PICOSEC
Micromegas

# *From Μικρομέγας (Micromégas*) to PICOSEC Micromegas Detector*

**Thursday, 5th October 2023**

*«Αυτός ο κόσμος ο μικρός ο μέγας» Οδυσσέας Ελύτης*
*«Aftos o kosmos o micros o megas» Odisseas Elytis*


**Alexandra Kallitsopoulou**[1], Eraldo Oliveri[2], Thomas Papaevangelou[1]

*(1)CEA/IRU/Université Paris – Saclay, (2)CERN/GDD*


**Voltaire*

# The PICOSEC Micromegas Technology

CERN 77-09
3 May 1977

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
**CERN** EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PRINCIPLES OF OPERATION OF MULTIWIRE PROPORTIONAL AND DRIFT CHAMBERS

F. Sauli

Lectures given in the
Academic Training Programme of CERN
1975-1976

GENEVA
1977

# The Physics of Ionization offers the means for precise spatial measurements (high spatial resolution) but inhibits precise timing measurements

bution is about 5 nsec. There is no hope of improving this time resolution in a gas counter, unless some averaging over the time of arrival of all electrons is realized.

1977

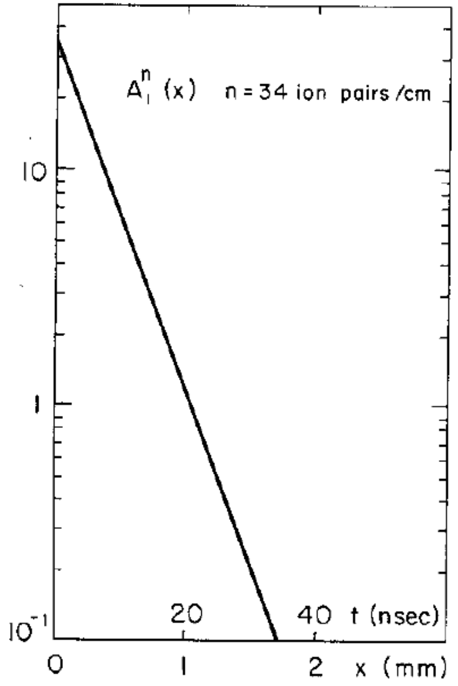



Fig. 8

Statistics of primary ion pair production: probability of finding the closest pair at a distance x from one electrode in a counter, in argon-isobutane 70-30. The corresponding electron minimum collection time is shown, for a typical drift velocity of electrons of 5 cm/μsec.

# The Back story

1991

Nuclear Instruments and Methods in Physics Research A310 (1991) 589–595
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

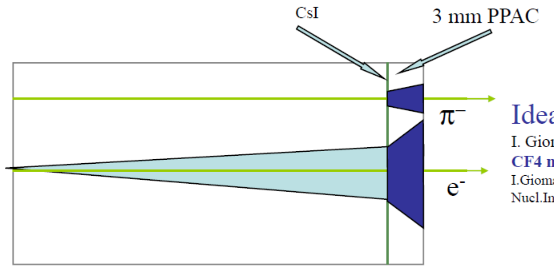
## A hadron-blind detector

Y. Giomataris [a] and G. Charpak [b]
[a] World Lab., Lausanne, Switzerland
[b] CERN, Geneva, Switzerland

Received 22 July 1991

The development of highly efficient solid photocathodes, compatible with high-gain gaseous detectors, has opened the possibility to build threshold Cherenkov counters with a good hadron rejection, with a minimum amount of matter, and a time resolution of the order of the nanosecond. We discuss the properties of a hadron-blind detector, with a granularity of a few millimetres. The study of the background sources shows that a rejection power of the order of 99% can be achieved for high-energy hadrons. It permits instantaneous multi-hadron rejection and, combined to a fast electromagnetic calorimeter, can ensure on-line electron selection, even when they are produced close to hadronic jets. It could permit the operation of lepton-tracking detectors in a magnetic field, in very high hadronic backgrounds.

Hadron Blind Detector(HBD) → Micromegas




Idea
I. Giomataris,G. Charpak, NIM A310(1991)589,
**CF4 magic HBD gas**
I.Giomataris,G.Charpak,V.Peskov,F.Sauli
Nucl.Instrum.Meth.A323:431-438,1992

HBD great result on 1992: $N_0$=500 and good signal to background ratio
M. Chen et al., Nucl.Instrum.Meth.A346:120-126,1994

HBD improvements
Very small PPAC gap:
1 mm gap sucessfully tested but no uniform gain
Micromegas is an ideal detector for HBD

I. Giomataris

# MICROMEGAS Invention

1996

N-H ELSEVIER
Nuclear Instruments and Methods in Physics Research A 376 (1996) 29–35
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

## MICROMEGAS: a high-granularity position-sensitive gaseous detector for high particle-flux environments

Y. Giomataris[a,*], Ph. Rebourgeard[a], J.P. Robert[a], G. Charpak[b]
[a] CEA/DSM/DAPNIA/SED-C.E.-Saclay, 91191 Gif/Yvette, France
[b] Ecole Superieure de Physique et Chimie Industrielle de la ville de Paris, ESPECI, Paris, ESPCI, Paris, France and CERN/AT, Geneva, Switzerland

Received 24 January 1996

**Abstract**
We describe a novel structure for a gaseous detector that is under development at Saclay. It consists of a two-stage parallel-plate avalanche chamber of small amplification gap (100 μm) combined with a conversion-drift space. It follows a fast removal of positive ions produced during the avalanche development. Fast signals (≤1 ns) are obtained during the collection of the electron avalanche on the anode microstrip plane. The positive ion signal has a duration of 100 ns. The fast evacuation of positive ions combined with the high granularity of the detector provide a high rate capability. Gas gains of up to $10^5$ have been achieved.

**& Me**

# The Back story

**1991**

Nuclear Instruments and Methods in Physics Research A310 (1991) 589–595
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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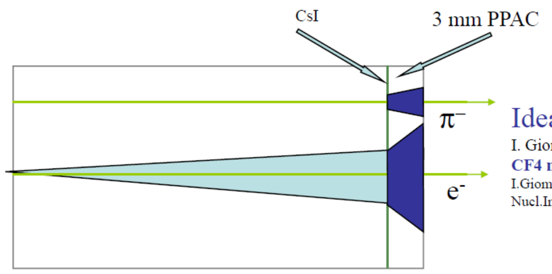
The development of highly efficient solid photocathodes, compatible with high-gain gaseous detectors, has opened the possibility to build threshold Cherenkov counters with a good hadron rejection, with a minimum amount of matter, and a time resolution of the order of the nanosecond. We discuss the properties of a hadron-blind detector, with a granularity of a few millimetres. The study of the background sources shows that a rejection power of the order of 99% can be achieved for high-energy hadrons. It permits instantaneous multi-hadron rejection and, combined to a fast electromagnetic calorimeter, can ensure on-line electron selection, even when they are produced close to hadronic jets. It could permit the operation of lepton-tracking detectors in a magnetic field, in very high hadronic backgrounds.

Hadron Blind Detector(HBD) → Micromegas

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HBD improvements
Very small PPAC gap:
1 mm gap sucessfully tested but no uniform gain
Micromegas is an ideal detector for HBD

I. Giomataris

**1999**

ELSEVIER
Nuclear Instruments and Methods in Physics Research A 449 (2000) 314–321
www.elsevier.n... ...a

## Fast signals and single electron detection with a MICROMEGAS photodetector

J. Derré[a], Y. Giomataris[a,*], Ph. Rebourgeard[a], H. Zaccone[a], J.P. Perroud[b], G. Charpak[c]
[a] CEA/DSM/DAPNIA/C.E.-Saclay, 91191 Gif-sur-Yvette, France
[b] IPHE, University of Lausanne, Lausanne, Switzerland
[c] CERN/LHC-EET, Geneva, Switzerland

Received 3 December 1999; accepted 14 December 1999

**Abstract**

The performance of a new gaseous photodetector was investigated. It consists of a solid photocathode and a gas amplification structure of the MICROMEGAS type. Using a mixture of helium and isobutane at atmospheric pressure, a stable and high amplification gain close to $10^7$ was achieved. Such a high gain and small fluctuations allowed the detection of single photoelectrons with a time resolution better than 700 ps. These performances are comparable with those obtained with the best photomultipliers. 

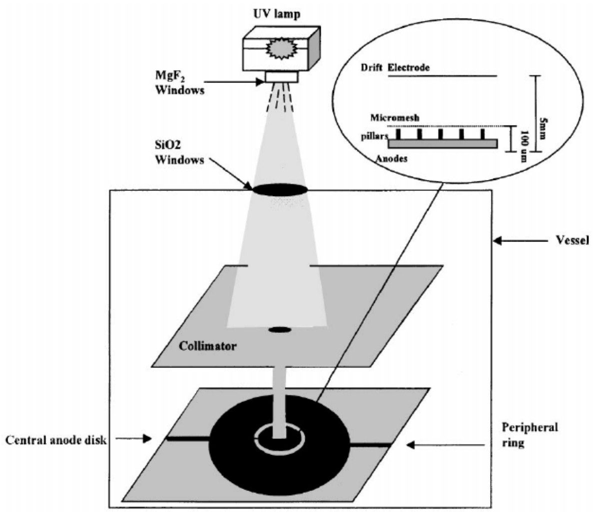
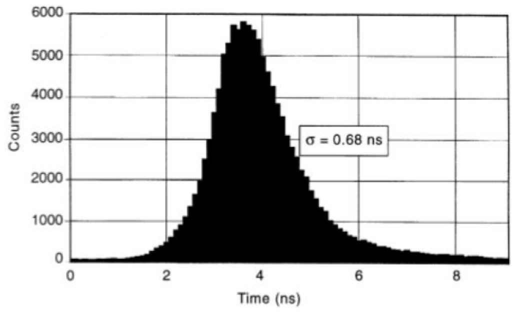



Fig. 2. Schematic view of the experimental set-up.

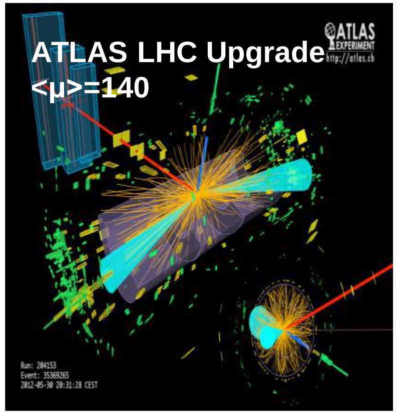
Operating in Reflective mode
CF4 gas & CsI photocathode



# What is our motivation?

## Timing with a few 10's of Picosecond

- **High Luminosity LHC**:
- Necessary timing resolution ~20ps
- Clean reconstruction of the events
- Reduction of mixing different events due to pile-up
- Timing can be an extra parameter




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

2014

Request for Project Funding from the RD51 Common Fund
- Date: *20-05-2014*

**Title of project:** Fast Timing for High-Rate Environments:A MicroMegas Solution

**Contact persons:** *Sebastian White(co-PI), Rockefeller/FNAL swhite@rockefeller.edu*
*Ioannis Giomataris(co-PI), Saclay ioa@hep.saclay.cea.fr*

**RD51 Institutes:**

**1.** *IRFU-Saclay, contact person Ioannis Giomataris ioa@hep.saclay.cea.fr*
+ Esther Ferrer, Alan Peyaud, Eric Delagnes, Thomas Papaevangelou

**2.** *Rockefeller/FNAL, contact person Sebastian White swhite@rockefeller.edu*
*+Umesh Joshi (FNAL)*

**3.** *CERN, contact person, Rui de Olivera Rui.de.Oliveira@cern.ch*
*+RD51&Uludag University, Rob Veenhof veenhof@mail.cern.ch*

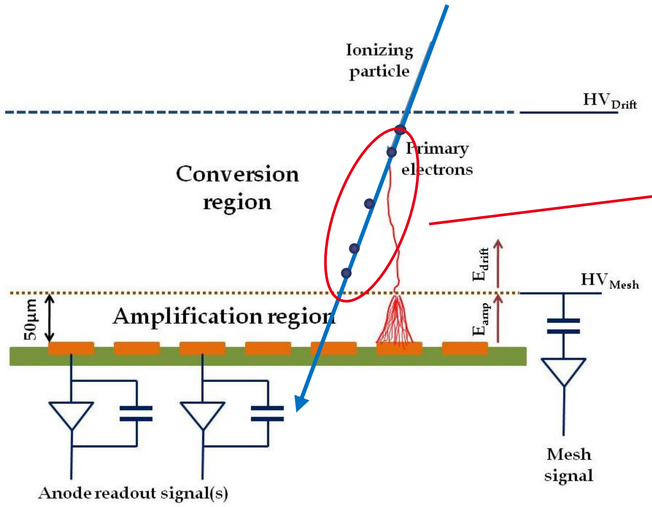
**4.** *Princeton University, contact person K.T. McDonald, kirkmcd@princeton.edu*
*+Changguo Lu*

**5.** *NCSR Demokritos, contact person George Fanourakis gfan@inp.demokritos.gr* + Theodoros Geralis.

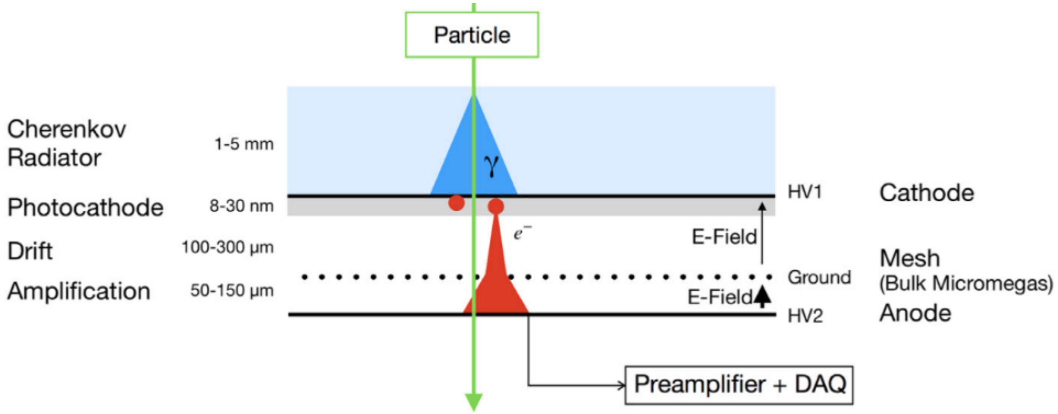
**Request to RD51:** *14'500 €*

**Total project cost:** *39'000 €*

# The PICOSEC Micromegas Technology




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




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

- Limitations of the Micromegas Timing Potential
  - Stochastic nature of ionization
  - Randomness of last ionization
  - Time jitter of a few ns

- Modifications in MM Geometry
  - Smaller Drift Gap
    - Elimination of the stochastic nature of ionization
  - Higher applied Drift Voltage ⟶ Pre-avalanche

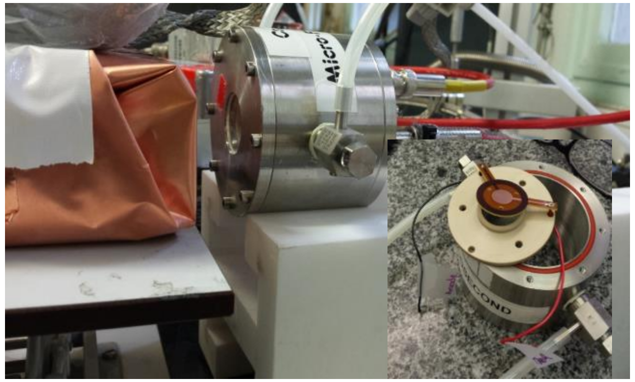
- Additional Components in MM geometry
  - Cherenkov radiator +
  - Solid converter ⟶ Photocathode
    Prompt photoelectrons

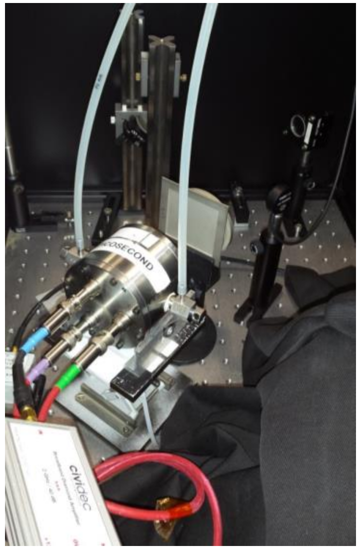
# Let the story begin…

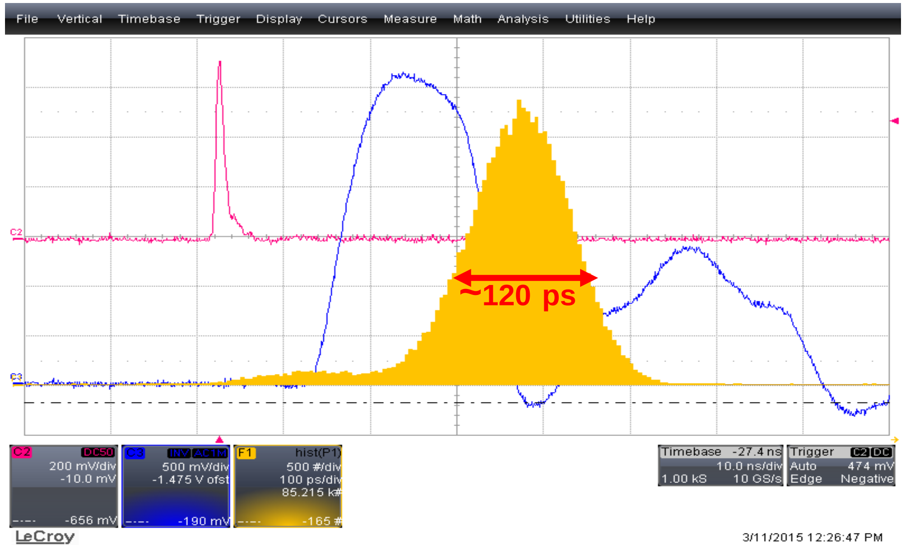
- **1st prototypes tested in Laser Tests at IRAMIS**

***Special Thanks to Thomas Gustavsson**

- μbulk detector technology
- Detector operating in sealed mode using Ne-10% ethane
- Not optimized system in a relevant test for the response to single photoelectrons, and a very well beginning



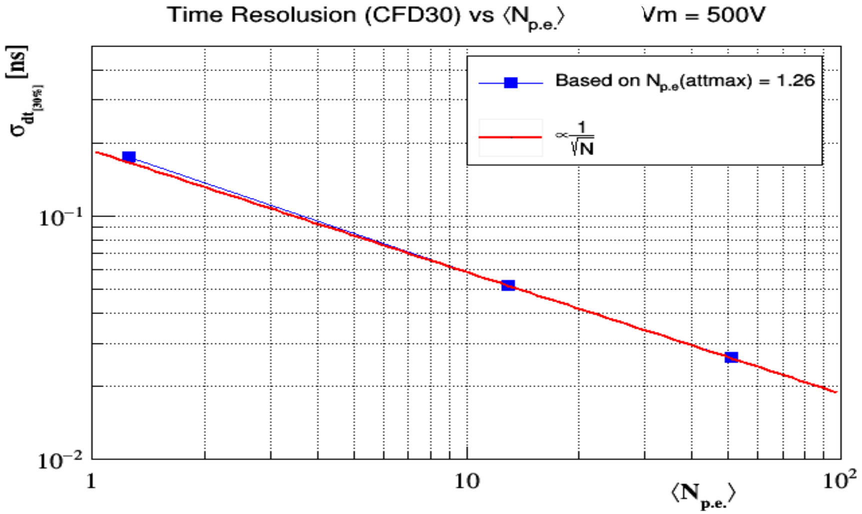




# Forming the PICOSEC Collaboration – MPGD in Trieste

2015

- Improved performance
  - Bulk detector technology
  - Better signals but still strong reflections
- Detector operating in sealed mode using Ne-10% ethane
- **The importance of preamplification**
  - Improvement compared to physical jitter
- **Dependence of resolution on number of photoelectrons**

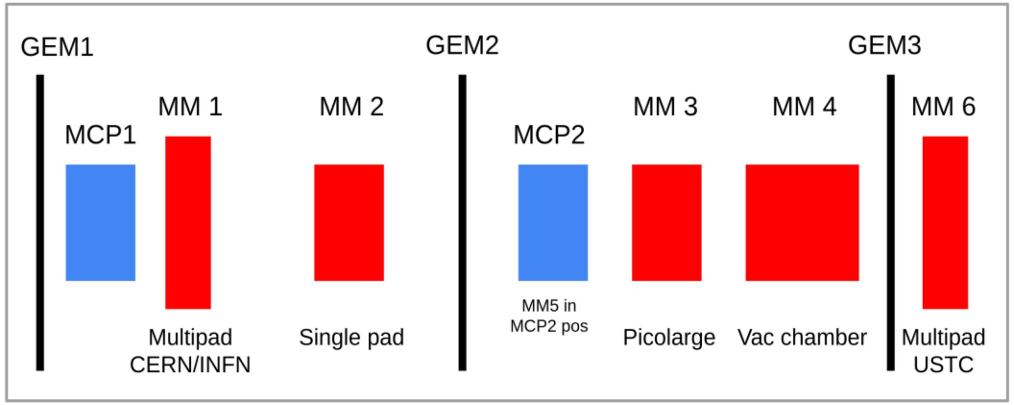



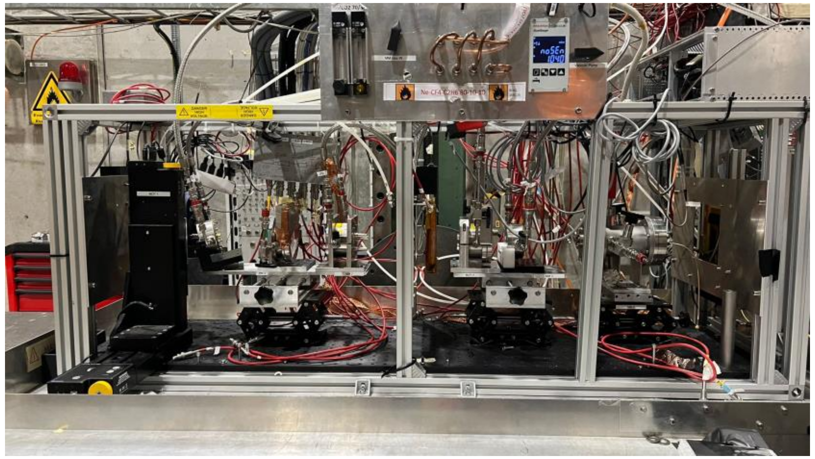

alexandra.kallitsopoulou@cea.fr

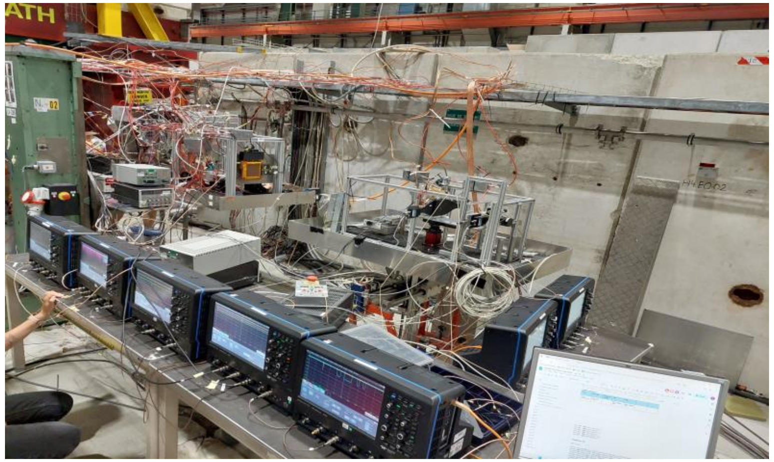
# Detector Testing - Particle beams

2017

- Particle Beams @ CERN SPS H4 Beamline
  Highly energetic muons (80-150GeV)

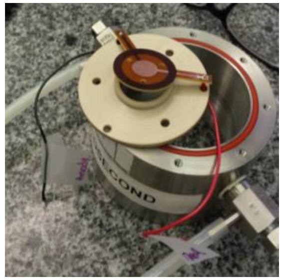




- The Setup
  - Use GEMs for tracking
  - Use MCP PMTs as timing reference devices and for triggering
  - Different Prototypes of Picosec Micromegas Detectors
  - Electronics: Commercial/Custom-made preamplifiers
  - Digitizers – Lecroy scopes

# Single anode PICOSEC Micromegas Prototype



**Single anode ∅ 1 cm**
***2016***

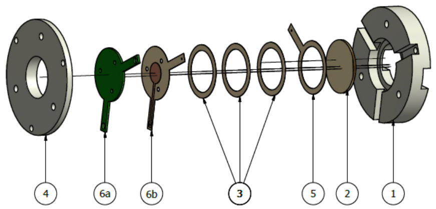
# The Single anode prototypes

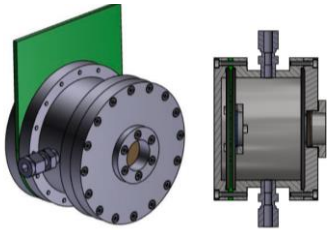
The Sensor:

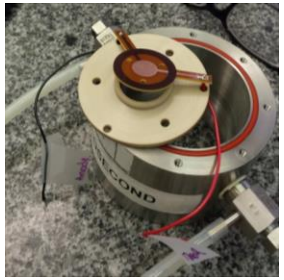
- Different Detector technologies
  - Bulk Micromegas ∅ 1cm
  - MicroBulk Micromegas ∅ 1cm

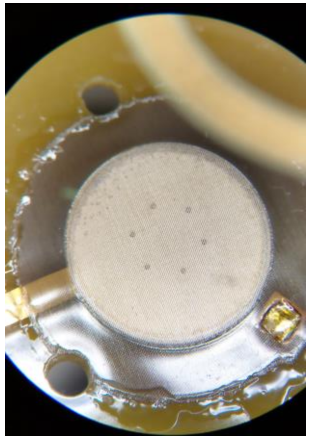
- Different Crystals & Photocathode materials
  - MgF2 / Sapphire crystal +
  - Metallic substrate (Cr) + CsI
  - Metallic substrate (Cr) + polycrystalline diamond, B4C, DLC
  - Metallic (Cr, Al), B4C, DLC

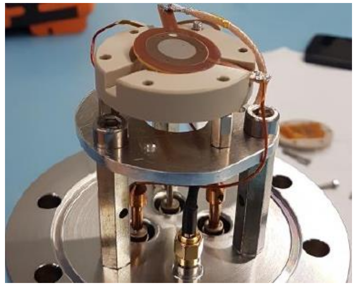
- Different Gas Composition Studies
- COMPASS Gas : 80% Ne – 10% $CF_4$-10%$C_2H_6$

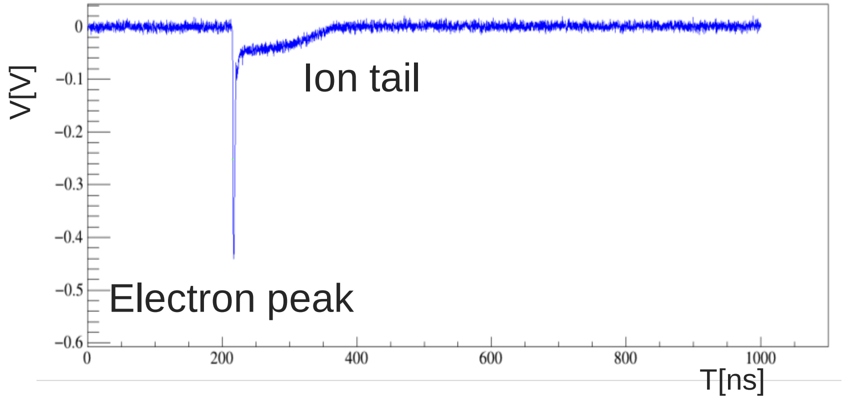






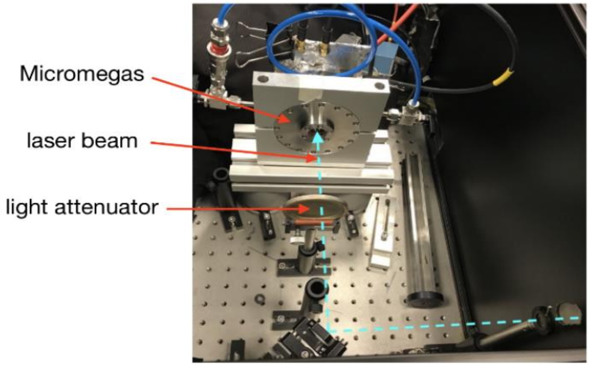




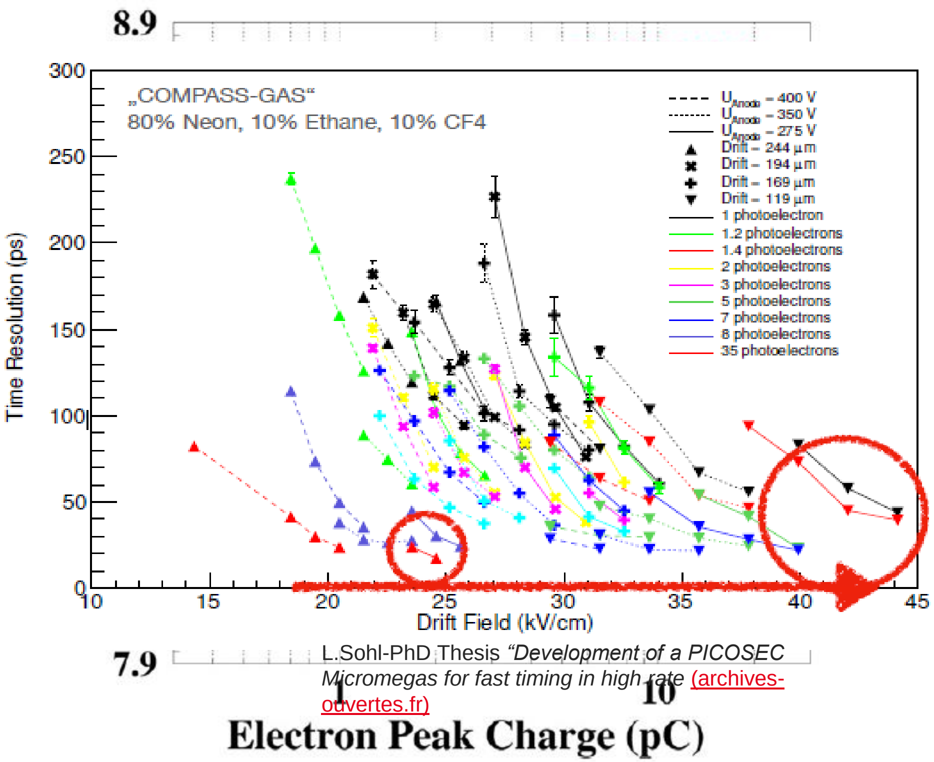
# Detector Testing

2018

- Pulsed Laser Beam (IRAMIS/CEA)
  - UV Ultra short laser pulses
  - Single Photoelectron response
  - Perform measurements independently of the photocathode material
  - Understanding the properties




- Data taking & Output
  - Timing reference device – fast photodiode (**$\sigma_T \sim 3$ps**)
  - Attenuator meshes to control the number of photoelectrons
  - Signal Arrival Time has a dependence on Electron peak charge
  - Timing resolution improves with **higher drift field** & **smaller gap(<50ps for 120μm** for single pe)




L.Sohl-PhD Thesis *"Development of a PICOSEC Micromegas for fast timing in high rate* (archives-ouvertes.fr)

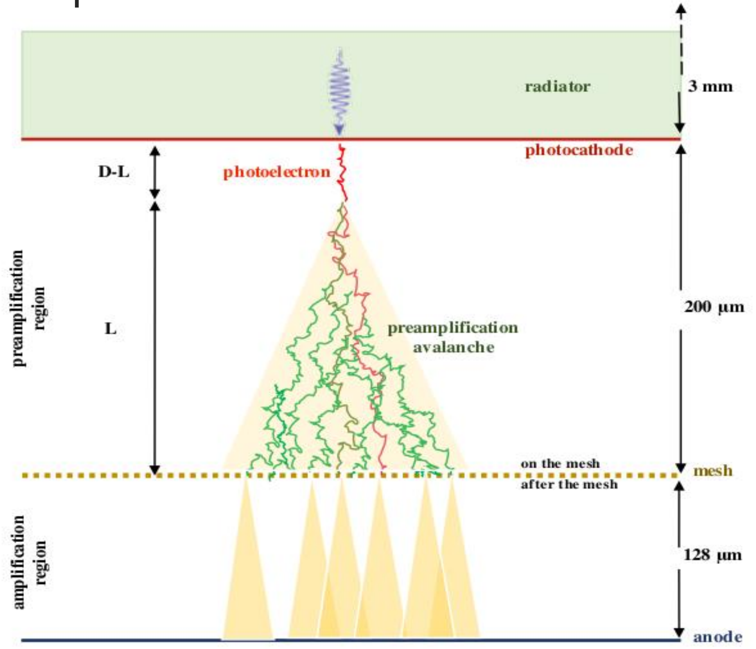
J.Borteldt, et al. "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector", Nuc. Instrum. Meth. A (2021)https://doi.org/10.1016/j.nima.2018.04.033

# A very well understood detector

2019

- Modeling Aspects*:
- SAT time walk seen in single photoelectron data is explained:
  - SAT reduces with avalanche length
  - Long avalanches → big electron peak charge
- SAT & Timing resolution are determined by:
  - The drift path of the primary photoelectron

→ number of photoelectrons in avalanche and its length




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

***AUTh, Spyros Tzamarias**

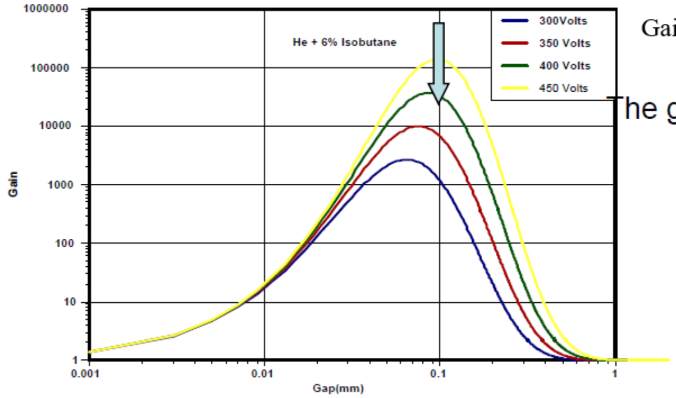
2008

## Virtue of the small gap

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

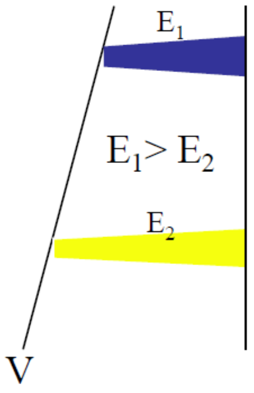
Townsend coefficient α: $\frac{\alpha}{p} = Ae^{-Bp/E} = Ae^{-Bpd/V}$

Gain variation: $\frac{\delta G}{G} = apd\left(1-\frac{Bpd}{V}\right) = apd\left(1-\frac{Bp}{E}\right)$




The gain variation exhibits a minimum for

**d = V/Bp**




**Optimum gap : 30 - 100 microns**

Ref: Y. Giomataris, NIM A419, p239 (1998)

**Stable gain and relative immunity to flatness defects or temperature and pressure variation**

**Good energy resolution**

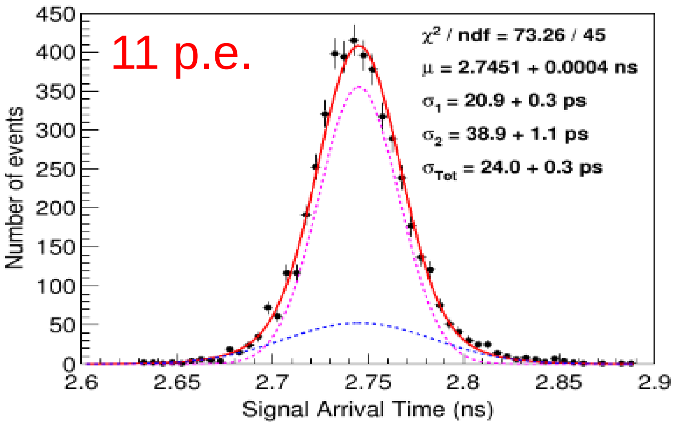
I. Giomataris

I. Giomataris-Micro-Pattern Gas Detectors (RD51) Workshop, Amsterdam, 2008
https://indico.cern.ch/event/25069/contributions/1575890/

# Detector Testing - Particle beams

- Particle Beams @ CERN SPS H4 Beamline
  - Muons 80-150GeV

- First timing measurement @ Particle Beam results - 2017
  - Single Prototype : Thin Gap (200μm) with MgF2 & CsI photocathode

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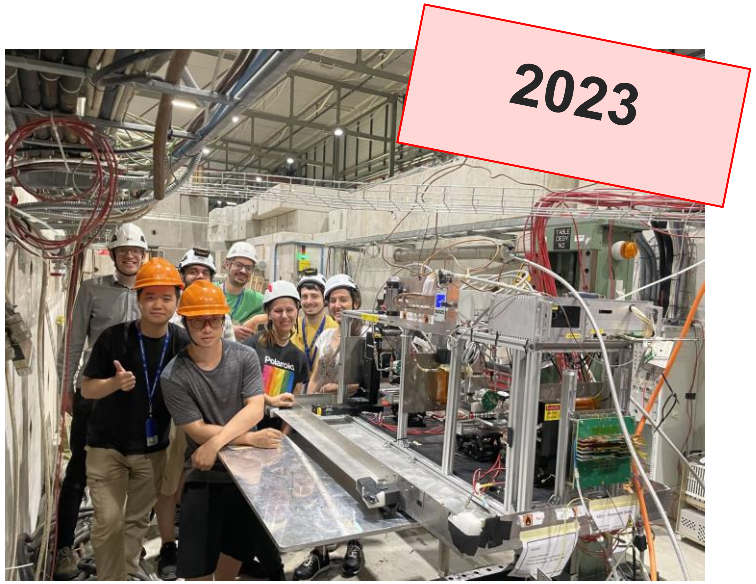
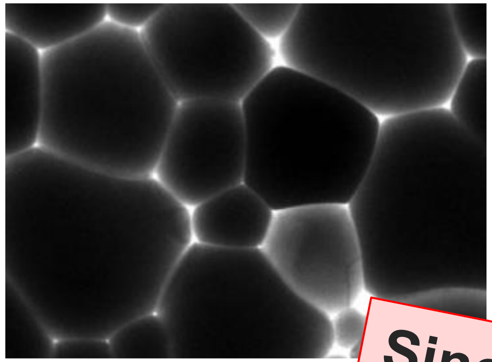
Timing Resolution → RMS of Signal Arrival Time Distribution



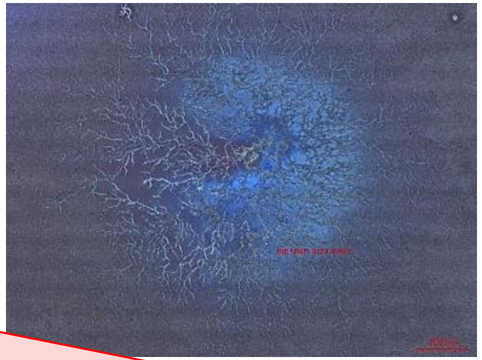



# The photocathode issue

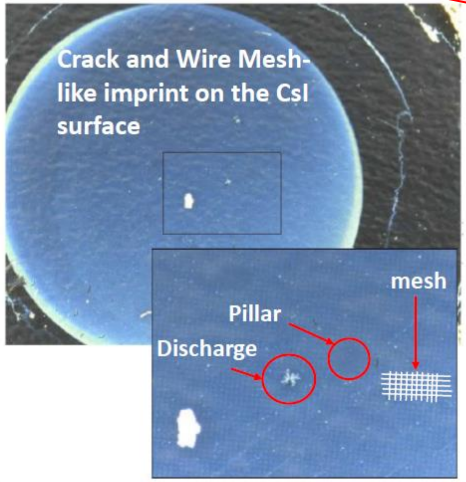
- In the research of photocathode materials
  - Standard photocathode: 18nm CsI +3nm Cr ~ 10pe/MIP
  - CsI sensitive to humidity/ion backflow & sparks

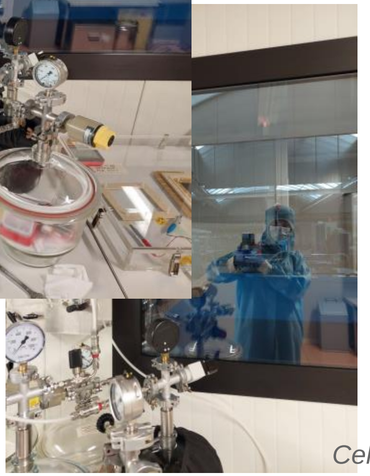


https://doi.org/10.1016/j.nima.2011

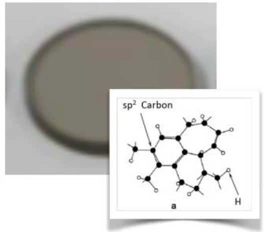


**Since 2016**

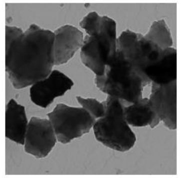


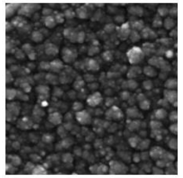
- New materials under test (B4C, DLC, Diamond, Metallic – Al, Cr)



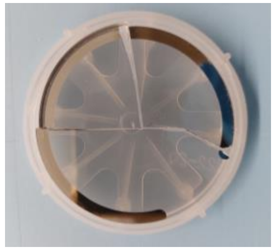

DLC, Y. Zhou et al.



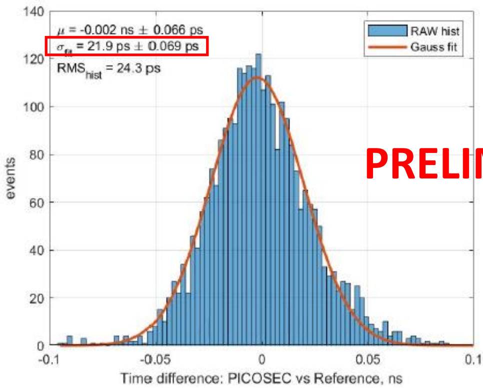
ND, L. Velardi et al.



$B_4C$, 10.1016/j.jnucmat.2015.01.015




$B_4C$ 12 nm photocathode




**2022**

*M. Lisowska - Towards robust PICOSEC Micromegas precise timing detectors-MPGD2022*
*https://indico.cern.ch/event/1219224/contributions/5130512*

# The PICOSEC Micromegas Collaboration

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**University of Pavia** (Italy) D. Fiorina

**Univeristy of Virginia** (USA) S. White

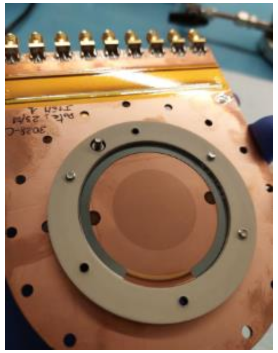
*12 institutes from 8 countries*

*46 collaborators*

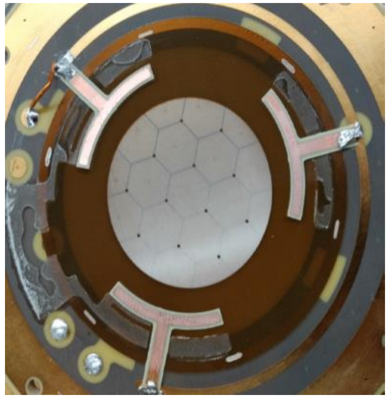
# A relevant series of publication (and contribution to conferences)

| | AUTHORS | YEAR | TITLE | SOURCE |
|---|---|---|---|---|
| ☆ | Lisowska M, Bortfeldt J, Brunbauer … | 2023 | Sub-25 ps timing measurements with 10 10 cm^2 PICOSEC Micromegas detectors. Sub-25 ps timing measu… | Nucl. Instrum. Methods Ph… |
| ☆ | Aimè C, Calzaferri S, Casarsa M, Fi… | 2023 | Muon detector for a Muon Collider | Nuclear Instruments and M… |
| ☆ | Manthos I, Aune S, Bortfeldt J, Brun… | 2022 | Precise timing and recent advancements with segmented anode PICOSEC Micromegas prototypes | JINST |
| ☆ | Tsiamis A, Kordas K, Manthos I, Tso… | 2022 | Timing techniques with picosecond-order accuracy for novel gaseous detectors | Journal of Instrumentation |
| ☆ | Aune S, Bortfeldt J, Brunbauer F, D… | 2021 | Timing performance of a multi-pad PICOSEC-Micromegas detector prototype | Nucl. Instrum. Methods Ph… |
| ☆ | Bortfeldt J, Brunbauer F, David C, D… | 2021 | Modeling the timing characteristics of the PICOSEC Micromegas detector | Nuclear Instruments and M… |
| ☆ | Kordas K, others | 2020 | Progress on the PICOSEC-Micromegas Detector Development: Towards a precise timing, radiation hard, la… | Nuclear Instruments and M… |
| ☆ | Sampsonidis D, Bortfeldt J, Brunbau… | 2020 | Precise timing with the picosec-micromegas detector | Nuovo Cimento della Socie… |
| ☆ | Sohl L, others | 2020 | Single photoelectron time resolution studies of the PICOSEC-Micromegas detector | Journal of Instrumentation |
| ☆ | Manthos I, others | 2020 | Recent Developments on Precise Timing with the PICOSEC Micromegas Detector | Journal of Physics: Confer… |
| ☆ | Bortfeldt J, Brunbauer F, David C, D… | 2020 | Modeling the Timing Characteristics of the PICOSEC Micromegas Detector | Nucl. Instr. and Meth. in Ph… |
| ☆ | Manthos I, Bortfeldt J, Brunbauer F, … | 2020 | Recent Developments on Precise Timing with the PICOSEC Micromegas Detector | J. Phys.: Conf. Ser. |
| ☆ | Sohl L, others | 2019 | PICOSEC-Micromegas: Robustness measurements and study of different photocathode materials | Journal of Physics: Confer… |
| ☆ | Iguaz F, Bortfeldt J, Brunbauer F, Da… | 2019 | Charged particle timing at sub-25 picosecond precision: The PICOSEC detection concept | Nuclear Instruments and M… |
| ☆ | Sohl L | 2019 | Spatial time resolution of MCP-PMTs as a t0-reference | Nuclear Instruments and M… |
| ☆ | Bortfeldt J, Brunbauer F, David C, D… | 2019 | Precise charged particle timing with the PICOSEC detector | arXiv |
| ☆ | Bortfeldt J, Brunbauer F, David C, D… | 2018 | PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector. PIC… | Nucl. Instrum. Methods Ph… |

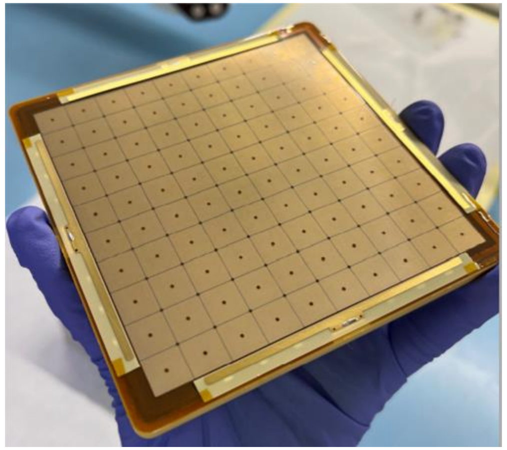
# Multi-anode PICOSEC Micromegas Prototype



7 channel anode ⬡ 1 cm



19 channel anode ⬡ 1 cm



100 channel anode ☐ 1 cm

# Ongoing Development

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

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

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

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

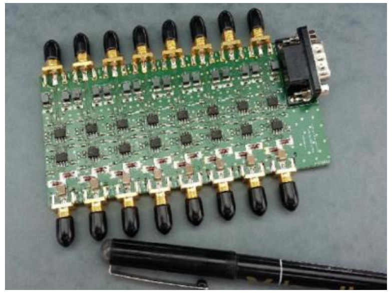
- **Possible Applications (LP2I Bordeaux/ IRFU/ Auth)**
  - T0 tagger and/or embedded in a calorimeter
  - Muon monitoring
  - As a photodetector for T0 tagging at the neutrino detector

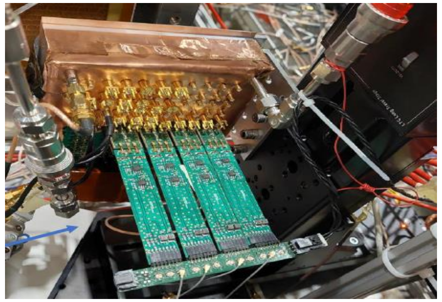
# Pixelated PICOSEC Detector

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

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

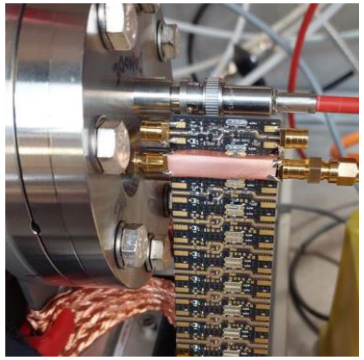
  } Philippe Legou (IRFU/CEA)

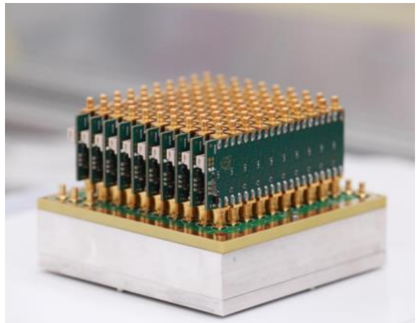




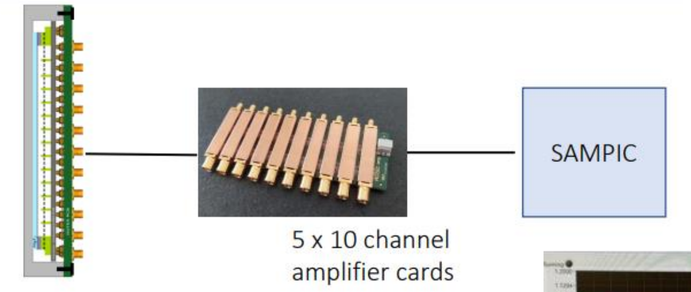
- Research on possible usage of customade charge-sensitive amplifiers (Hans Muller/ CERN)

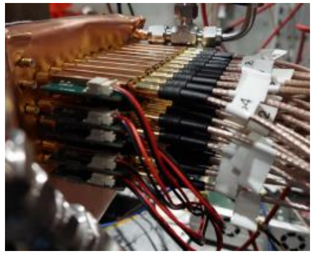
- Recent development @ CERN
  - 10 ch amplifier boards(M.Kovacic, A. Utrobicic)

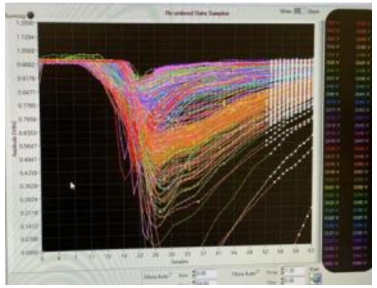




- Research on different digitization ways → SAMPIC digitizer (E. Delanges et al. IRFU /CEA)



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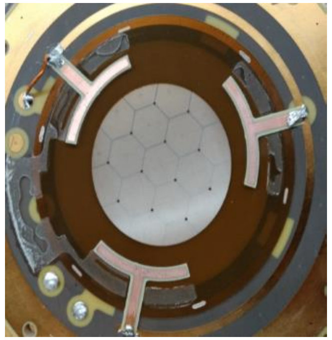
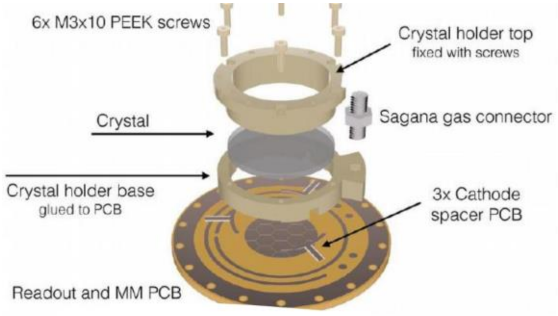
# Scalability…The importance of planarity

2018

université PARIS-SACLAY PICOSEC Micromegas

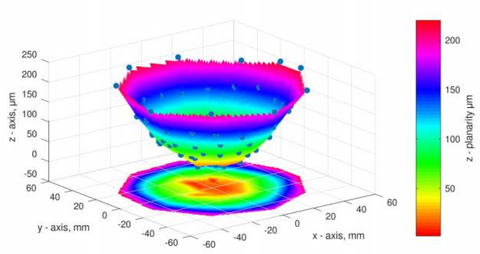
- The importance of planarity
  - 1st multichannel prototype tested
  - 19-hexagonal pad prototype, MgF2, CsI, 200µm drift gap

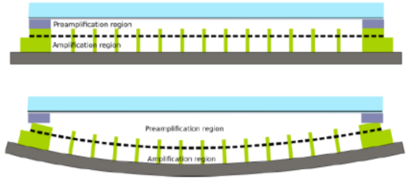


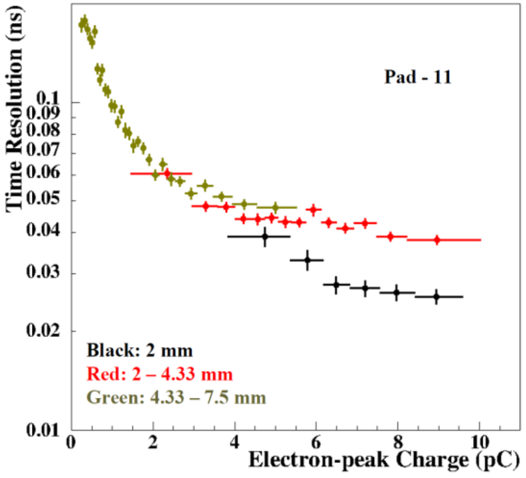



**19 channel anode ⬡ 1 cm**

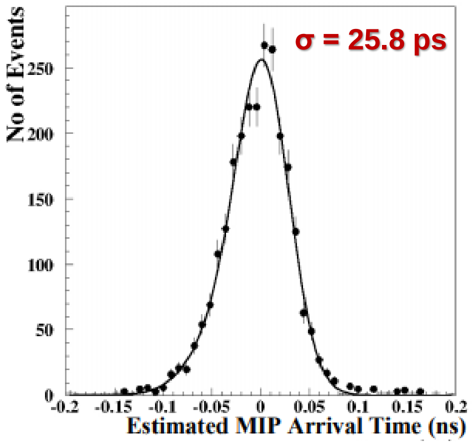
- Variation on timing resolution
  - Non uniformity of the drift field gap
  - Different gain in single pad area

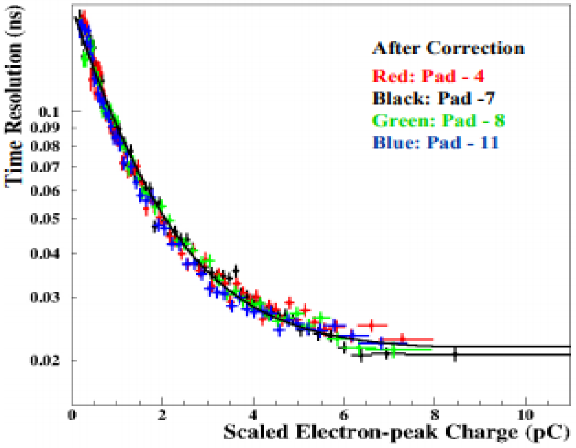


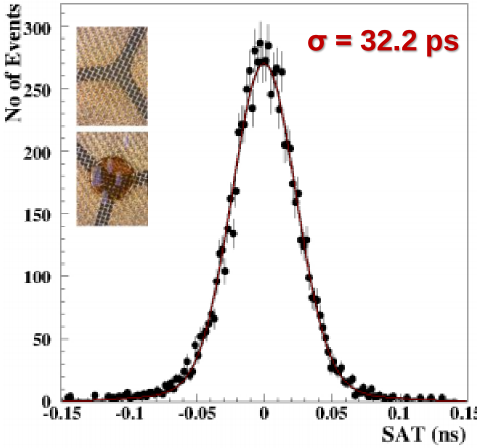




All tracks passing within R<2mm from the center of any pad




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

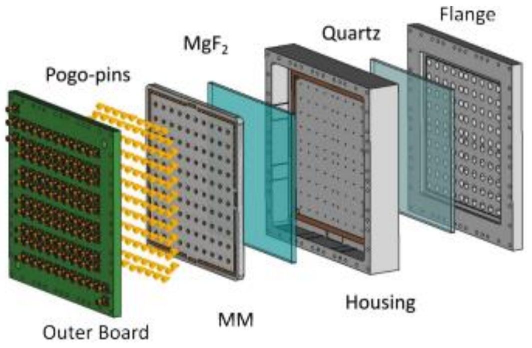
***AUTh-Spyros Tzamarias**

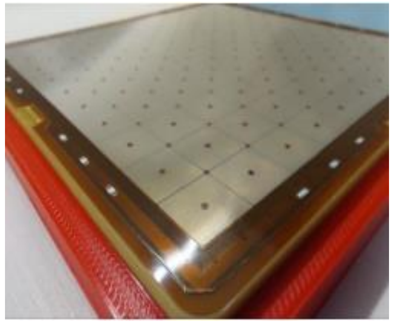
# Ensure the planarity

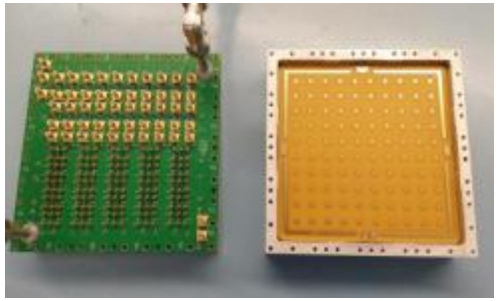
- Tree possible approaches for modular prototypes with 10x10$cm^2$ active zone :

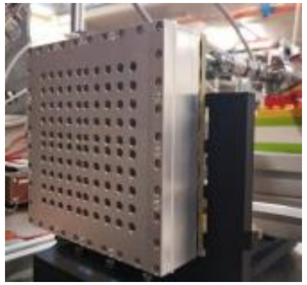
2021

- **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



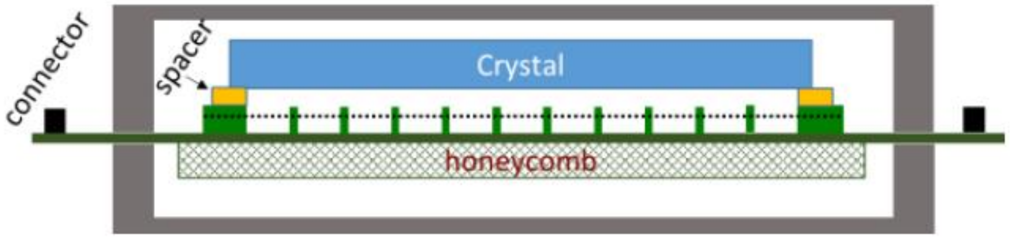




**Ready and operational from CERN-GDD Group**

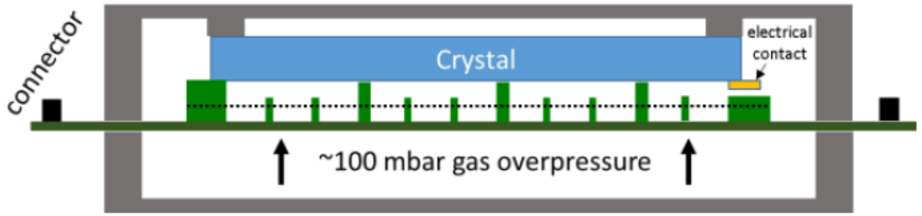
2024+

- **The ATLAS NSW Approach**



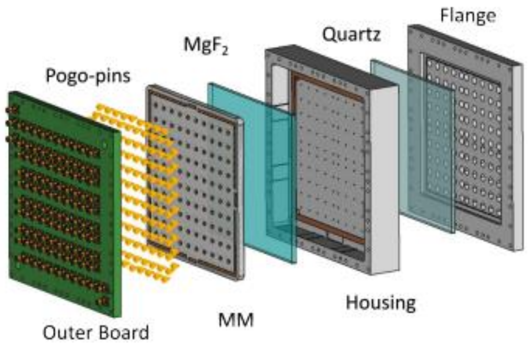

- **Advantage:**
  - Low material budget on the detector
  - Allow the fabrication of large flat boards

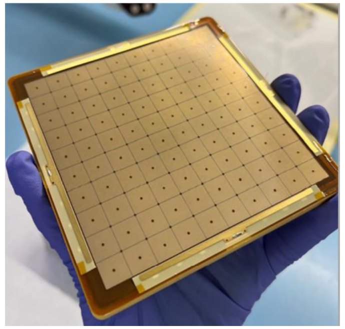
- **Longer pillars MM module**



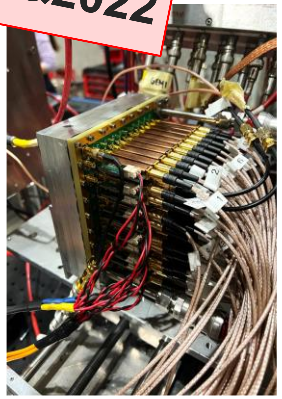
# 100channel PICOSEC Micromegas

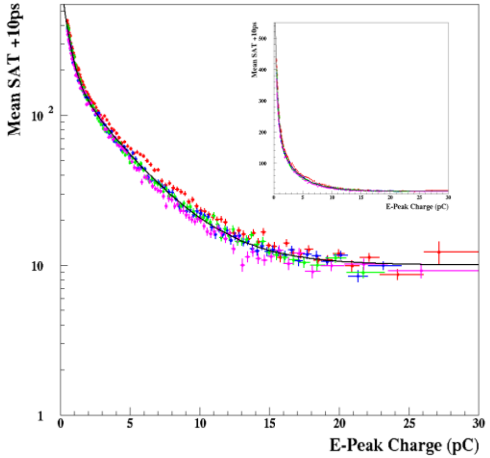
2021&2022



100 channel anode ☐ 1 cm

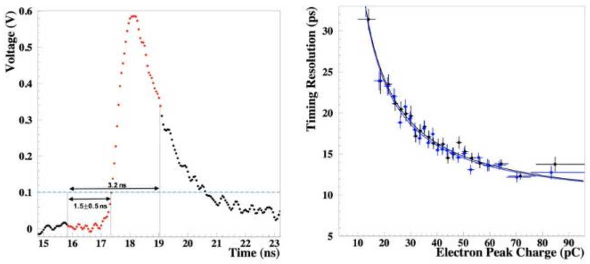





- 1st prototype tested
  - 200μm drift gap
  - CsI photocathode
  - Timing resolution ~25ps
- Reducing the drift gap
  - 180μm drift gap
  - CsI photocathode
  - Timing resolution ~17ps

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)* https://indico.cern.ch/event/1071632/sessions/408832/#20211116

"Global" behavior ➔ excellent homogeneity of the detector



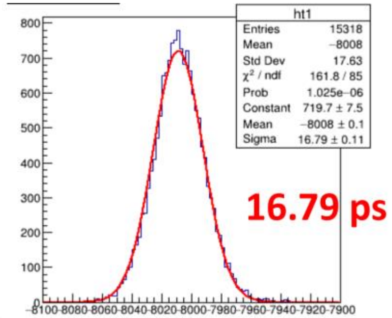
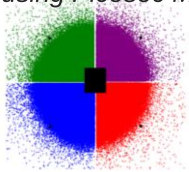



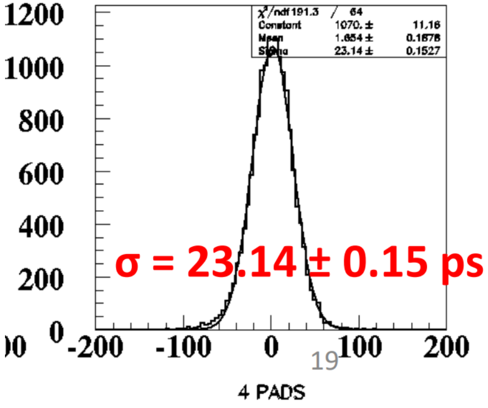

**Figure 3.** (Left) A typical PICOSEC digitised waveform. The red points denote the digitised information that is presented to the ANN. In this example, the ANN is fed with 64 inputs. (Right) The timing resolution using ANN (black) and full analysis of the electron peak waveforms (blue), as a function of the electron peak charge. A 18.3 ± 0.6 ps timing resolution is achieved in both cases.

**A.Kallitsopoulou**-*Master Thesis: Development of a Simulation Model and Precise Timing Techniques using Picosec Micromegas Detectors:* https://doi.org/10.48550/arXiv.2112.14113

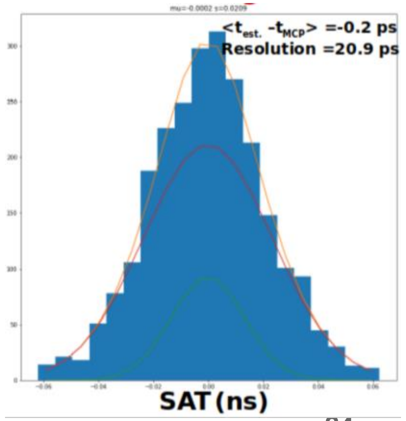


Recovering the resolution in the common corner, for signal-sharing events.

Analytical way of signal Processing




Using Artificial Intelligence-Training a Neural Network

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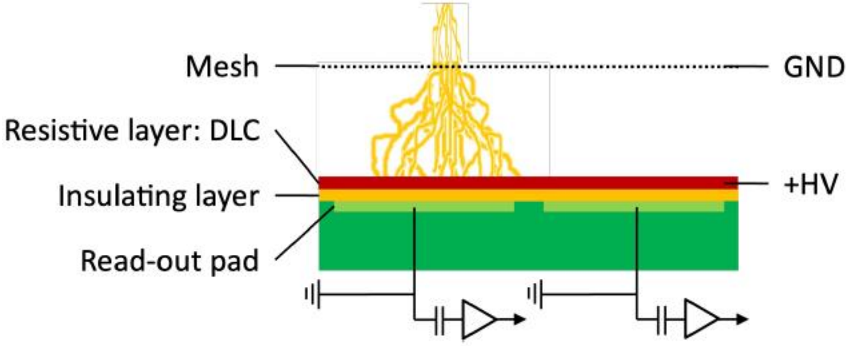
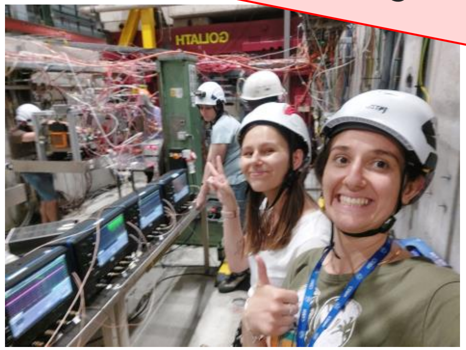
# Robustness & Efficiency ≡ Resistive prototypes

2023

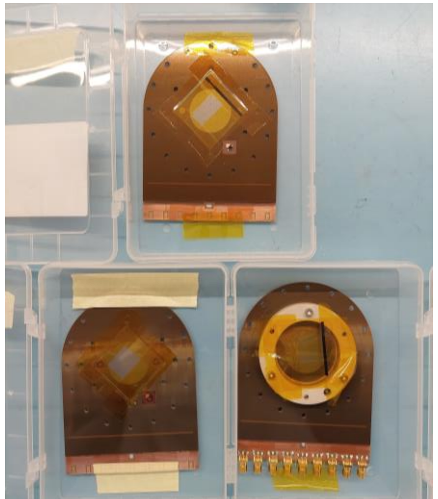
- Advantages of the resistive technology
  - Elimination of destructive effects of discharges
  - Stable operation in harmful environment (e.g. pions)
  - Possibility to improve position reconstruction

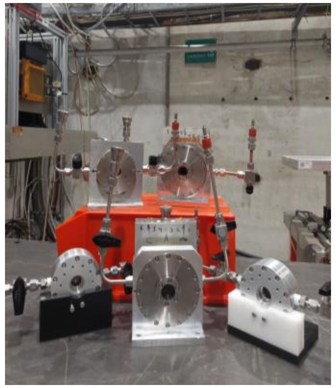


The goal is to profit from those advantages while maintaining a good timing resolution

- Focus on Timing properties
  - Testing different resistivity values & architectures
  - Ensure the homogeneity of prototype response over the full area
  - Effectively spatial resolution studies

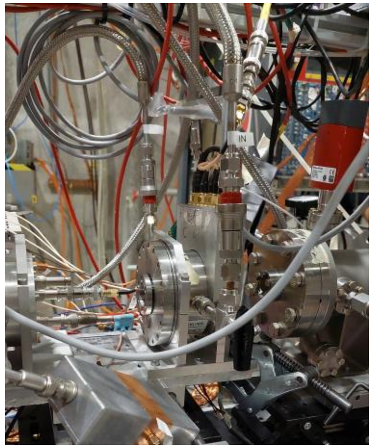

7-ch (∅ 2.6 cm)

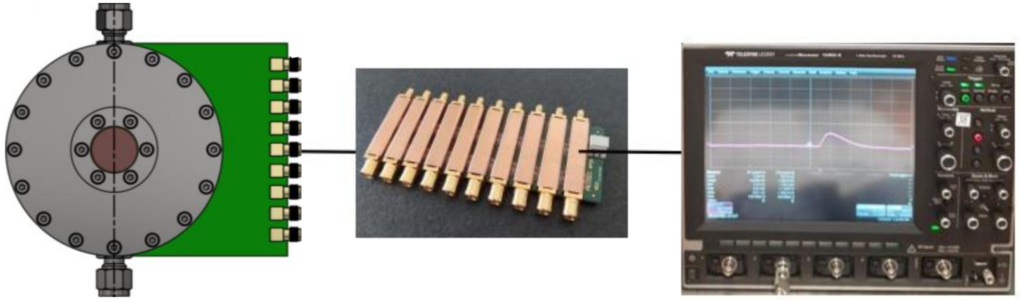


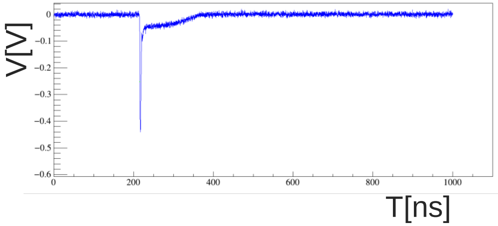
# Detectors Under Test - Comparison



- Multi-Pad Prototypes (7-pad)
  - Hexagonal pads ø 1cm
  - MgF2 crystal
  - CsI & B4C photocathodes

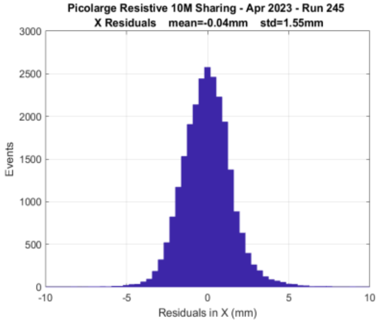




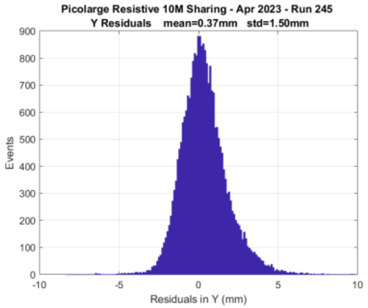



## 1st time spatial resolution measurements for the 10MO resistive detector

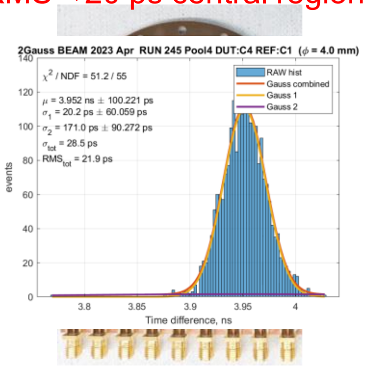
σx= 1.5 mm



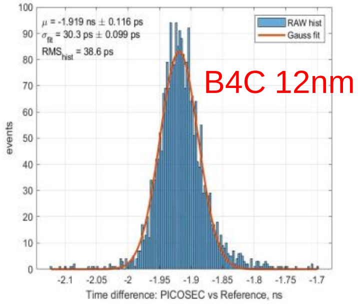

σy = 1.55 mm



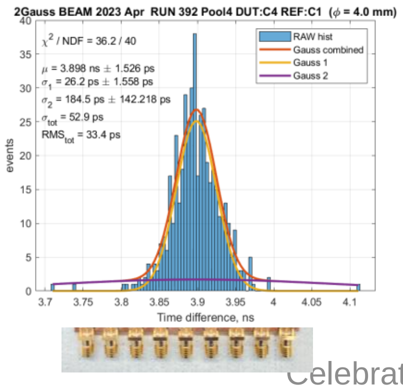

RMS→20 ps central region



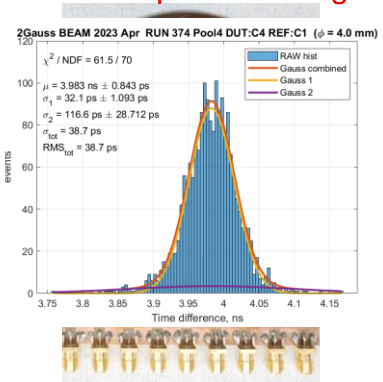

RMS→30 ps central region



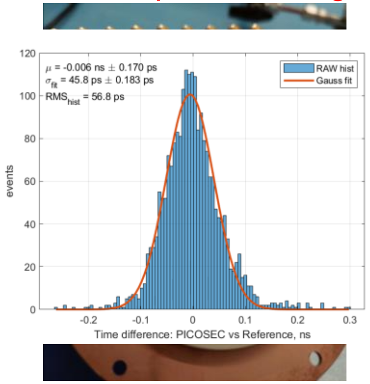

RMS → 27 ps central region



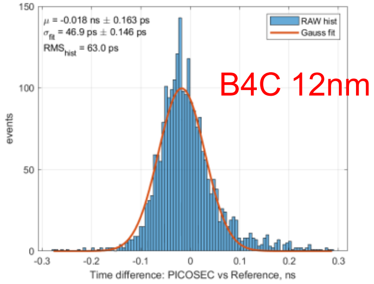

RMS → 33ps central region




RMS → 41ps central region




RMS → 42ps central region



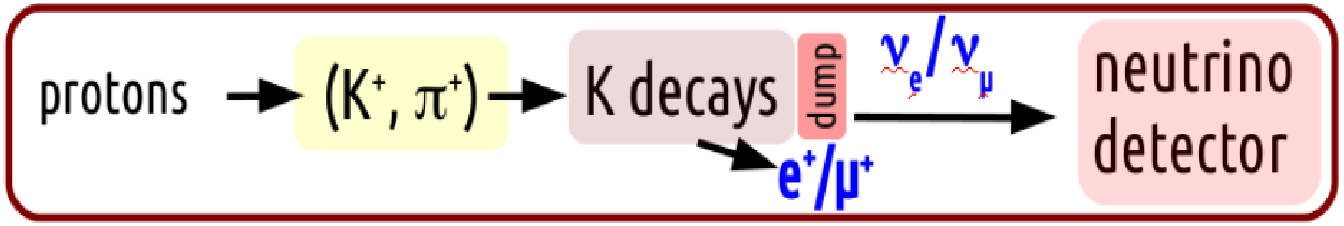
# Physics Studies for Possible Applications

# Event Triggering and Tagging Context

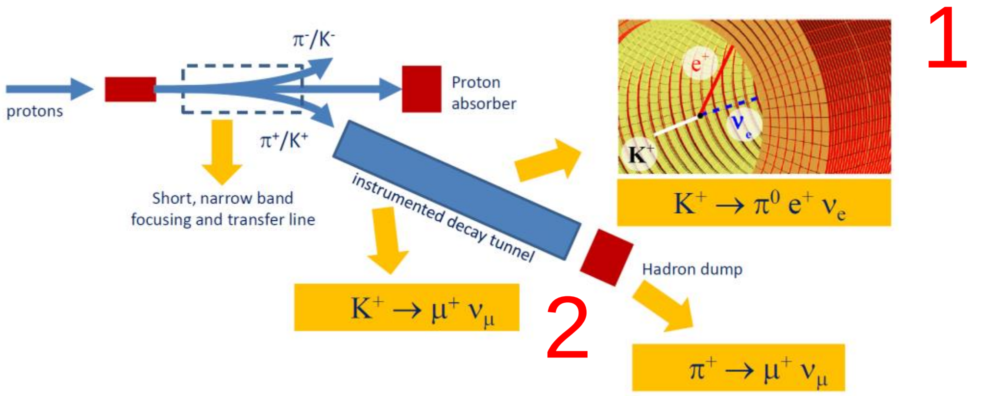
## Follow up on Cross-section measurements

### CERN NP06/ENUBET(**E**nhanced **N**e**U**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 positrons tagged in beamline and neutrinos tagged in the far detector



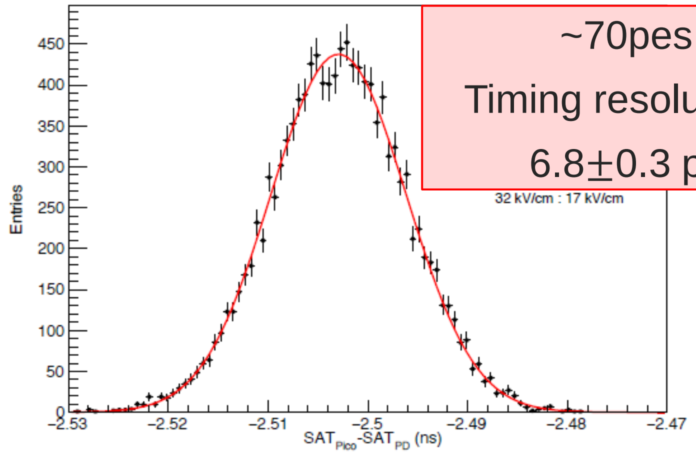

- Sub-ns sampling would offer this correlation
  - On an event-by-event basis
  - Determine the flavor of neutrino

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

# From Simulation to Reality

## Embed a PICOSEC-Micromegas layer inside an electromagnetic calorimeter after a few radiation lengths

## First Indications from laser test measurements @ IRAMIS /CEA

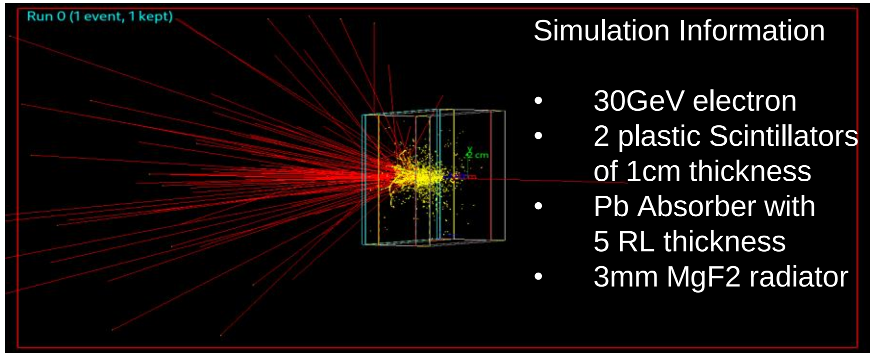


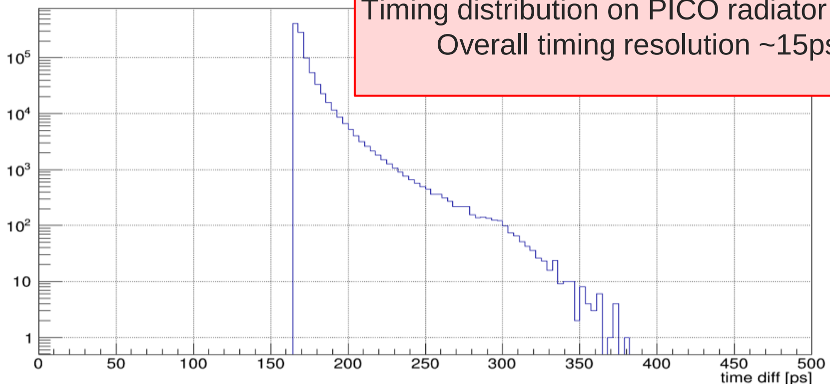

~70pes

Timing resolution :

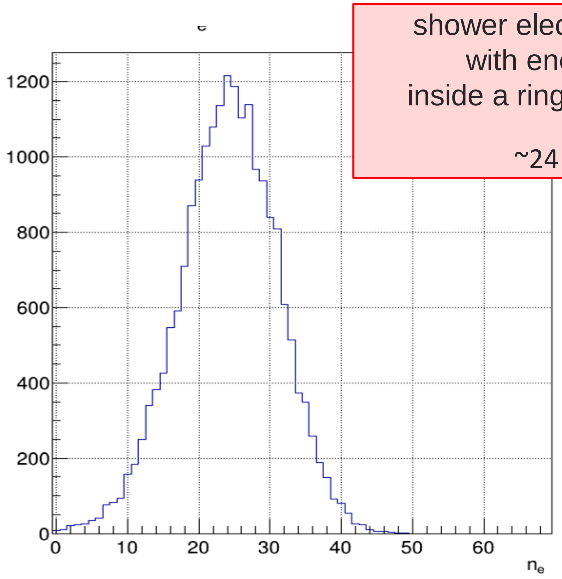
6.8±0.3 ps

## First Simulation Studies with Geant4




Timing distribution on PICO radiator ~12ps
Overall timing resolution ~15ps




shower electrons multiplicity
with energy > 5MeV
inside a ring of a 3mm radius

~24 electrons

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

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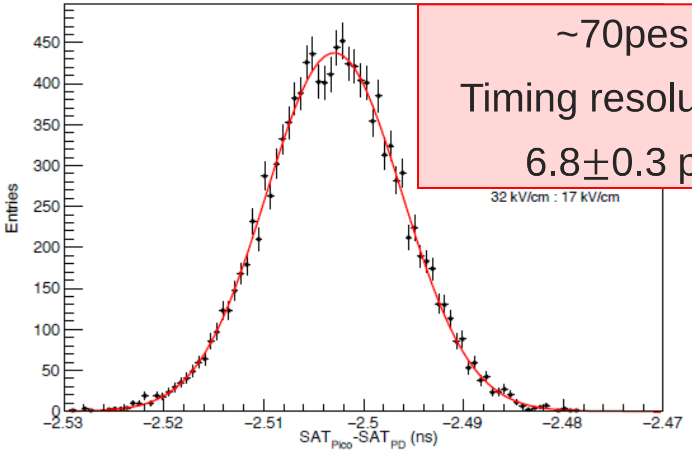
# From Simulation to Reality

**Embed a PICOSEC-Micromegas layer inside an electromagnetic calorimeter after a few radiation lengths**

**First Indications from laser test measurements @ IRAMIS /CEA**

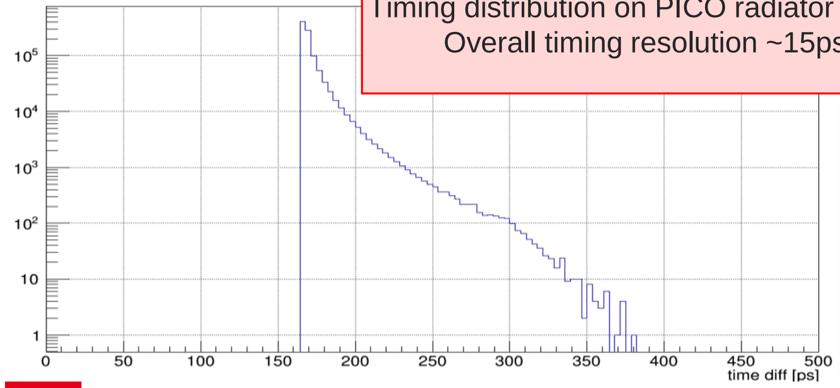



~70pes

Timing resolution :

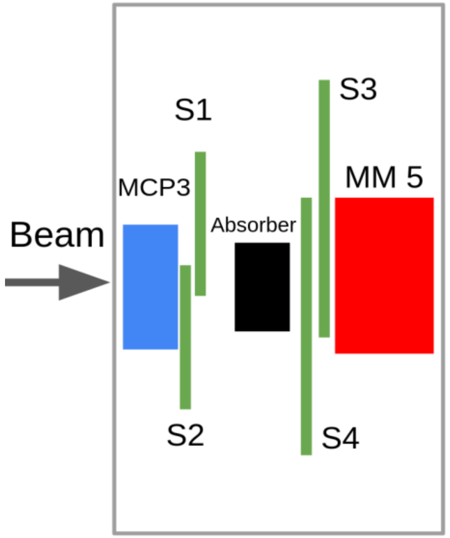
6.8±0.3 ps

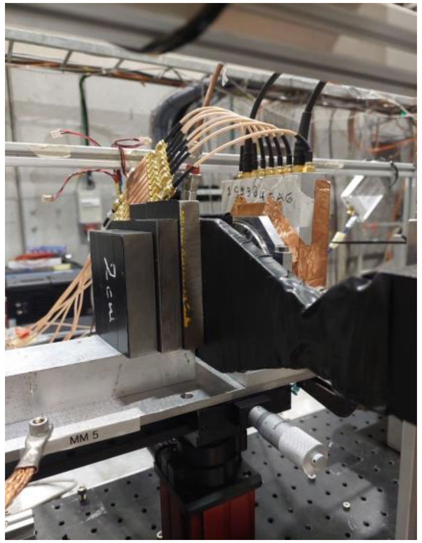
**First Simulation Studies with Geant4**



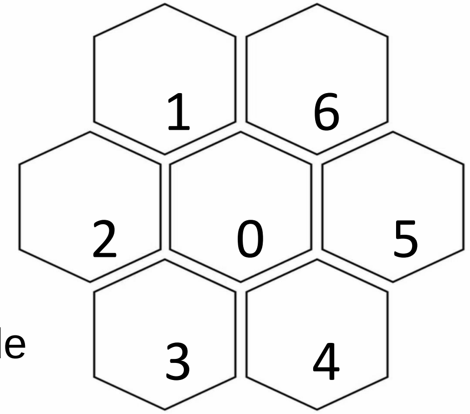

Timing distribution on PICO radiator ~12ps
Overall timing resolution ~15ps

- Particle Beams @ CERN SPS H4 Beamline
  - Electrons 10-50GeV



- Multi-Pad Prototype (7-pad)
  - Resistive prototype
  - Hexagonal pads ø 1cm
  - $MgF_2$ crystal
  - $B_4C$ (12min) photocathode

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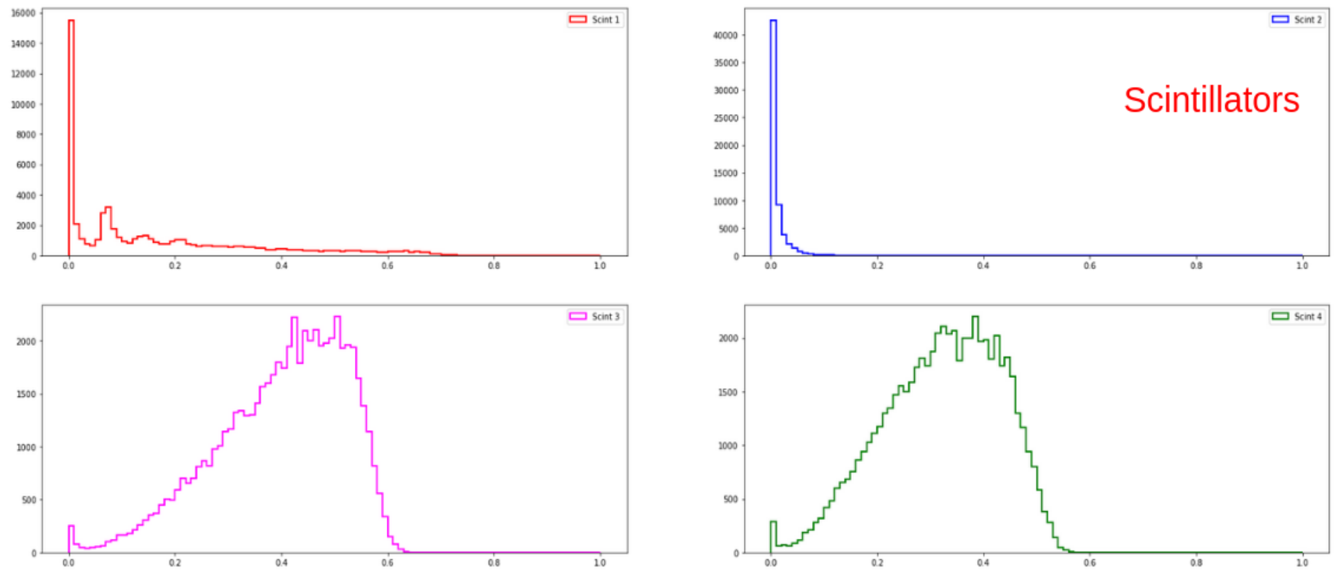
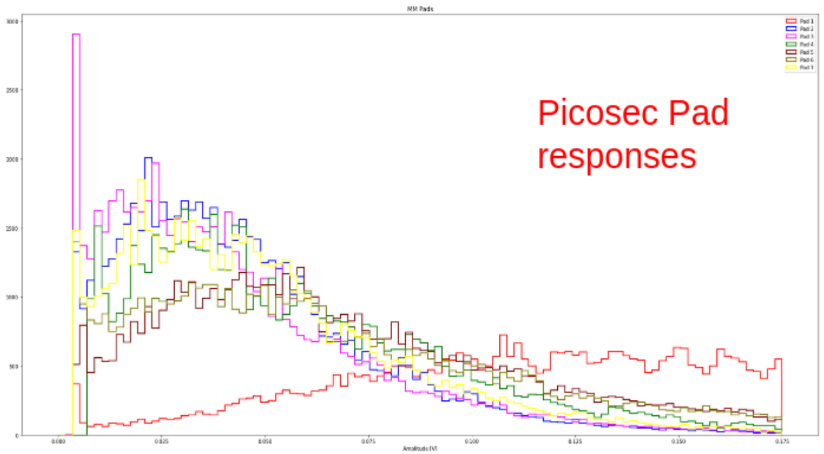
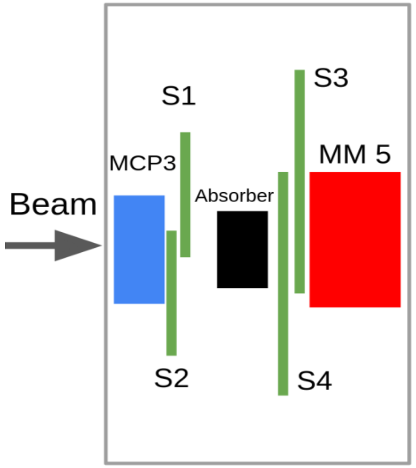
# Detector response to Electrons



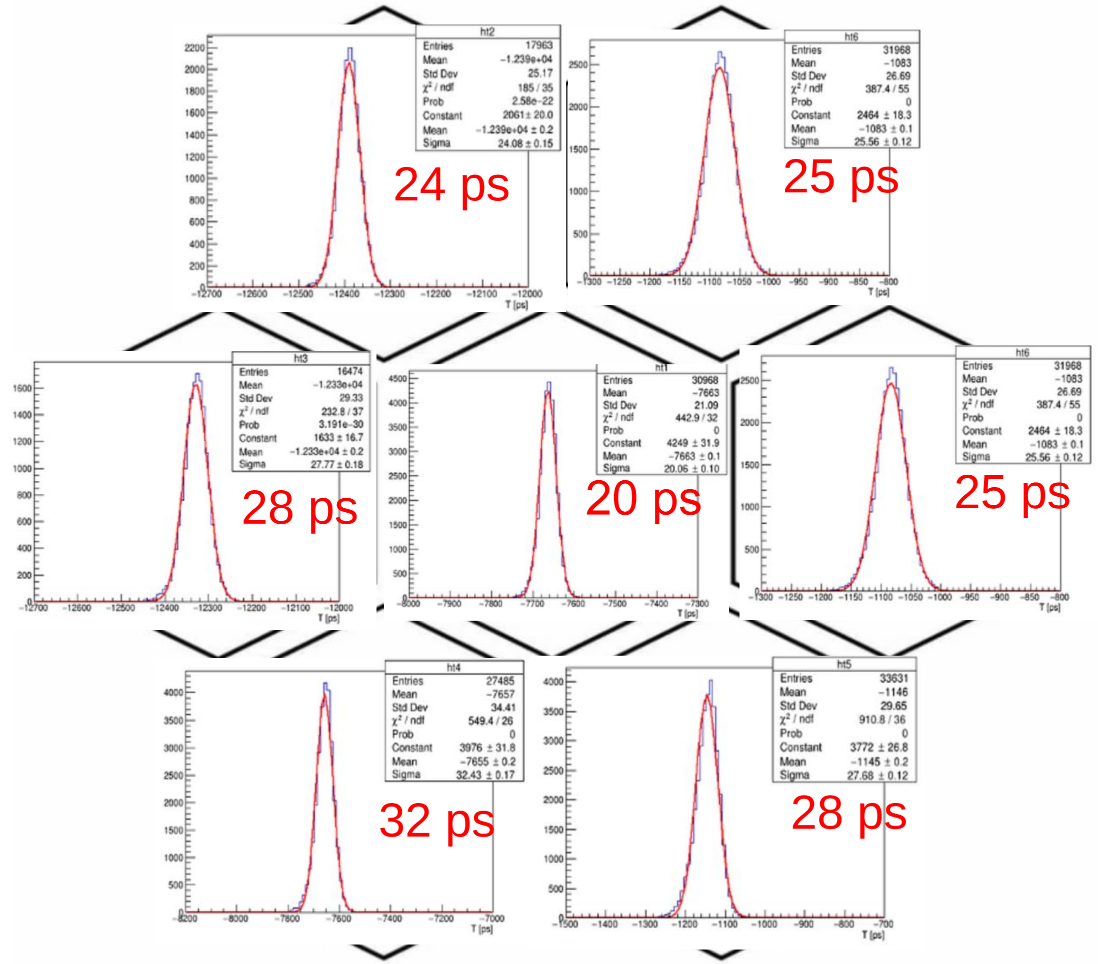
30GeV electrons with 5cm Fe absorber




## Overall timing response to showers below 30 ps



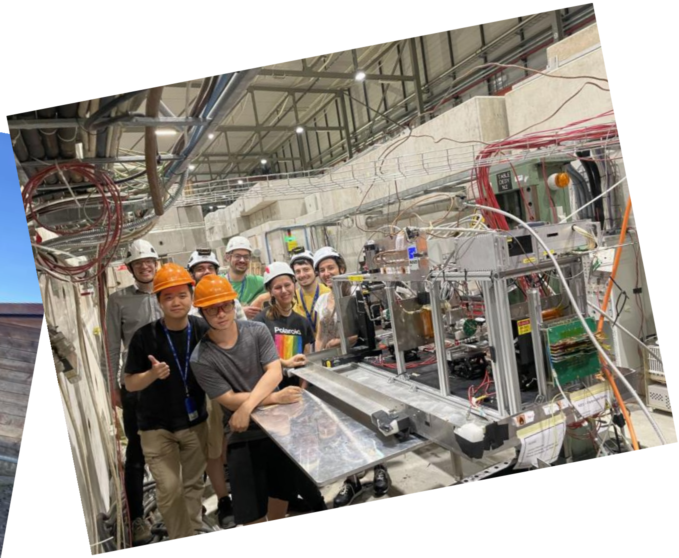
# Conclusions

- The importance of a brilliant idea….Special detector physicists needed more than the technology itself
  - Thanks to Yannis!

- Prof of concept ending up to be our research line

- An R&D needs more than 10 years to give possible applications based on team efforts to prove the scalability and robustness of the prototypes

“ In the end, it’s all a matter of timing…



# Ευχαριστούμε
# Grazie
# Thank you
# Merci

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*« Αυτός ο κόσμος ο μικρός ο μέγας» Οδυσσέας Ελύτης*
*«Aftos o kosmos o micros o megas» Odisseas Elytis*