PICOSEC
Micromegas

ARISTOTLE
UNIVERSITY
OF THESSALONIKI

Precise timing with the PICOSEC-Micromegas Detector

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on behalf of the

RD51 PICOSEC-Micromegas Collaboration

FATA2019

Fast Timing Applications for nuclear physics and medical imaging”
Acireale (Catania), 3-5 September 2019

Outline

- PICOSEC MicroMegas: a detector with precise timing:
  - Single-channel prototype in Laser and Particle beams
- A well-understood detector:
  - reproduce observed behavior with detailed simulations and a phenomenological model
- Towards a large-scale detector: multi-channel
  - response of multi-channel PICOSEC prototype
- Towards a practical detector: robustness
  - resistive anodes & robust photocathodes

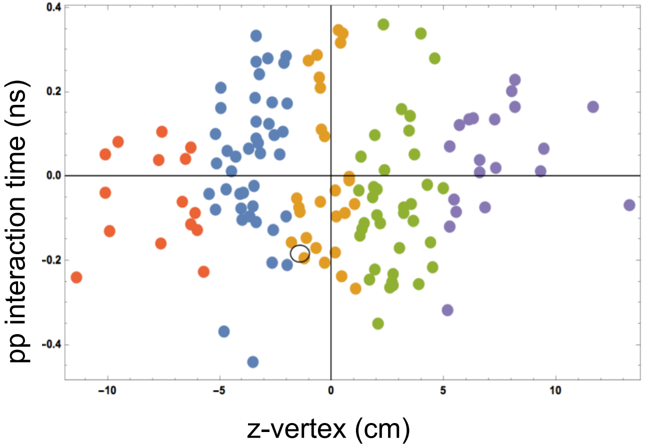
The need for precise timing in HEP

Precise timing needs → picosec domain

A Review: "PID techniques: Alternatives to RICH methods",
J. Va'vra, NIMA 876 (2017) 185-193, https://dx.doi.org/10.1016/j.nima.2017.02.075

In the High Luminosity LHC, ~140 "pile-up" proton-proton interactions ("vertices") in the same pp bunch-crossing
140 pp interactions / bunch-crossing (Gaussian σ~45mm) :
crowded along beam-axis

(3D) tracking of charged particles is not enough to associate them to the correct vertex.
Using the time-dimension → separates vertices:
needed precision ~ order 30ps



S. White: *https://arxiv.org/abs/0707.1500*

Precise Track reconstruction in the very demanding HL and very HE environments of future colliders (e.g. FCC), require 4D treatment.

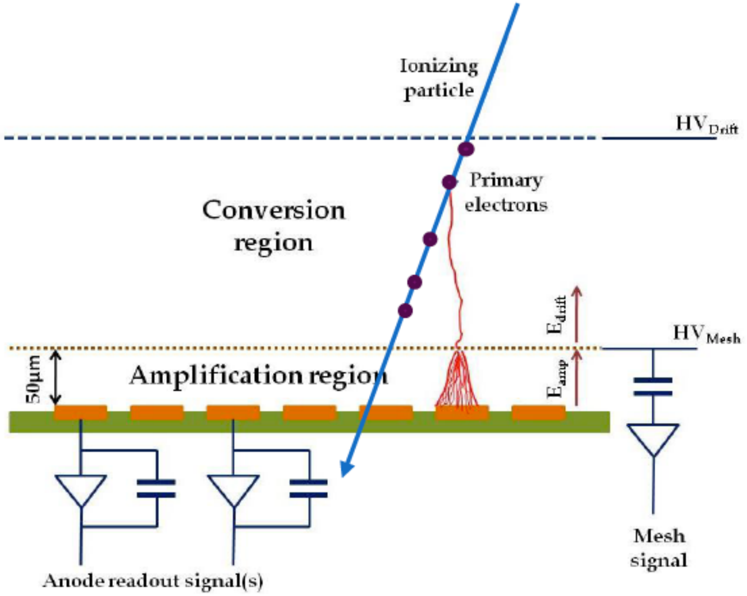
Precise time detectors embedded in EM calorimeters offer correlated arrival time in energy information which can benefit astroparticle observations (e.g. GRB burst, EM counterparts of Gravitational waves)

The Micromegas detector

Giomataris Y. et al., NIMA 376 (1996) 29

Conversion region
Particle creates electrons, which drift to the readout plane.

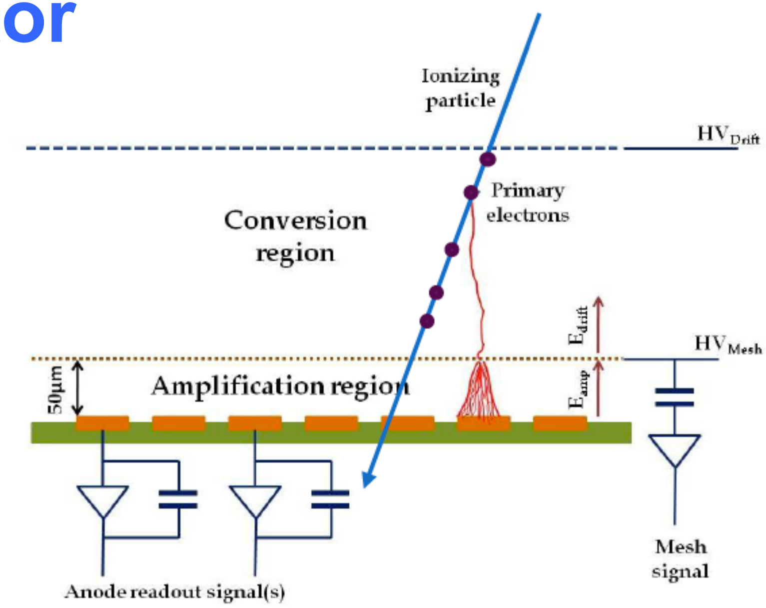
Amplification region
Electrons are amplified & the charge movement induces signals.



Interesting features for many applications
Simplicity, Granularity, Homogeneity, Scalability, High rate capabilities, Radiation hardness, Low cost

The Micromegas detector

Giomataris Y. et al., NIMA 376 (1996) 29



Conversion region
Particle creates electrons, which drift to the readout plane.

Amplification region
Electrons are amplified & the charge movement induces signals.

Timing limitation factors:
Large conversion region: charges created in different positions.
Diffusion effects: for 3 mm drift distance → ~6 ns time jitter!

Timing performance can be improved by:
- simultaneous creation of primary electrons at the same distance from the mesh
- shorten the drift length → suppress direct gas ionization

The PICOSEC-Micromegas concept

- A particle produces Cerenkov light.
- Photons extract electrons from the photocathode.
- The electrons are amplified by a two stage Micromegas detector.

Two signal components:

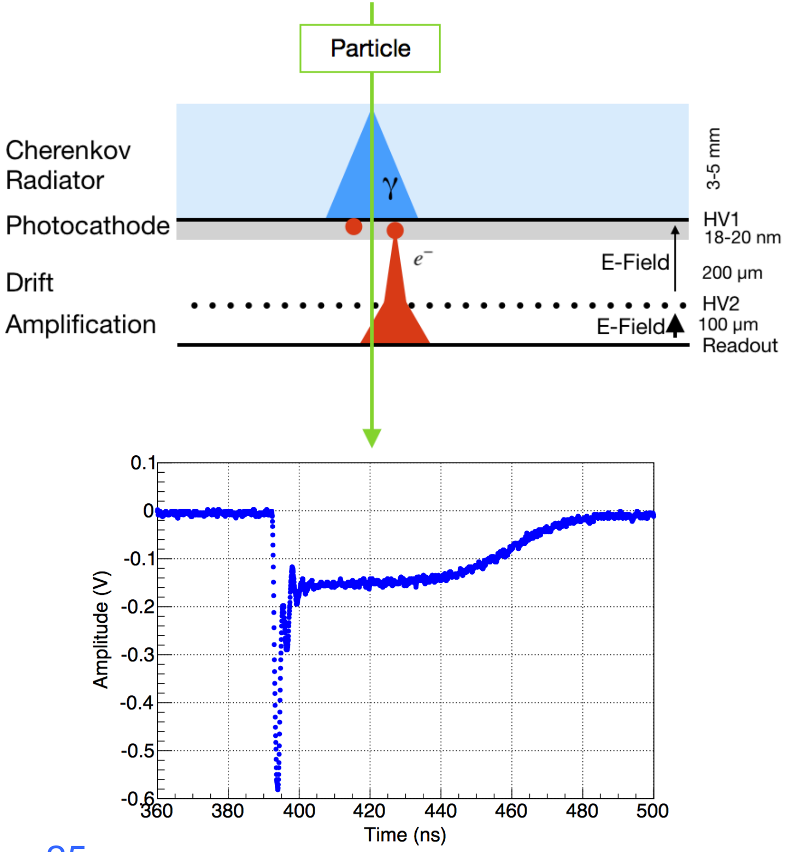
- Fast: ***electron peak*** (~1 ns). → Timing features.
- Slow: ***ion tail*** (~100 ns).

Small drift gap (200 μm):

- Pre-amplification possible
- Limited direct ionization
- Reduced diffusion

Cerenkov radiator/Photocathode:

- Photoelectrons emitted simultaneously by the photocathode (fixed distance from the mesh)



Aiming at

- single photoelectron time jitter ~100 ps
- produce sufficient photoelectrons to reach timing response ~25 ps.

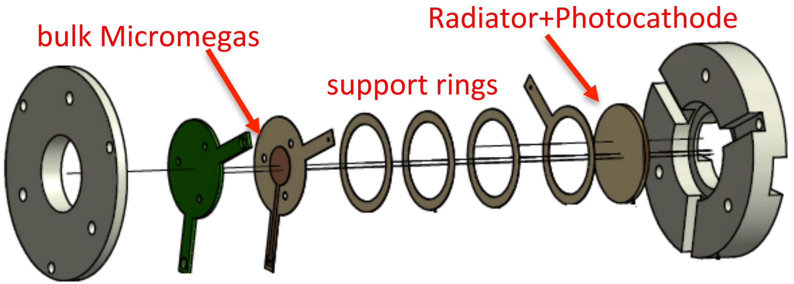
First attempt: The single channel “PICOSEC” prototype

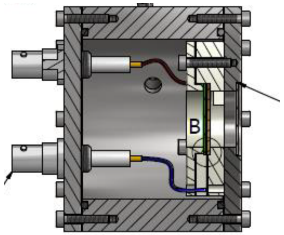
Single pad prototypes (<u>1 cm diameter active area</u>)

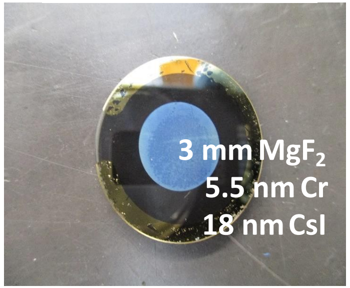
- Bulk MicroMegas readout (6 pilars)
- 4 kapton rings spacers → 200 μm Drift gap
- Radiator + photocathode
- Mesh thickness = 36 μm (centered at 128 μm above anode)
- Amplification gap = 128 μm

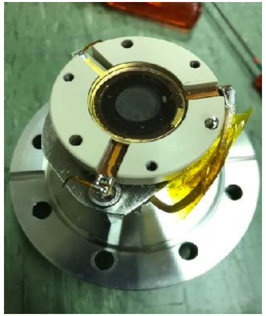
- Cherenkov Radiator:
  MgF_2 3mm thick → <u>3mm Cherenkov cone</u>
- Photocathode: 18nm CsI on 5.5 nm Cr
  (many other photo cathode materials have been tested)

- **COMPASS gas (80% Ne + 10% CF_4 + 10% C_2H_6)**
  Pressure: 1 bar.



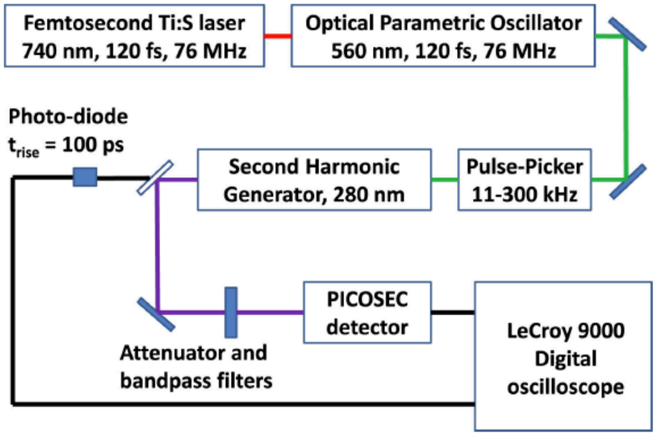






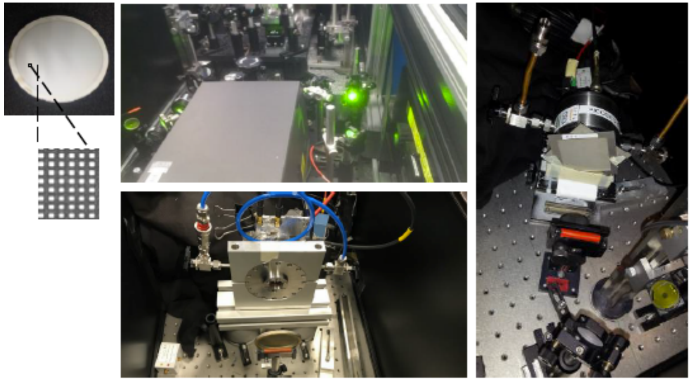
Laser beam tests: response to single photoelectron (1)

Unique capabilities of **FLUME** setup at the IRAMIS/LIDYL laser facilities @ CEA Saclay: *Study the **single photoelectron timing** performance and **optimize** the detector*

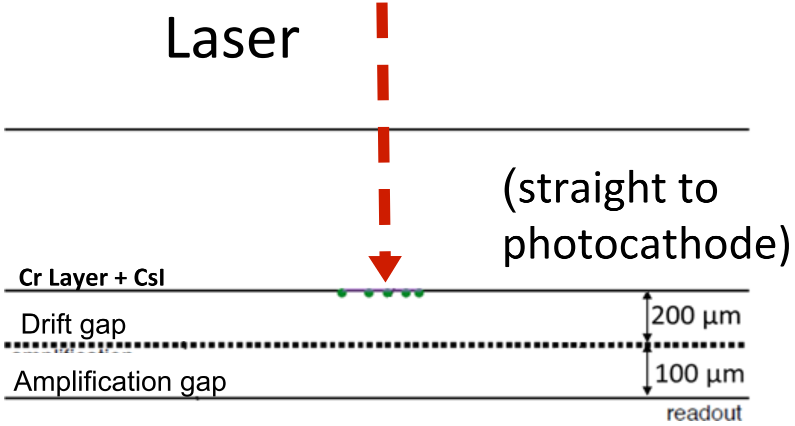


FLUME setup:

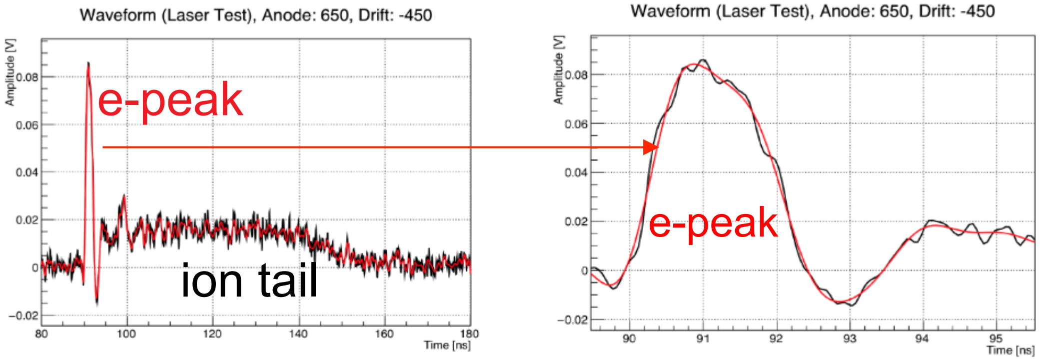
- IR Ti:S laser with pulse width 120 fs
- λ = 267-285 nm after doubling
- Energy ~ 10 -100 pJoule/ pulse
- Spot size: ~1 mm^2
- Repetition 9 kHz – 4.75 MHz
- Light attenuators (fine micro-meshes 10-20% transparent)
- t_0 reference: fast PD (σ_T~10 ps)
- Cividec 2 GHz, 40 db preamplifier
- DAQ: 2.5 GHz LeCroy scope.
- Gas mixture: Ne+ 10% CF4+20% C2H6.



Laser beam tests: response to single photoelectron (2)



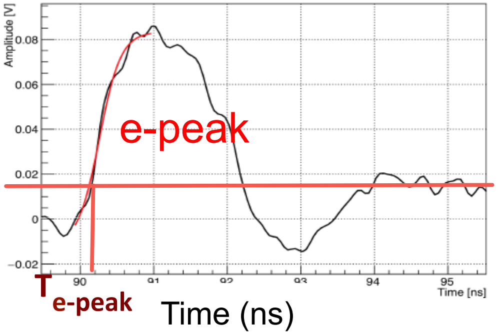
Signal inverted



Signal from Laser runs (right is zoom in e-peak)

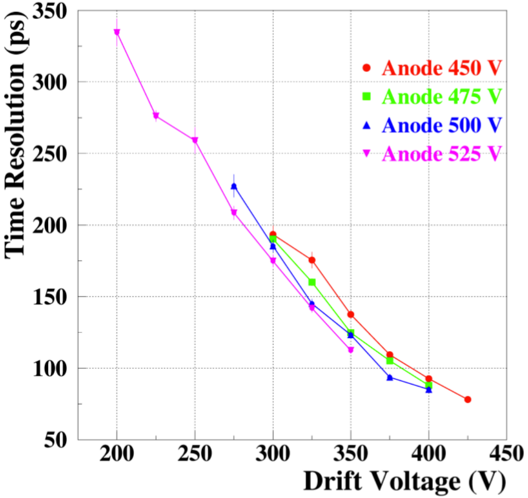
Laser beam: understanding the timing properties (1)

$T_{e\text{-}peak}$ = Signal Arrival Time (SAT) wrt the t_0 ref.
* SAT of a sample of events = $<T_{e\text{-}peak}>$
* Time Resolution = RMS[$T_{e\text{-}peak}$]



→ **Time the signal arrival with Constant Fraction Discrimination (CFD)** on the fitted noise-subtracted e-peak (CFD @ 20% of the e-peak amplitude)

t_0 reference: fast photodiode (~10 ps resolution)
Detector response at different field settings
Timing resolution 76.0 ± 0.4 ps achieved @ Vd/Va: -425V / +450 V improves strongly with higher drift field, less with anode field



Laser beam: understanding the timing properties (2)

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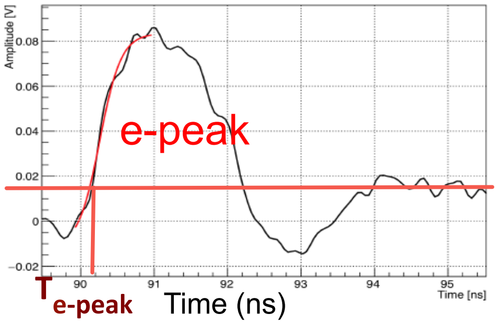


The Signal Arrival Time (SAT) depends on the e-peak charge:
- bigger pulses → smaller SAT
- higher drift field → smaller SAT

- Shape of pulse is identical in all cases → timing with CFD method does not introduce dependence on pulse size

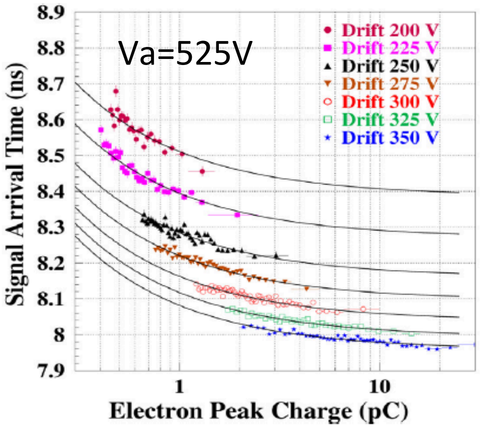
* Responsible for this "slewing" of the SAT: physics of the detector

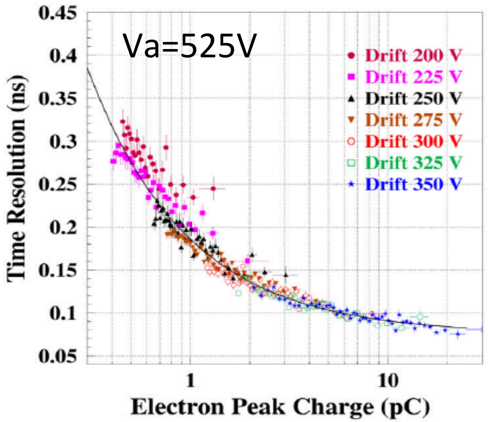
t_0 reference: fast photodiode (~10 ps resolution)

Detector response at different field settings

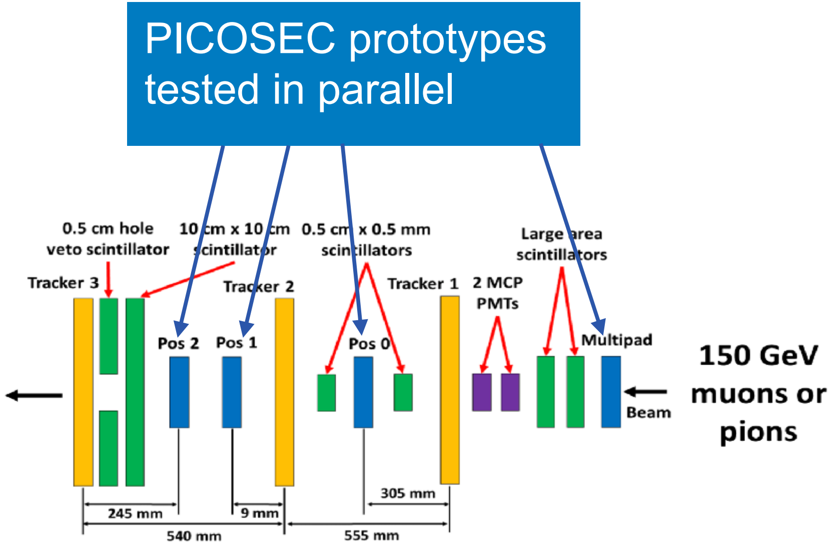
Timing resolution 76.0 ± 0.4 ps achieved @ drift/anode: -425V / +450 V improves strongly with higher drift field, less with anode field

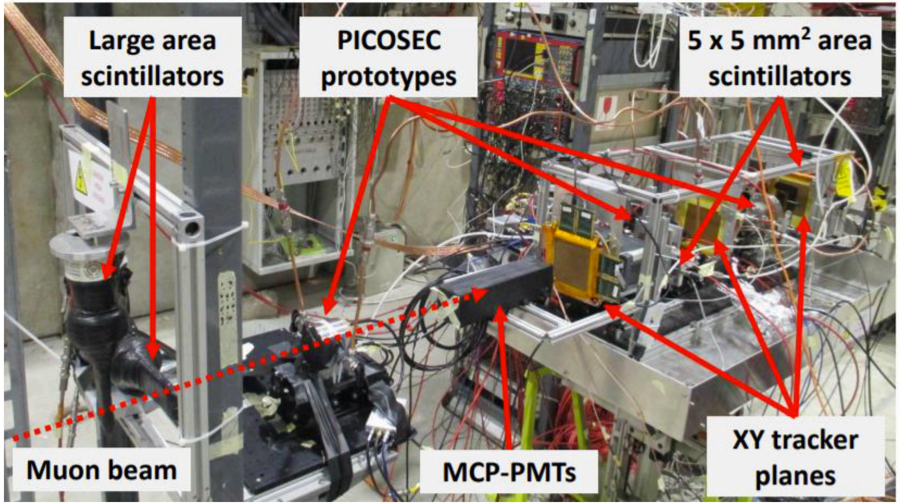
Time Resolution depends mostly on e-peak charge:





Testing with Particle Beams @ CERN SPS H4

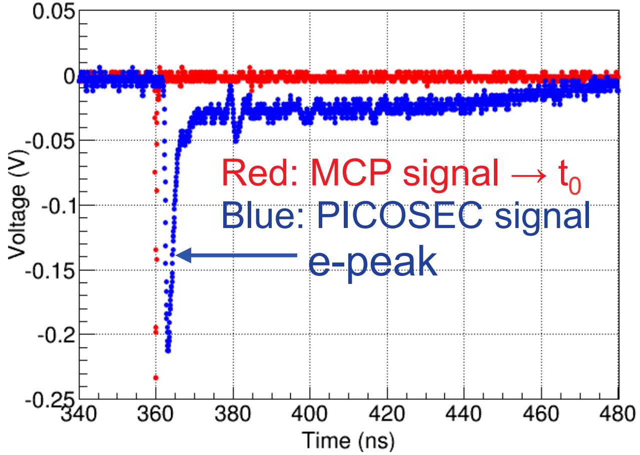


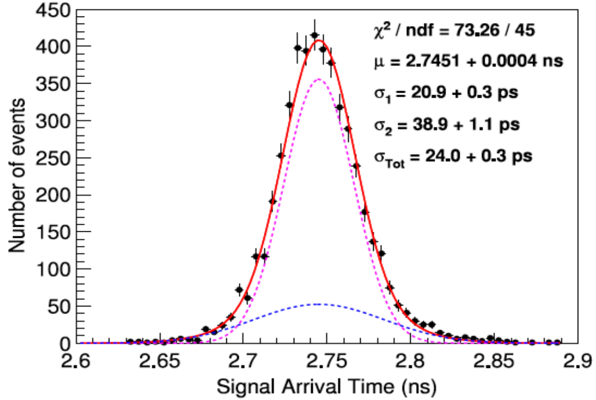


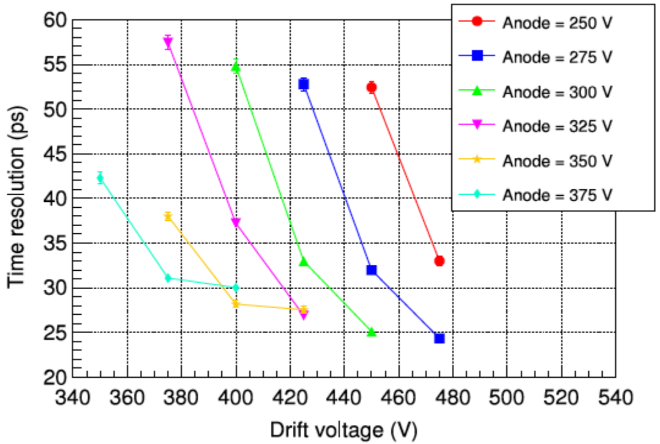
Last run Oct. 2018

- **Time reference:** two MCP-PMTs (<u><5 ps</u> resolution).
- **Scintillators:** used to select tracks & to avoid showers.
- **Tracking system:** 3 triple-GEMs (<u>40 µm</u> precision).
- **Electronics:** CIVIDEC preamp. + 2.5 GHz LeCroy scopes.

Time resolution for MIPs



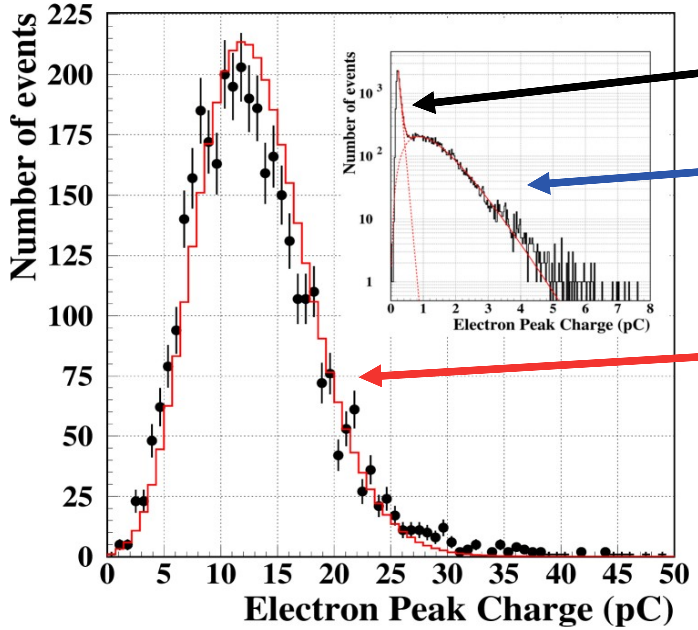




- Same detector as for Laser tests (MgF$_2$ radiator, CsI photocathode, Bulk MicroMegas, COMPASS gas)
- **Best time resolution: 24ps 24.0±0.3 ps**
- **@ Drift/Anode: -475V/+275V**

"PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector",
J. Bortfeldt et. al. (RD51-PICOSEC collaboration), NIM A 903 (2018) 317-325

Number of photoelectrons per MIP



Noise component

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

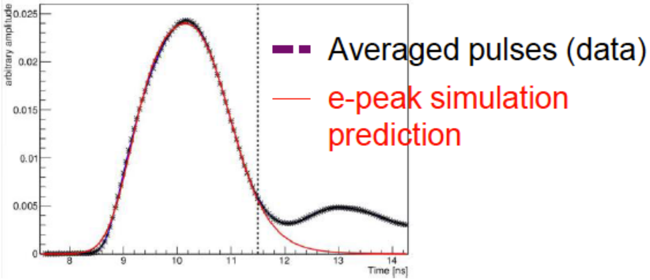
Signal of MIPs: the Red histogram represents the convolution of Poison and single p.e response (Polya)

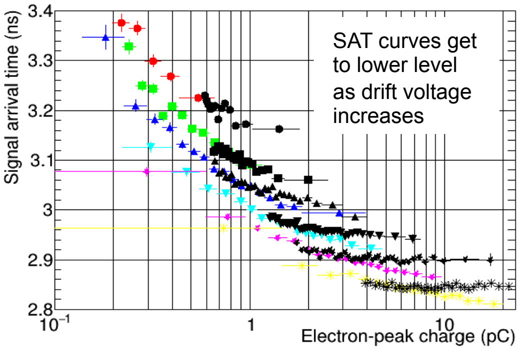
Estimated Mean number of photoelectrons per muon produced in the CsI photocathode = **10.4 ± 0.4**

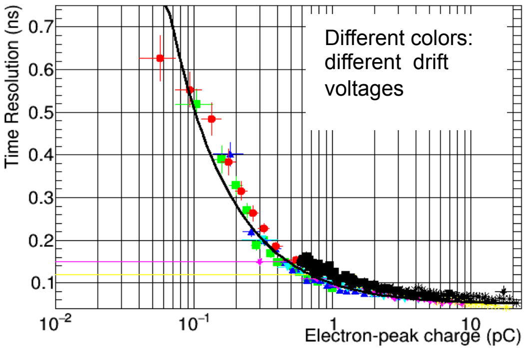
“PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector”,
J. Bortfeldt et. al. (RD51-PICOSEC collaboration), NIM A 903 (2018) 317-325

Detailed Simulations

Garfield++ and electronics response

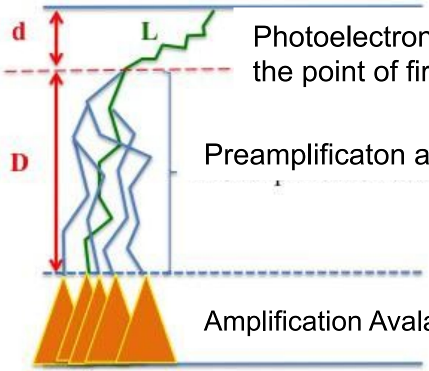






All behaviors seen in single p.e. laser data are also seen in these detailed Garfield++ simulations

Studding the dynamics of the signal information



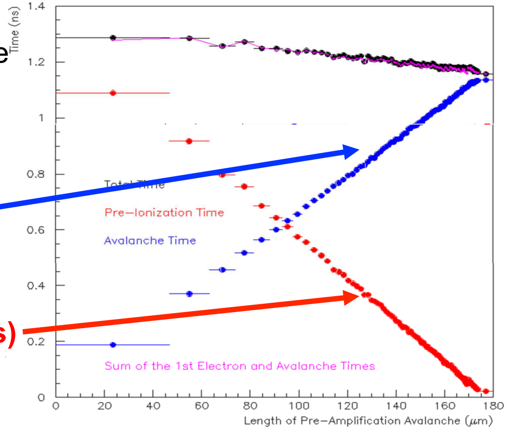
Photoelectron drift up to the point of first ionisation

Preamplificaton avalanche evolution

Amplification Avalanches

According to GARFIELD++ simulation the photoelectron drifts slower that the preamplification avalanche

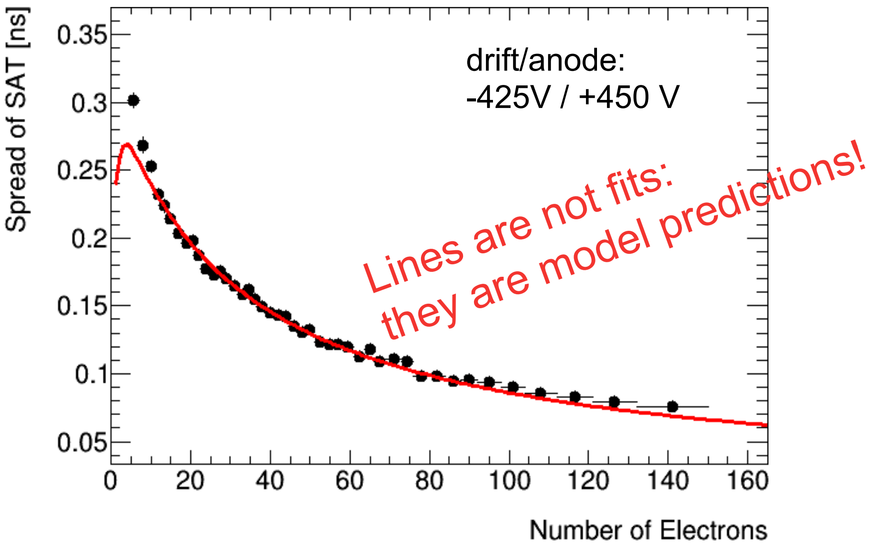
The avalanche transmition speed **(185μm/s)** is higher than the drift velocity of its constitute electrons (170μm/s) , which in tern is higher than the drift velocity of the primary electrons **(151μm/s)**

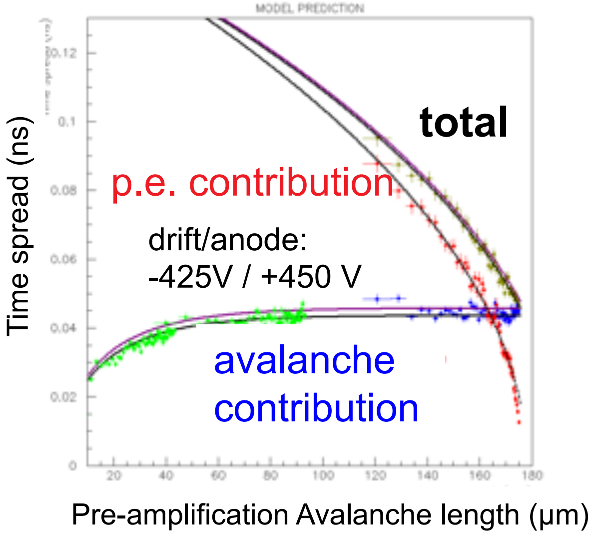


Quantitative description of the PICOSEC timing characteristic by phenomenological model

arXiv:1901.10779v1 [physics.ins-det]

- Known in literature that quenchers in the gas-mix increase drift velocity →
- **Model**: assume a time-gain per inelastic interaction compared to an elastic interaction





The model describes SAT and Resolution
a) vs. avalanche length &
b) vs. number of electrons in avalanche (i.e, vs. e-peak charge)
→ Before and after the mesh

Not only averages and RMS, but full distributions,
vs. values of operational parameters (e.g., drift voltage)

Towards a realistic, large size PICOSEC detector

- *Proof-of-principle* that Micromegas can reach **~25 ps time resolution**

However, in order to prove that a viable detector can be built for particle physics experiments we also need to achieve:

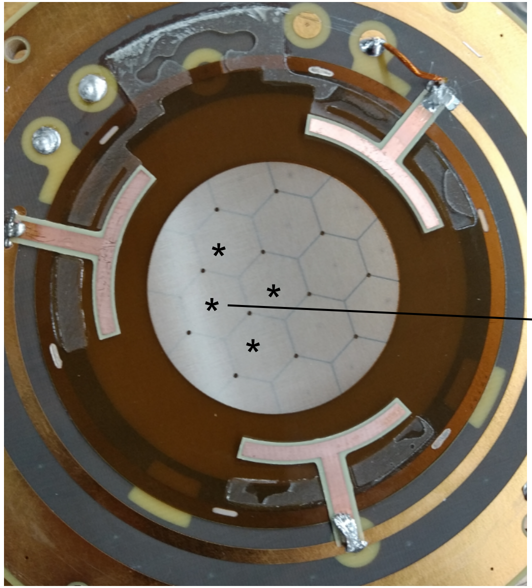
- Multichannel readout
  - Cerenkov p.e. sharing among pixels
  - Multi-channel electronics
- Spark quenching in the amplification gap
  - Resistive Micromegas

- *Most critical: an efficient & robust photocathode against sparks & ion backflow*
- Protection or robust photocathode
- Graphite – DLC – polycrystalline diamond
- Detector optimization
- Secondary Emitter

Multi-pad: individual pad response vs. R

- Like the MgF_2/CsI/bulkMM/COMPAS gas single-pad PICOSEC which achieved 24ps per MIP

Study response vs. R : distance of track impact from pad center

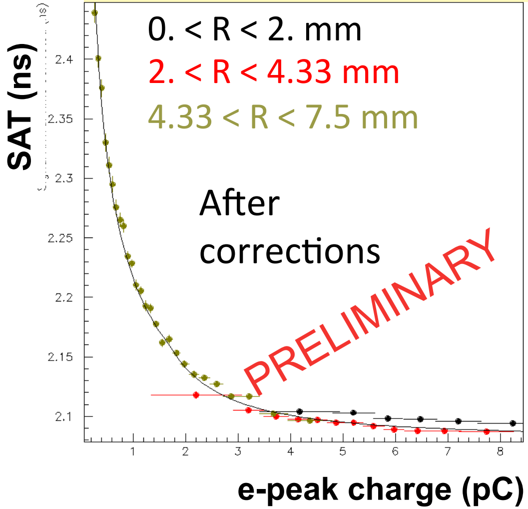


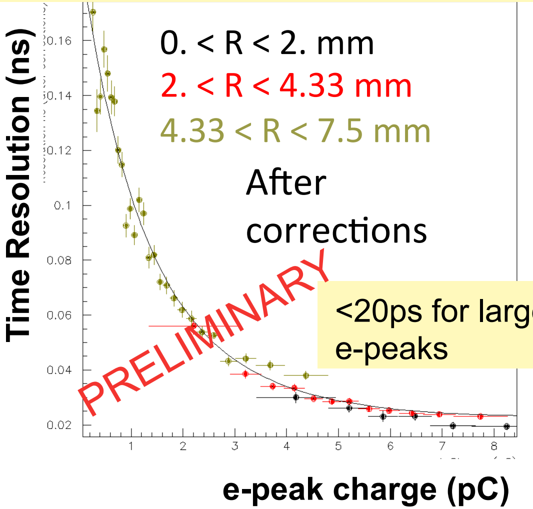
Hexagonal pads 5mm side

0<R<2mm: full Cherenkov cone (3mm) inside pad

4.33 < R < 7.5mm: Cherenkov cone (3mm) mostly outside pad

e-peak charge should have all info about where is Cherenkov cone compared to pad. Indeed, universal curves vs. e-peak charge:





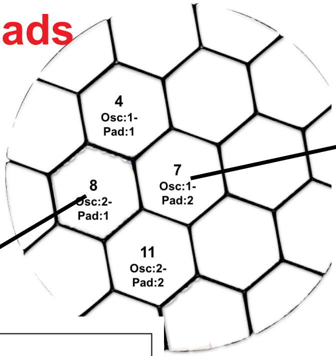
<20ps for large e-peaks

Multi-pad: Same resolution as single-pad

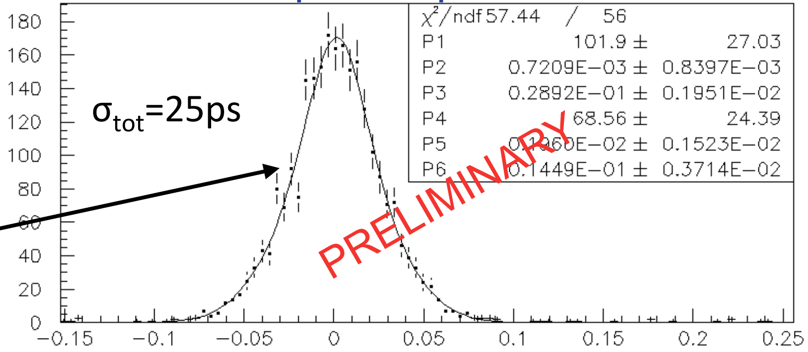
At center of each pad (0<R<2mm):

a time resolution of 25ps for all pads

E.g.:

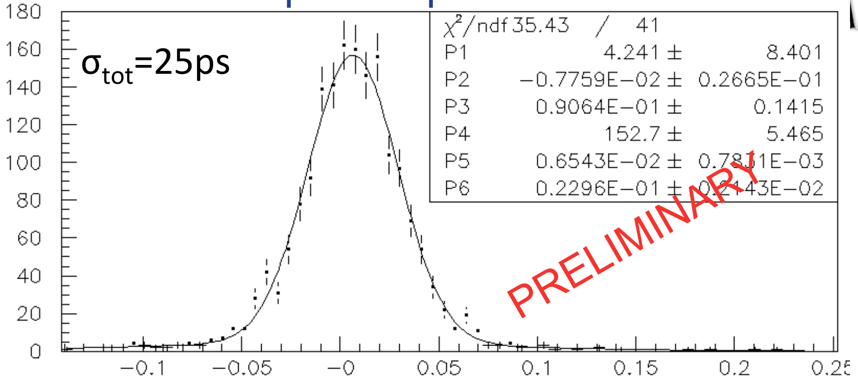


Individual pad response



ΔT = Time after all corrections (ns)

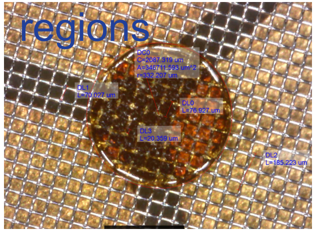
Individual pad response



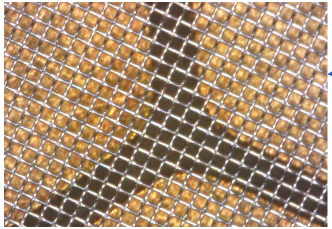
ΔT = Time after all corrections (ns)

Multi-pad: pad responses for any impact point

These are not the easiest regions



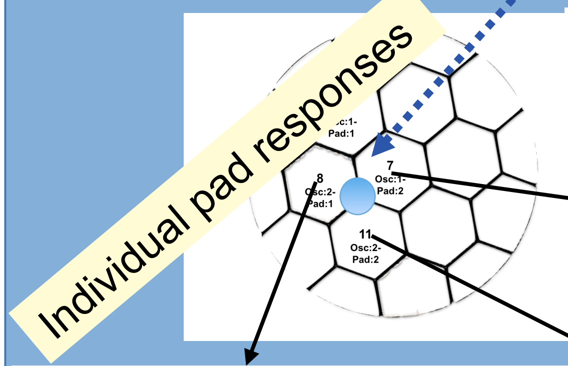
Pilars of ~650μm diameter

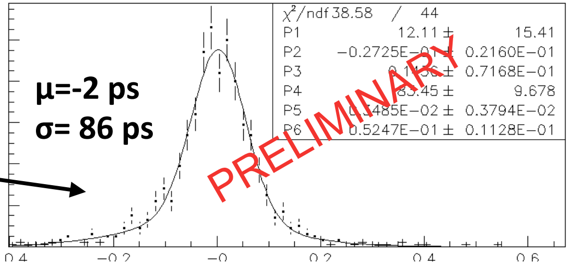


200μm inter-pad space

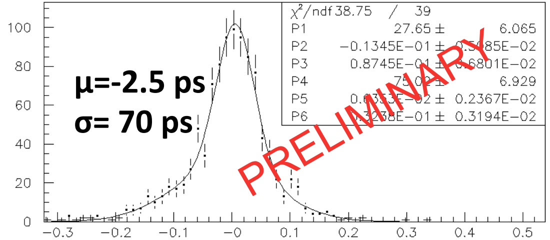
For tracks falling around a "three-pads" region:

Each individual pad: resolution worsens moving outwards





ΔT = Time after all corrections (ns)



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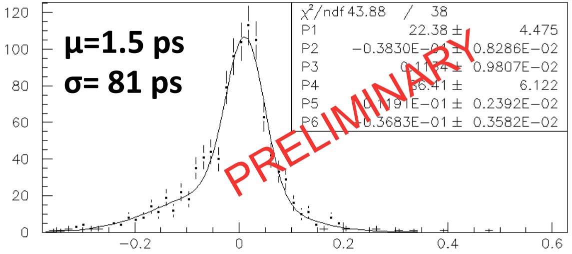
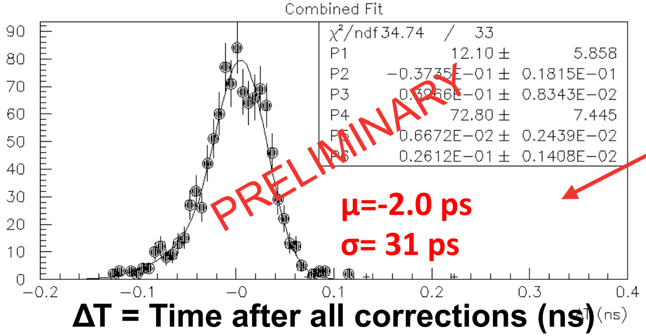


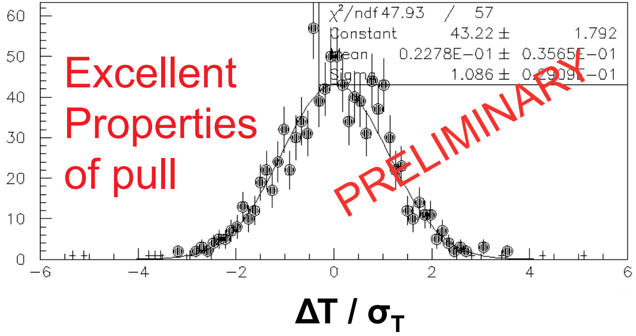
ΔT = Time after all corrections (ns)

Multi-pad: Combining pads

For tracks falling around a “three-pads” region:

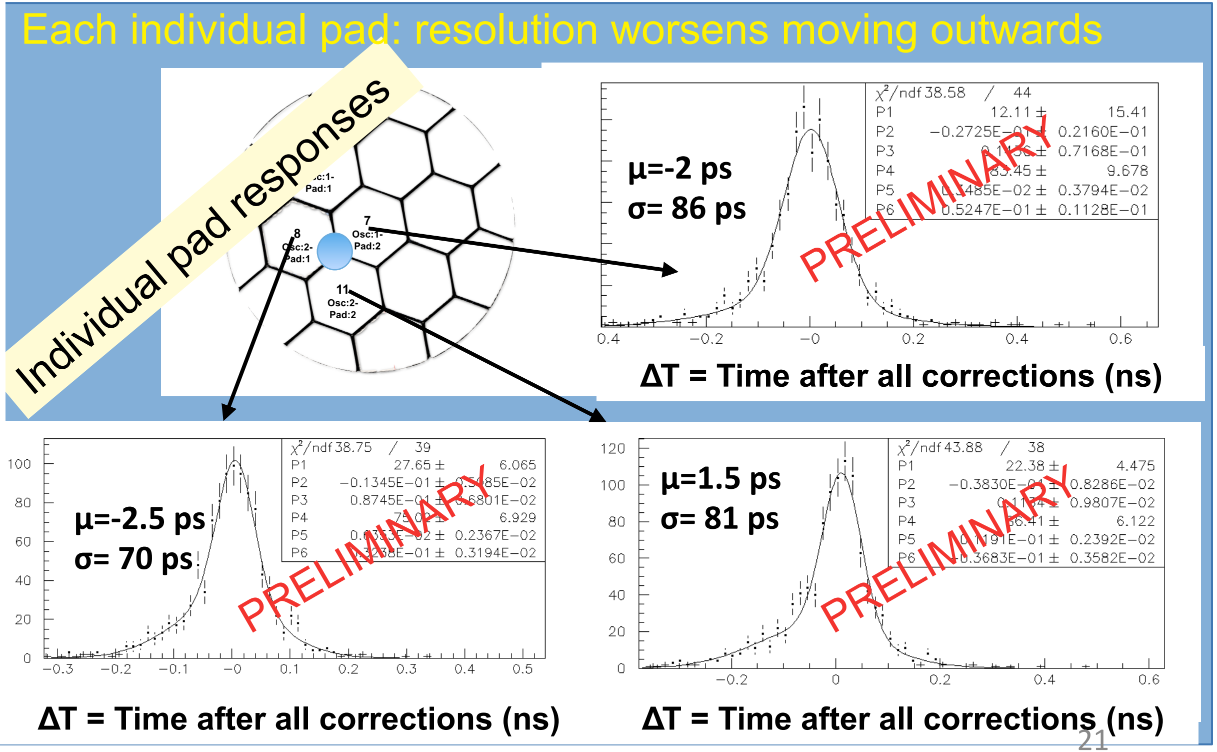
Combining pads event-by-event → Excellent time resolution



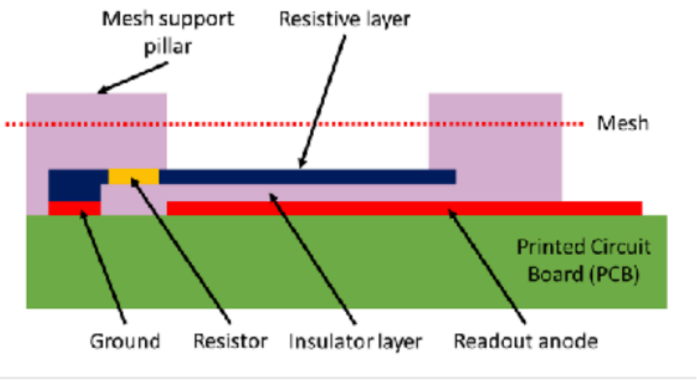


Excellent Properties of pull

Similar results all across the area covered by the 4 pads

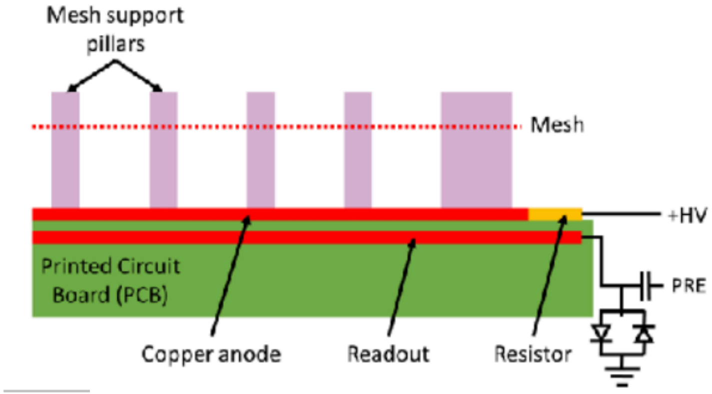


Best resolution was at voltages which give high currents on anode: robust anode



Readout beneath resistive layer: picks up signal from above

Resistive strip grounded



Copper Layer to HV via resistor; Readout "floating"

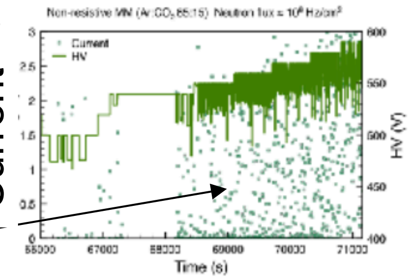
Developed in the MAMA project

Resistive readouts operate stably at high gain in neutron fluxes of 10^6 Hz/cm^2.

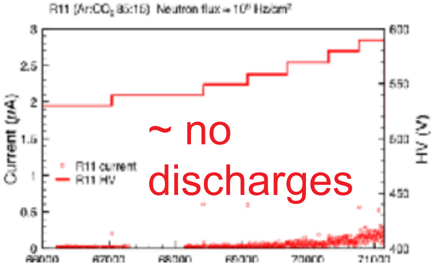
T. Alexopoulos *et al.*, *NIMA* **640** (2011) 110-118.

Non resistive ← MAMA results → With resistive strip

Current →



discharges



~ no discharges

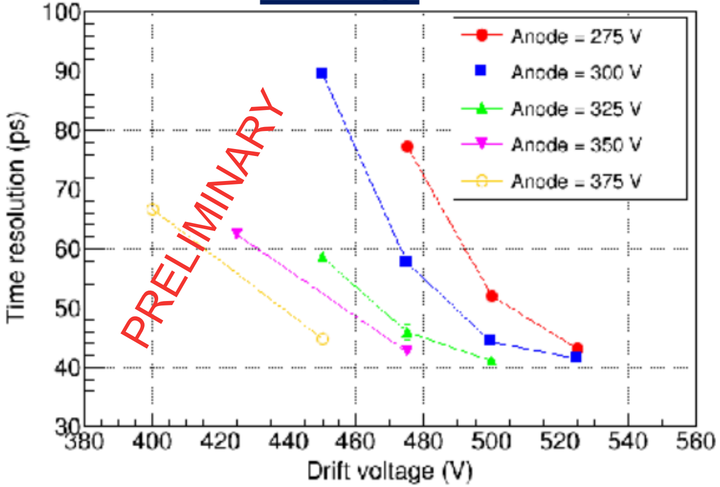
Irradiation time →

Beam results with protected anodes

Time resolution

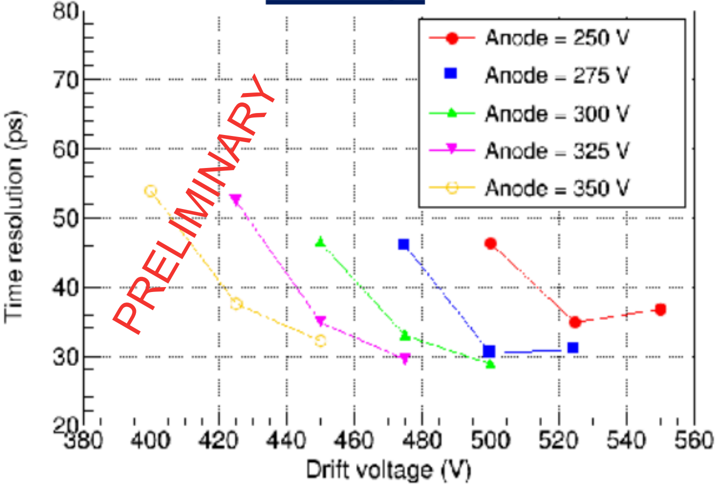
Resistive strips

σ = 41 ps



Floating strips

σ = 28 ps



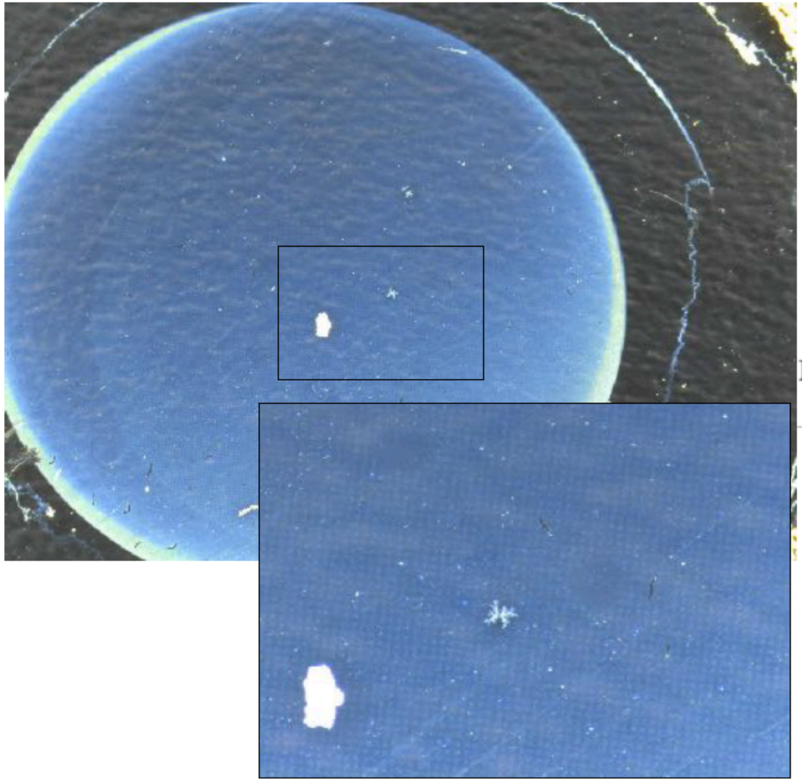
PRELIMINARY

- Values not far from the Picosec bulk readout.
  - **Resistive strips:** **41 ps** (10 MΩ/□), **35 ps** (300 kΩ/□).
  - **Floating strips:** **28 ps** (25 MΩ).

Studies on going

R&D on efficient & robust photocathode

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% for high drift fields)

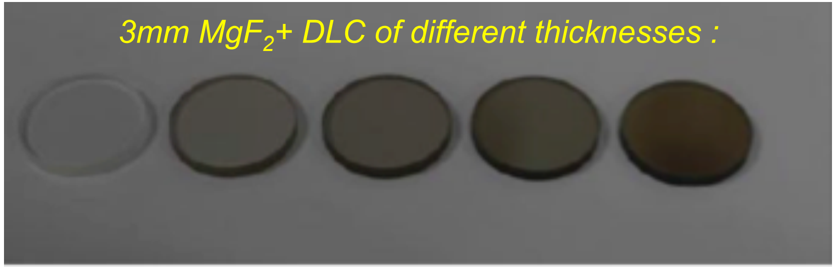
R&D in two directions:

New photocathodes
Diamond-Like Carbon (DLC)
Pure metallic (Al, Cr, …)
Polycrystalline Diamond or thick diamond films as electron emitters

Photocathode protection
Protection layers (LiF, MgF_2,…)
New detector structure: double mesh Micromegas

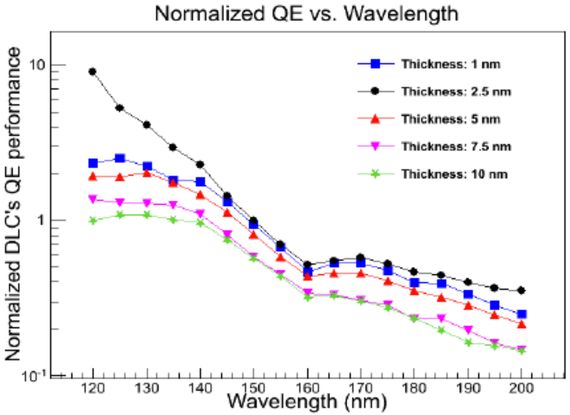
→ Also: **improve resolution** for **single photoelectrons** through **detector optimization**

Investigating Photocathodes (DLC)



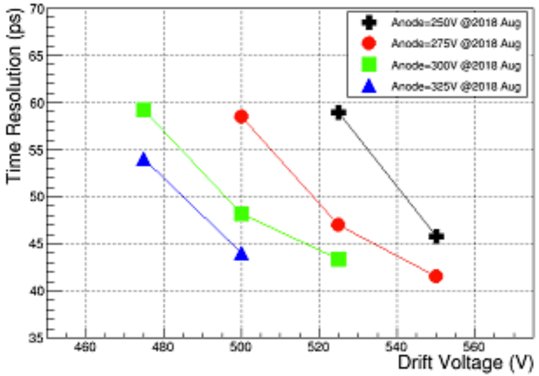
Performance studies:
- QE measurements with UV light in the lab
- Beam test at CERN SPS
- Aging studies with pion beams and laser

Relative Q.E meassurements



Results from beam tests

- **2.5 nm** thickness is the best performing one: 97% efficiency
- Time resolution: **40 ps** level with 2.5 nm DLC



DLC thickness [nm]	Detection Efficiency
2.5	97%
5	94%
7.5	70%
10	68%
CsI photocathode	*100%*

PRELIMINARY

Xu Wang et al, proc MPGD2019

Optimization

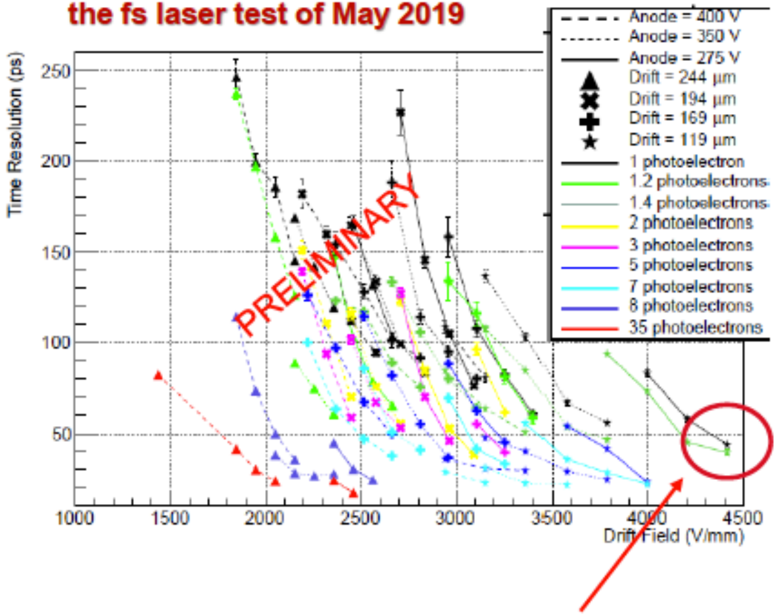
There is margin for further improvement of the time resolution for single photoelectrons: performance is dominated by the size (= gain) of the pre-amplification avalanche.

- Drift gap: The majority of the tests was done with 200 µm gap. Reducing it is expected to improve avalanche size and stability. *Tests were performed in May 2019 at the fs laser* for gaps of 120,170,195 and 245 µm

- Gas composition. CF_4 is increasing drift velocity, however is decreasing the maximum gain. Ne or He mixtures with only C_2H_6 as quencher are expected to increase maximum gain and improve the "polya" distribution of single p.e. *Tests are planned for Sep. 2019*.

- Gas pressure: decreasing pressure is equivalent with decreasing the amplification gaps. *Tests are planned for Oct. 2019*

First overview of the data from gap tests with the fs laser test of May 2019



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

Summary - Conclusions

Coupling a Micromegas detector with a radiator / photocathode we have surpassed the physical constrains on precise timing with MPGDs, achieving two orders of magnitude improvement:

- $\sigma_t \sim$ 76 ps for single p.e.
- $\sigma_t \sim$ 24 ps for 150 GeV muons with 3 mm MgF_2 + 5.5 nm Cr substrate + 18 nm CsI photocathode.
- $\langle N_{p.e.} \rangle \approx 10$

PICOSEC Micromegas is a well-understood detector

- Reproduce observed behavior with detailed simulations and a phenomenological model : valuable tool for parameter-space exploration

Towards a large-scale detector:

- Resistive Micromegas OK for timing
- Response of multi-channel PICOSEC prototype: similar precision as the single channel prototype, for any impact point of a MIP
- Robust photocathodes promising progress

The optimization of the detector is expected to establish sub-50 ps precision for single photoelectrons

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Thank you