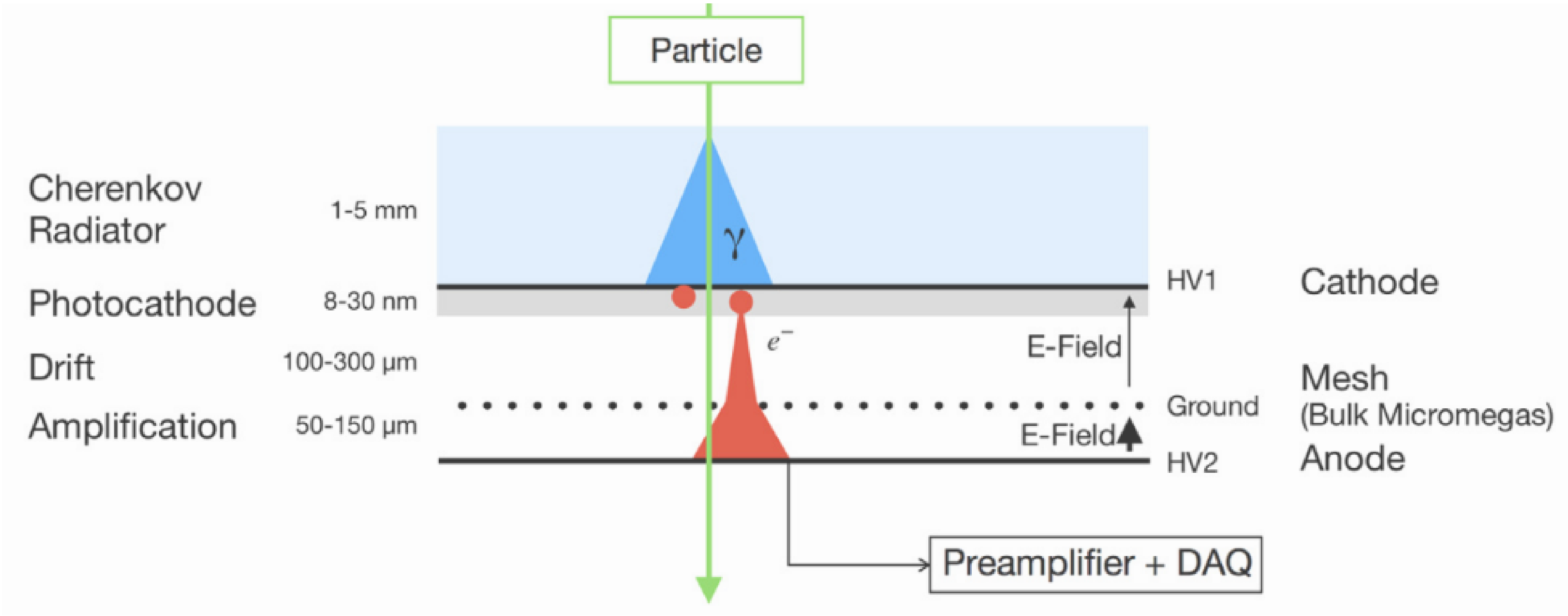
I. PICOSEC MM embedded in bulk of EC as time tagger of EM showers

II. Thin T0-layers for individual particles

III. Instrumentation of the hadron dump (muon monitoring)

IV. * Micromegas photodetector for T0 at far detector



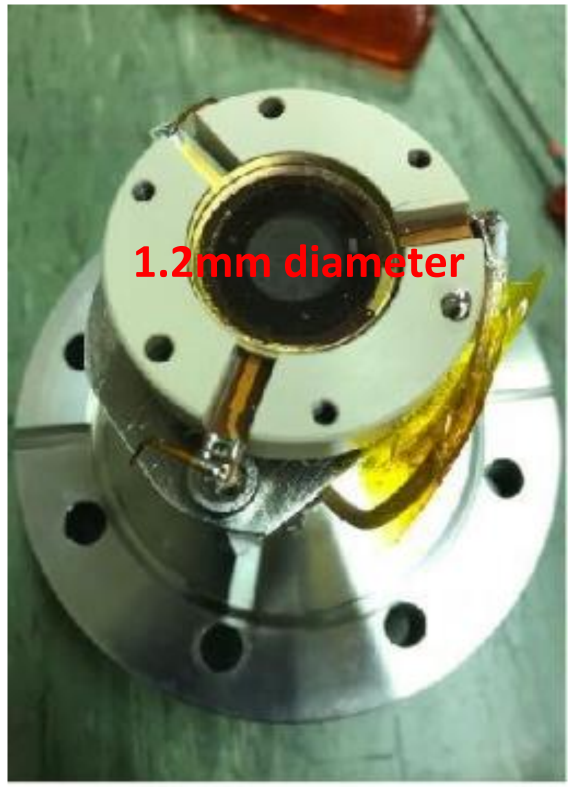


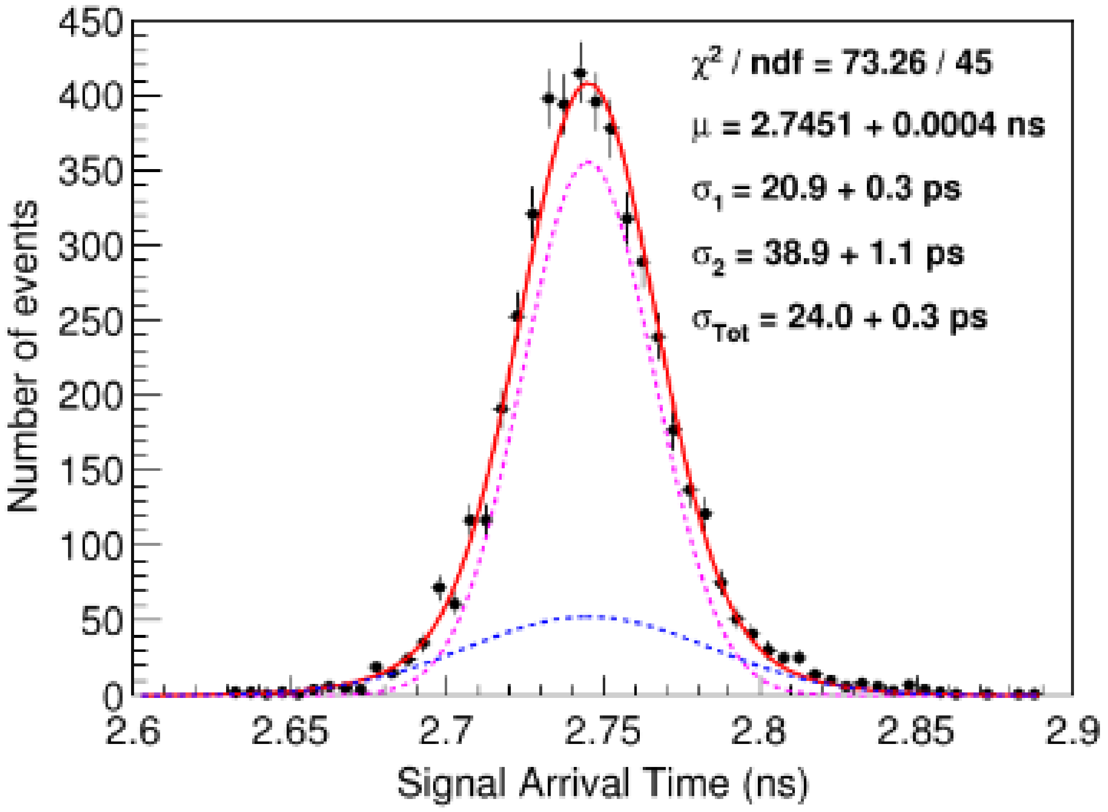
Classical MM modification

- Stochastic nature of ionization
- Randomness of the last ionization
- Time jitter of a few ns
- PICOSEC Concept → Timing with tens of Picosecond precision
- Modifications in MM geometry :
  - Smaller Drift Gap (3mm ⟶ 200µm)
  - Elimination of stochastic nature of ionization
  - Higher applied Drift Voltage -> Pre-avanalache
- Additional Components in MM geometry :
  - Cherenkov Radiator
  - Photocathode (prompt photoelectrons)

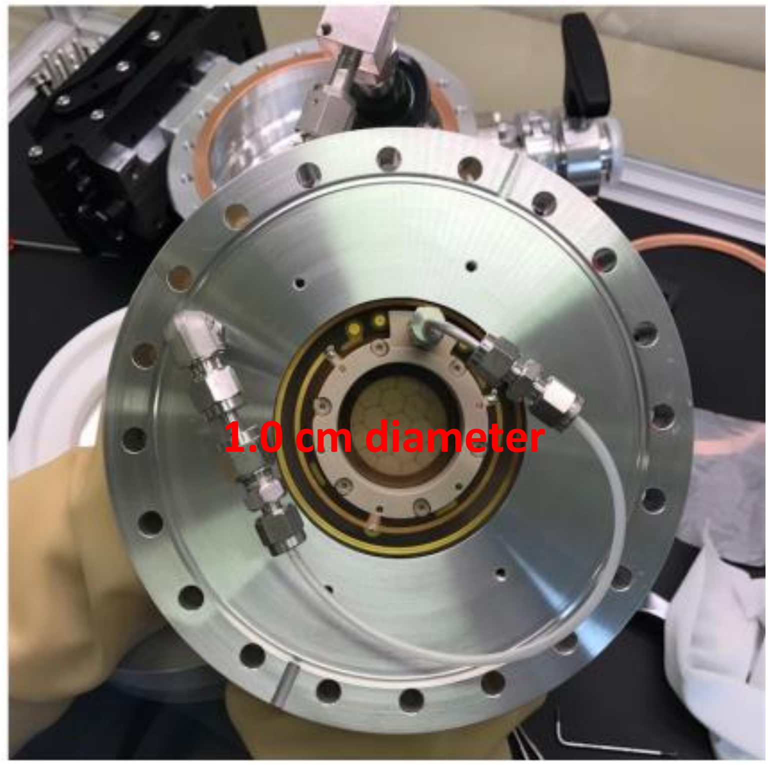
PICOSEC Micromegas Detector Performance

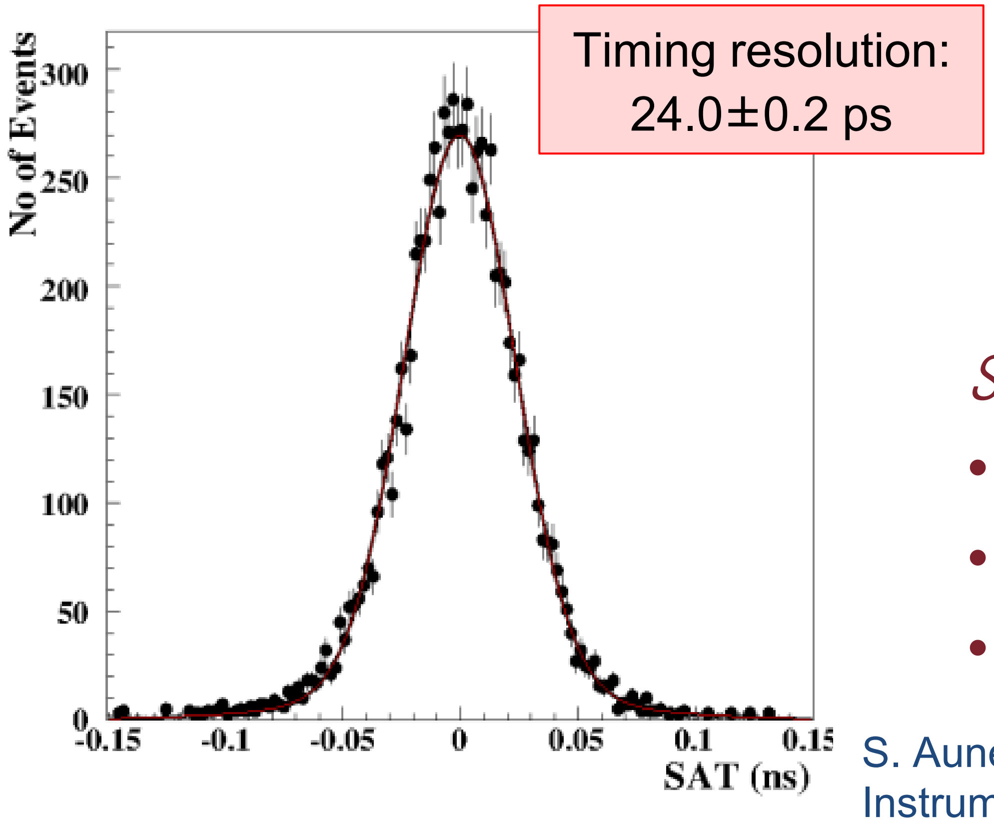
- SinglePad Prototype: Thin Gap with MgF2 & CsI photocathode



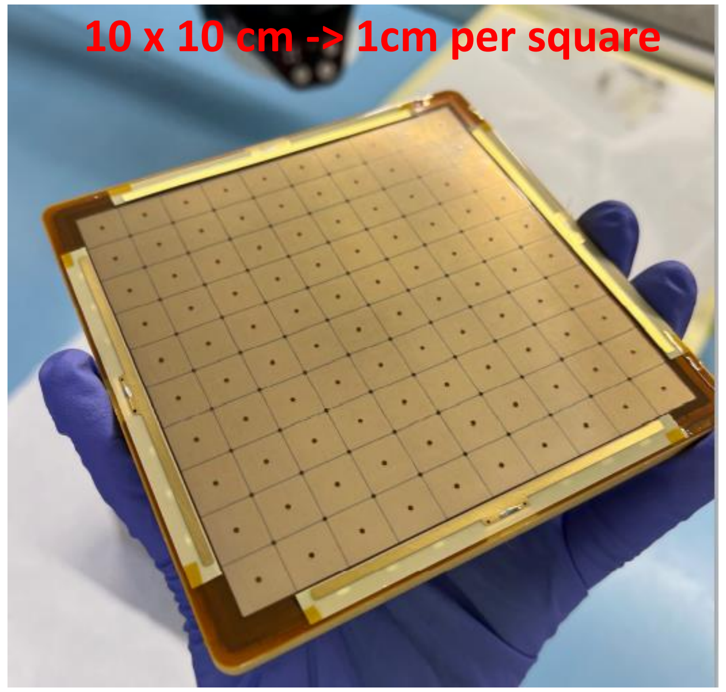


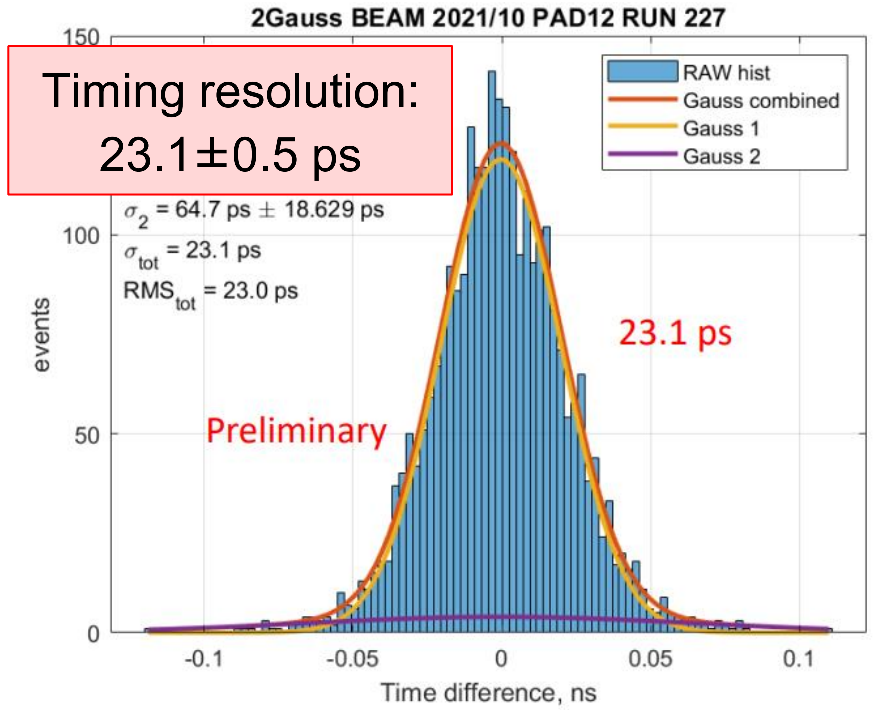
- MultiPad Prototype: Thin Gap with MgF2 & CsI photocathode





- Large Area MultiPad Prototype: Thin Gap with MgF2 & CsI photocathode





- Detector's Performance studied in :
  - Muon Test Beam @ 150GeV muons
  - Laser Test Beam @ IRAMIS

- Reaching extremely precise timing resolution for gaseous detectors so far

Successful goals:

- *Proof-of-principle* ⟶ **picosec** order timing resolution
- Anode segmentation, BUT special care for detector planarity
- Different photocathode candidate materials have been tested

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

Next steps Towards an engineered PICOSEC MM module for PIMENT: multiple directions in detector development

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

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

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

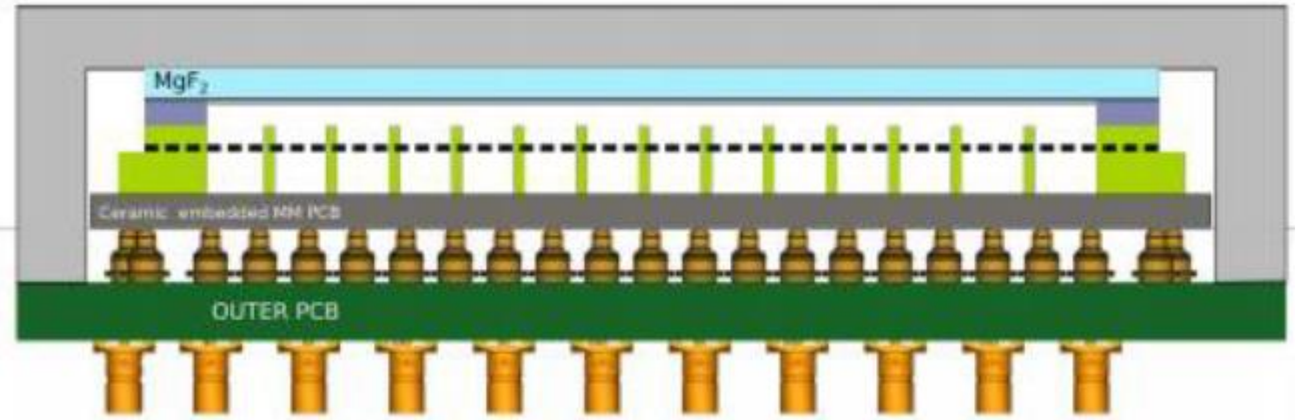
- **Physics Studies (LP2I Bordeaux/AUTh /IRFU)**
  - T0 tagger and/or embedded in a calorimeter
  - Muon monitoring

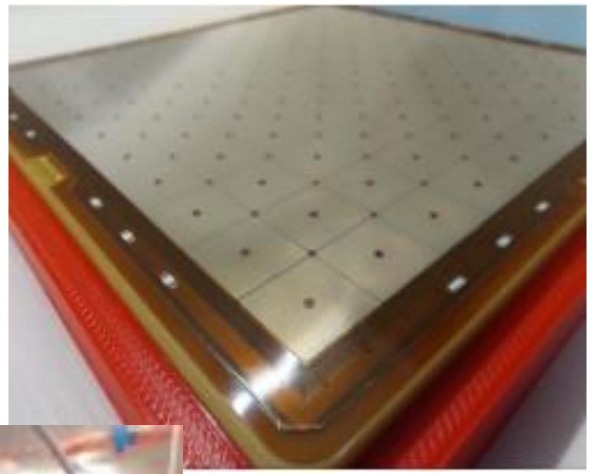
- As a photodetector for T0 tagging at the neutrino detector

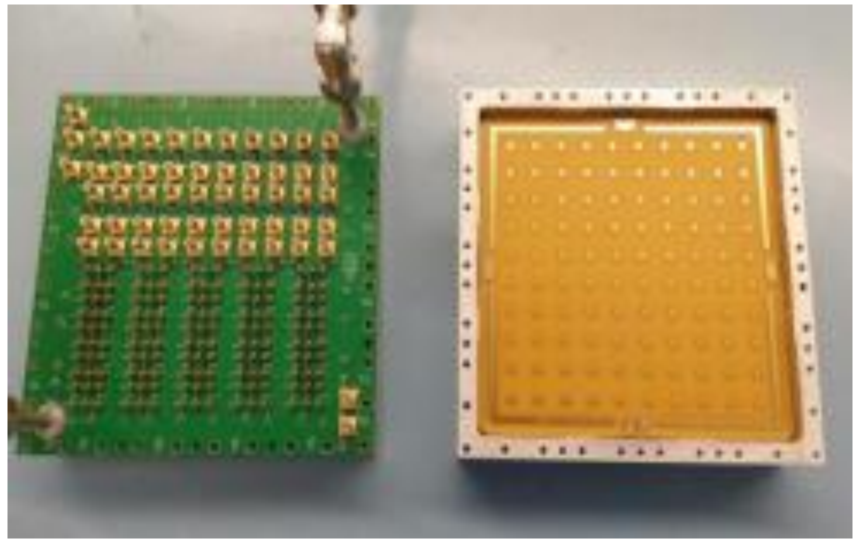
Ensure FLATNESS <10μm

- Tree possible approaches for modular prototypes with 10x10cm2 active zone :

- **Rigid, ceramic-core PCB for the MM readout**
  - Crystal coupled to the PCB with spacers
  - MgF_2 crystal & MM board will be decoupled from the chamber
  - Second PCB will be used for signals towards the amplifiers

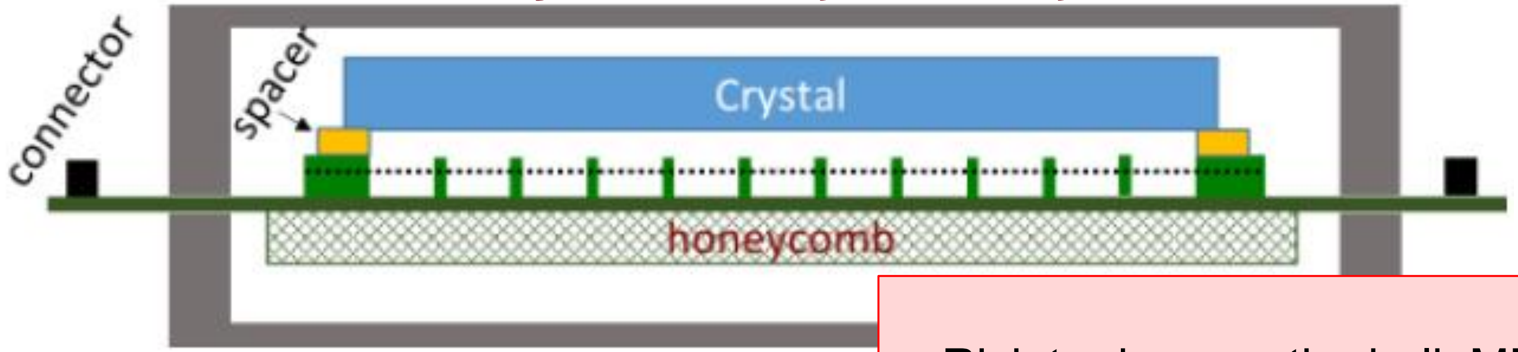






- **Drawback: Increased detector material ->timing layers**

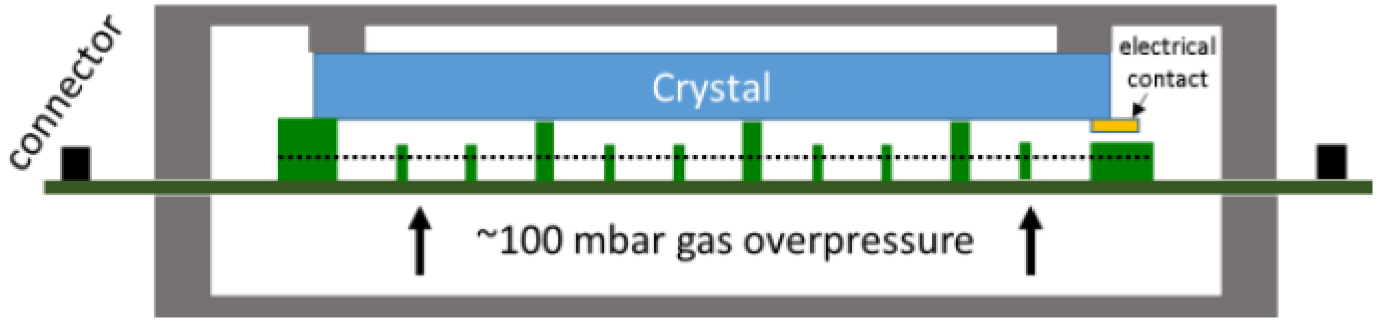
- **The ATLAS NSW Approach:**
  - Pillars on MM bulk readout
  - Pressing against the marble table
  - Backwards with a glued honeycomb layer



Risk to damage the bulk MM

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

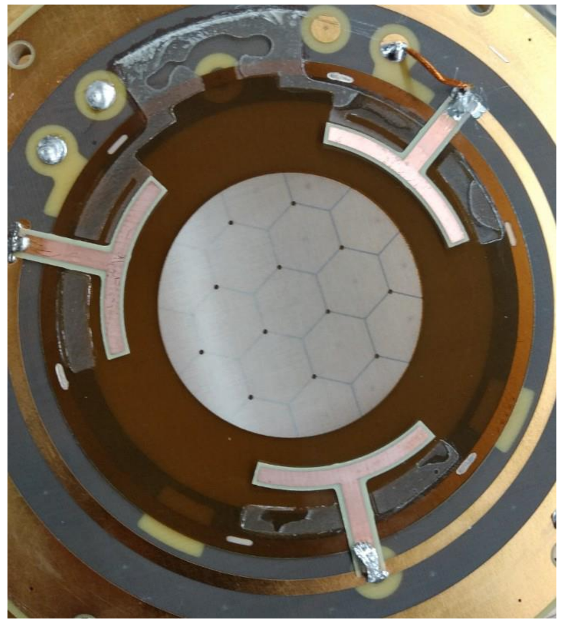
- **Longer pillars MM module:**
  - Pressed against Cherenkov radiator



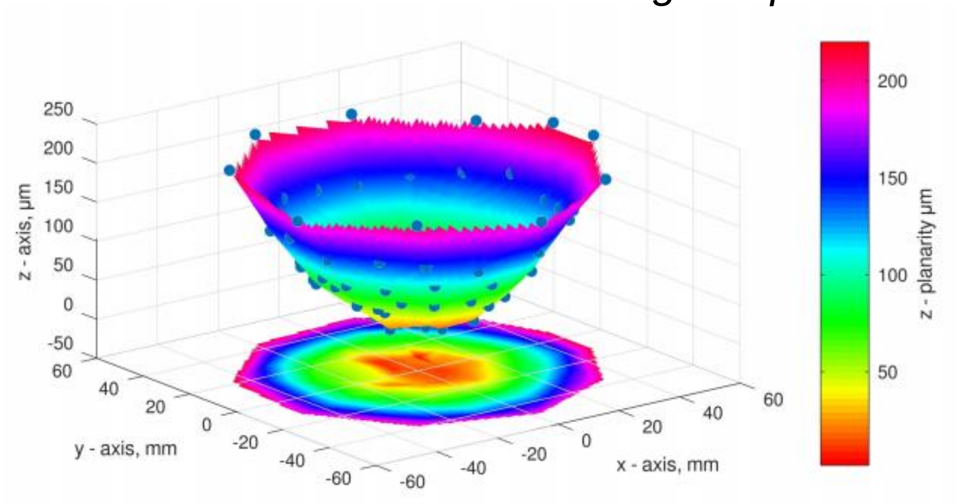
Risk to damage the photocathode

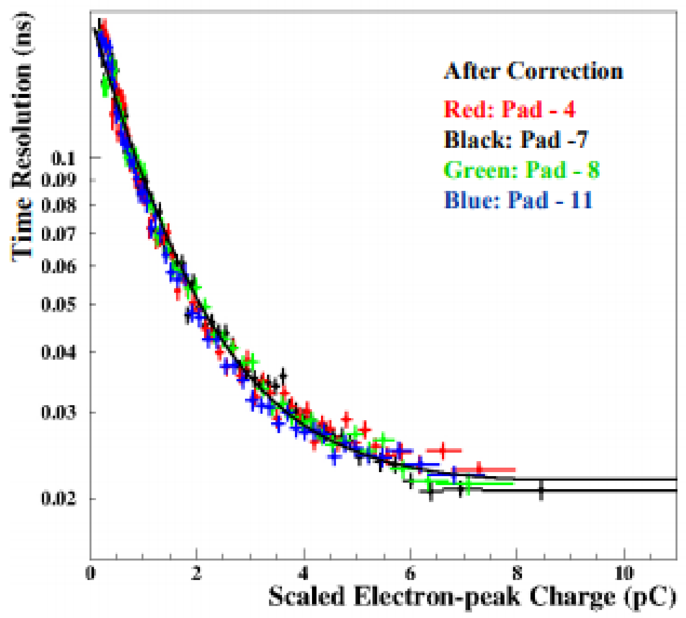
First multi-pad prototype: single-pad response

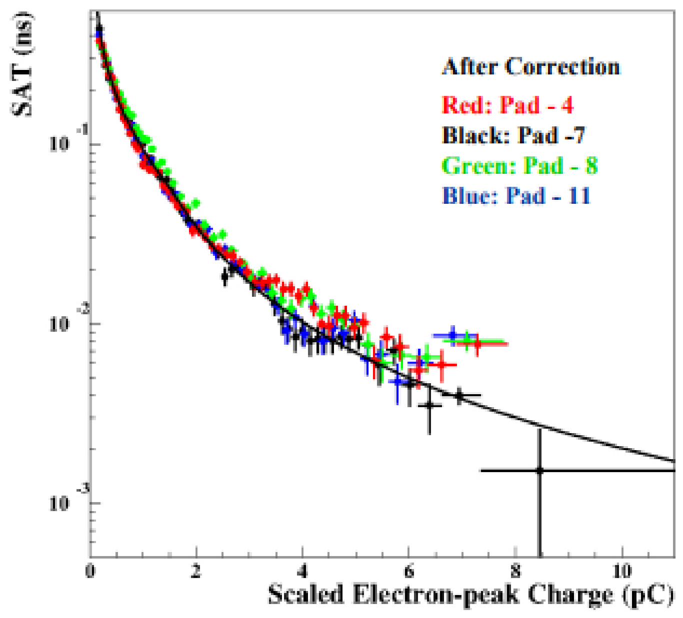
- MgF2 radiator 3 mm thick,18 nm CsI on 5 nm Cr, 200 µm drift gap, operation point: V_{drift}/V_{anode}: -475V/+275V



19 hexagonal pads 5mm side

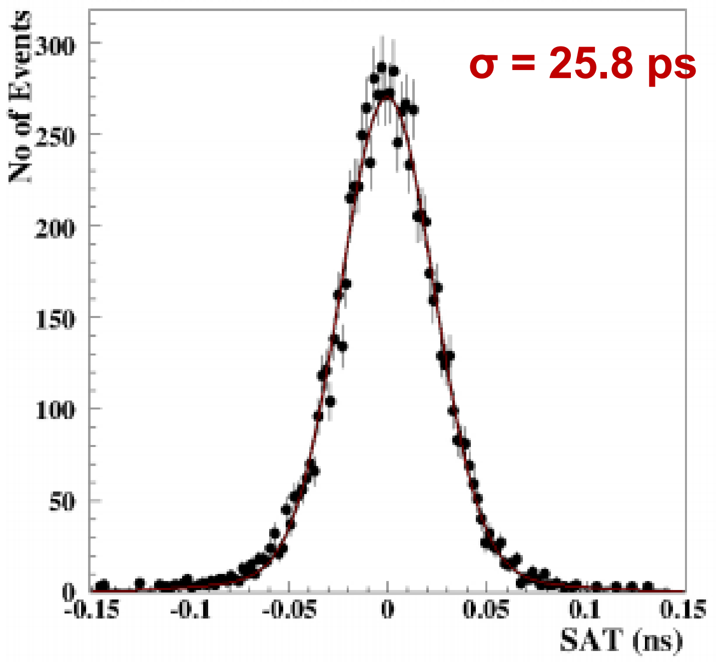




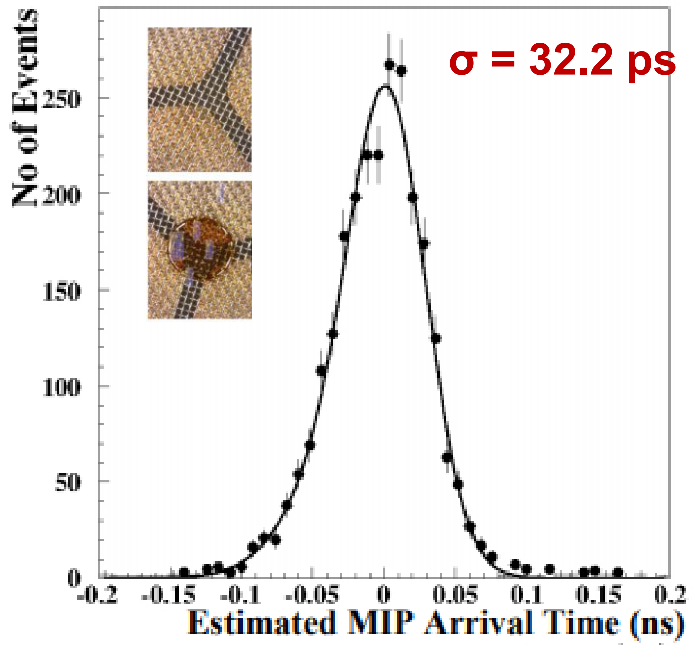


S. Aune et al, "*Timing performance of a multi-pad PICOSEC-Micromegas detector prototype*", Nucl. Instrum. Meth.A 993 (2021) 165076, https://doi.org/10.1016/j.nima.2021.165076

After corrections, we can restore the timing performance of 25ps for all tracks



All tracks passing within R<2mm from the center of any pad

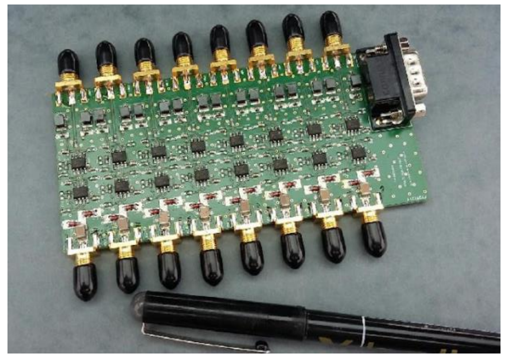
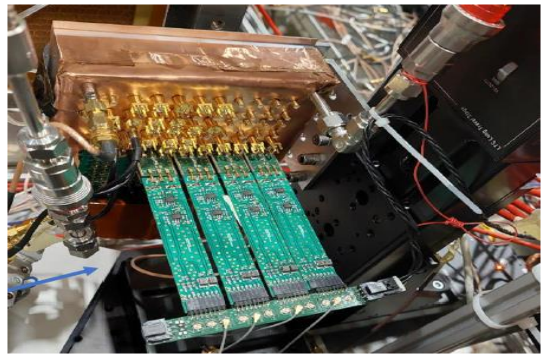


All tracks passing within R<2mm from any pad corner

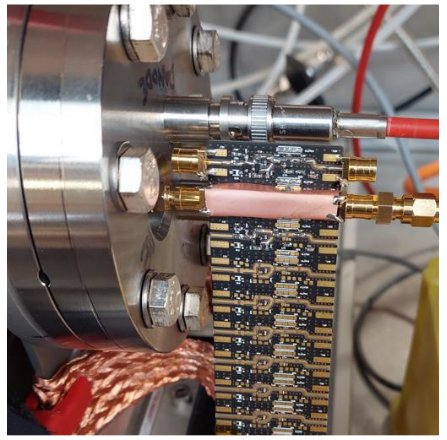
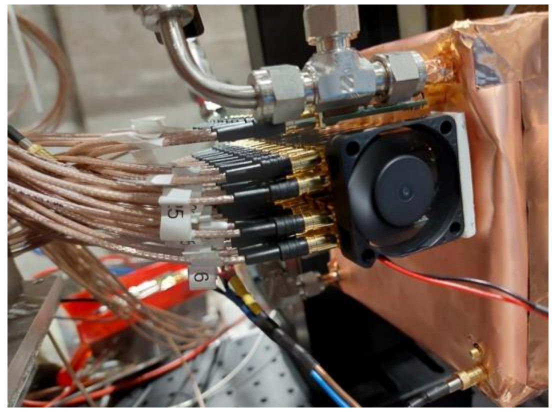
Pixelated MM Detector

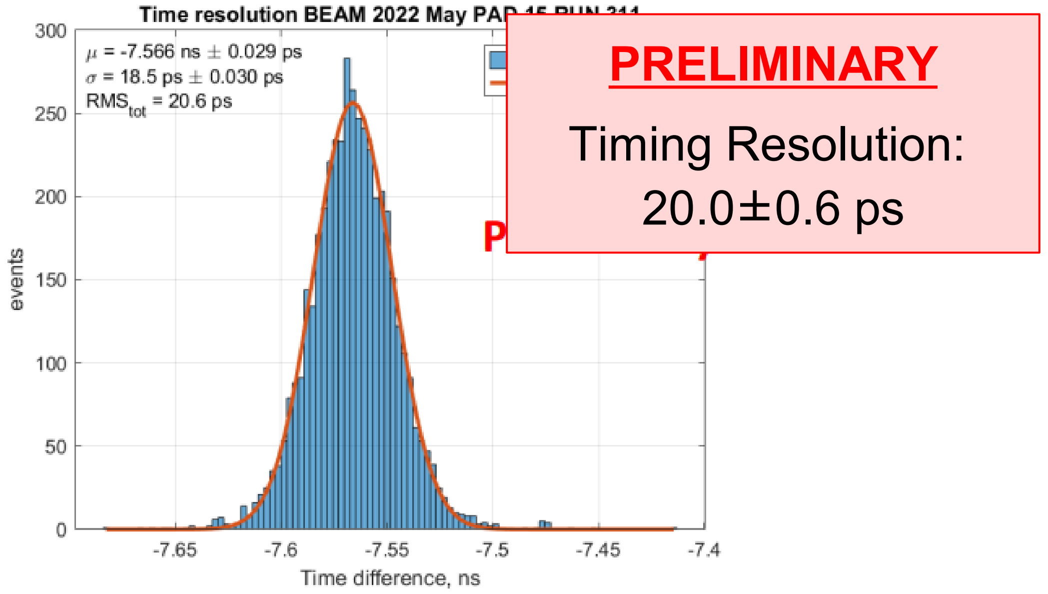
- Develop appropriate frond-end & back-end electronics ~100channels
- **Discrete current preamplifiers**
  - Low noise RMS < 1mV
  - High gain > 30dB
  - Bandwidth >1GHz

Phillipe Legou CEA Saclay

- **Discrete current preamplifiers**
  - **Recent development @ CERN**
  - 10-channel amplifier boards

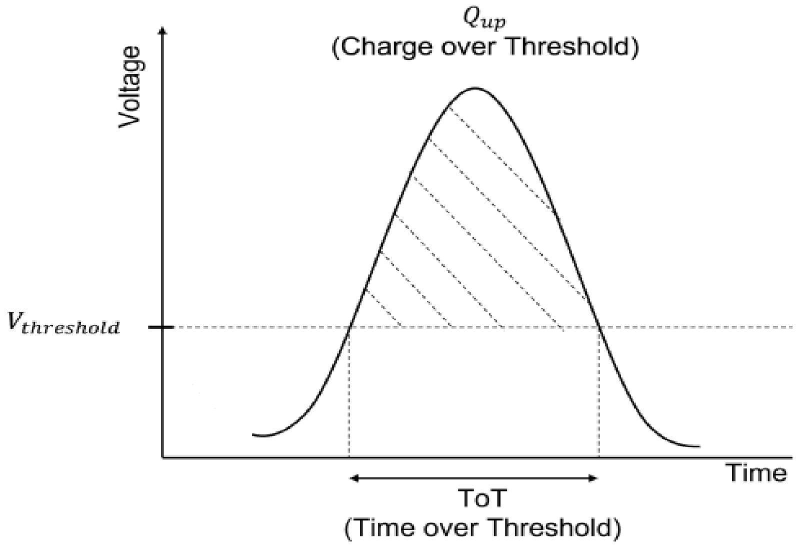



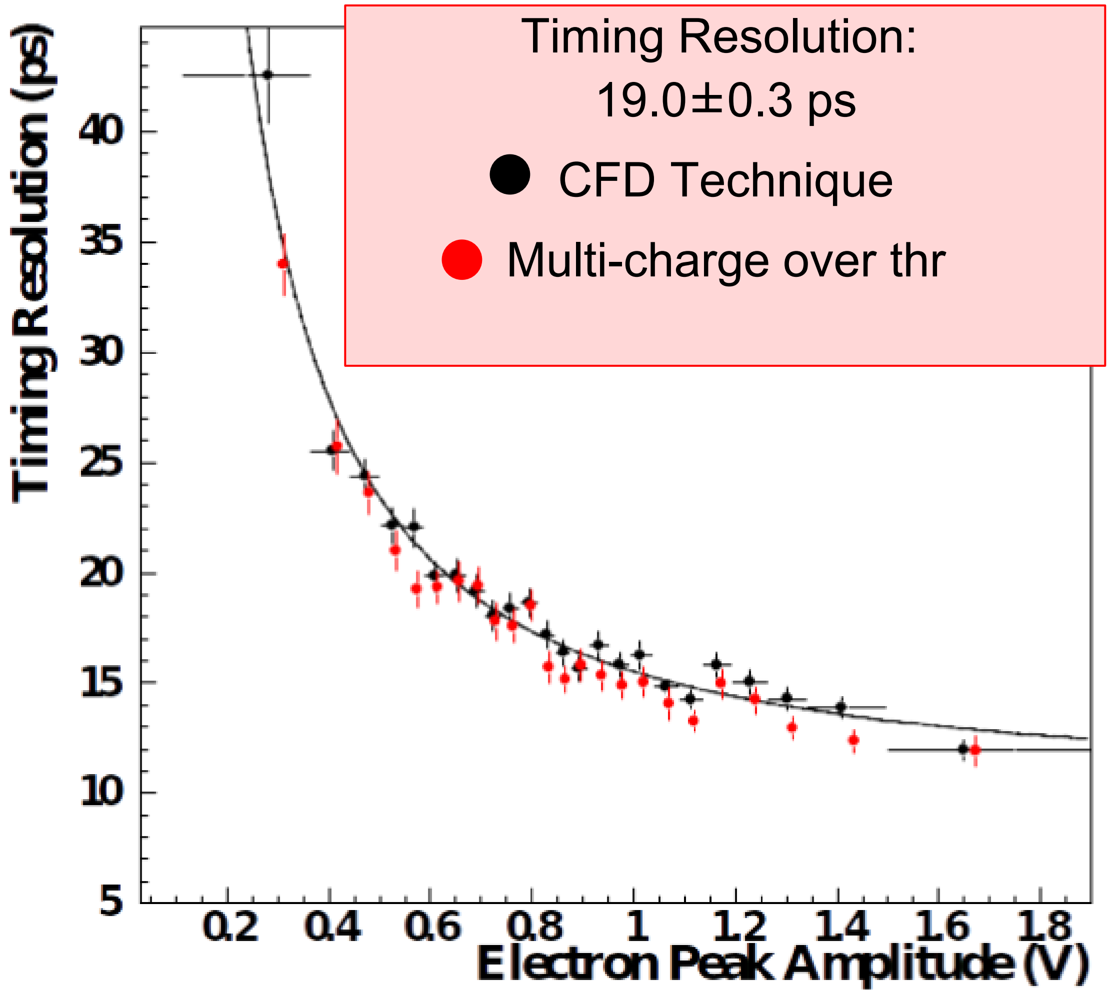


More info : A. Utrobičić on RD51 collaboration meeting

https://indico.cern.ch/event/1138814/timetable/#20220614.detailed

- **Research on possible usage of customade charge-sensitive amplifiers ⟶ Hans Muller (CERN)**
- **Simulation Studies shown:**
  - Use multiple thresholds (based on amplitude distribution of sample)
  - Reaching timing resolution **BELOW** 20ps





More details on Master Theses- *Development of a Simulation model and Precise Timing Techniques for PICOSEC-Micromegas Detectors* by A.Kallitsopoulou on https://arxiv.org/pdf/2112.14113.pdf

Pixelated MM Detector II

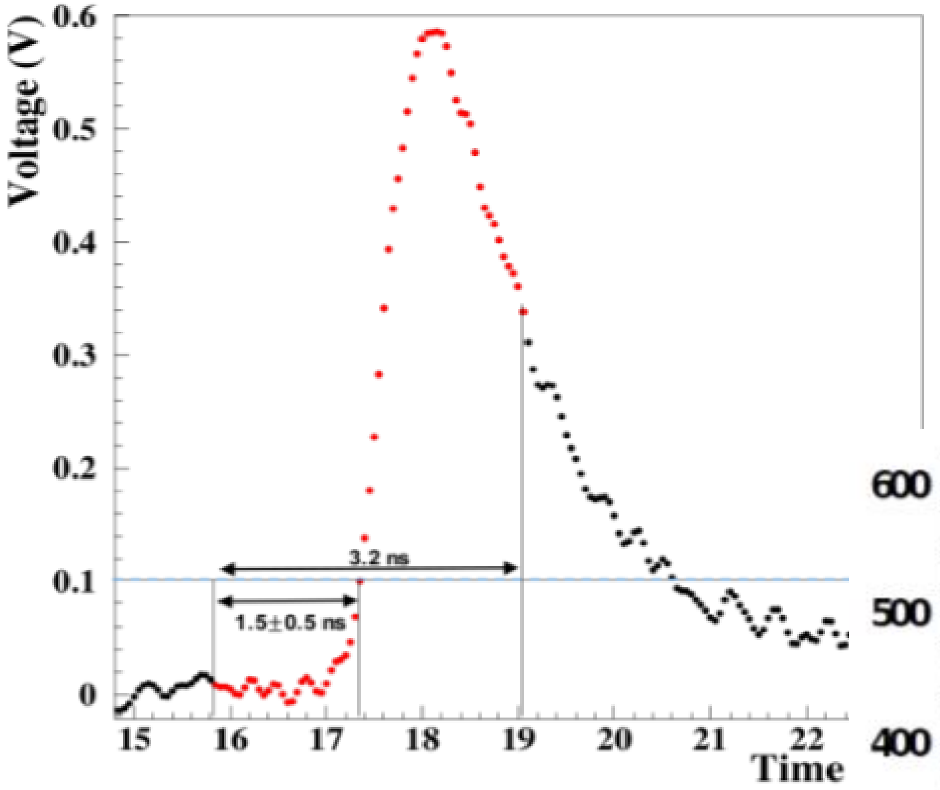
- Develop appropriate frond-end & back-end electronics ~100channels

- **Multi-channel digitizer SAMPIC**
  - 8.5 GS/s sampling frequency
  - Possible 64-ch to stack
  - Bandwidth 1.6GHz
  - Intergal FPGA-algorithms for signal processing

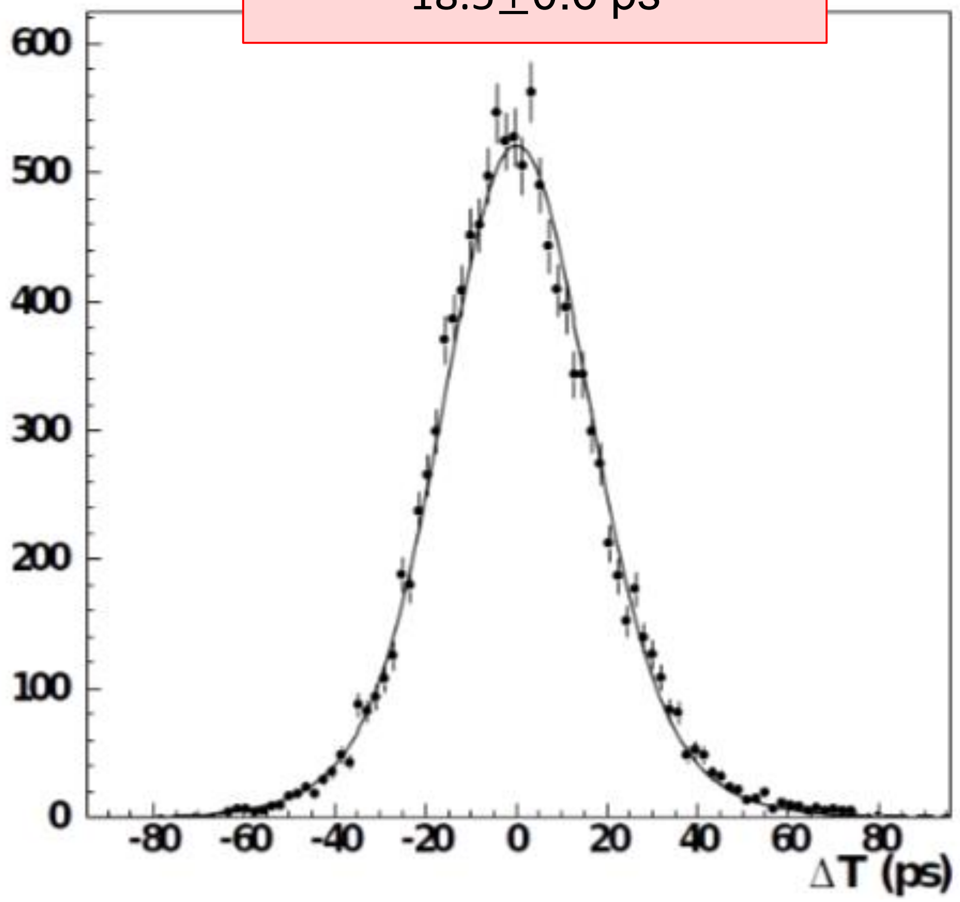
Dominique Breton (IJCLAB/CEA)

Alternative of multi -ToT algorithm

- **Feasibility test for SAMPIC digitizer:**
  - Feed an Artificial Neural Network
  - Use an input layer with 64 digitization points of waveforms recorded with oscilloscope



Timing resolution : 18.5±0.6 ps



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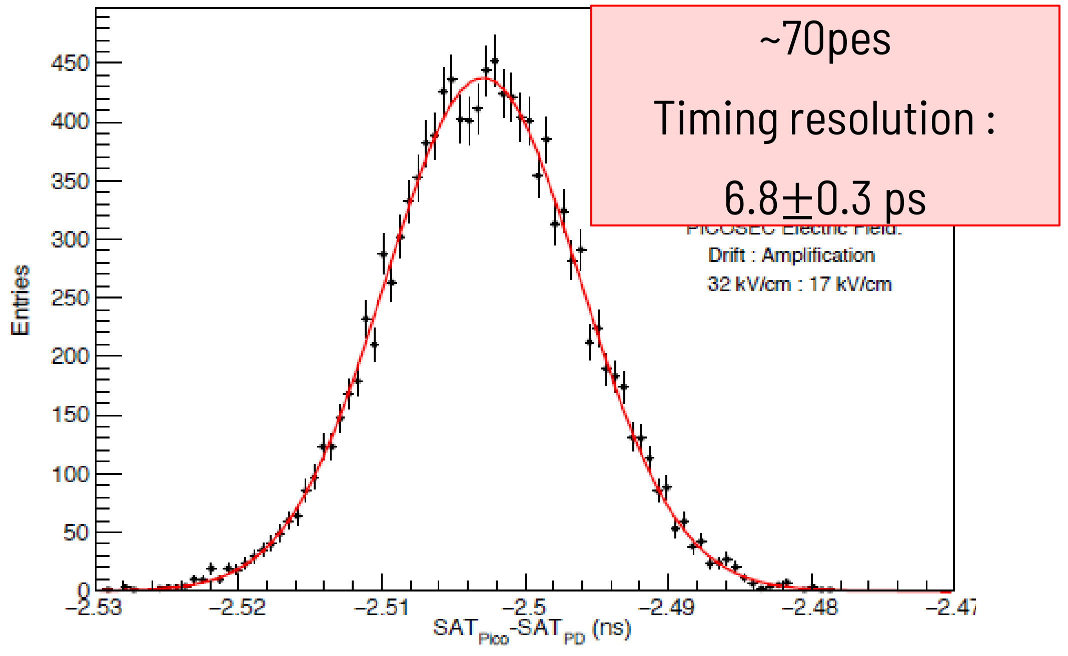
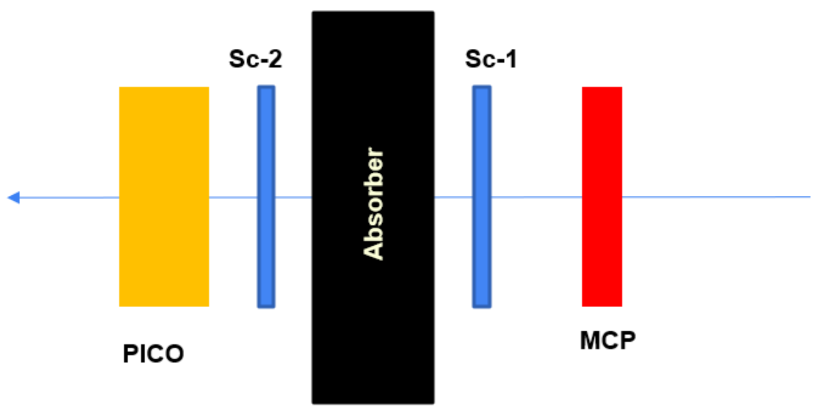
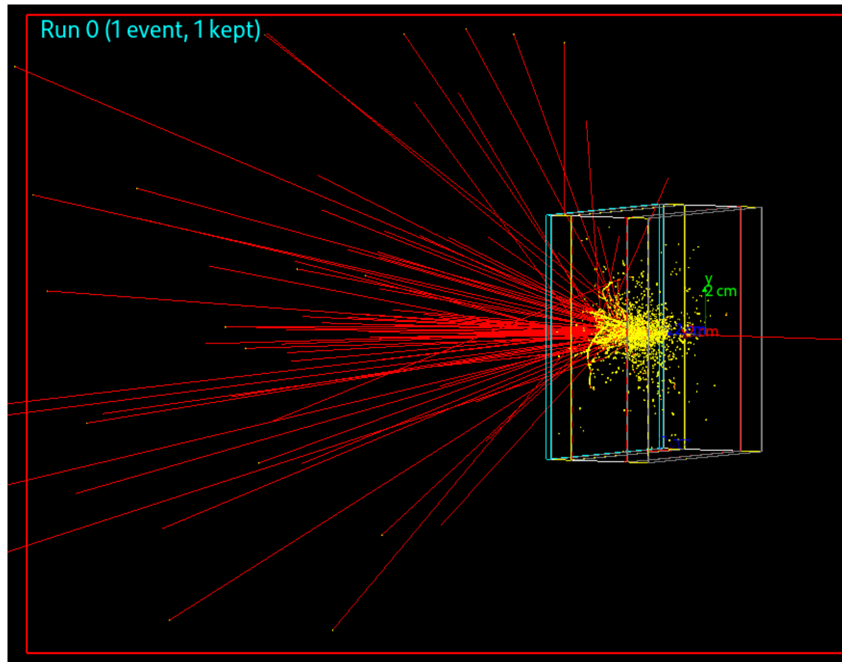
Studies on Detector performance

- Embed in EM Calorimeter
- First indications from laser test measurements @ IRAMIS/CEA





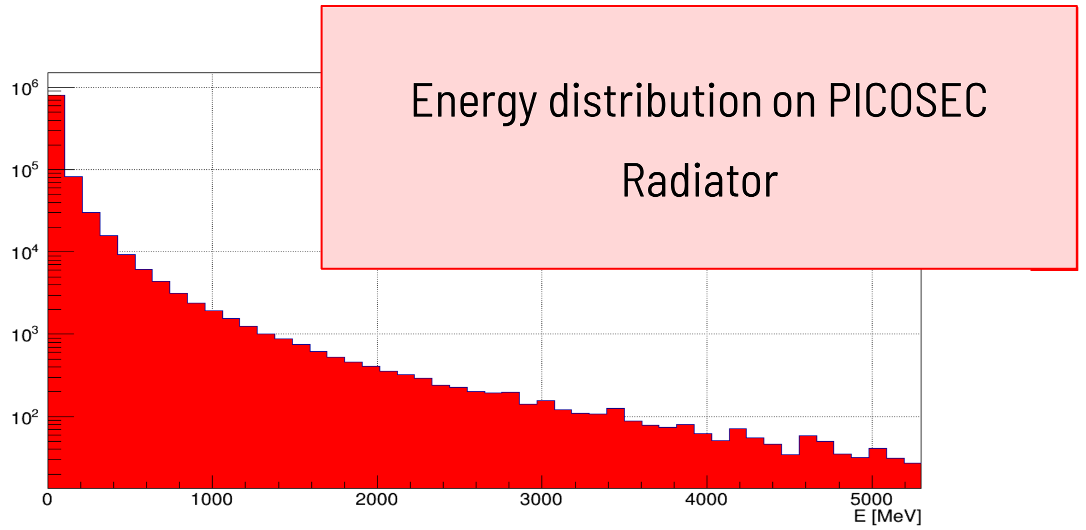
- First Simulation Studies with Geant4

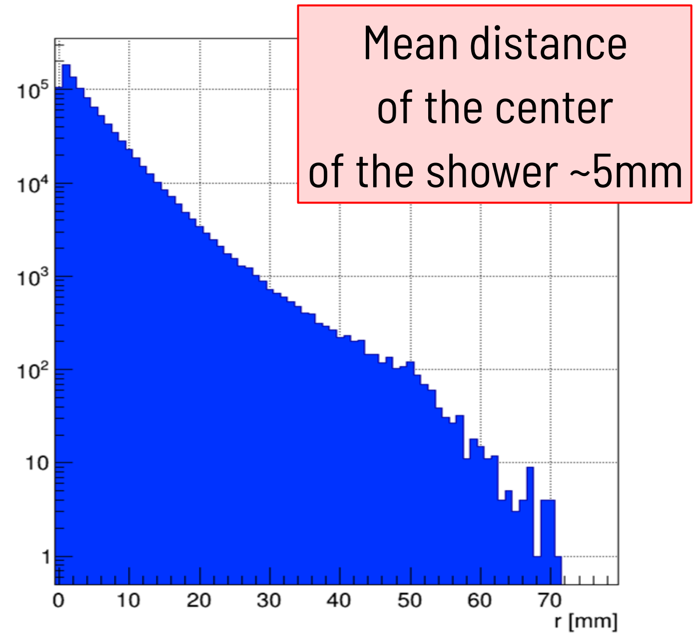


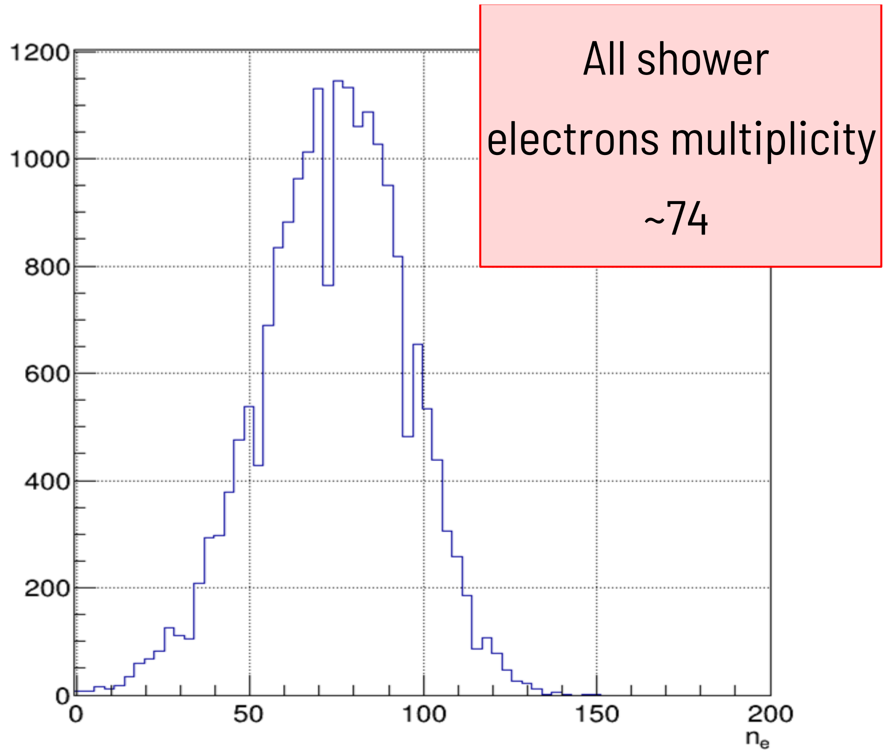
Simulation Information

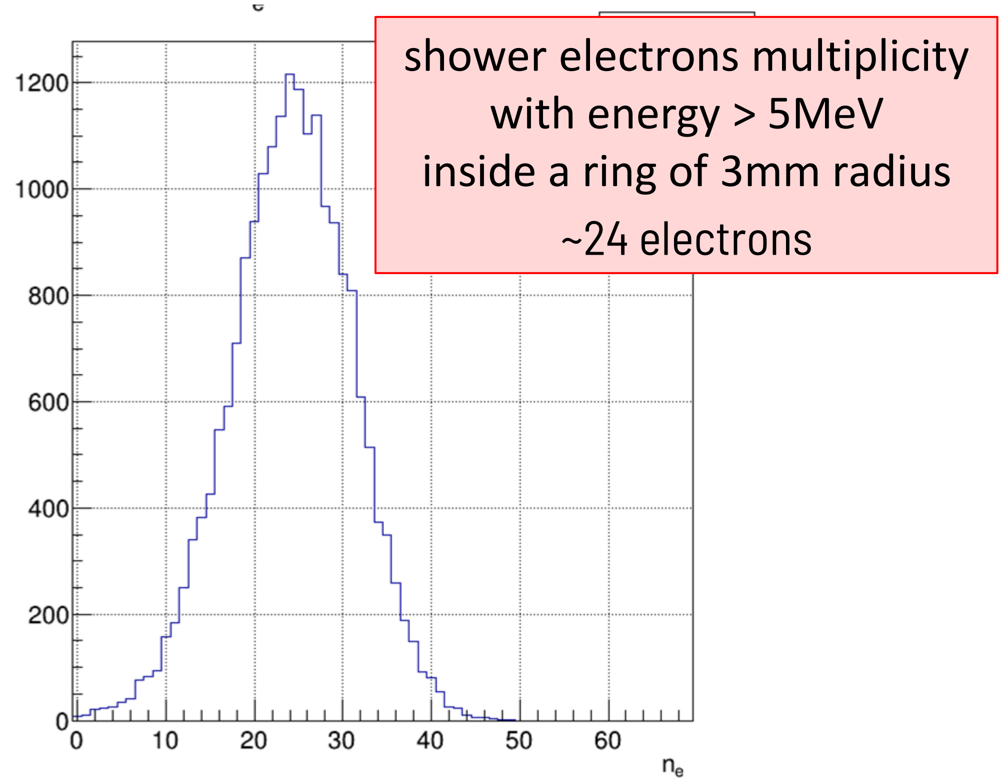
- 30GeV electron
- 2 plastic Scintillators of 1cm thickness
- Pb Absorber with 5 RL thickness
- 3mm MgF_2 radiator

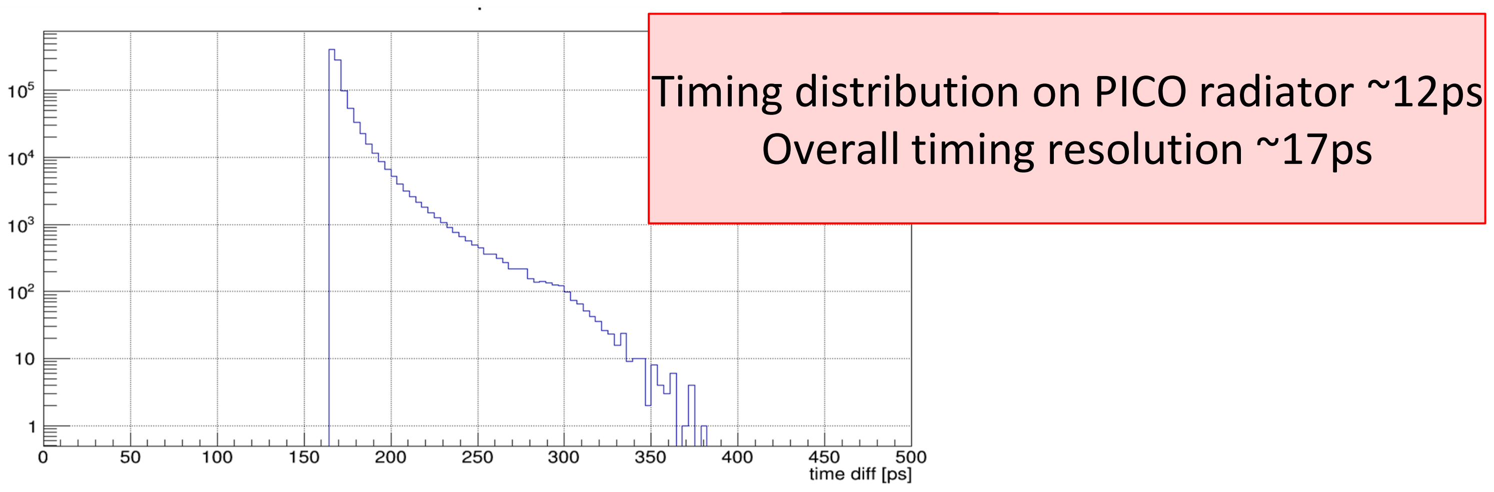
For more info see the presentation by **A. Kallitsopoulou** *the RD51 Mini Week, CERN (7-10 Feb 2022)*
https://indico.cern.ch/event/1110129/contributions/4733737/attachments/2388605/4082733/PICOSEC_in_electron_beam.pdf





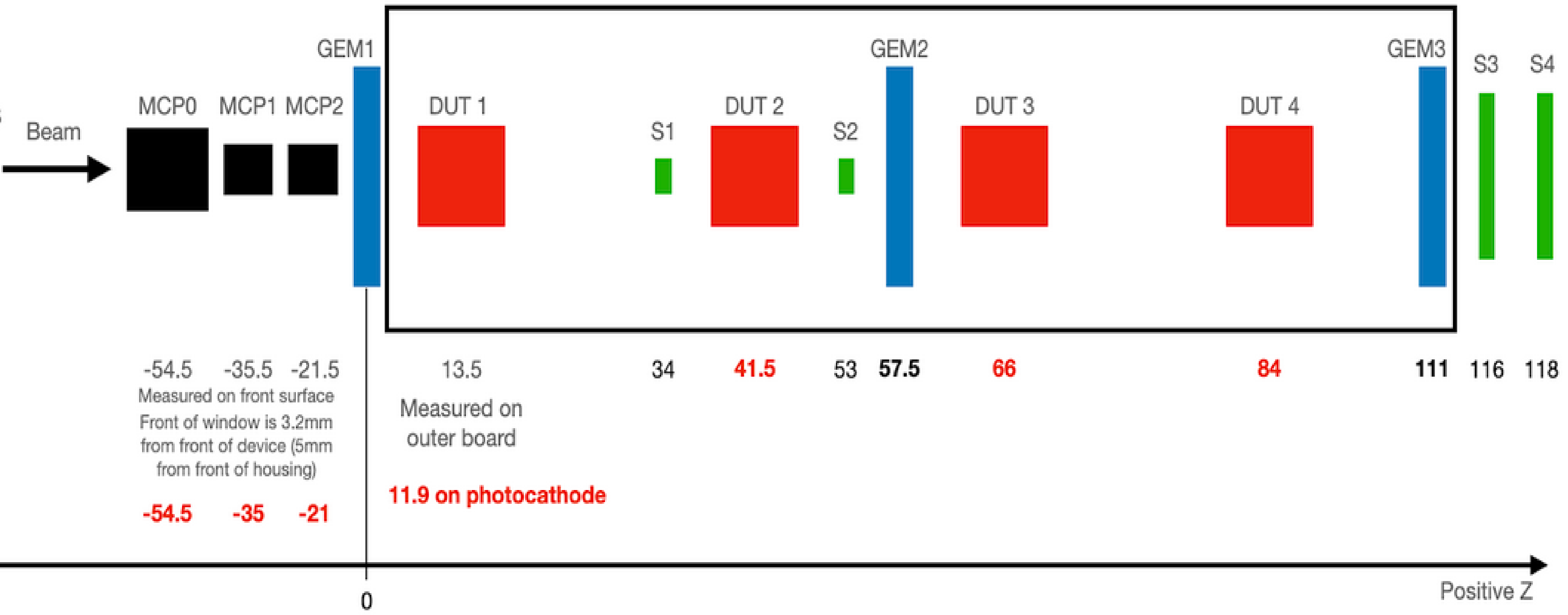




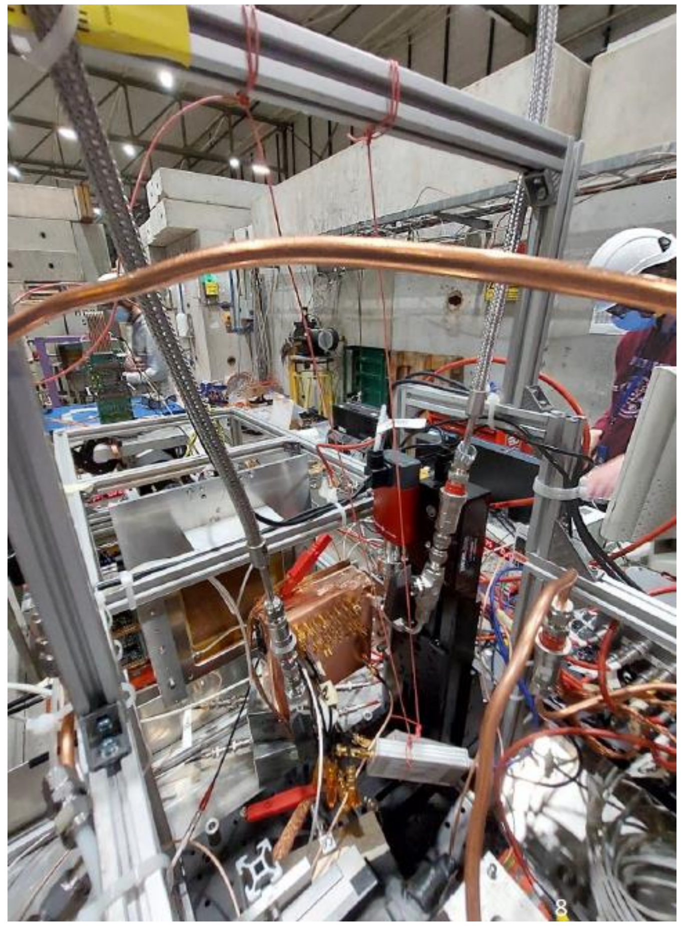


Test Beam Set Up

- CERN SPS H4 Beam Line
- 80GeV muon beam

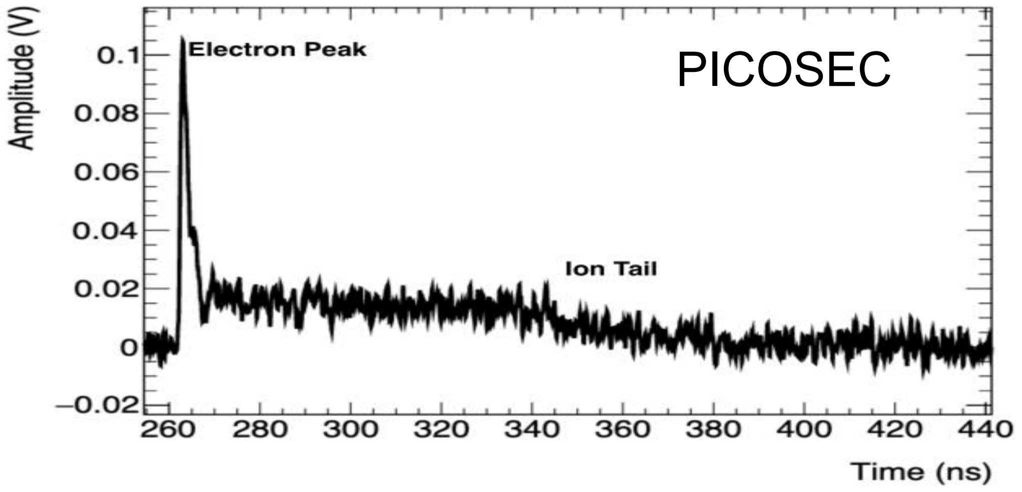


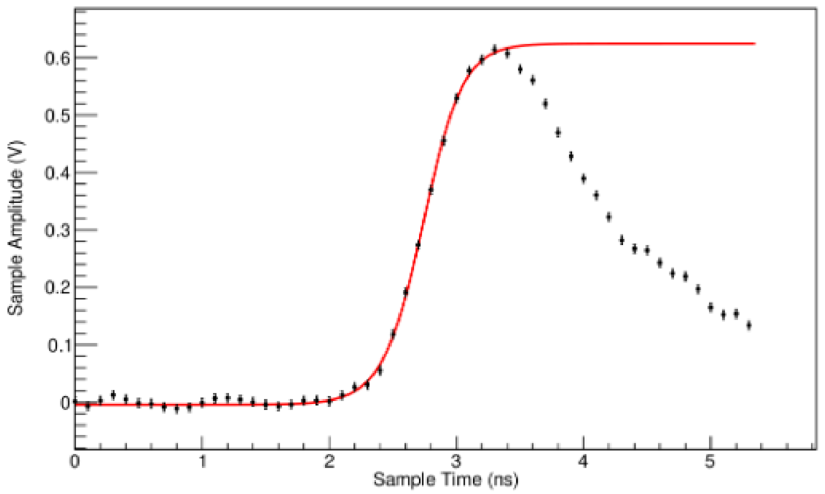
- Trigger / Tracking / Timing Telescope
  - Triggering
    - Scintillators (small & large area)
  - Tracking
    - Triple GEM detectors, XY readout
  - Timing
    - MCP PMT (11mm diameter)
- Goals:
  - Optimization/Stability
    - Single pad & Multi pad detectors

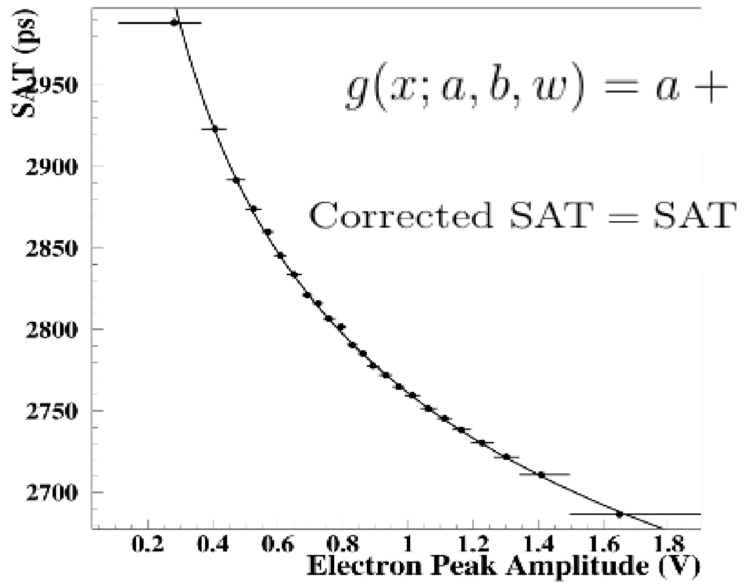


PICOSEC Signal Processing Analysis

- Analysis of the Experimental data
- Adjust a curve, i.e. fitting the leading edge with a logistic function
- Timing at 20% of peak amplitude both for the reference device and PICOSEC signals (Signal Arrival Time)
- Subtract the PICOSEC signal from the reference signal
- Create Calibration curves (Correct for dynamical errors)

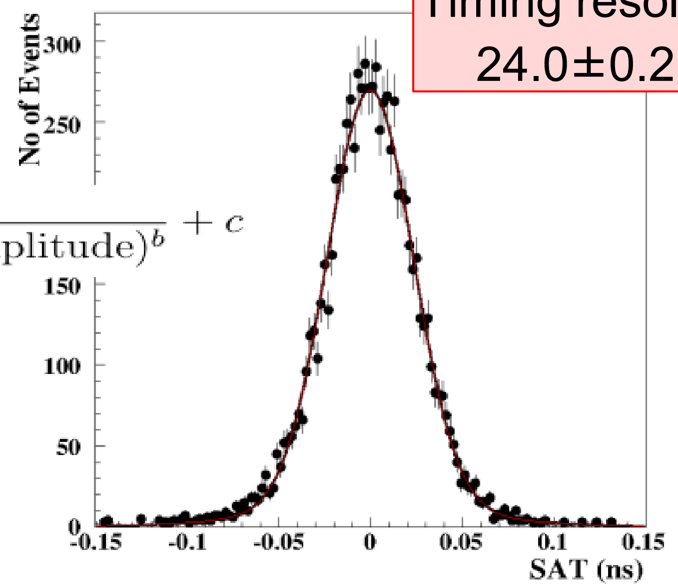






$$g(x; a, b, w) = a + \frac{b}{x^w}$$

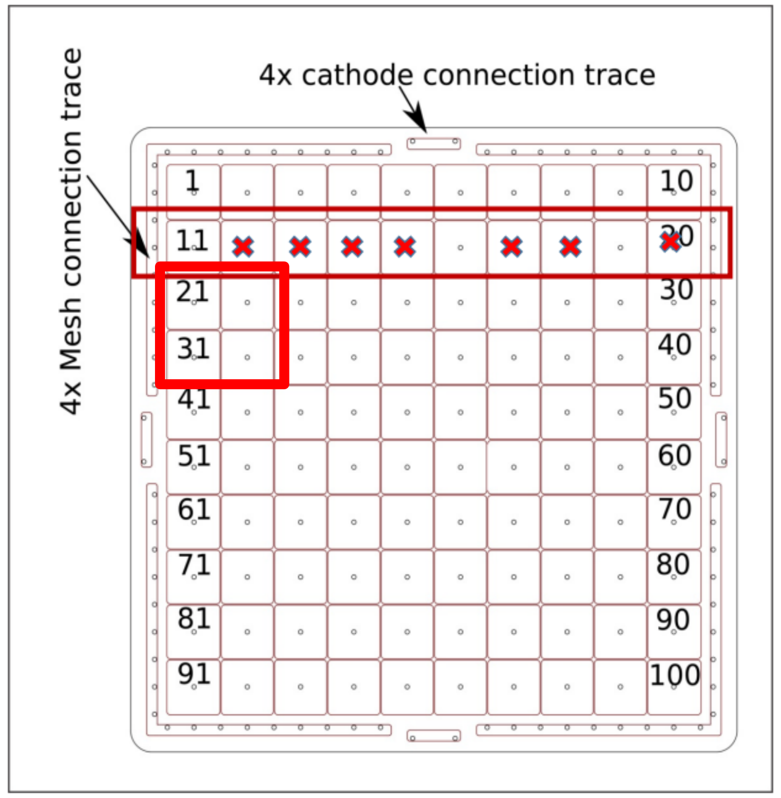
$$\text{Corrected SAT} = \text{SAT} - \frac{a}{(\text{Pulse Amplitude})^b} + c$$

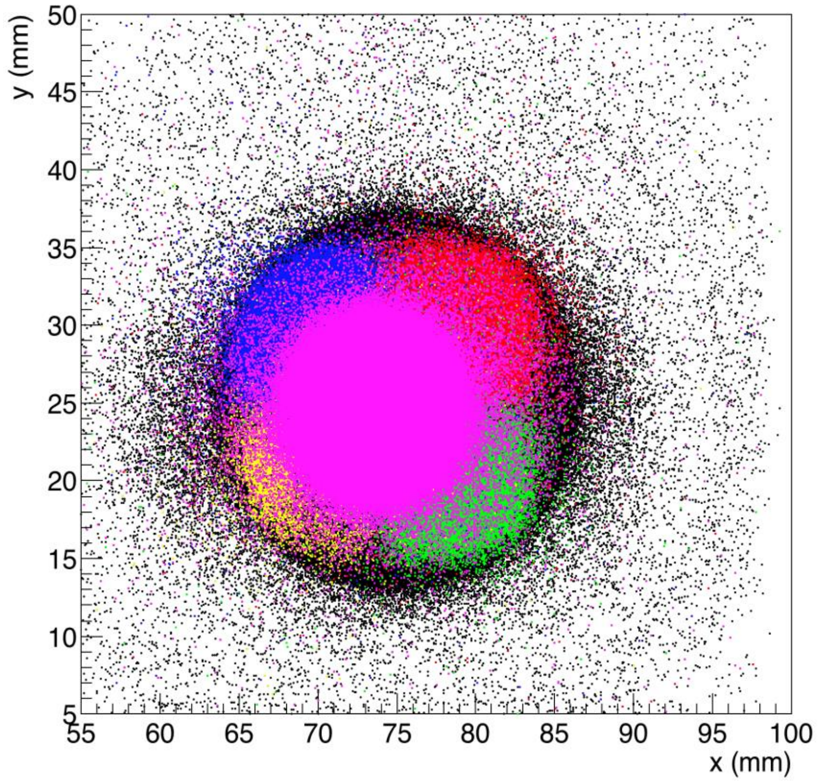


Timing resolution: 24.0±0.2 ps

Detector performance- Most Recent Results

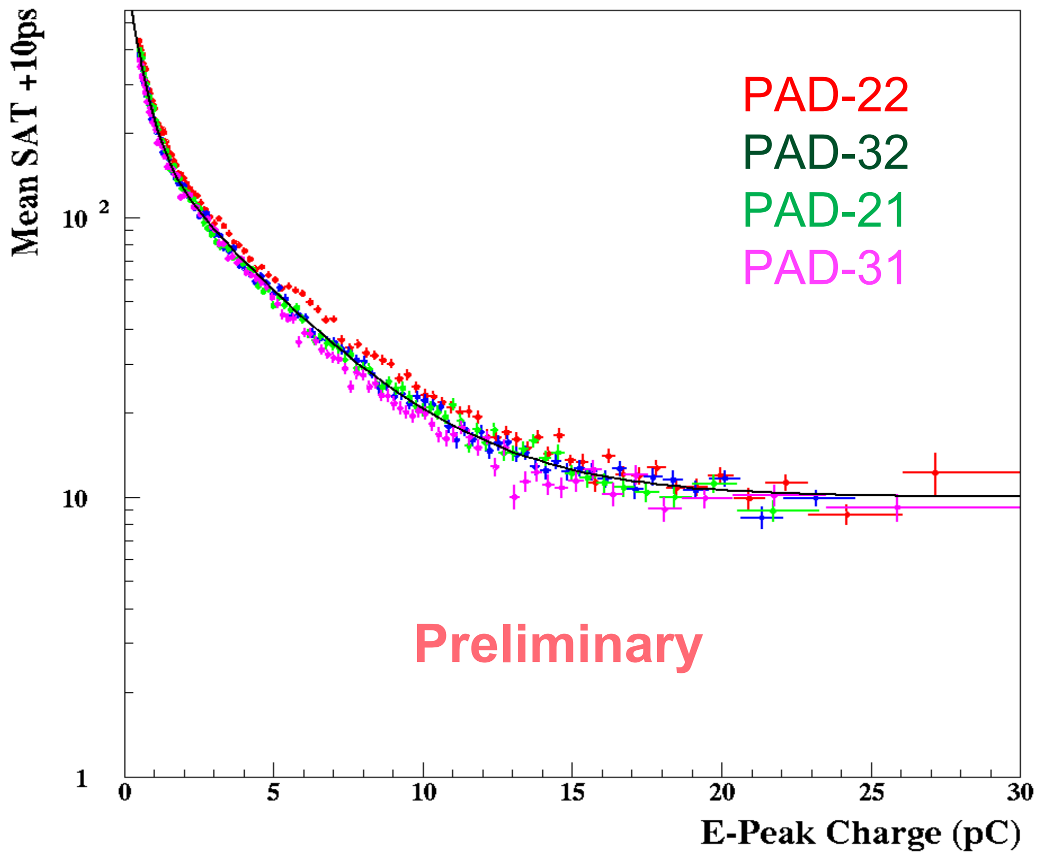
- **Multi-Pad with CsI photocathode (Tested in Oct 2021 Test Beam)**
- Horizontal and vertical scan of PADs.
- Measurements of time response within the pad
- Measurements of signal sharing between 4 pads.

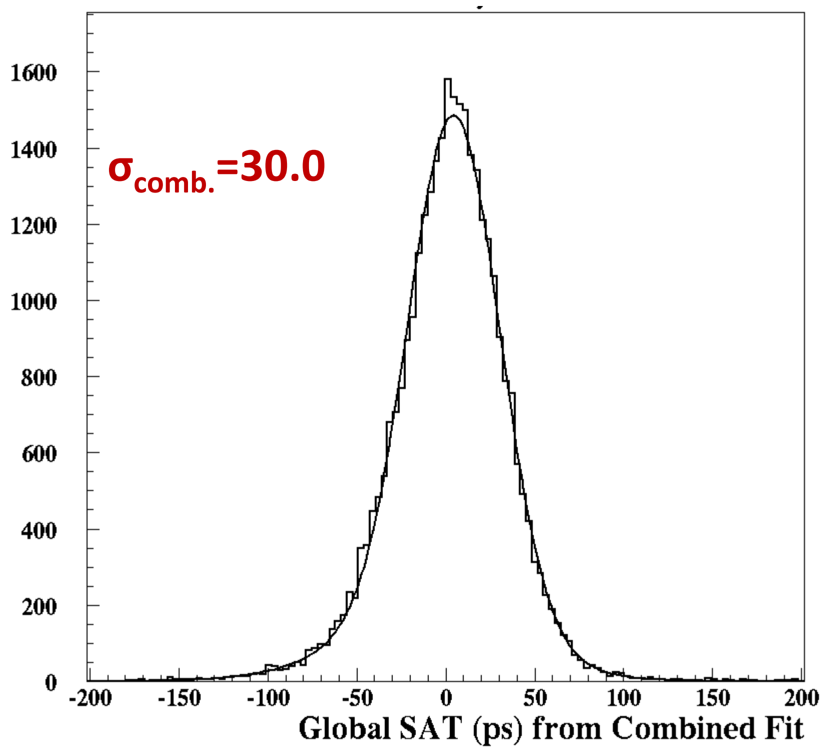


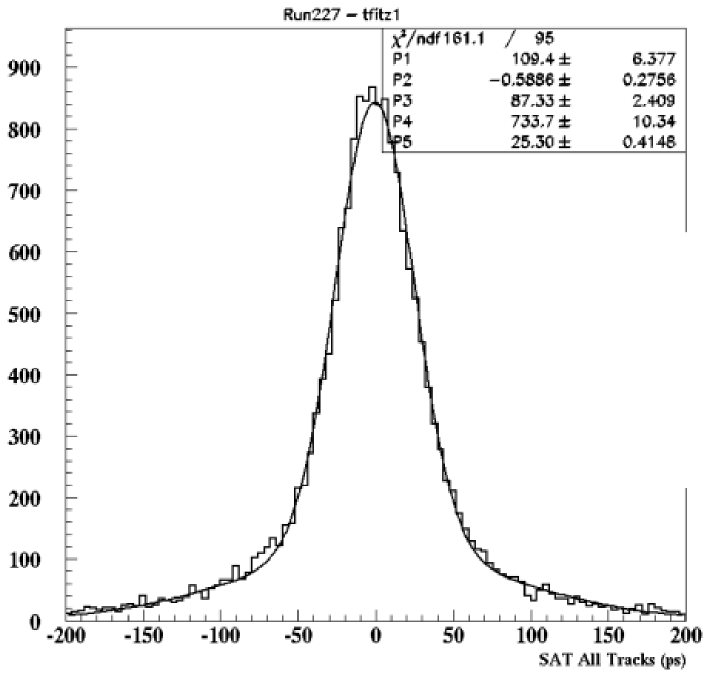


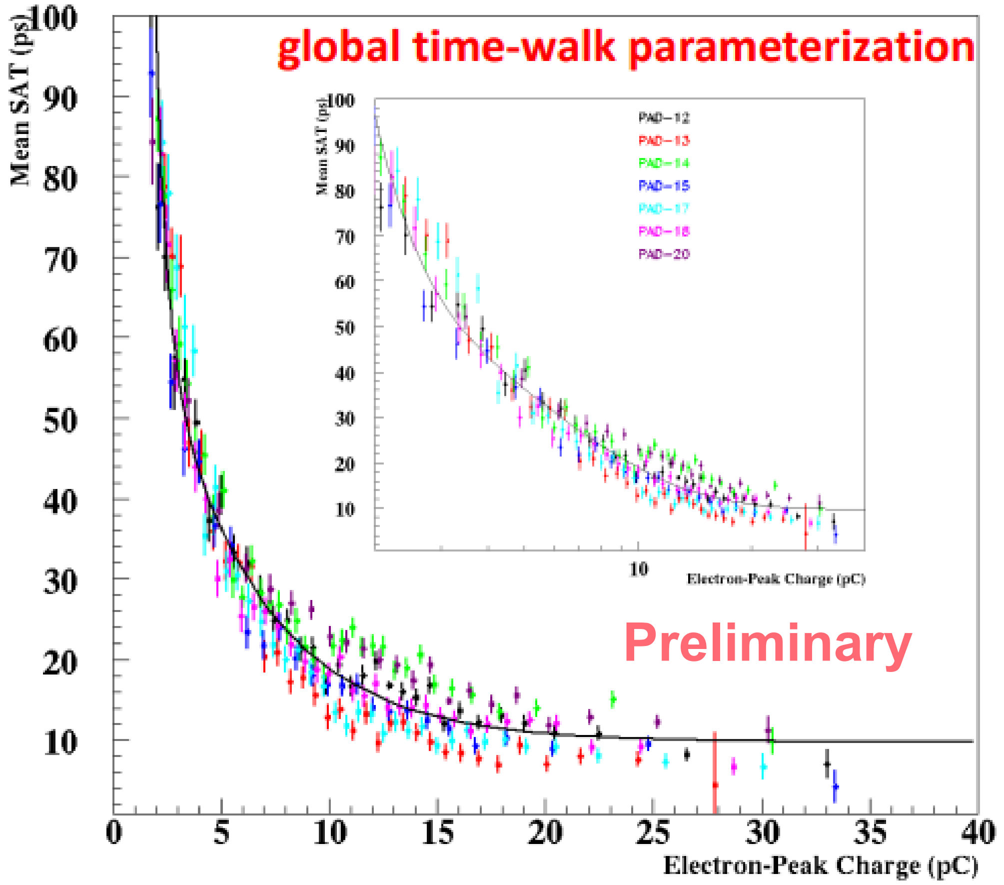
Analysis by **Alexandra Kallitsopoulou**, **Ioannis Maniatis** and **Spyros Tzamarias.** More info in the contribution to the *RD51 Collaboration Meeting and "Wide Dynamic Range Operation of MPGDs" workshop, CERN (15-19 November 2021)* by A. **Kallitsopoulou**
https://indico.cern.ch/event/1071632/sessions/408832/#20211116

- **Proof of the uniformity of our detector**





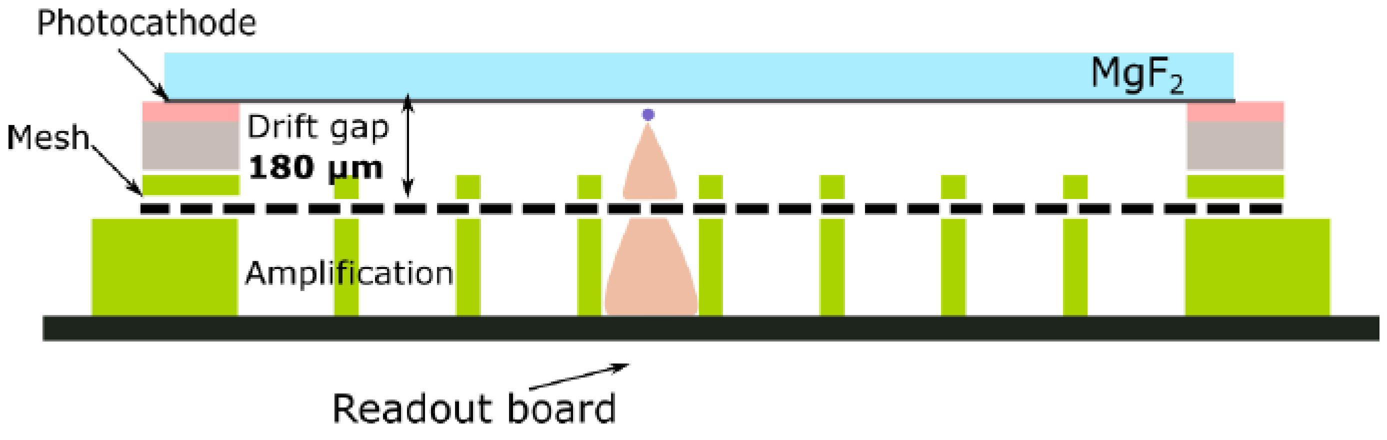


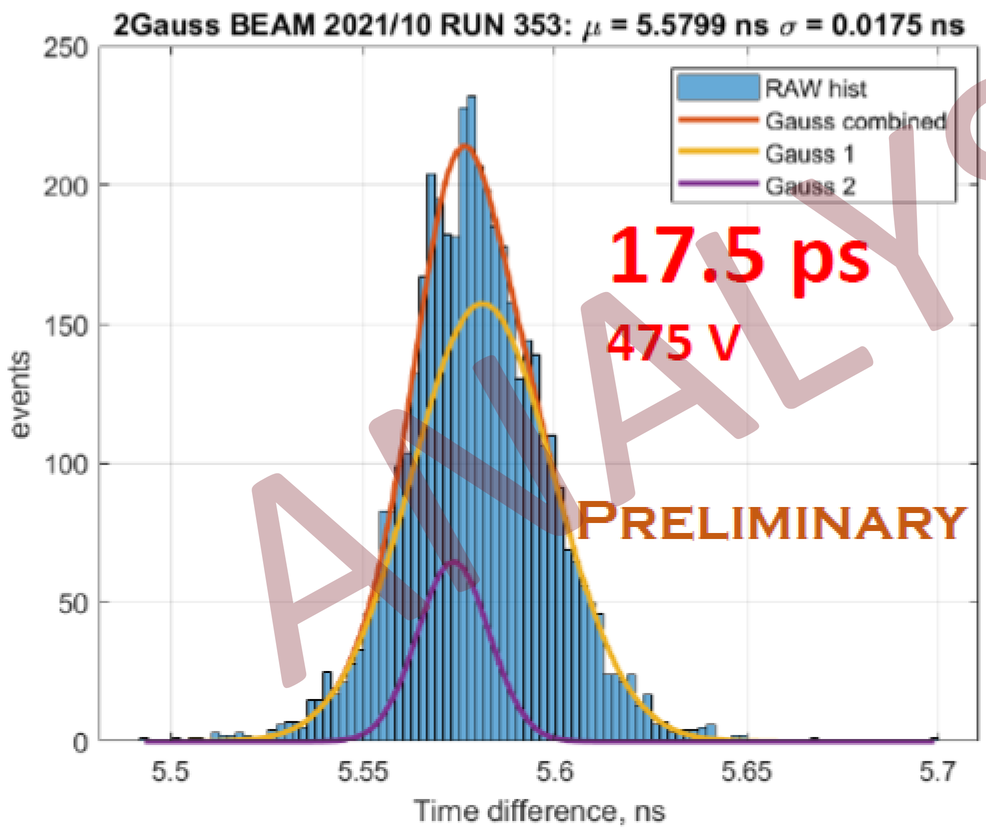


Detector performance- Most Recent Results

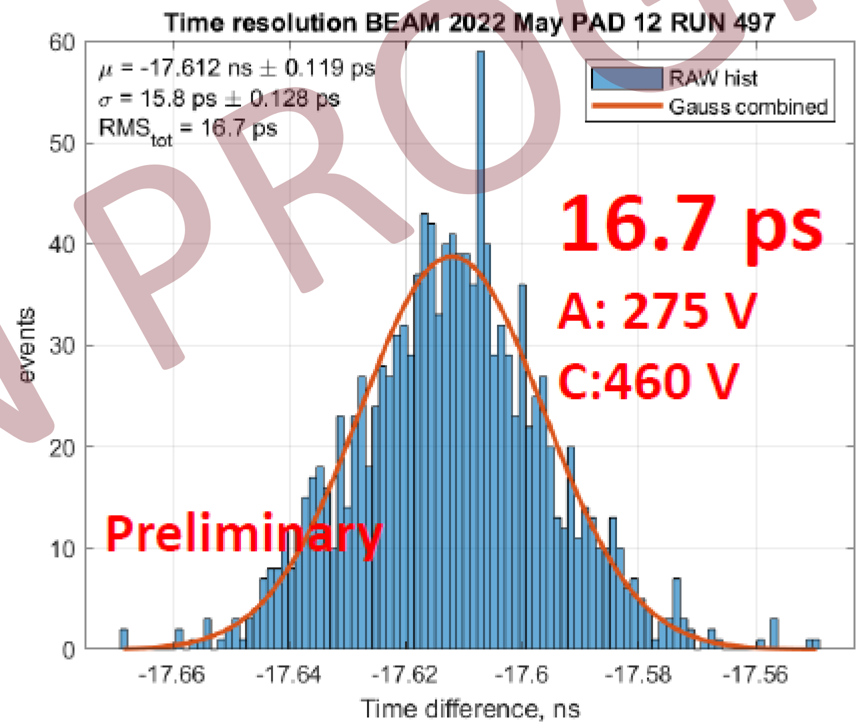
- Different Prototypes Tested in Oct 21/May 2022 Test Beam

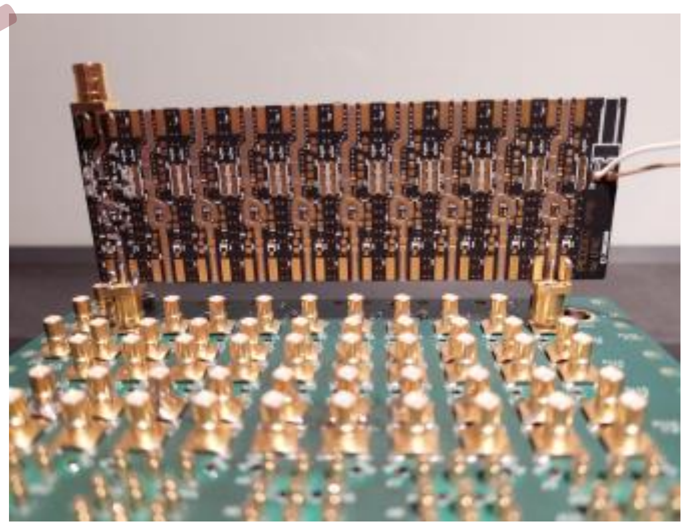
Thin gap – Single pad Prototype

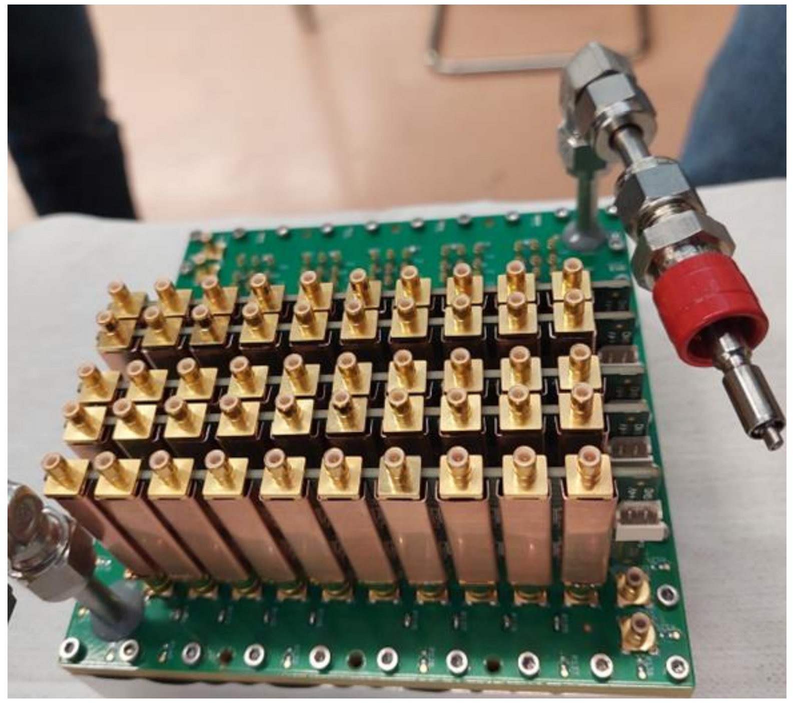




Thin gap – 100 channel Multi-pad Prototype
& Customade electronics





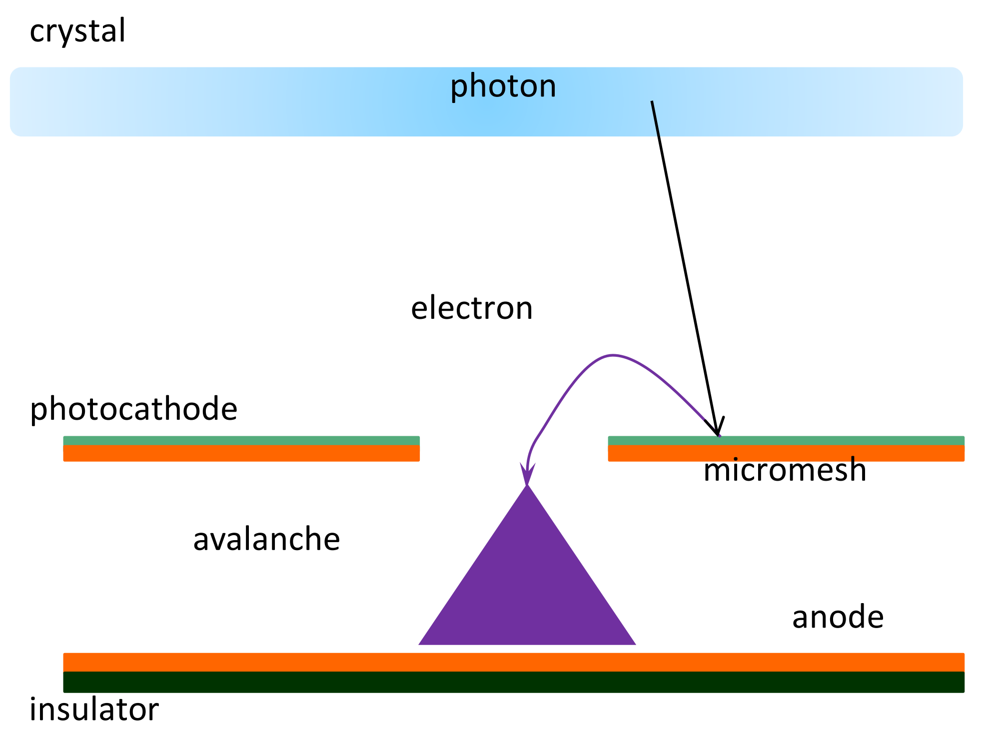


For more info see the presentation by **A. Utrobičić** *the RD51 Collaboration Meeting, CERN (13-17 June 2022)* https://indico.cern.ch/event/1138814/timetable/#20220614.detailed

- Use as a **photodetector for T_0 tagging** at the neutrino detector (detection of liquid argon scintillation light)

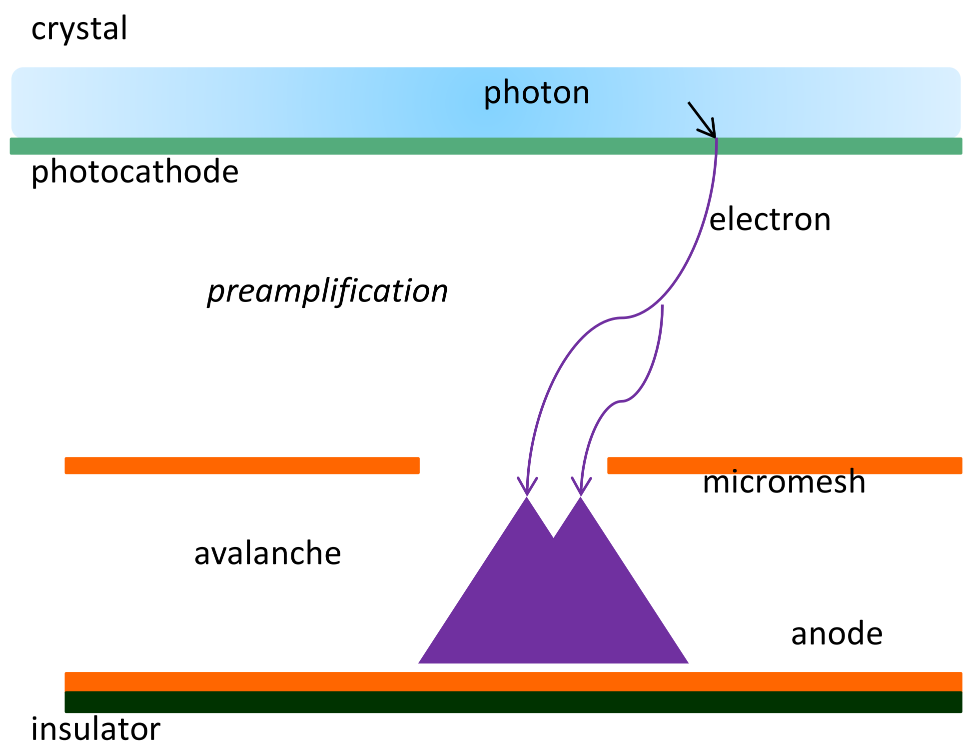
Reflective photocathode:

- Photosensitive material the micromesh
- Photoelectrons 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 a single stage (~ 10^5)
- Higher electron extraction efficiency



Semi-transparent photocathode:

- Photosensitive material on MgF_2 window (drift electrode)
- Extra preamplification stage ➔ better long-term stability
- Higher total gain
- Decoupling of chamber - photocathode
- Lower photon extraction efficiency
- Photocathode exposure to sparks
- **Ion backflow ➔ radiation hardness**



Further Information – Publication List

PhD Theses:

- 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

Publications:

- 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. https://doi.org/10.1016/j.nima.2018.04.033
- 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
- 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
- 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
- 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
- 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
- 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

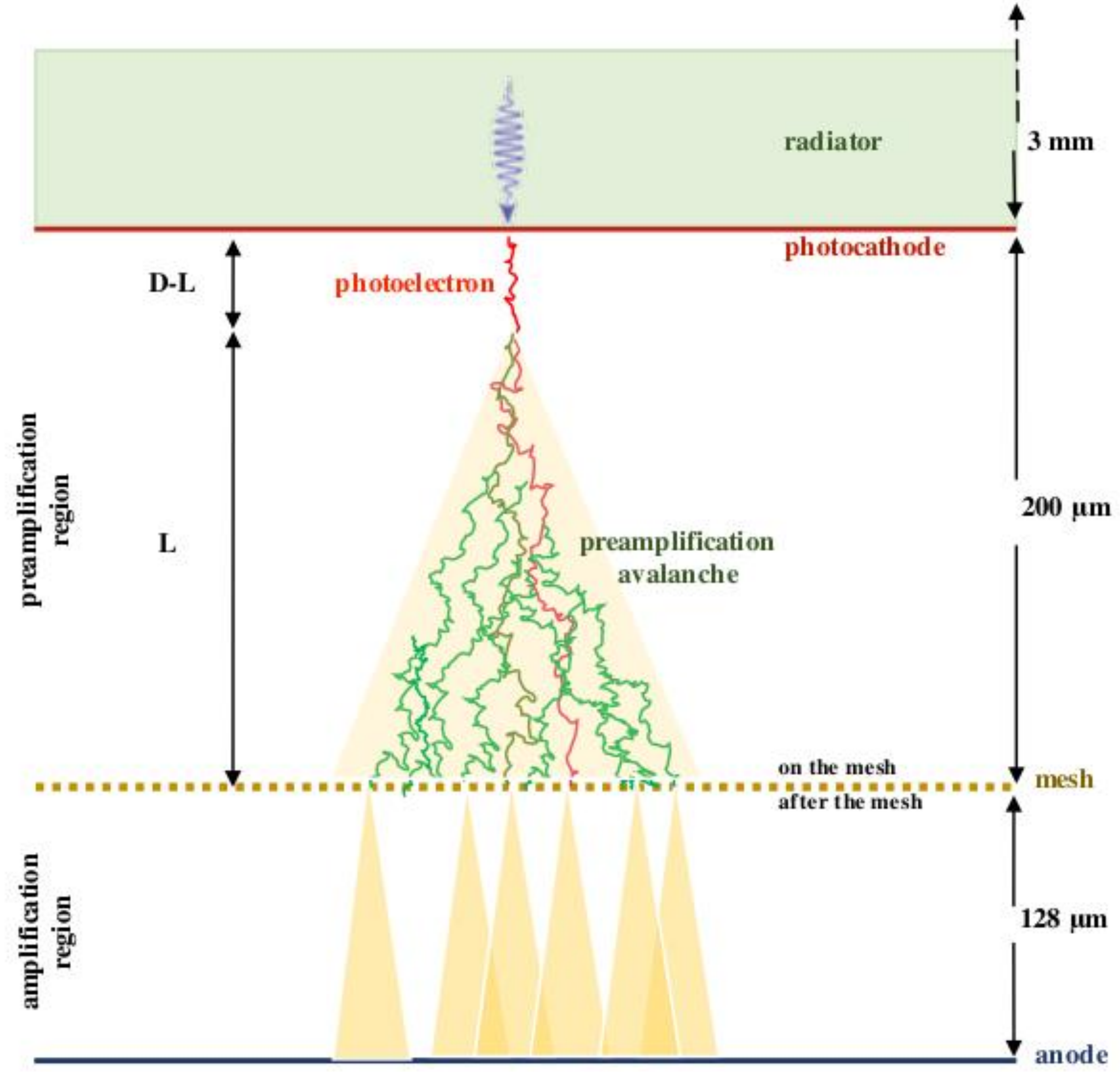
Conclusions

- In this project we examine alternative applications of PICOSEC MM detector technology
- We plan to test prototypes in 3 Test Beam campaigns each year @ CERN SPS H4 Beam Line
- We plan to participate in common test beams of ENUBET @ CERN
- The importance of precise timing is necessary in future Particle Physics experiments
- PICOSEC for ENUBET will substantially mitigate the pile-up
  - AND enable bunch tagging to determine the neutrino energy without relying on final state reconstruction
  - AND would increase the PID capabilities of the Near Detector

Thank you for your attention

Back up slides

PICOSEC Signal Processing Analysis



Physics

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

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 993, 21 March 2021, 165049

Modeling the timing characteristics of the PICOSEC Micromegas detector

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The PICOSEC MM Protypes

Sensors:

Bulk Micromegas (ø 1cm)

- ➢ Capacity ~ 8 pF
- ➢ Amplification gap 64 / 128 / 192 µm

Thin-mesh (~5 µm) Bulk Micromegas

- ➢ High optical transparency
- ➢ Amplification gap 128 µm

Resistive Bulk Micromegas (ø 1cm)

- ➢ Resistive pads: (10 MΩ/□, 300 kΩ/□).
- ➢ Floating pads (25 MΩ).
- ➢ Amplification gap 64 / 128 / 192 µm

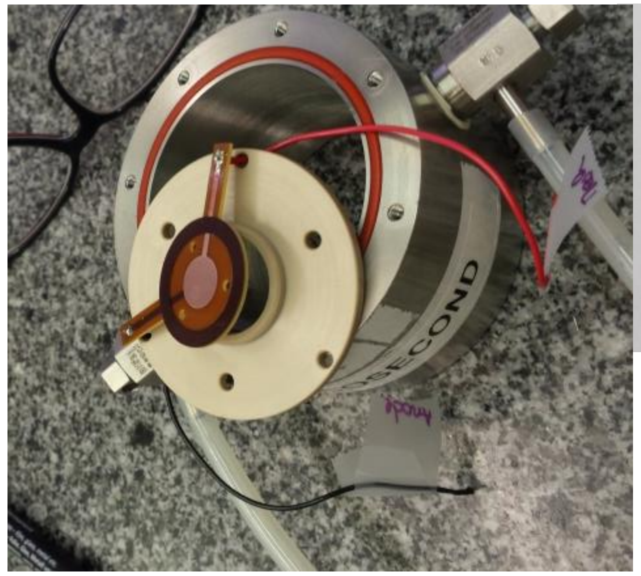
Multipad Bulk Micromegas

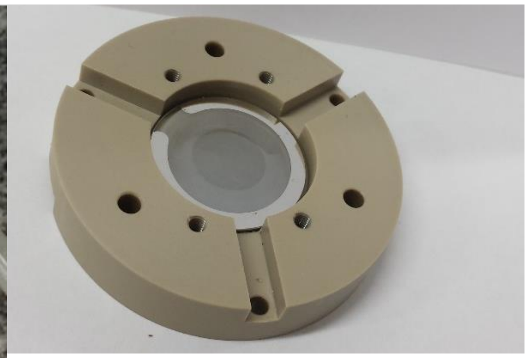
- ➢ Hexagonal pads ø 1cm.
- ➢ Normal & resistive

☞ *Ensure homogeneous small drift gap & photocathode polarization*

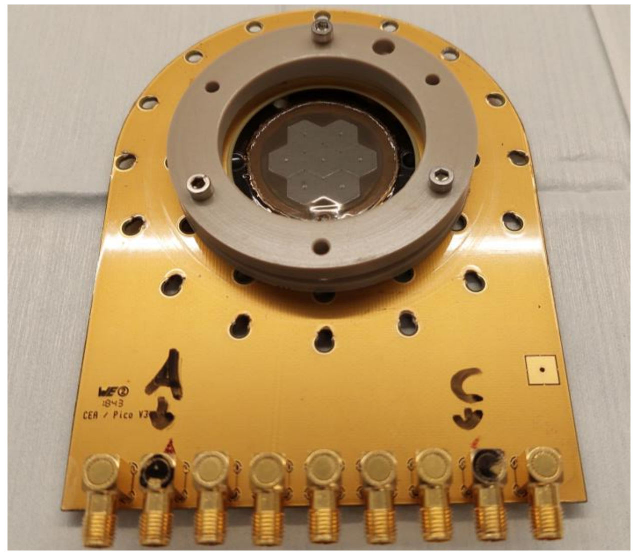
Photocathodes: MgF2 crystal +

- Metallic substrate + CsI
- Metallic (Cr, Al)
- Metallic substrate + polycrystalline diamond
- ***DLC***
- B4C, Metallic substrate + B4C

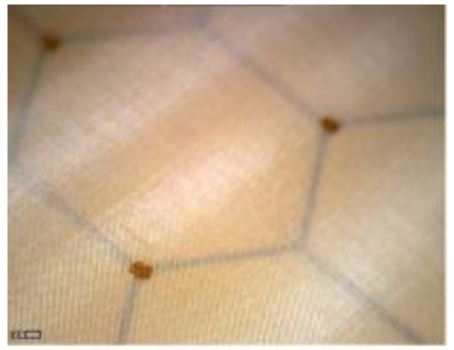


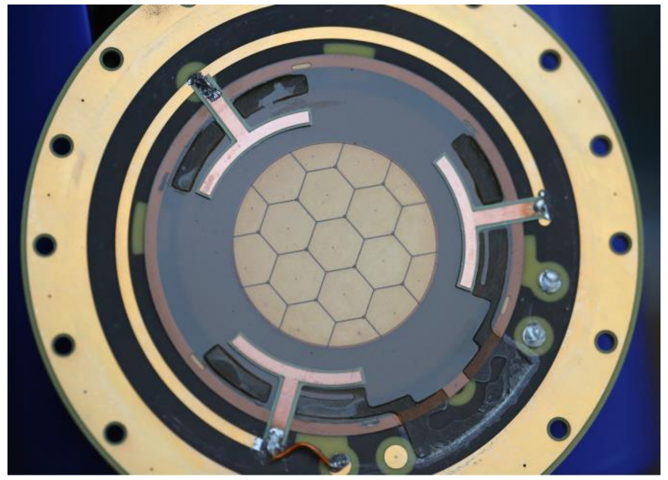


1-ch (∅1cm)
Proof of concept
Resistive and non-resistive prototypes.



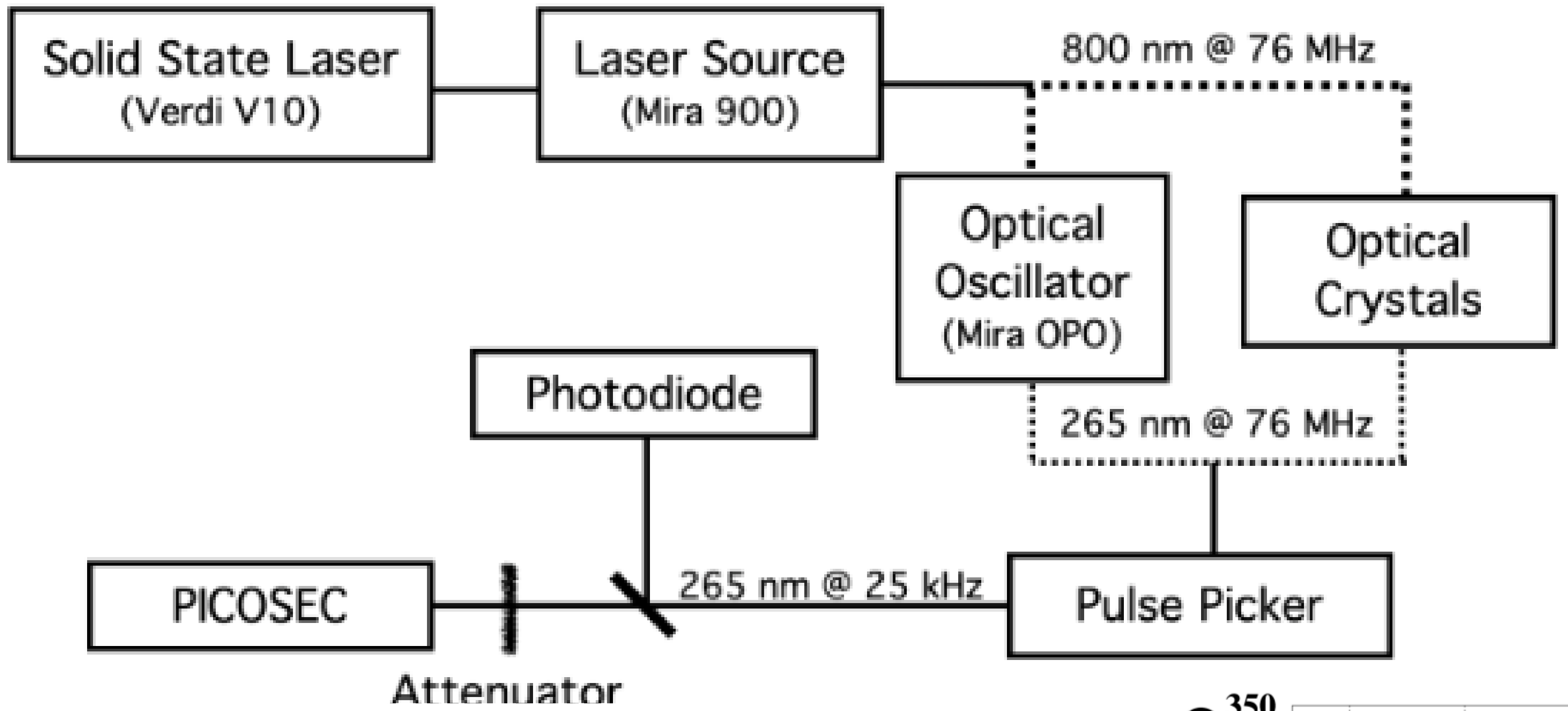
7-ch (∅ 2.6 cm)
Resistive prototypes
Signal sharing



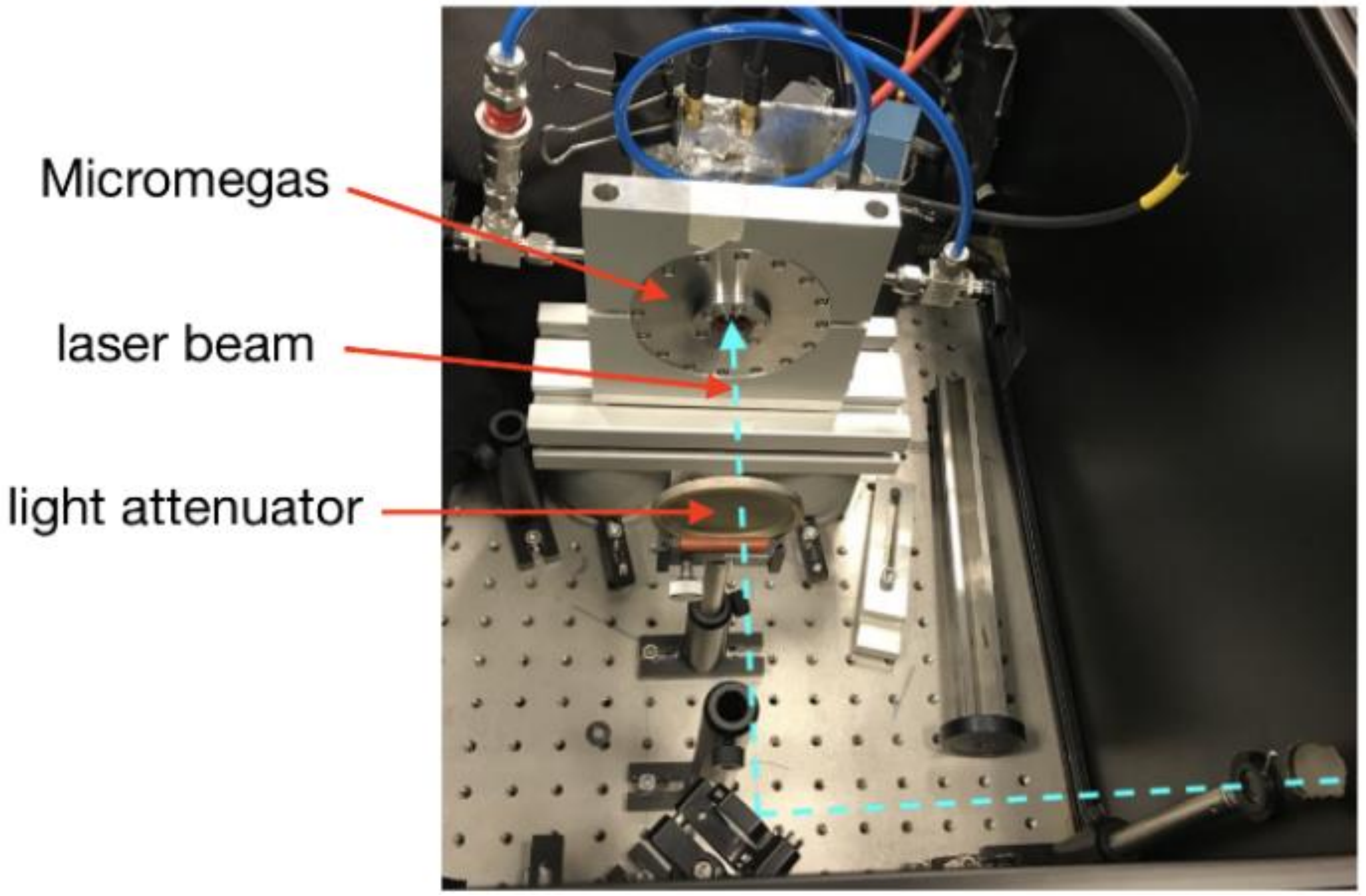


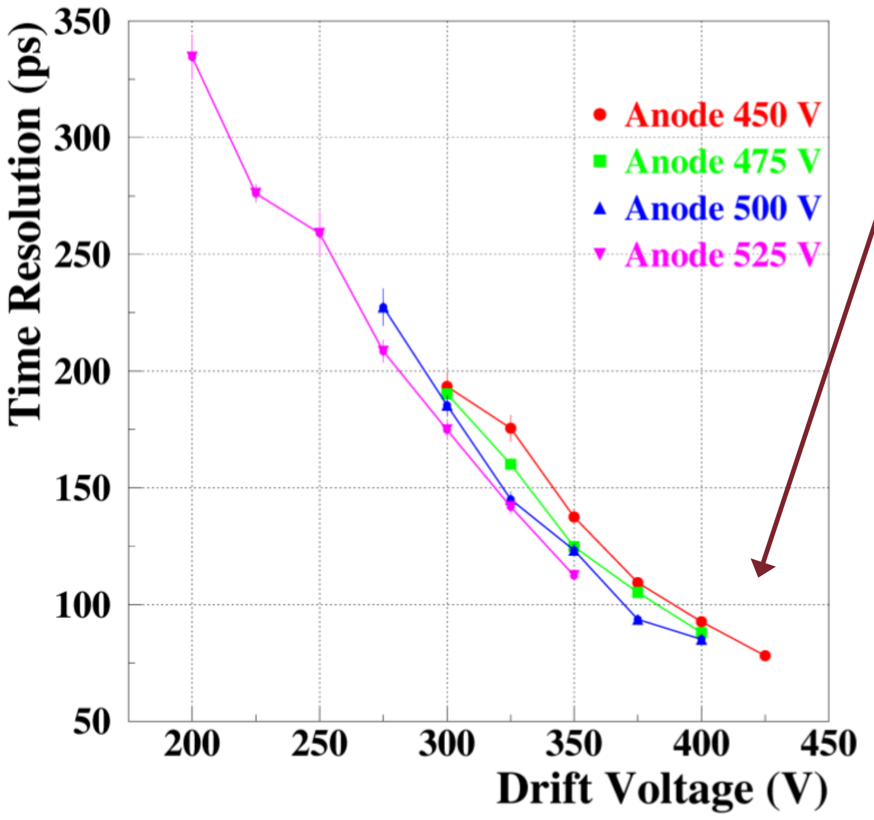
19-ch (∅ 3.6cm)
Signal sharing.

Very thin detector active part (<5 mm)



- First investigation of timing response
- Laser Beam Test (IRAMIS/SLIC, CEA Saclay)
- UV laser light
- Ultra short pulses with duration of a few ps το 120 fs
- Beam adjusted to 265 nm
- Pulse Picker to adjust the repetition rate
- Beam is split between a reference device and PICOSEC-MM
- Attenuator filters to control number of photoelectrons



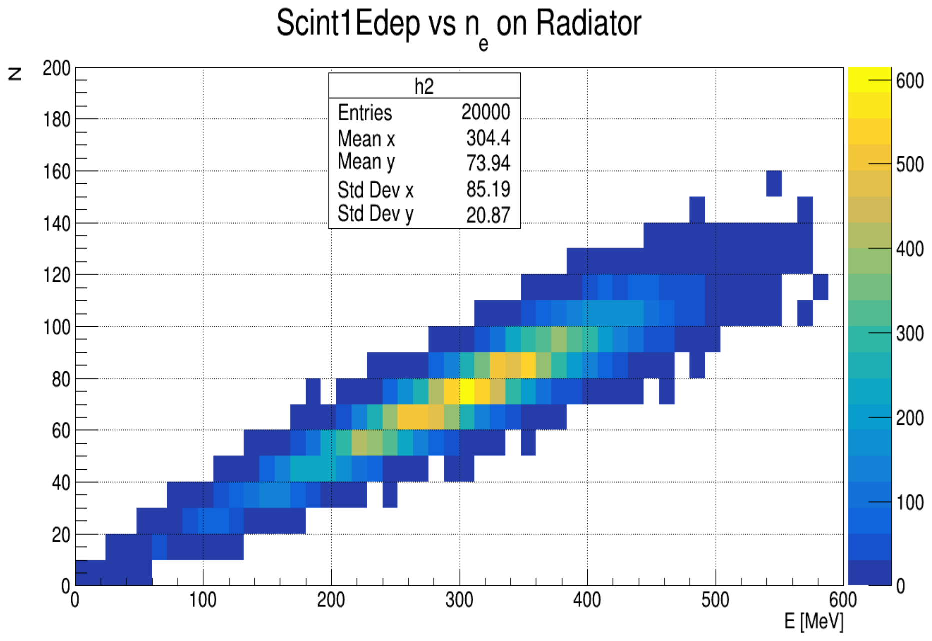


- Best time resolution for single photoelectron measurements : 76.0 ± 0.4 ps @ -425/450V

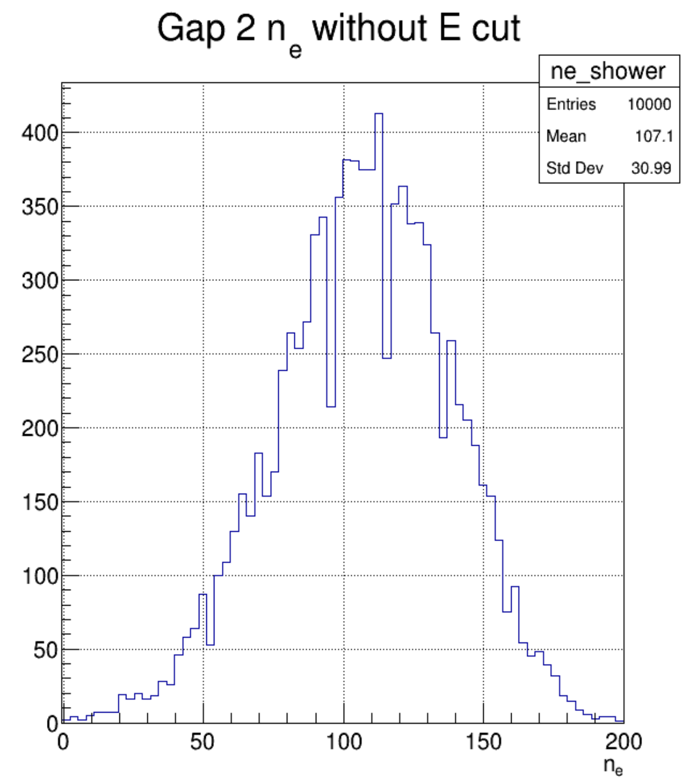
Strong dependence with electric field

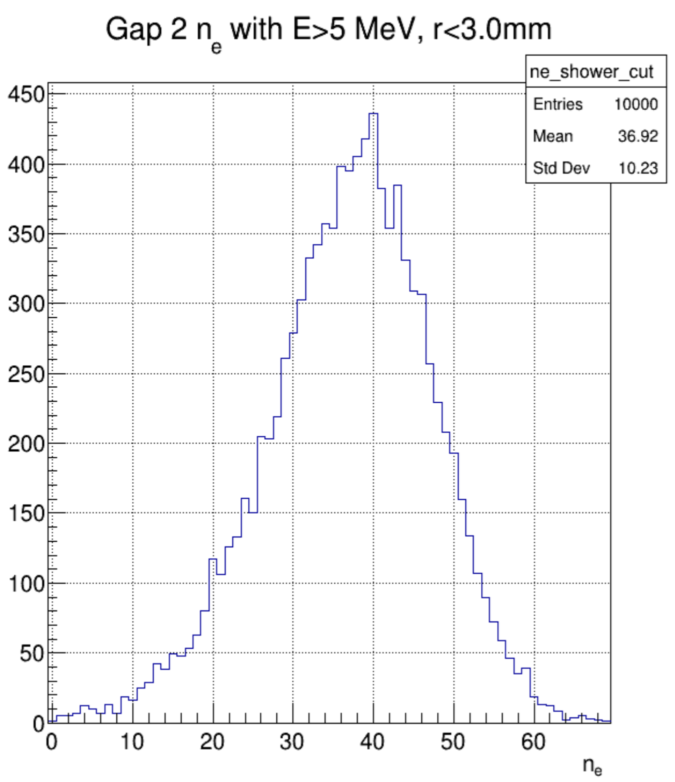
Simulation of Electron Beam Test

50 GeV electrons
on 5 radiation length absorber

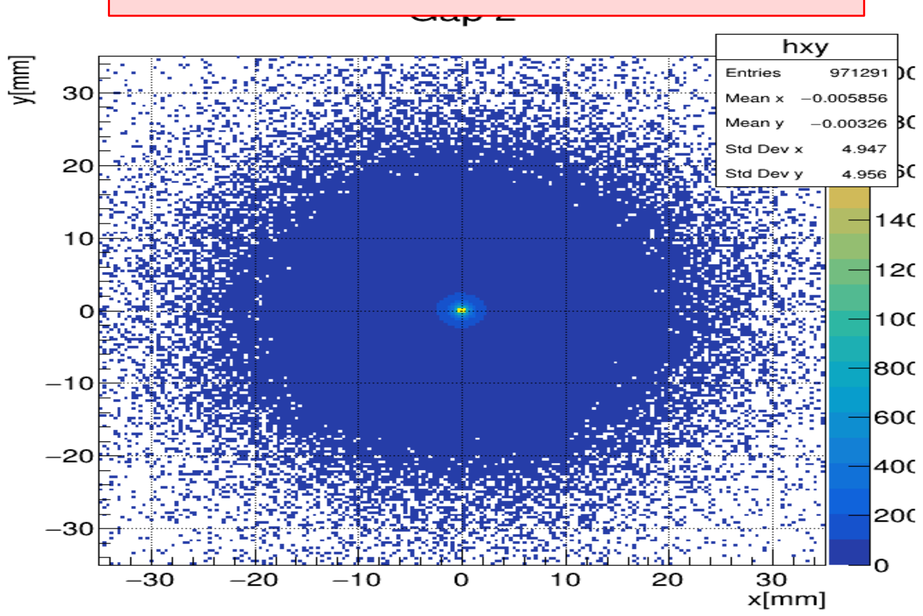


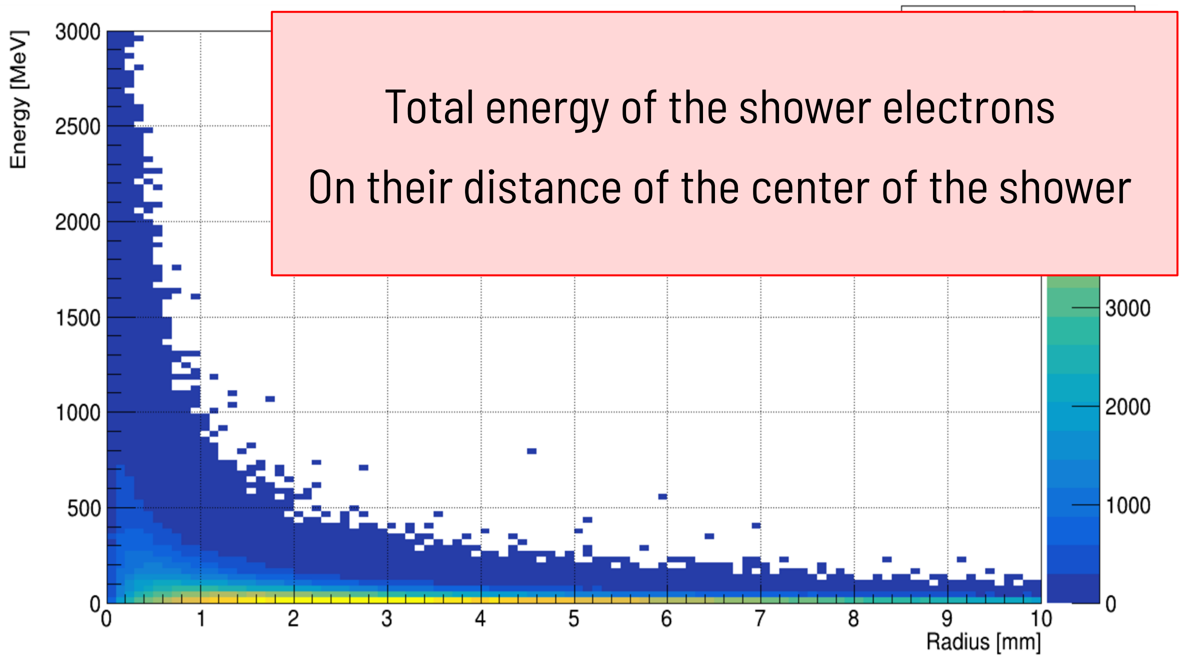
Total energy after the absorber





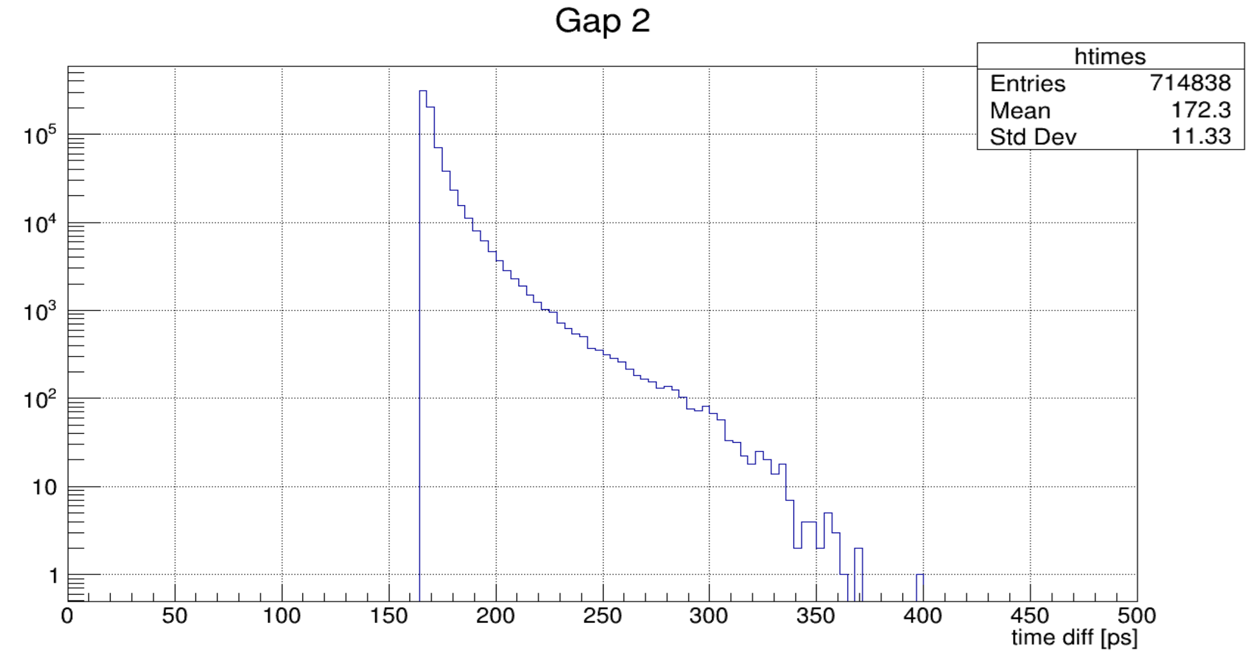
Spatial distribution of shower electrons on radiator





Total energy of the shower electrons

On their distance of the center of the shower



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