DE LA RECHERCHE À L'INDUSTRIE

PICOSEC
Micromegas

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Fast Timing measurements with Micromegas

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on behalf of the
RD51 – PICOSEC Collaboration

The RD51 “PICOSEC” Collaboration

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PICOSEC
Micromegas

Motivation: particle tracking with ~10 ps timing

High Luminosity Upgrade of LHC:

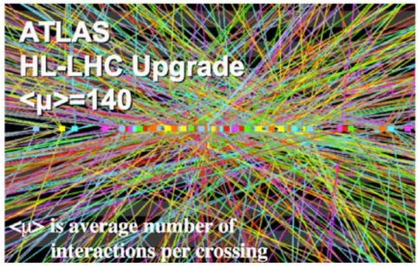
➔ To mitigate pile-up background.
ATLAS/CMS simulations: ~150 vertexes/crossing (RMS 170 ps).

➔ order of 20 ps timing + tracking info.

Extra detector requirements:

- Large surface coverage.
- Multi-pad readout for tracking.
- Resistance to aging effects.

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



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

State-of-art:

Solid state detectors

- Avalanche PhotoDiodes: (σ_t ~ 20 ps)
- Low Gain Avalanche Diodes (σ_t ~ 30 ps)
- HV/HR CMOS (σ_t ~ 80 ps)

➔*Radiation hardness ?*
➔*Cost*

Gaseous detectors

- RPCs: (σ_t ~ 30 ps)
  ➔ *High rate limitation*
- Micro-Pattern Gaseous Detectors (σ_t ~ 1 ns)

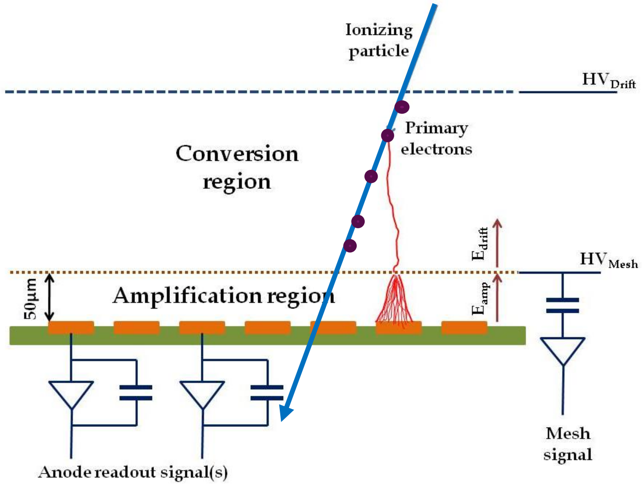
➔ *Improve Micromegas performance by* ***~2 orders of magnitude***

- ***First step: proof of concept***
- ***Next steps: Large-area, aging, radiation hardness***

The Micromegas detector

- Multi-Pattern Gaseous Detector, invented in 1995 at CEA Saclay[1]
- Parallel plate detector with a thin metallic mesh dividing the gas volume in 2 parts:
  - conversion (drift) region (1 to 100 mm) → E ≈ 100 V/cm
  - amplification region (30 to 150 µm) → E ≈ 100 kV/cm
- Grounded read-out: conductive strips connected to FEE
- Pillars are used to reinforce the response uniformity

[1] 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.



Conversion region
Radiation create 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

Timing limitation factors:

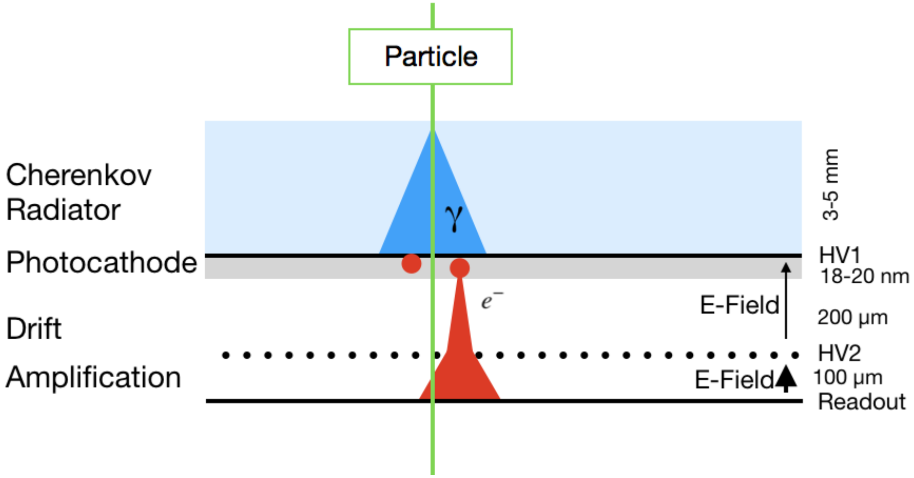
- **Large conversion region:** charges created in different positions.
- **Diffusion effects:** ~0.1 mm/cm$^{0.5}$ -> **~2 ns for 5 mm drift distance!**

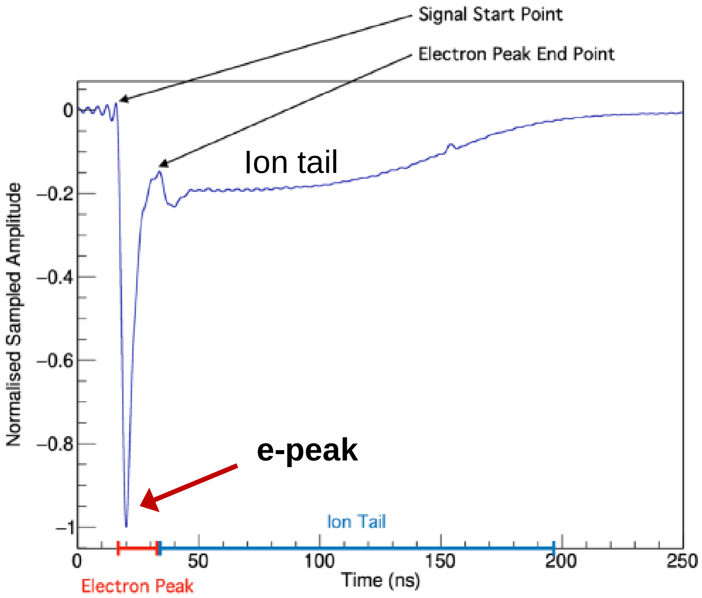
$$\sigma_t = \frac{\sigma_I}{v_d} = \frac{124\,\mu\mathrm{m}}{84\,\frac{\mu\mathrm{m}}{\mathrm{ns}}} > 1.47\,\mathrm{ns}$$

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 produce Cerenkov light.
- Photons produce electrons in the photocathode.
- 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 nm):

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

Cerenkov radiator:

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

Aiming in:

- **single photoelectron time jitter <100 ps**
- **produce sufficient photoelectrons to reach timing response ~20 ps.**

The “Picosec” Micromegas prototypes

Sensor:

Bulk Micromegas ø 1cm

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

Thin-mesh Bulk Micromegas (~5 µm)

- 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

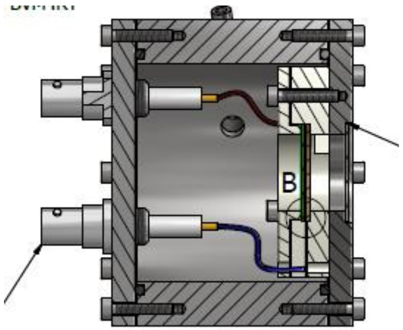
- Hexagonal pads ø 1cm.

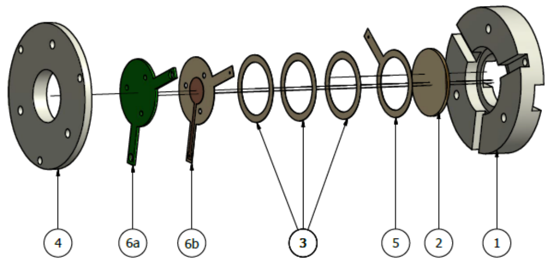
☞ Ensure homogeneous small drift gap & photocathode polarization

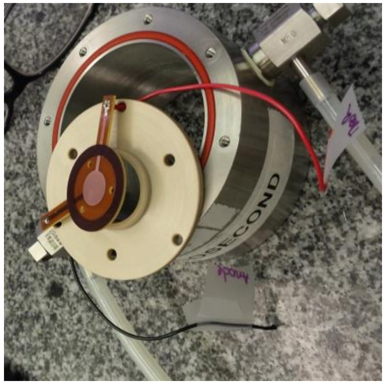
Photocathodes: MgF2 crystal +

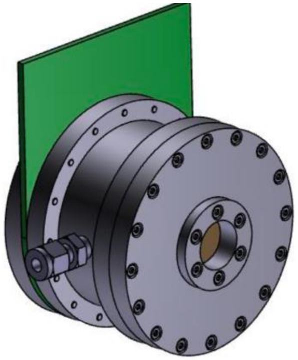
- Metallic substrate + CsI
- Metal (Cr, Al)
- Metallic substrate + polycrystalline diamond
- Metallic substrate + B4C
- *Boron-doped diamond*

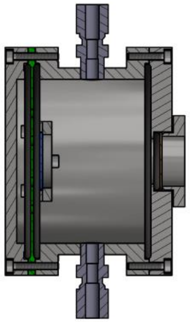
Very thin detector active part (<5 mm)

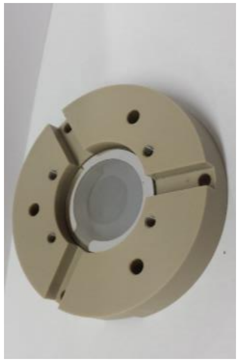












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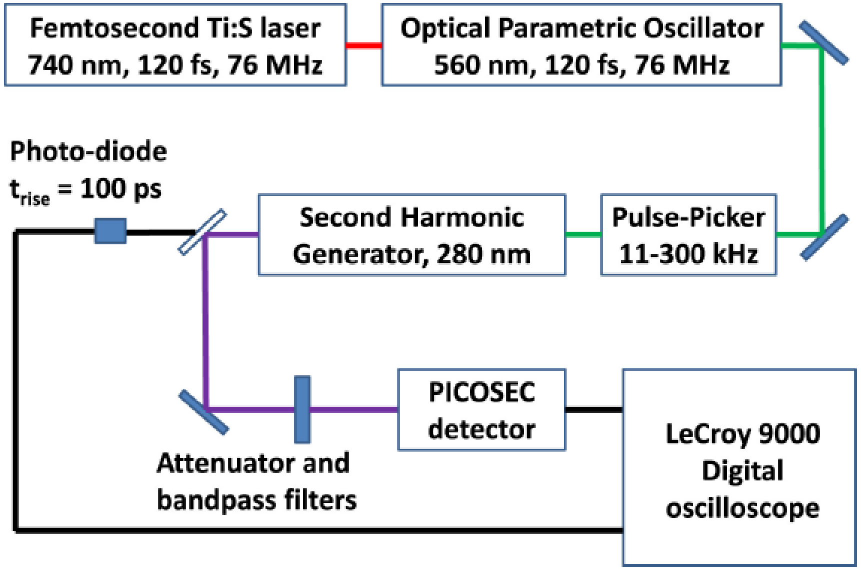
Understanding the timing properties: laser tests

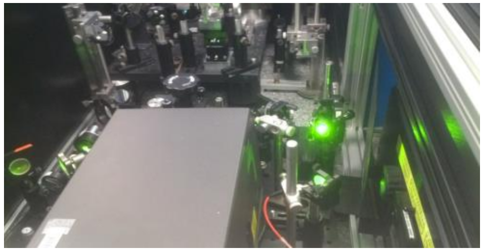
Unique capabilities of **FLUME** setup at the IRAMIS/LIDYL laser facilities @ CEA Saclay:

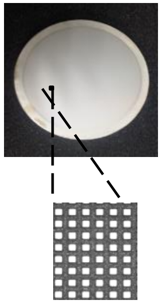
➔ *Study the **single photoelectron timing** performance and **optimize** the detector*

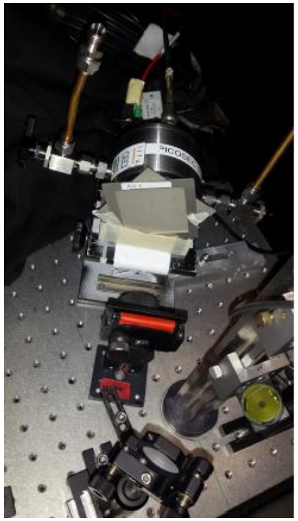
FLUME setup:

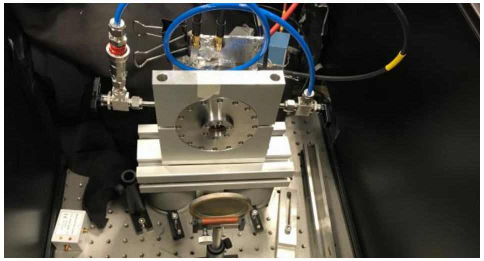
- IR Ti:S laser with pulse width **120 fs**
- **λ = 267-285 nm** after doubling
- Energy ~ 10 -100 pJoule / poulse
- Spot size: ~1 mm^2
- Repetition 9 kHz – 4.75 MHz
- Light attenuators (fine micro-meshes 10-20% transparent)
- t0 reference: fast PD (**σ_T << 10 ps**)
- Cividec 2 GHz, 40 db preamplifier
- DAQ: 2.5 GHz LeCroy scope.
- Gas mixture: **Ne** + 10% **CF_4**+20% **C_2H_6**.











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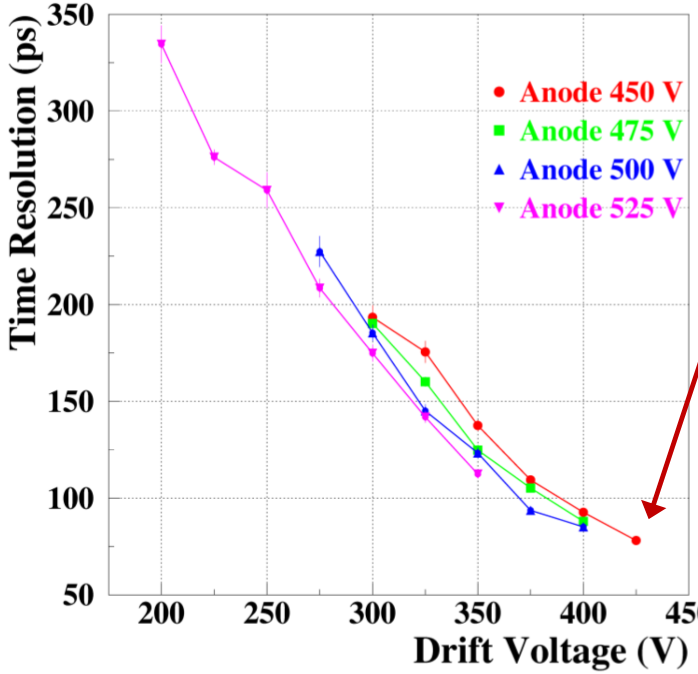
Understanding the timing properties: laser tests



Best time resolution for **1 photo-electron**:
76.0 ± 0.4 ps @ Vd/Va = -425V / +450V

improves strongly with higher drift field, less with anode field

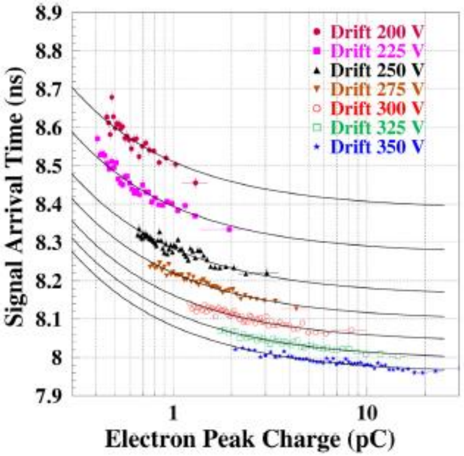
The Signal Arrival Time (SAT) depends on the e-peak charge:

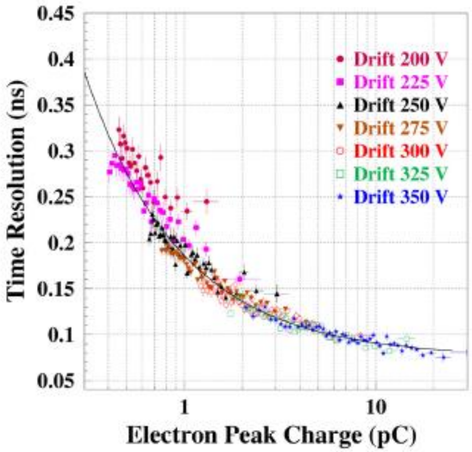
- bigger pulses ➔ smaller SAT
- higher drift field ➔smaller SAT

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

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

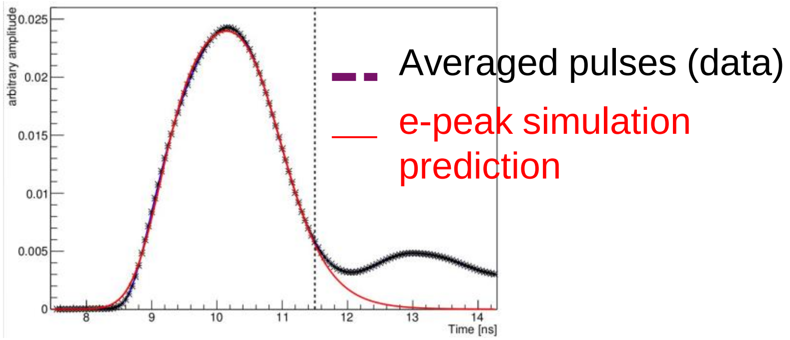
J. Bortfeldt et al. (PICOSEC Collaboration), "*PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector*", Nucl. Instrum. Meth. A903 (2018) 317-325. https://doi.org/10.1016/j.nima.2018.04.033

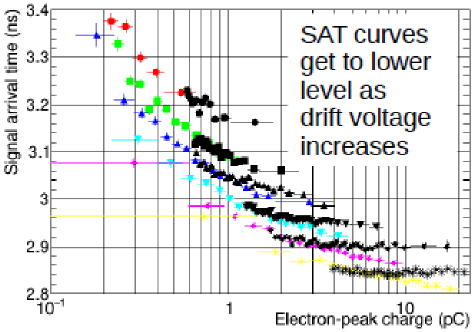


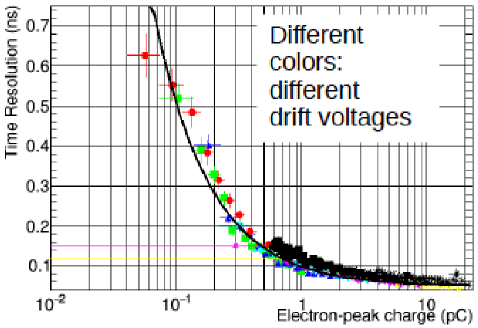


Understanding the timing properties: detailed modeling / simulations

Garfield++ and *electronics response*

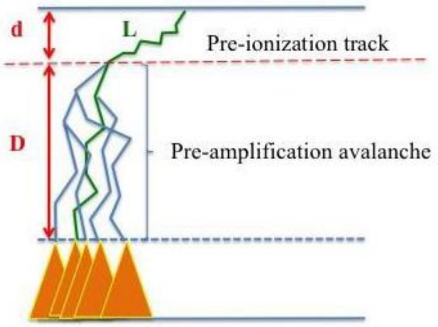




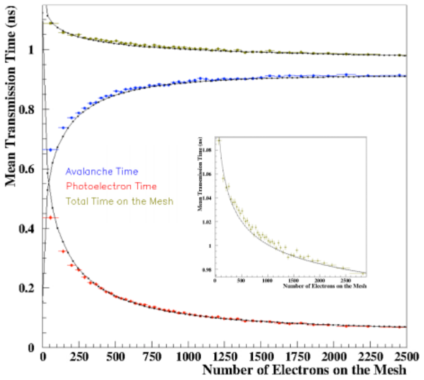


All behaviors seen in single p.e. laser data are also seen in these detailed Garfield++ simulations.

Phenomenological model describing stochastically the dynamics of the signal formation

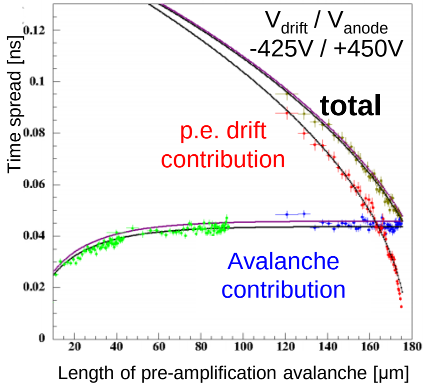


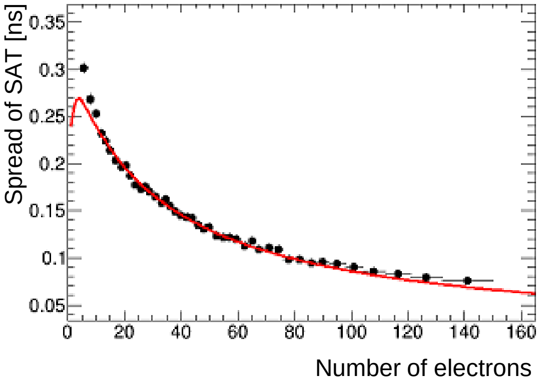
The model describes **SAT** and **Resolution** vs. **avalanche length** & vs. **number of electrons** in avalanche (i.e, e-peak charge)



Avalanche speed = 154 μm/ns

Electron speed = 134 μm/ns





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

J. Bortfeldt et al., "*Modeling the Timing Characteristics of the PICOSEC Micromegas Detector*", submitted to NIM-A, arXiv:1901.10779 [physics.ins-det], https://arxiv.org/abs/1901.10779

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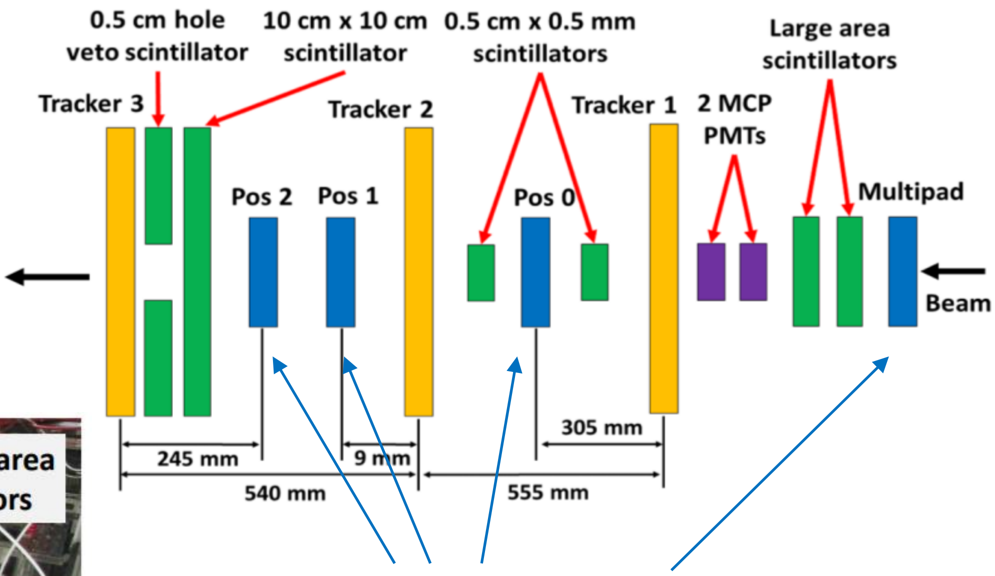
Beam tests: systematic study of detectors & photocathodes

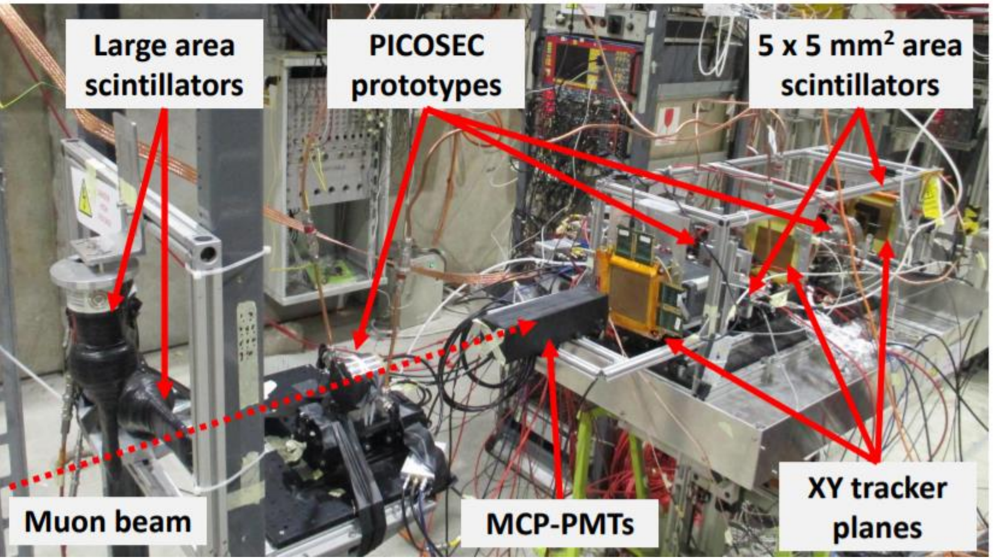
3 beam periods per year (2017-2018)

Beam tests with 150 GeV muons @ CERN SPS H4:

- timing measurements
- **photocathode quantum efficiency** (number of photoelectrons per muon)



PICOSEC Prototypes



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

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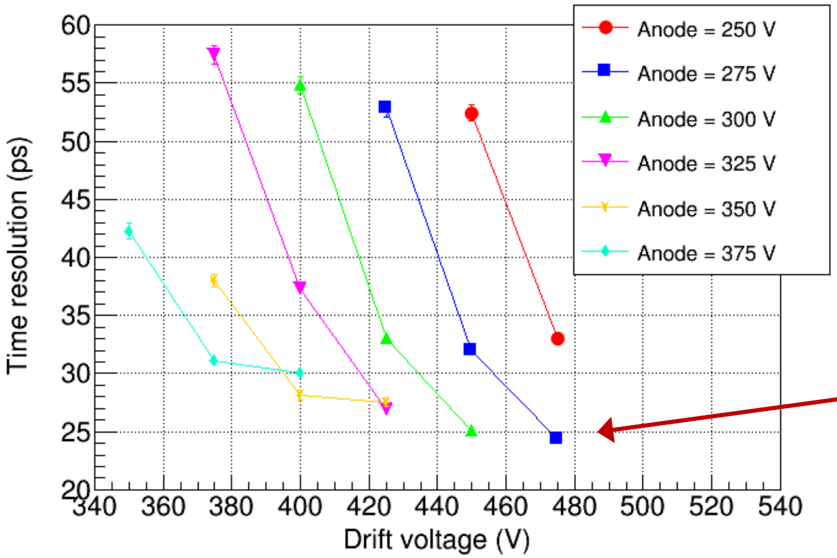
Response to 150 GeV muons



Same detector as for Laser tests:

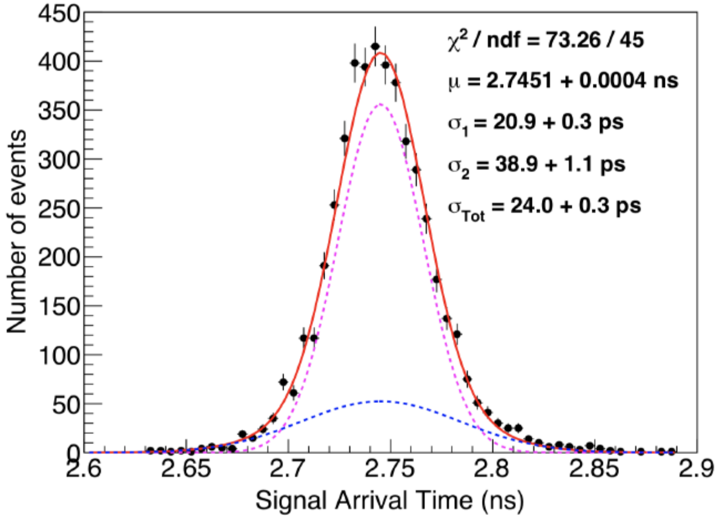
- MgF2 radiator 3 mm thick,
- 18 nm CsI on 5.5 nm Cr
- Bulk MicroMegas, 200 µm drift gap
- “COMPASS gas”

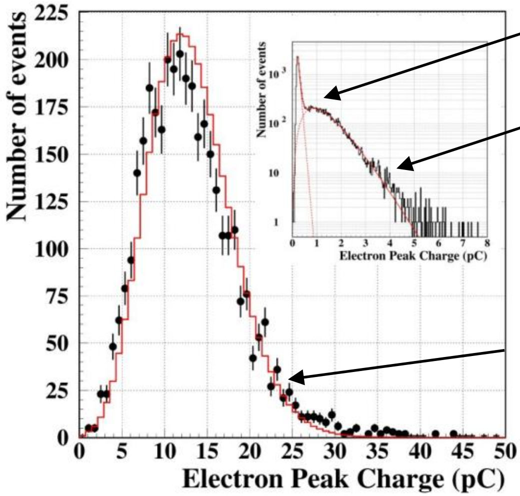
Optimum operation point: **V_{drift}/V_{anode}: -475V/+275V**

Best result: **24 ± 0.3 ps**

$N_{p.e.}$ = **10.1 ± 0.7**

- *Result repeated in two different beam campaigns.*





Noise component

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

Signal of MIPs

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

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

Scaling the PICOSEC concept for HEP applications

Towards an engineered PICOSEC MM module that can be scaled up and used in HEP applications:

☞ *Proof-of-principle* that Micromegas can reach **~20 ps time resolution** for MIPS

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

- ➢ Spark quenching in the amplification gap
  - ☞ Resistive Micromegas ➔ tests in 2018 OK!
- ➢ Large area & multichannel readout
  - ➢ *Cerenkov photoelectron sharing among pads*
  - ➢ Multi-channel electronics
- ➢ *Photocathode aging / deterioration due to ion backflow & sparks*
  - ☞ Protection of CsI or other robust &efficient photocathode
  - ☞ Detector optimization ➔ compensate for lower photocathode Q.E.
  - ☞ High efficiency photocathode ➔ smaller field
  - ☞ *Secondary Emitter instead of photocathode*

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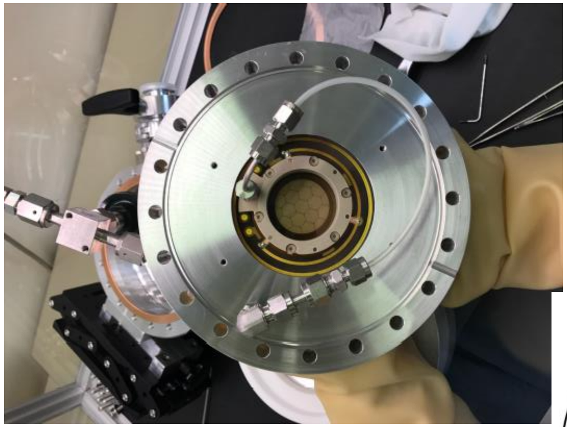
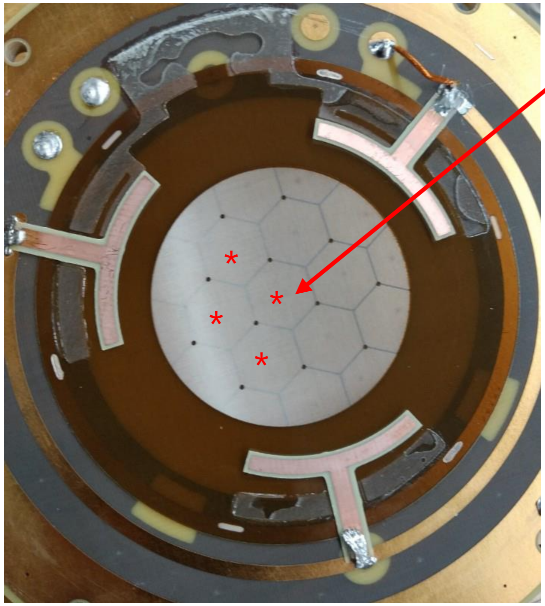
First multi-pad prototype: single-pad response



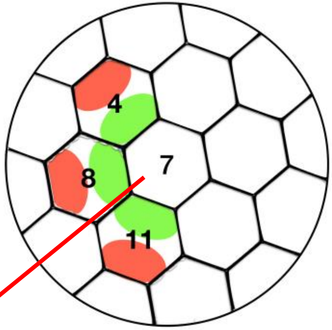
19 hexagonal pads 5mm side



Similar detector configuration as for single pad:

MgF_2 radiator 3 mm thick,18 nm CsI on 5 nm Cr, 200 µm drift gap, operation point: **V_{drift}/V_{anode}: -475V/+275V**

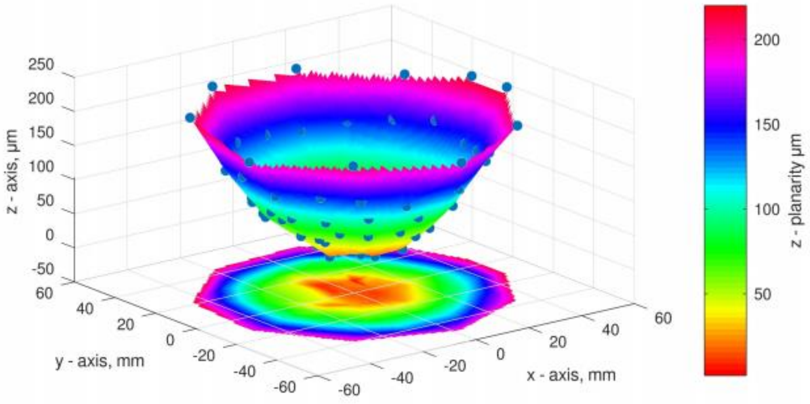
➔ **25 ps** time resolution preserved for the **center of each pad.** However:



Pad Number	Colour	SAT (ps)
4	Green	-1858 ± 4
	Red	-1882 ± 6
	Δ	24 ± 7
8	Green	-1818 ± 7
	Red	-1844 ± 6
	Δ	26 ± 9
11	Green	-1798 ± 8
	Red	-1822 ± 6
	Δ	24 ± 10

- ➢ Bad overall resolution (~70 ps) when combining all pads
- ➢ SAT difference between the pads (radially)
- ➢ Constant SAT difference between inner and outer part of pad
- ➢ Gain increases with the distance from the center

Curvature of the PCB ➔ not uniform drift gap (*micromesh is bulked on the PCB*) ➔ different drift/amplification distance for the electrons (~20 µm)



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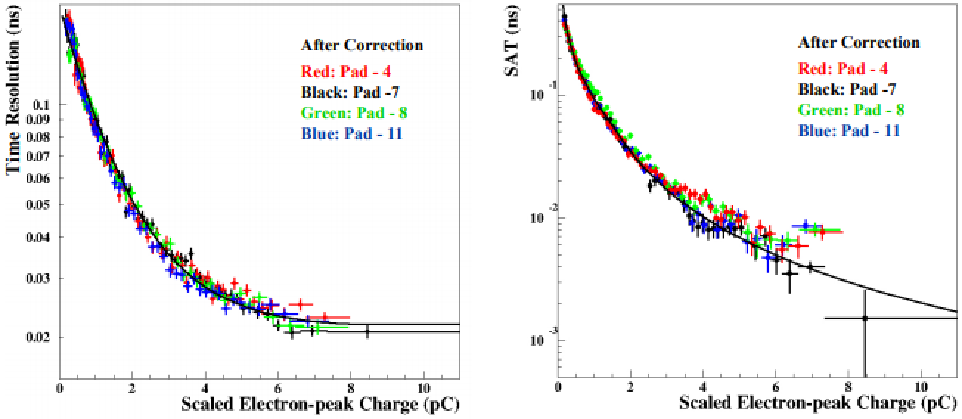
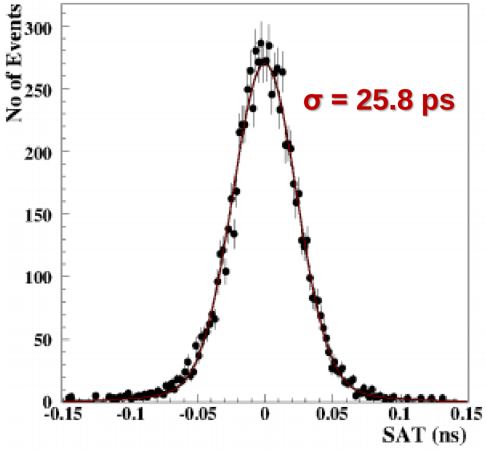
First multi-pad prototype: combining pads

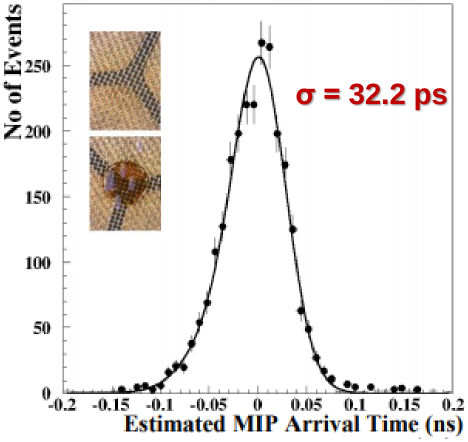
After corrections we can restore the timing performance of 25 ps for all tracks



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

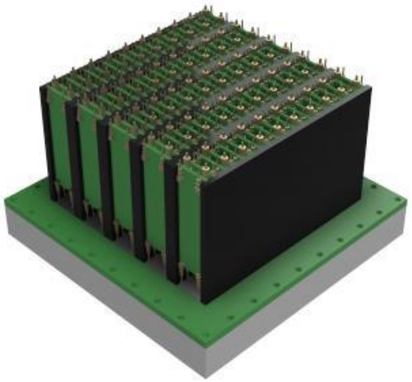


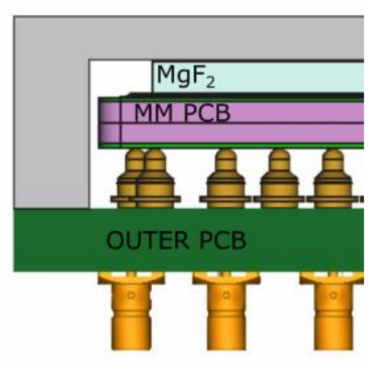
All tracks passing within R<2mm from any pad corner



Two approaches to ensure ***future large area & modular detector*** *planarity*:

- **Micromegas made on a ceramic PCB**, which is entirely contained in the chamber. 100-pad prototype (10×10 cm^2) ~ready @ CERN



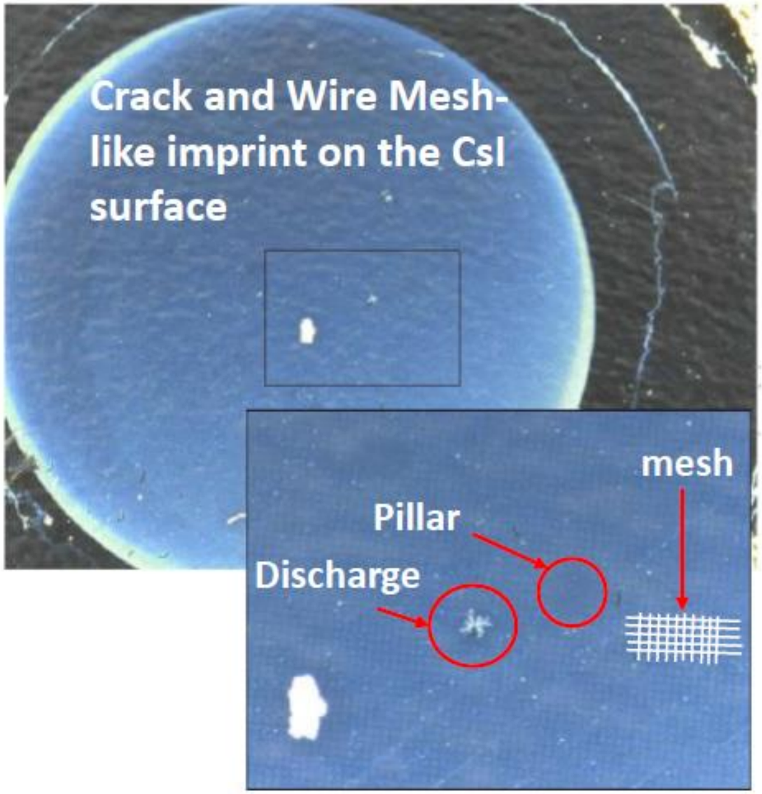


- **The ATLAS NSW Micromegas approach**: bulk Micromegas on a thin PCB that is backed by a honeycomb, glued on a marble-table (flatness <10 μm @ 1 m)

S. Aune et al, "*Timing performance of a multi-pad PICOSEC-Micromegas detector prototype*", approved by NIM-A, https://arxiv.org/abs/2012.00545

R&D on efficient & robust photocathodes

A typical CsI photocathode used in a test beam



CsI: 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

Robust:

- ☞ Diamond-Like Carbon (DLC)
- ☞ B_4C
- ☞ Pure metallic (Al, Cr, …)
- ☞ Polycrystalline Diamond or thick diamond films as electron emitters

High Efficiency:

- ☞ GaN (high number of photoelectrons ➔ modest field)

Photocathode protection

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

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

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PICOSEC
Micromegas

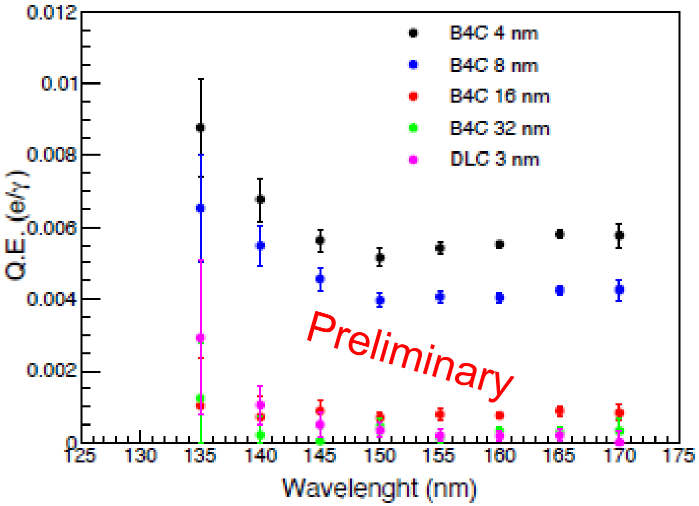
R&D on efficient & robust photocathodes (DLC)


MgF2 crystals with DLC photocathode

Performance studies:

- ➢ Q.E measurements with UV light in lab
- ➢ Beam tests at CERN SPS
- ➢ Aging tests with pion beams & laser

Relative Q.E meassurements



B4C 5 times higher q.e. compared to DLC!!

Results from beam tests

- ➢ **2.5 nm** thickness is the best performing one: 97% efficiency
- ➢ Time resolution: **~35 ps** with 2.5 nm DLC

Anode/Drift Voltage (V)	Time resolution (ps)	
	Aug.	Oct.
250/-550	45	37
275/-525	47	38
275/-550	42	34
300/-500	48	39
300/-525	43	34

Preliminary

DLC thickness [nm]	Detection Efficiency	<N $_{p.e.}$>
2.5	97%	3.7
5	94%	3.4
7.5	70%	2.2
10	68%	1.7
CsI	*100%*	*7.4*

Preliminary

Xu Wang et al, proc MPGD2019

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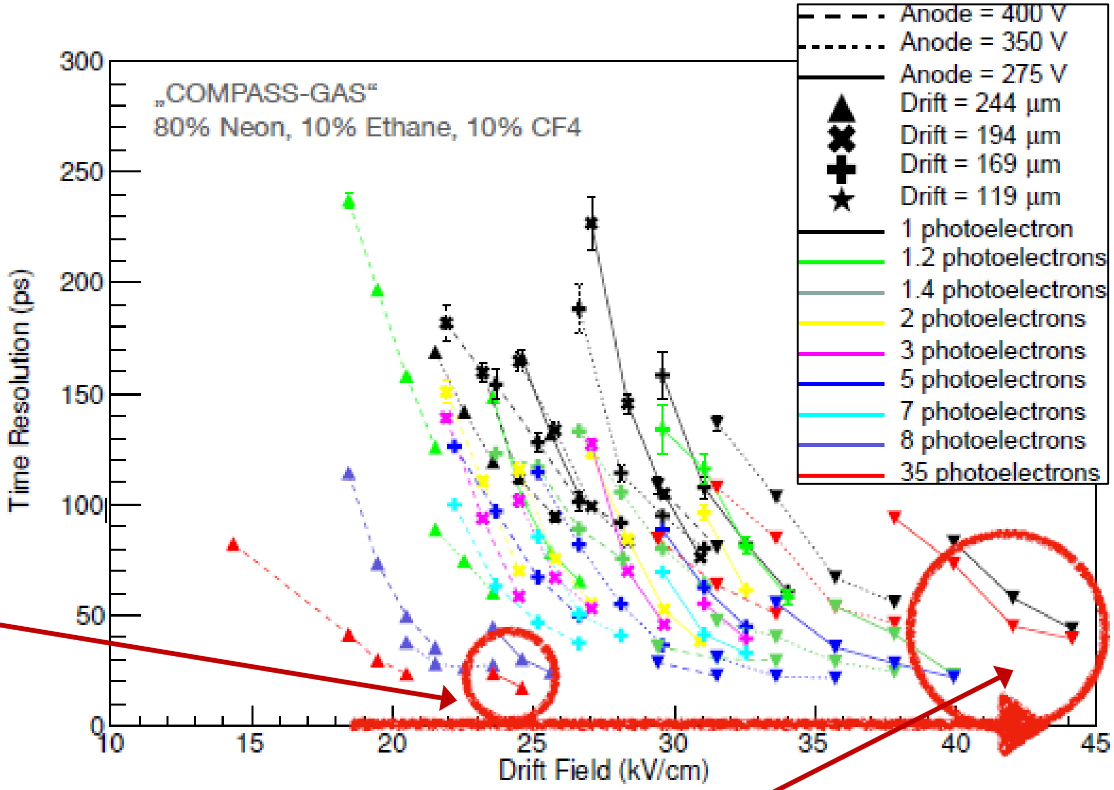
Optimizing the detector performance

Detector optimization:

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

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

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



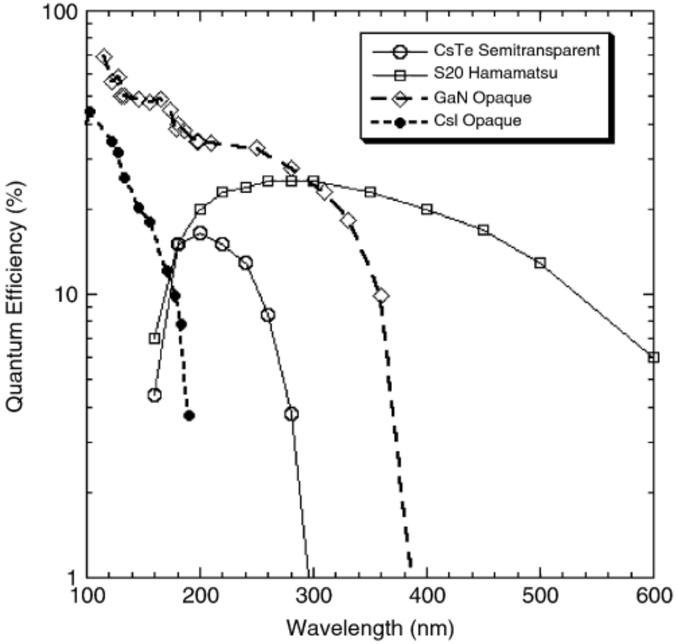
Best time resolution for **1 photo-electron**: **44.0 ± 1.0 ps**
@ V_d / V_a = -525V / +275V, 120 μm drift gap

Sohl L., “***Development of PICOSEC-Micromegas for fast timing in high rate environments***”, PhD Thesis, CEA Saclay 17/12/2020, CEA Saclay, https://lsohl.web.cern.ch/lsohl/

High number of photoelectrons

GaN:

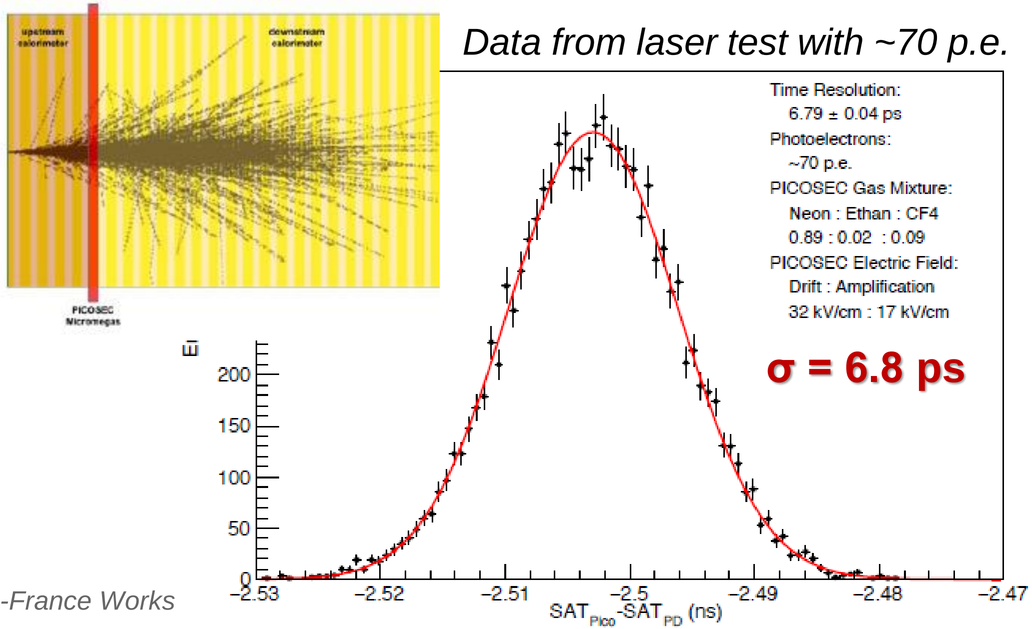
- Higher quantum efficiency than CsI
- Broader bandwidth towards higher wavelengths ➔ Quartz instead of MgF_2 ?
- Aging & Stability in the gas?
  → A GaN sputtering target just received!



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

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

- From some simple simulations: a 30 GeV electron produces **~200 p.e.** in MgF2 with a metallic (**Cr**) photocathode after **2 radiation lengths**
- **Time resolution < 10 ps !!**
- No need for high efficiency photocathode
- No need for extremely high electric fields
- To be tested at SPS in 2021



Data from laser test with ~70 p.e.

Summary & outlook

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:

- **σ_t ~ 76 ps** (***44 ps** in an optimized setup*) **for single p.e.**
- **σ_t ~ 24 ps** (with the “standard” setup) 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, we plan the following steps for the near future:

- Commission & test the new, modular prototype with Micromegas on a ceramic PCB
- Utilize the experience from ATLAS NSW Micromegas to produce flat large area detectors
- Test BLC & B_4C photocathodes on MIP beams to address Q.E. and robustness
- Investigate GaN potential for high efficiency photocathodes
- Address the concept of the PICOSEC Micromegas embedded in an EMC. Test in electron beams.

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Further information

PhD Thesis:

Sohl L., “*Development of PICOSEC-Micromegas for fast timing in high rate environments*”, CEA Saclay 17/12/2020, https://lsohl.web.cern.ch/lsohl/

Published papers:

1. J. Bortfeldt et al. (PICOSEC Collaboration), “*PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector*”, Nucl. Instrum. Meth. A903 (2018) 317-325. https://doi.org/10.1016/j.nima.2018.04.033
2. J. Bortfelt et al. (PICOSEC Collaboration), "*Timing Performance of a Micro-Channel-Plate Photomultiplier Tube*", Nucl.Instrum.Meth.A 960 (2020) 163592, https://doi.org/10.1016/j.nima.2020.163592
3. J. Bortfeldt et al. (PICOSEC collaboration), "*Modeling the Timing Characteristics of the PICOSEC Micromegas Detector*", submitted to NIM-A, arXiv:1901.10779 [physics.ins-det], https://arxiv.org/abs/1901.10779
4. S. Aune et al. (PICOSEC collaboration), "*Timing performance of a multi-pad PICOSEC-Micromegas detector prototype*", submitted to NIM-A, arXiv:2012.00545 [physics.ins-det], https://arxiv.org/abs/2012.00545

Selected Conference proceedings:

1. T. Papaevangelou et al., “*Fast Timing for High-Rate Environments with Micromegas*“ , EPJ Web Conf. 174 (2018) 02002, https://doi.org/10.1051/epjconf/201817402002
2. F.J. Iguaz et al. (PICOSEC collaboration), “*Charged particle timing at sub-25 picosecond precision: The PICOSEC detection concept*”, Proceeding of Pisa 2018 conference, accepted in Nucl. Inst. Meth. A, https://doi.org/10.1016/j.nima.2018.08.070
3. L. sohl et al. (PICOSEC collaboration), “*Progress of the Picosec Micromegas concept towards a robust particle detector with segmented readout*”, 9th international symposium on Large TPCs for low-energy rare event detection, 2018, https://doi.org/10.1088/1742-6596/1312/1/012012
4. L. Sohl et al. (PICOSEC collaboration), “*Single photoelectron time resolution studies of the PICOSEC-Micromegas detector*”, JINST 15 (2020) 04, C04053, Contribution to: IPRD1, https://doi.org/10.1088/1748-0221/15/04/C04053
5. J Manthos et al. (PICOSEC Collaboration), “*Recent Developments on Precise Timing with the PICOSEC Micromegas Detector*“, J.Phys.Conf.Ser. 1498 (2020) 1, 012014, https://doi.org/10.1088/1742-6596/1498/1/012014
6. Kordas et al. (PICOSEC collaboration), “*Progress on the PICOSEC-Micromegas Detector Development: Towards a precise timing, radiation hard, large-scale particle detector with segmented readout*”, Nucl.Instrum.Meth.A 958 (2020) 162877, https://doi.org/10.1016/j.nima.2019.162877
7. D Sampsonidis et al. (PICOSEC collaboration), “*Precise timing with the PICOSEC-Micromegas detector*“, Nuovo Cim.C 43 (2020) 1, 13, https://doi.org/10.1393/ncc/i2020-20013-8

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Thank you for your attention!

Quenching sparks: Resistive Micromegas

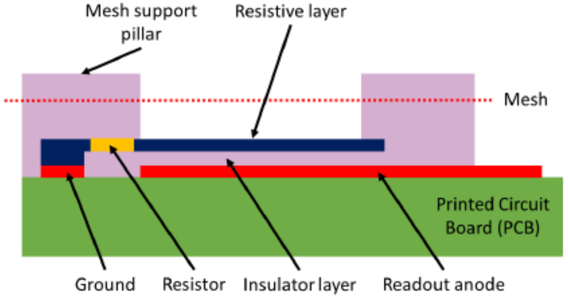
Different types tested during 2017 & 2018 runs

Values not far from the Picosec bulk readout.

- **Resistive strips**: **41 ps** (10 MΩ/□), **35 ps** (300 kΩ/□).
- **Floating strips**: **28 ps** (25 MΩ).
- ✓ Resistive readouts worked during hours in intense pion beam.

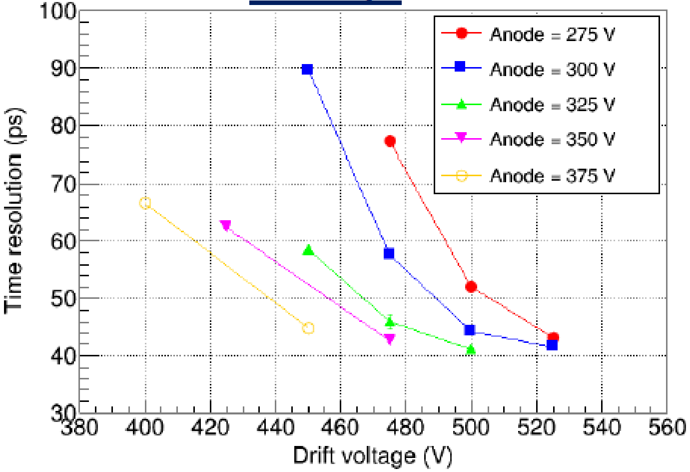
Resistive readouts operate stably at high gain in neutron fluxes of 10^6 Hz/cm^2

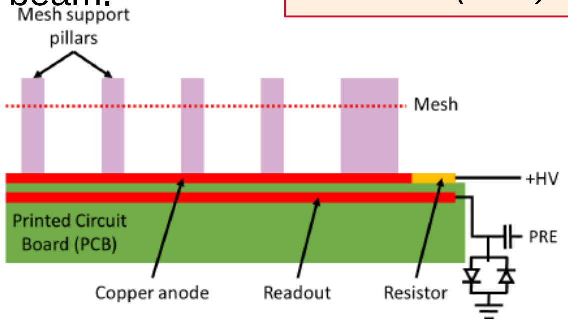
*T. Alexopoulos et al., NIMA **640** (2011) 110-118.*



Resistive strips

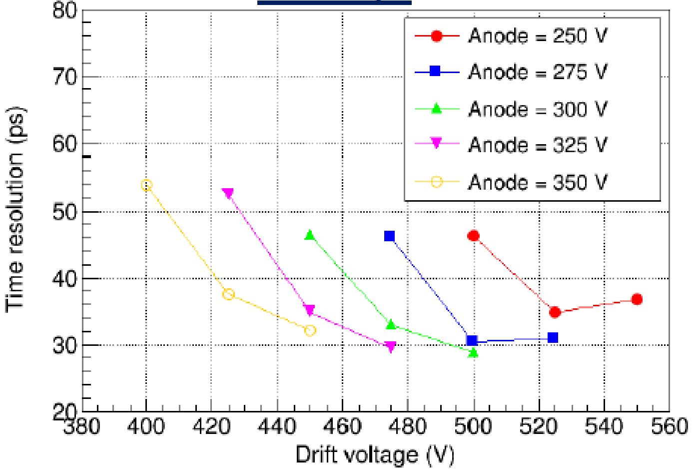
σ = 41 ps





Floating strips

σ = 28 ps



L. sohl et al., "*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