Recent Developments on Precise Timing with the PICOSEC Micromegas Detector

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on behalf of the
RD51 PICOSEC-Micromegas Collaboration

6th International Conference on Micro Pattern Gaseous Detectors

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RD51 PICOSEC-MicroMegas Collaboration

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1) Now at Synchrotron Soleil, 91192 Gif-sur-Yvette, France

2) Also MEPhI & Uludag University.

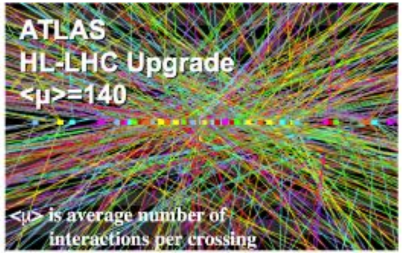
3) Also University of Virginia.

Outline

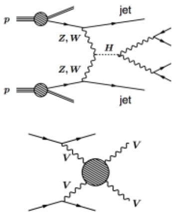
- PICOSEC MicroMegas: a detector with precise timing:
  - Single-channel prototype in Laser and Particle beams
- A well-understood detector:
  - reproduce observed behavior with detailed simulations and a phenomenological model
- Towards efficient photocathodes
  - Estimation of the number of photoelectrons per MIP
- Towards a large-scale detector: multi-channel
  - response of multi-channel PICOSEC prototype

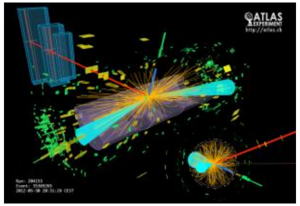
Timing with a few 10's of picosecond

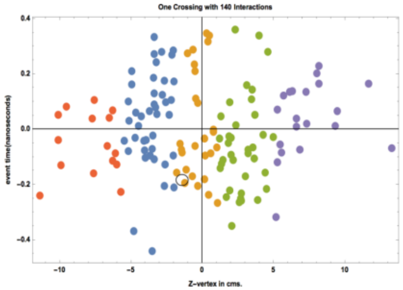
- Needs for Precise timing bring us to the picosec domain
- E.g., in the High Luminosity LHC, 140-200 "pile-up" proton-proton interactions ("vertices") with happen in the same LHC clock, in close space (Gaussian +- 45mm).
- Using precise timing can separate particles coming from the various vertices.
- (3D) tracking of charged particles is not enough to associate them to the correct vertex . Including precise time offers an extra dimension of separation to achieve this.
- Needed precision
- ~ order 30ps



The association of the time measurement to the energy measurement is crucial for physics analysis, and requires time resolution of 20-30ps.







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

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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PRINCIPLES OF OPERATION OF MULTIWIRE PROPORTIONAL AND DRIFT CHAMBERS

F. Sauli

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

GENEVA
1977

which is represented in Fig. 8, for n = 34, as a function of the coordinate across a 10 mm thick detector. If the time of detection is the time of arrival of the closest electron at one end of the gap, as is often the case, the statistics of ion-pair production set an obvious limit to the time resolution of the detector. A scale of time is also given in the figure, for a collection velocity of 5 cm/μsec typical of many gases; the FWHM of the distribution 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.

In order to use gaseous detectors for precise (ps) timing of charged particles we should turn other Physics phenomena against the stochastic Nature of ionization

- Cherenkov radiation → provide prompt photons
- Photoelectric effect → convert photons to prompt electrons

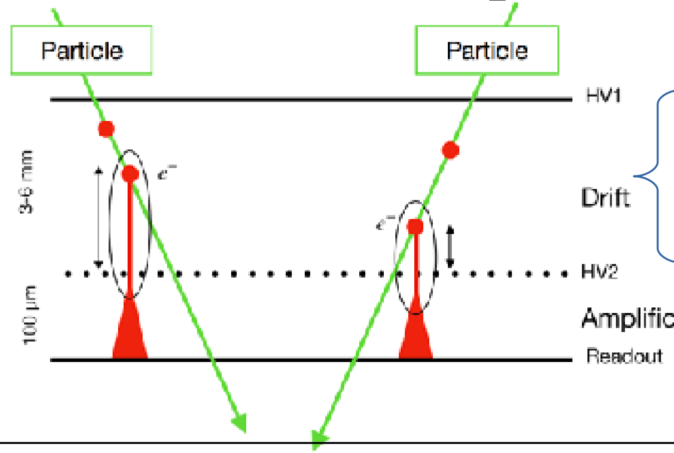
1. A precise-timing detector

Detector concept and the proof with results of single-channel prototypes

PICOSEC detector concept

- Classic MicroMegas
- *Giomataris Y. et al., NIMA 376 (1996) 29*
- *Multiple electrons produced at different points along particle's path in the ~3-6mm drift region →* <u>*Time jitter order **few ns***</u>

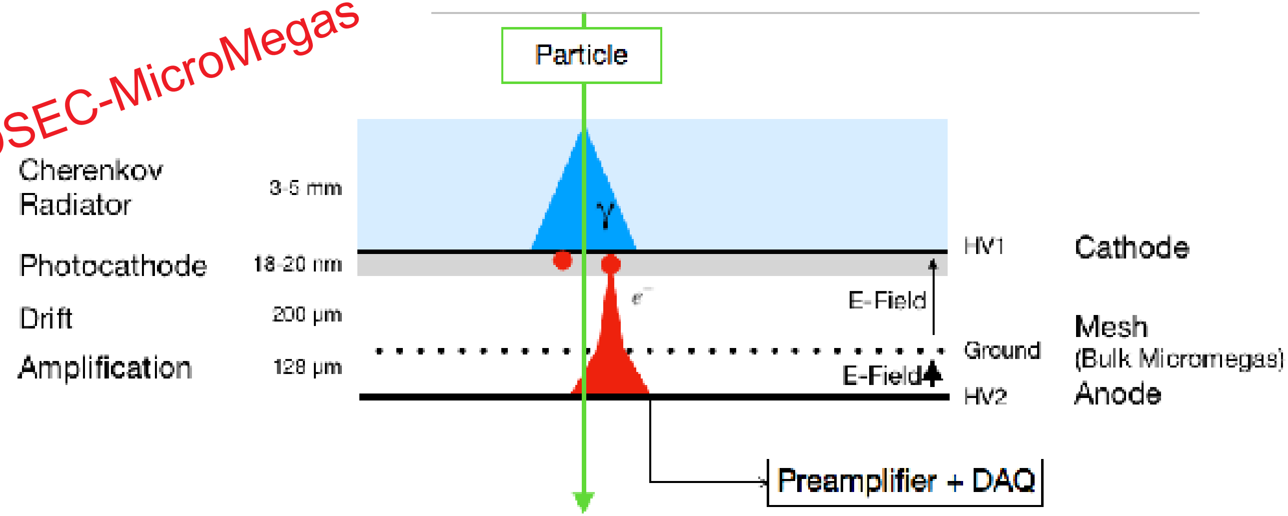
MicroMegas



Needed to get enough original electrons

- With Cherenkov radiator + photocathode → *synchronous photo-electrons (p.e) enter MicroMegas*
- Small drift gap & high field → *avalanches start as early as possible* with minimal time jitter → <u>*Timing resolution a **few tens of ps***</u>

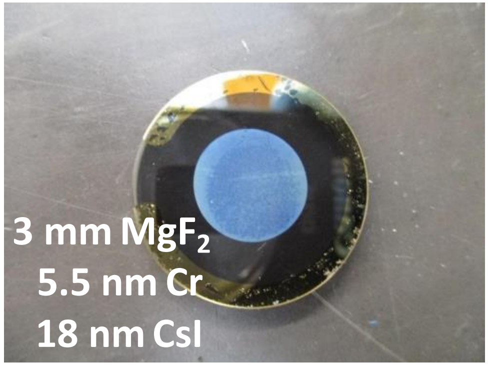
PICOSEC-MicroMegas



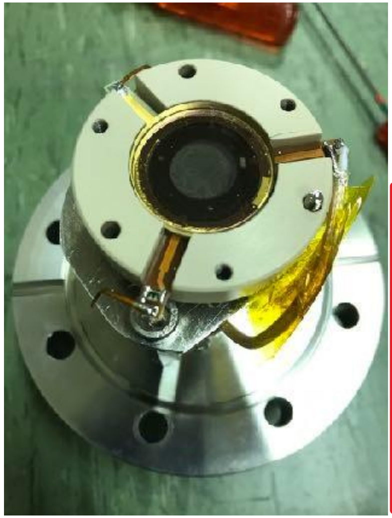
PICOSEC single-channel Prototype

Single pad prototypes
(1 cm diameter active area)

- Bulk MicroMegas readout (6 pilars)
- 4 kapton rings spacers → 200 μm drift
- Radiator + photocathode.



1st prototype



(see Xu Wang talk)

* Cherenkov Radiator:
MgF_2 3mm thick → 3mm Cherenkov cone

* Photocathode: 18nm CsI (with 5.5 nm Cr)

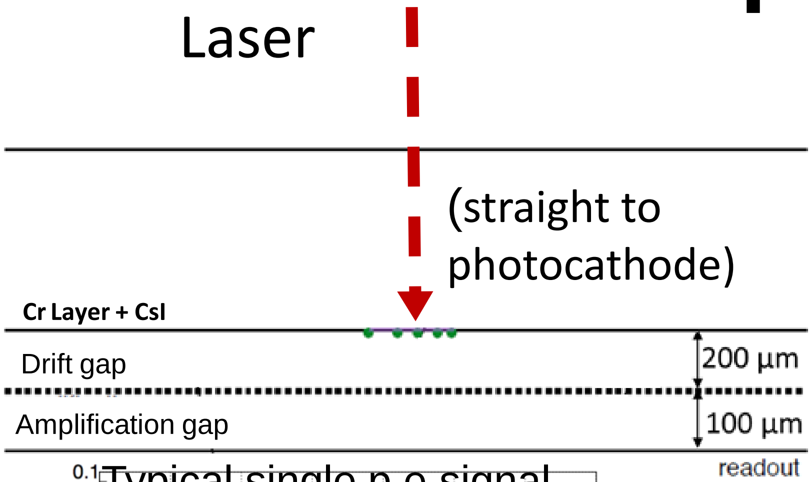
* COMPASS gas (80% Ne + 10% CF_4 + 10% C_2H_6)
Pressure: 1 bar.

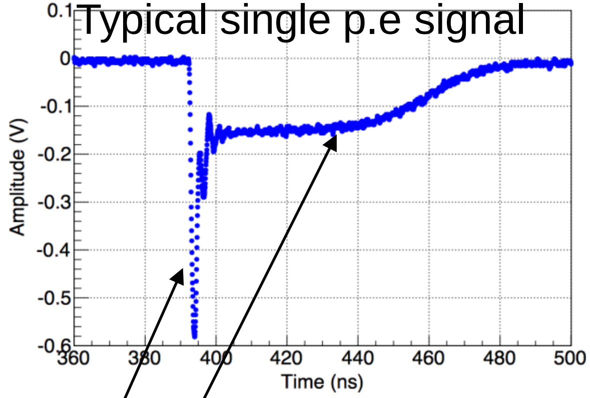
* Drift gap = 200 μm
* Amplification gap = 128 μm
* Mesh thickness = 36 μm (centered at 128 μm above anode)

Results from Laser and Beam tests presented next are from this detector
Since 2016, different prototypes studied (bulk, thin mesh etc. MM, multipad MM, different gas, anode schemes, photocathodes)

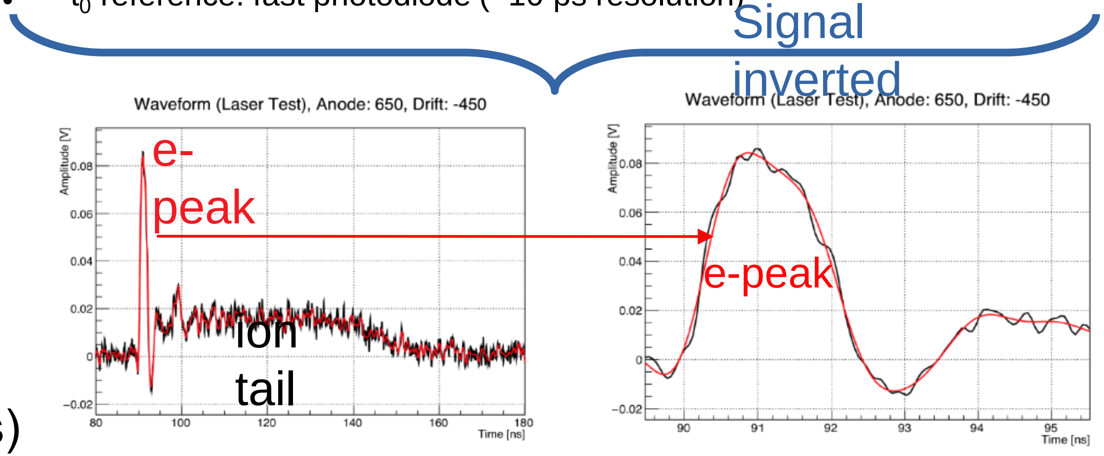
1a.
Response to single photoelectrons

Laser beam: response to single electron (1)





- **Pulsed laser** at IRAMIS facility (CEA Saclay)
- Wavelength: 267-288 nm
- Repetition rate: up to 500 kHz
- **Intensity: attenuated to get single photoelectron directly on photocathode**
- Read out with CIVIDEC preamp
- **Digitized waveform by 2.5GHz LeCroy oscilloscope @ 20GSamples/s = 1 sample/50ps.**
- t_0 reference: fast photodiode (~10 ps resolution)



→ **Two-component signal:**

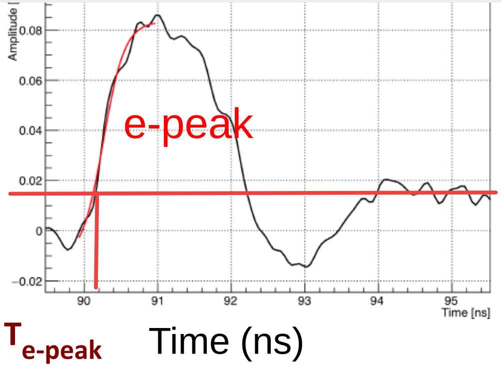
* Electron peak ("e-peak") → fast (~0.5ns)

* Ion tail (~100ns)

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

Laser beam: response to single electron (2)

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

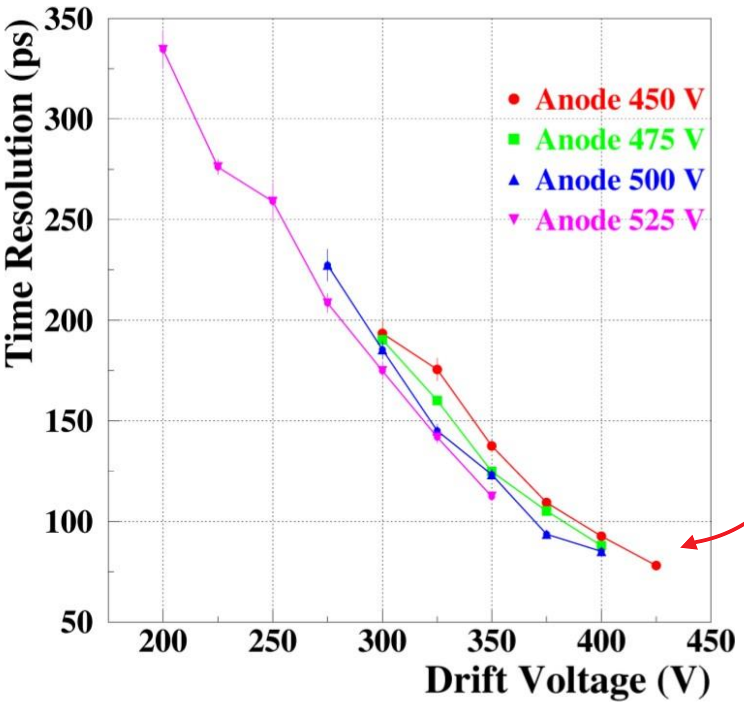


→ **Time the signal arrival with Constant Fraction Discrimination (CFD)** on the fitted noise-subtracted e-peak

(CFD @ 20% of the e-peak amplitude)

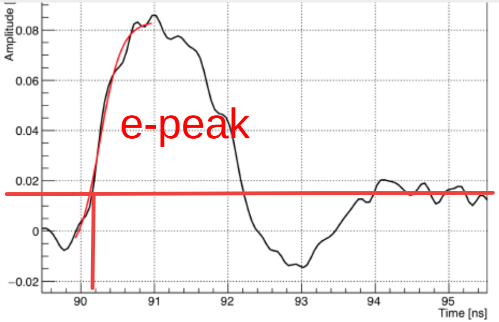
"PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector",
J. Bortfeldt et. al. (RD51-PICOSEC collaboration),
Nuclear. Inst. & Methods A 903 (2018) 317-325

- 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



Laser beam: response to single electron (3)

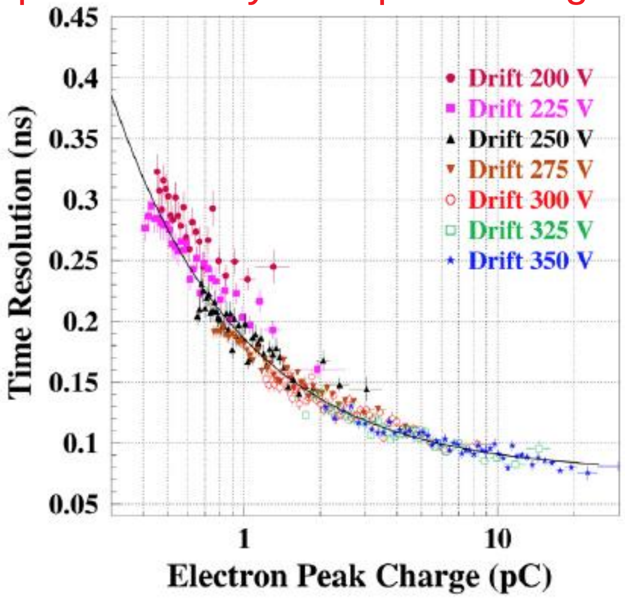
$T_{e\text{-peak}}$ = Signal Arrival Time (SAT)
* SAT of a sample of events = <$T_{e\text{-peak}}$ >
* Time Resolution = RMS[$T_{e\text{-peak}}$]



$T_{e\text{-peak}}$ Time (ns)

- 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:



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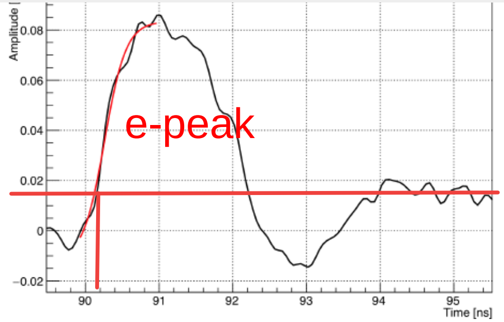
Laser beam: response to single electron (4)

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



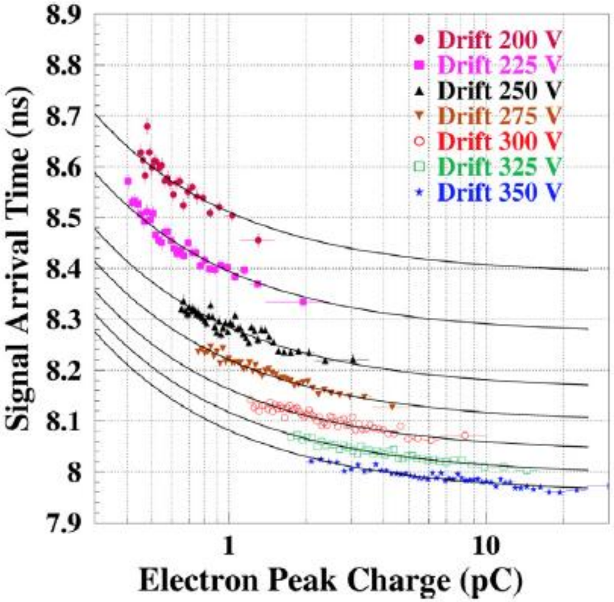
$T_{e\text{-peak}}$ Time (ns)

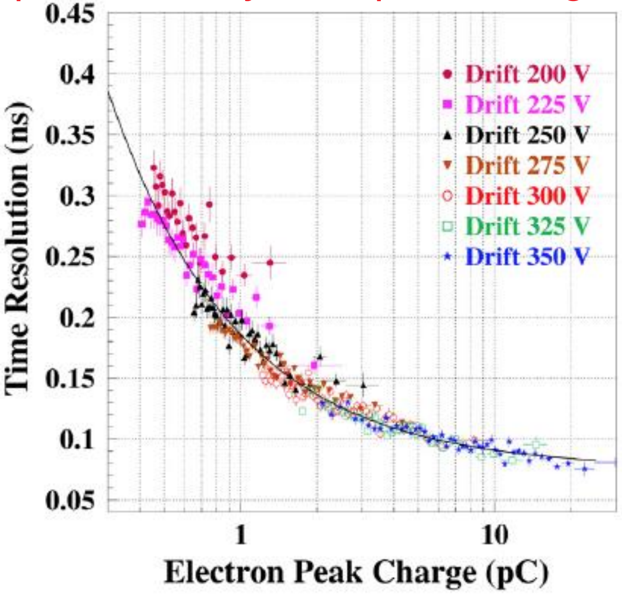
The Signal Arrival Time (SAT) depends non- trivially on the e-peak charge:
- bigger pulses → smaller SAT
- higher drift field → smaller SAT

* 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

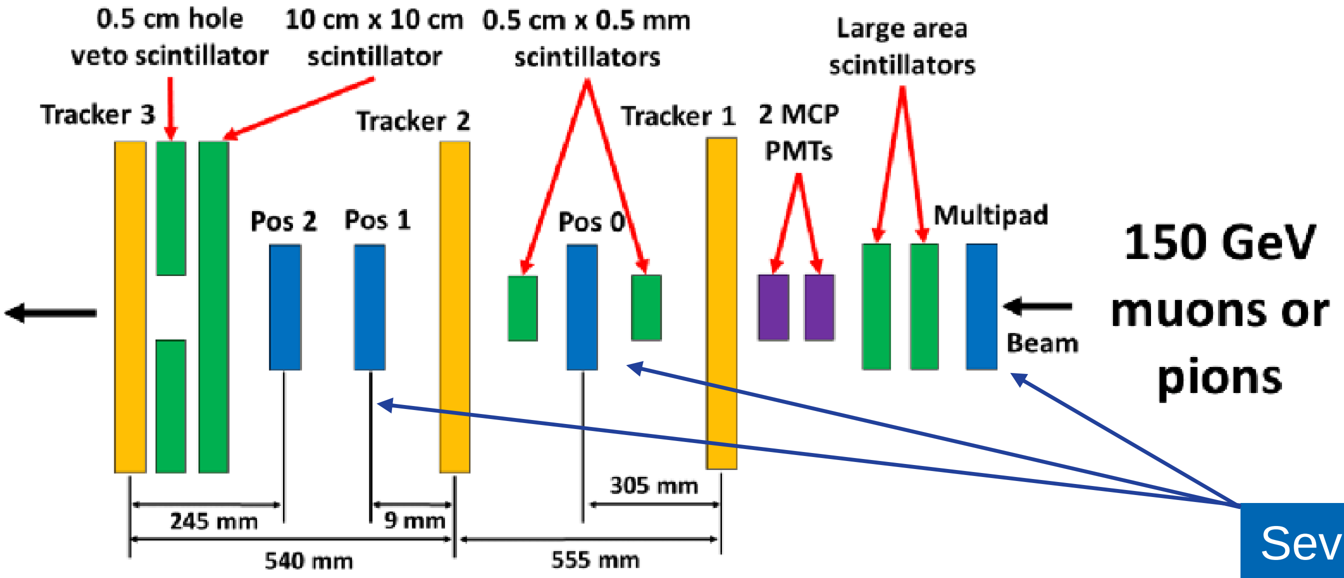
Time Resolution depends mostly on e-peak charge:





1b.
Response to Minimum Ionizing Particles (MIPs)

Testing with Particle Beams @ CERN SPS H4

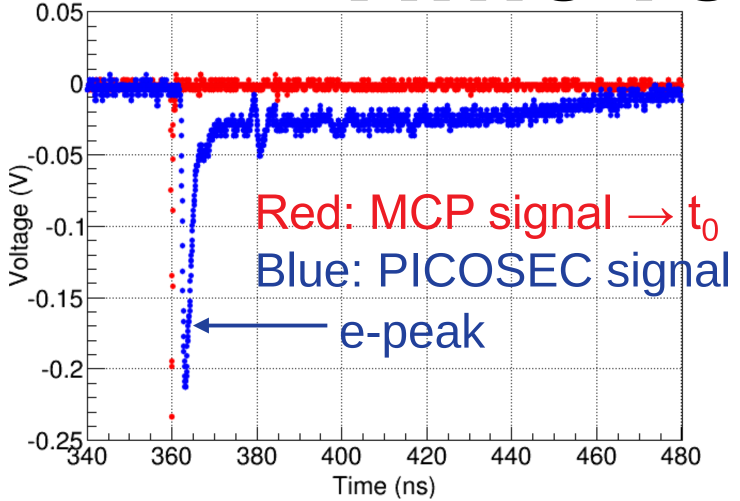


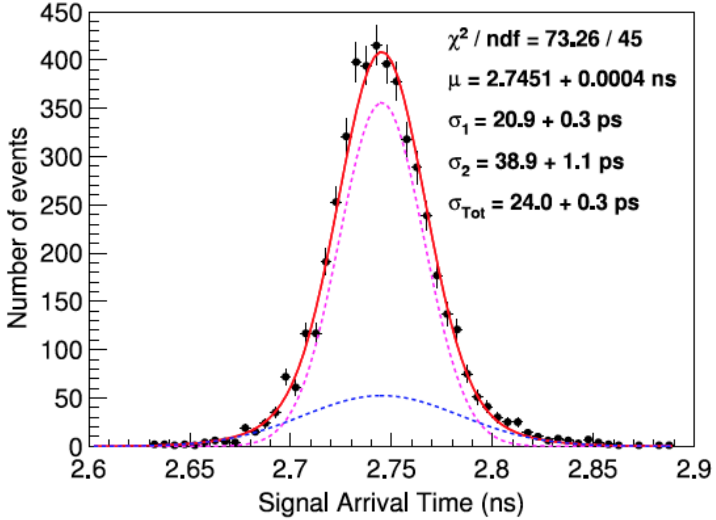
Several PICOSEC prototypes tested in parallel

- **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.

Last run Oct. 2018:
The latest for the next 2 years at CERN

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**

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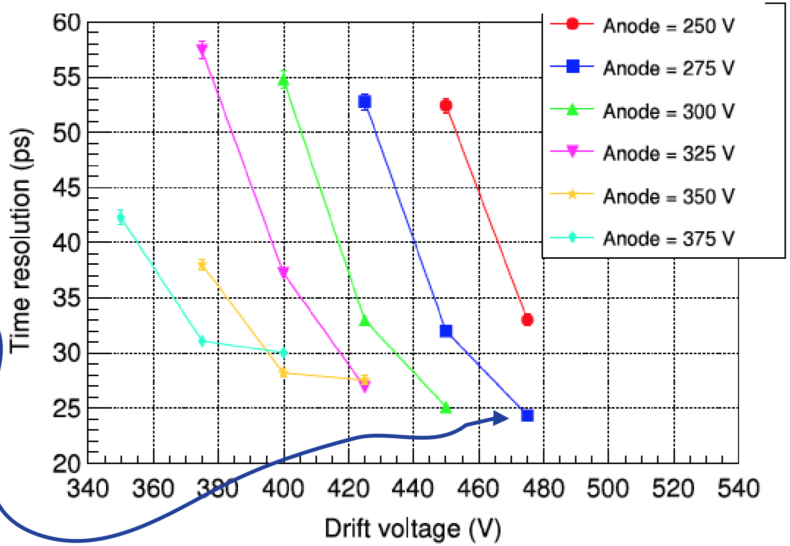


2. A well understood detector

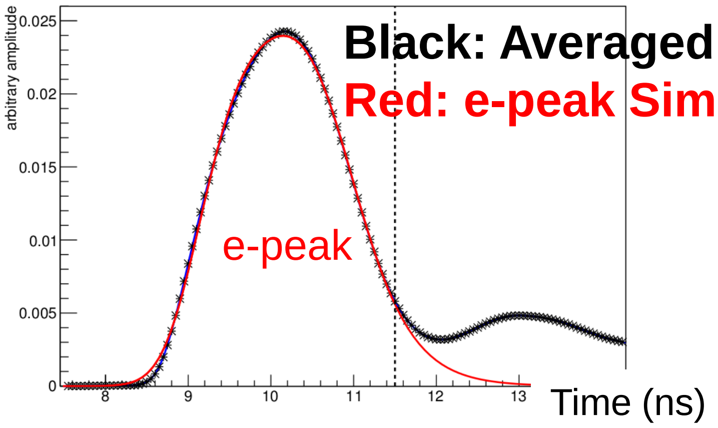
detailed simulations and modeling

Modeling the Timing Characteristics of the PICOSEC Micromegas Detector

J. Bortfeldt[b], F. Brunbauer[b], C. David[b], D. Desforge[a], G. Fanourakis[e], J. Franchi[b], M. Gallinaro[g], F. García[k], I. Giomataris[a], T. Gustavsson[i], C. Guyot[a], F.J. Iguaz[a], M. Kebbiri[a], K. Kordas[d], P. Legou[a], J. Liu[c], M. Lupberger[b], O. Maillard[a], I. Manthos[d], H. Müller[b], V. Niaouris[d], E. Oliveri[b], T. Papaevangelou[a], K. Paraschou[d], M. Pomorski[j], B. Qi[c], F. Resnati[b], L. Ropelewski[b], D. Sampsonidis[d], T. Schneider[b], P. Schwemling[a], L. Sohl[a], M. van Stenis[b], P. Thuiner[b], Y. Tsipolitis[f], S.E. Tzamarias[d,*], R. Veenhof[h,l,m], X. Wang[c], S. White[b], Z. Zhang[c], Y. Zhou[c]

arXiv:1901.10779v1 [physics.ins-det]

Detailed simulation with “trimmed” Garfield++



Black: Averaged PICOSEC waveforms in a certain e-peak charge region

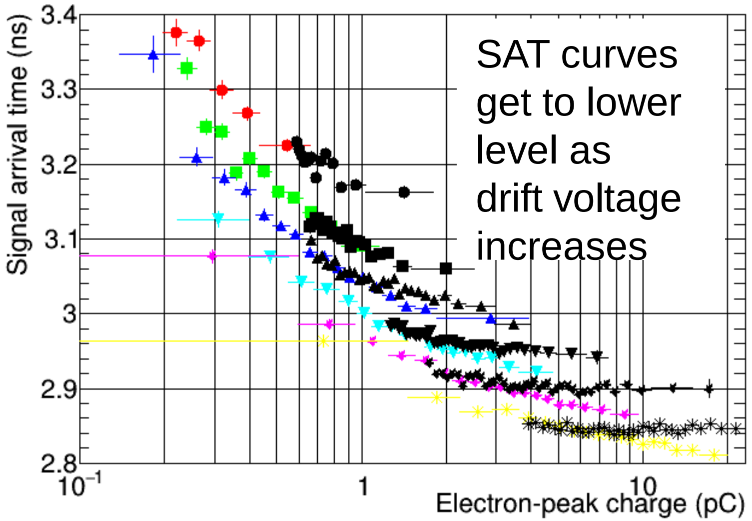
Red: e-peak Simulation Prediction (Garfield++ and *Electronics Response*)

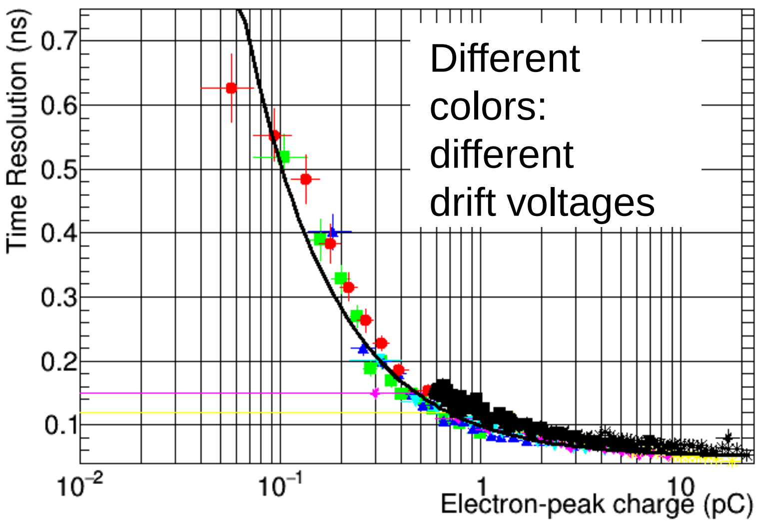
derived from single p.e data
(our “impulse response”)

All behaviours seen in single p.e. laser data are also seen in these detailed Garfield++ simulations. e.g., see below:

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

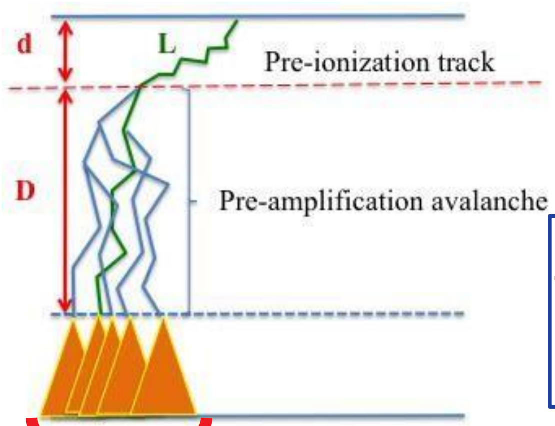
* Time resolution depends mostly on e-peak charge





Color: Simulation – Black: Data

Detailed simulations:under the hood



Gives e-peak pulse

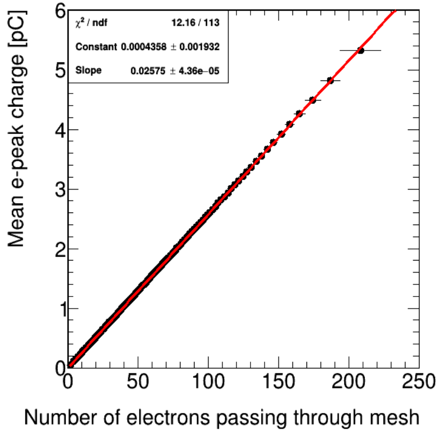
Microscopic equivalent to e-peak's SAT = Mean Time (T) of all electron arrival times on the mesh

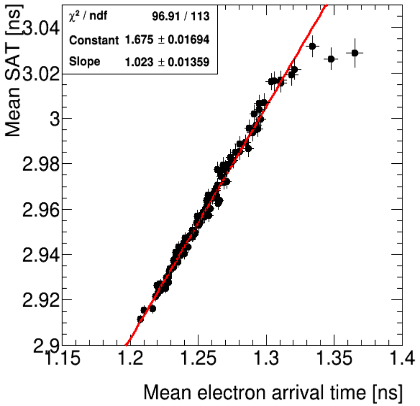
*** <SAT> linear with <T>**

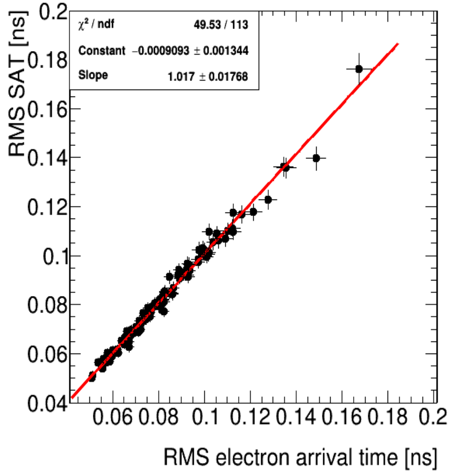
*** RMS(SAT) linear with RMS(T)**

Correspondence of experimental Observables to Relevant Microscopic Variables

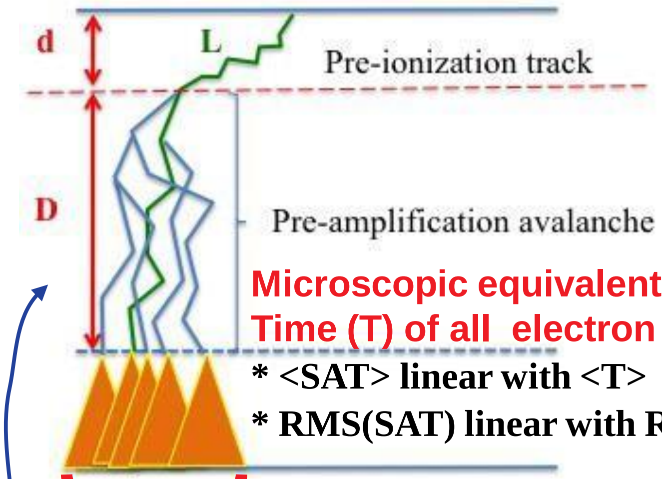
Sets of avalanches of a certain e-peak charge







Detailed simulations:under the hood



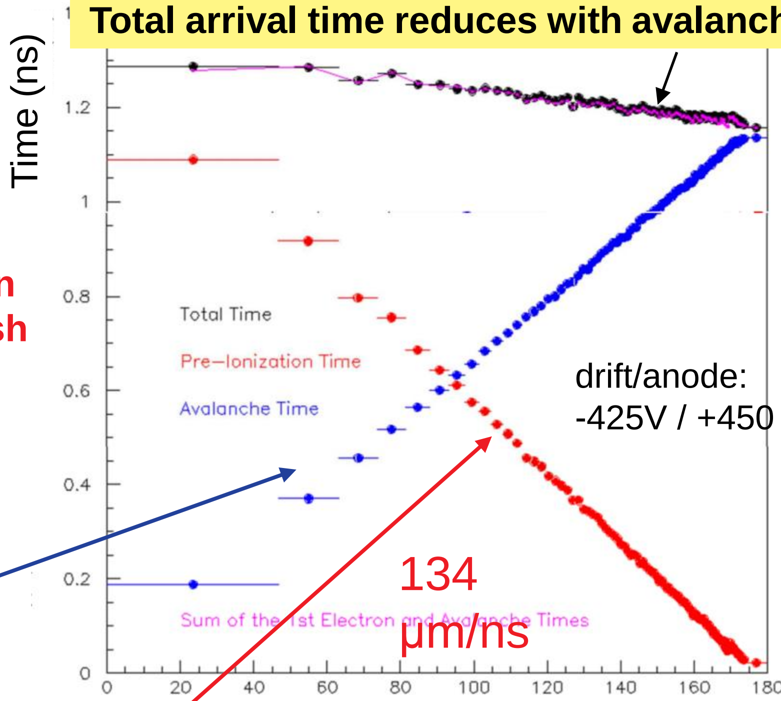
Microscopic equivalent to e-peak's SAT = Mean Time (T) of all electron arrival times on the mesh

* <SAT> linear with <T>
* RMS(SAT) linear with RMS(T)

Gives e-peak pulse

154 μm/ns

Total arrival time reduces with avalanche length



Avalanche length, D (μm)

drift/anode:
-425V / +450 V

134 μm/ns

!

Avalanche runs with higher drift velocity than pre-ionization electron
So, SAT slewing seen in single p.e data is explained:
SAT reduces with avalanche length
Long avalanches → big e-peak charge } **SAT reduces with e-peak charge**

!

More counter-intuitive observations found related to collective, emerging properties of the avalanche!!

Modeling the Timing Characteristics of the PICOSEC Micromegas Detector

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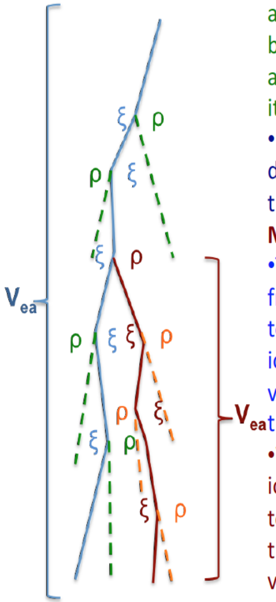
arXiv:1901.10779v1 [physics.ins-det]

The Model



•An ionizing electron in the avalanche, every time it ionizes, will gain a time ξ_l relative to an electron that undergoes elastic scatterings only.

• Any newly produced electron by ionization starts with low energy; at the start of its path, it suffers less delay due to elastic backscattering compared to its parent. Therefore, the model assumes that such a newly produced electron will gain, relative to its parent, a time-gain ρ_l.

• The parameters ξ_l and ρ_l should follow a joint probability distribution determined by the physical process of ionization and the respective properties of interacting molecules.

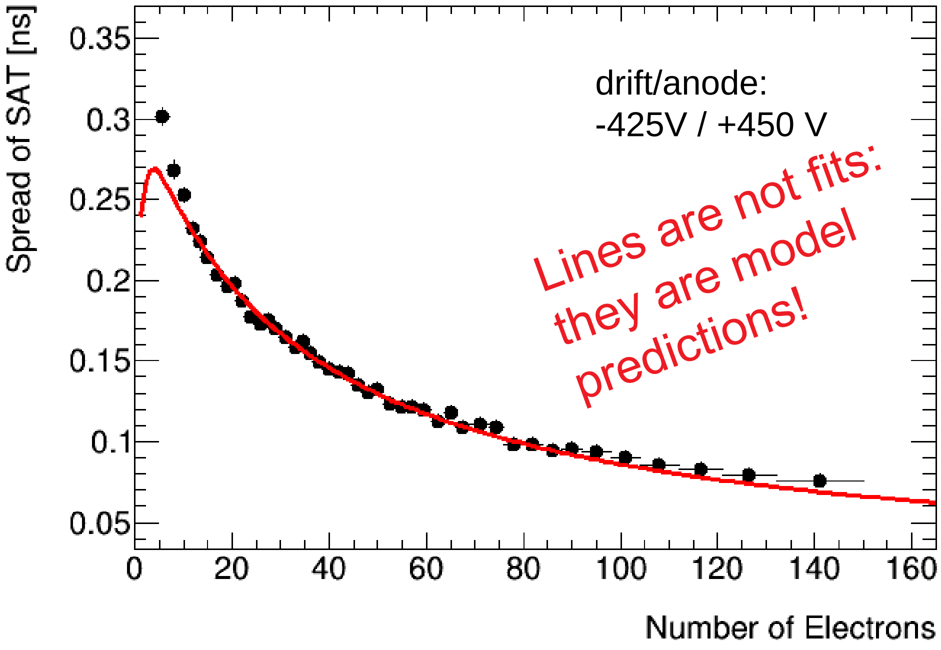
Model Approximations

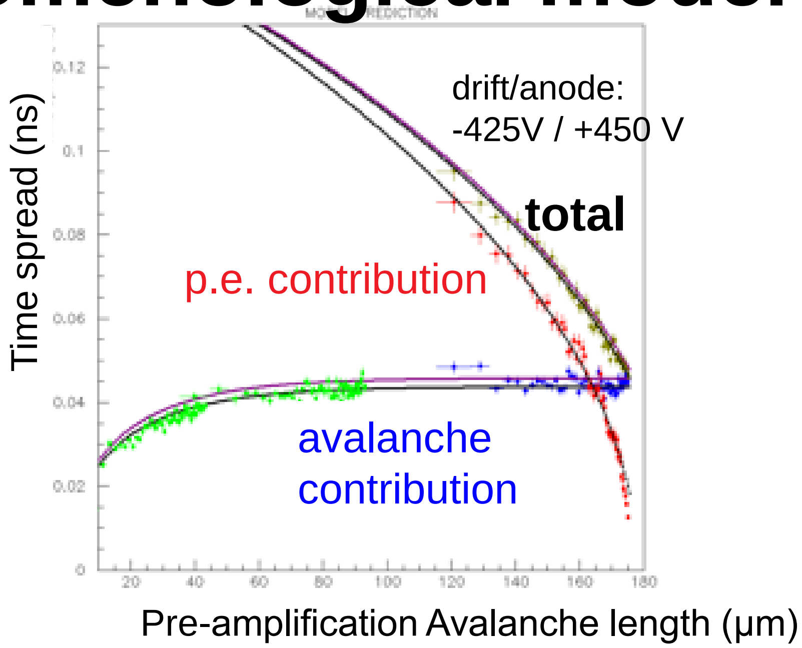
•The collective effect of time-gains ξ_l is a change in drift velocity from V_p, which is the photoelectron drift velocity before ionization, to an effective drift velocity V_{ea}, which is the drift velocity of an ionizing electron in the avalanche. By taking V_{ea} to be the drift velocity of any electron in the avalanche, the energy-loss effect on the drift of the parent electron has been taken into account.

•When a new electron is produced in the avalanche, through ionization, it will gain time ρ_l, at its production, which it is assumed to follow a distribution with mean value ρ and variance w^2. From that moment onwards, this new electron propagates with drift velocity V_{ea}, as any other existing electron in the avalanche.

Understood in terms of phenomenological model

- 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) **arXiv:1901.10779v1 [physics.ins-det]**

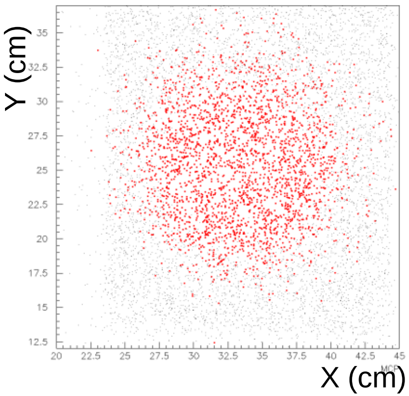
!

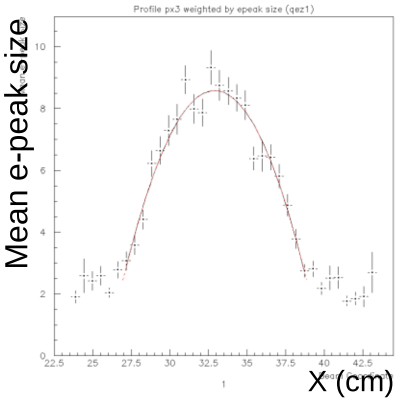
3. Estimation of the No of pes per MIP

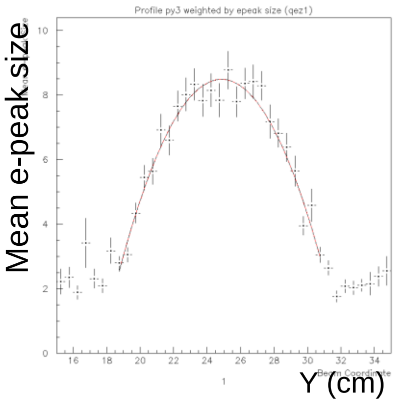
(see also Xu Wang talk)

A consistent and unbiased procedure to estimate the number of photoelectrons per MIP

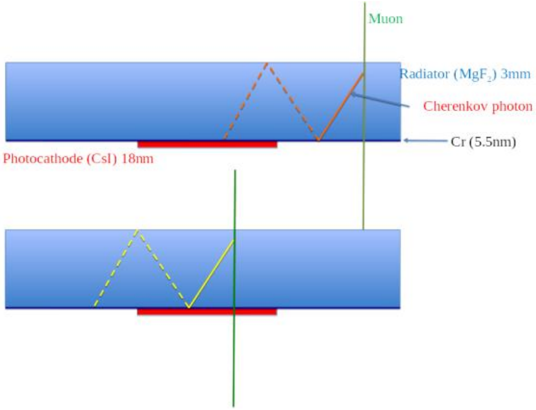
Precise alignment based on the charge-weighted beam profile

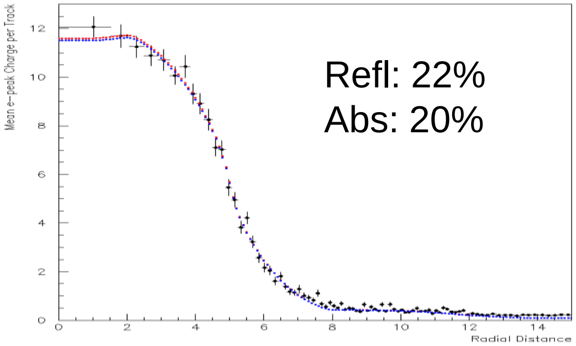






Determination of the anode geometrical acceptance taking into account reflections

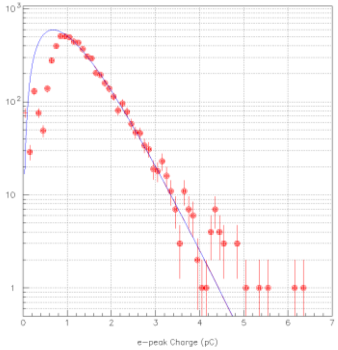




Mean charge per track (pC) vs the track radial distance (mm)

A consistent and unbiased procedure to estimate the number of photoelectrons per MIP

Determination of the charge distribution parameters when the PICOSEC MM responds to a single-pe using UV calibration data



A Polya fit to the single-pe charge distribution

$$P_{spe}\left(Q;a=b=\theta+1,\bar{Q}_e\right)dQ=\frac{1}{\bar{Q}_e}\frac{(\theta+1)^{(\theta+1)}\left(Q/\bar{Q}_e\right)^{\theta}}{\Gamma(\theta+1)}e^{-(\theta+1)Q/\bar{Q}_e}dQ$$

$$E\left[Q_{spe}\right]=\bar{Q}_e=\langle Q_e\rangle$$

$$V\left[Q_{spe}\right]=\frac{1}{\theta+1}\langle Q_e\rangle^2=RMS^2$$

RMS	Mean
0.6433	1.0668
0.6498	1.1102
0.6452	1.117
0.6388	1.0786
0.6398	1.028
0.64305	1.0118

Take into account systematic errors due to threshold effects

Fit the charge distribution of the PICOSEC response to muons

If N is the mean number of pes produced per muon track, then a muon passing through the radiator at distance R from the anode center will result to a PICOSEC signal with charge Q.
Q follows a p.d.f. F(Q,R;N) which can be expressed using the geometrical acceptance A(R), as a convolution of a Poissonian distribution with mean N·A(R)

$$\Pi(N_{pe};N,A(R))=\frac{[N\cdot A(R)]^{N_{pe}}}{N_{pe}!}\cdot\exp[-N\cdot A(R)]$$

and the multi-Polya distribution

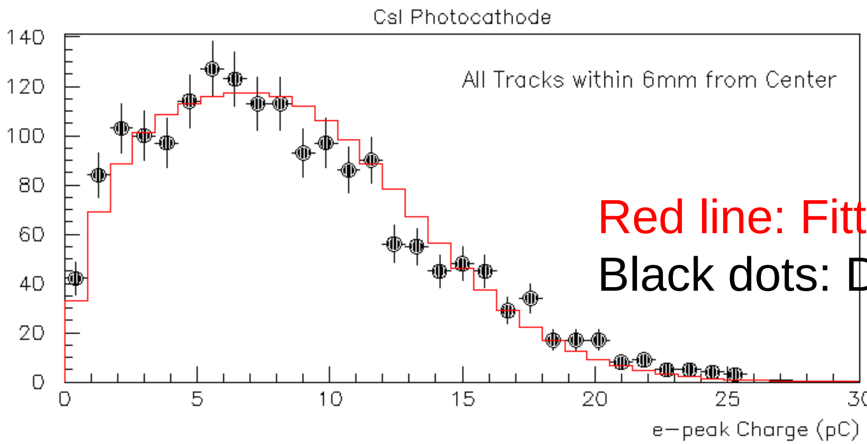
$$P(Q;N_{pe},\theta,\overline{Q}_e)=\underbrace{P_{spe}\otimes P_{spe}\cdots\otimes P_{spe}}_{N_{pe}\ times}=\frac{1}{\overline{Q}_e}\frac{(\theta+1)^{N_{pe}(\theta+1)}(Q/\overline{Q}_e)^{N_{pe}(\theta+1)-1}}{\Gamma(N_{pe}(\theta+1))}\cdot\exp[-(\theta+1)\cdot Q/\overline{Q}_e]$$

as

$$F(Q,R;N)=\sum_{N_{pe}=0}^{\infty}\Pi(N_{pe};N,A(R))\cdot P(Q;N_{pe},\theta,\overline{Q}_e)$$

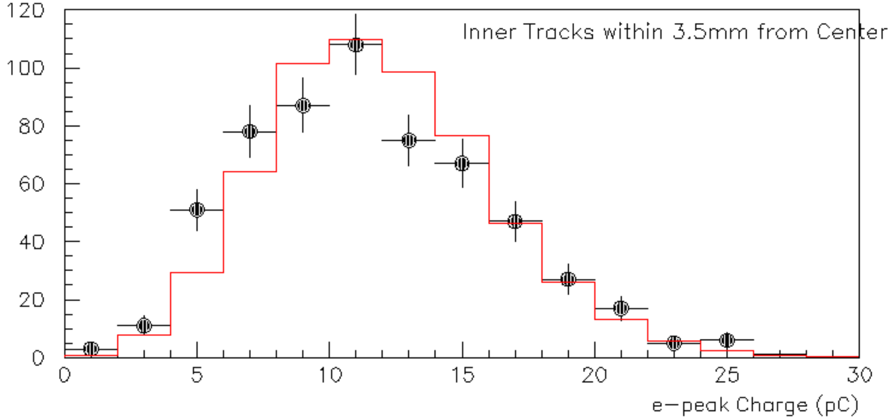
A consistent and unbiased procedure to estimate the number of photoelectrons per MIP

11.5 ±0.4(stat)±0.5(syst) photoelectrons per muon track

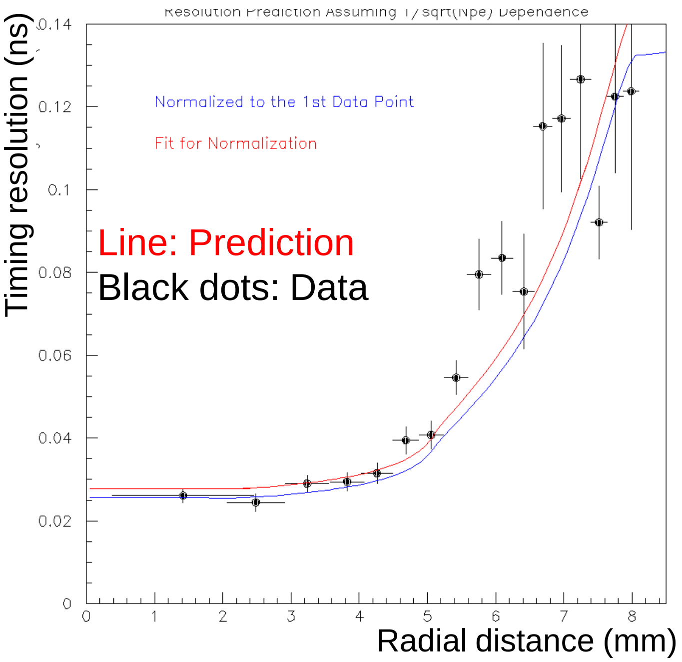


Red line: Fitted curve

Black dots: Data



Resolution prediction vs distance from the anode center, assuming 1/sqrt(Npe) dependence

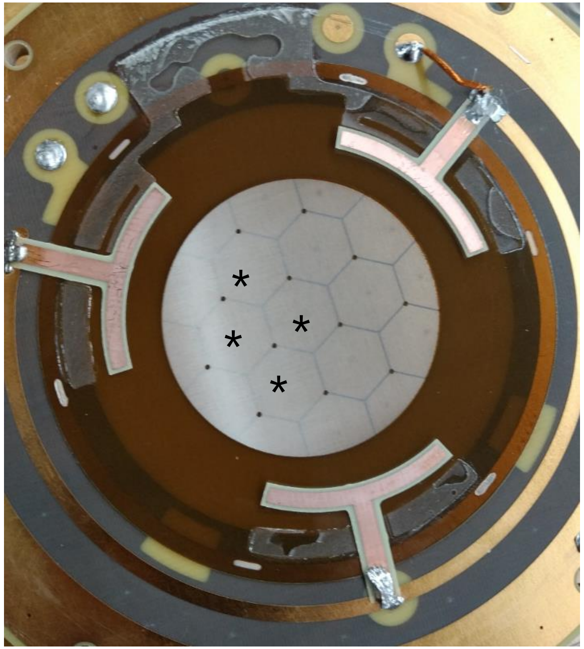


4. Towards a large scale detector

Results from a multi-channel prototype

Multi-pad MicroMegas

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



Hexagonal pads 5mm side

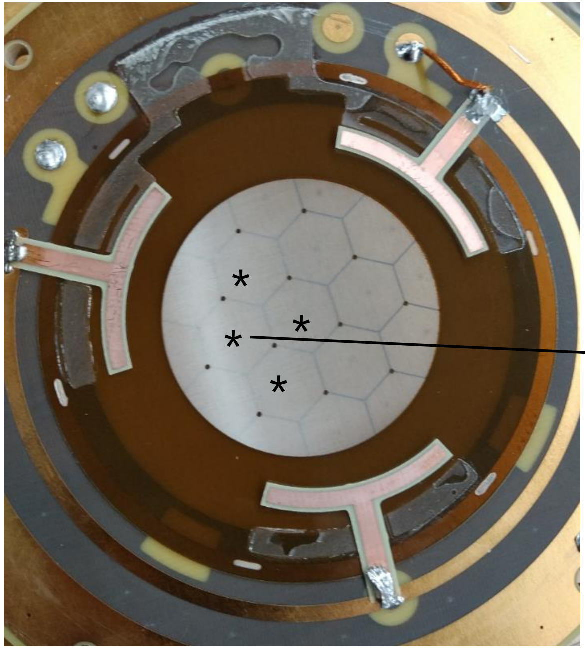
Readout 4 pads → 2 osciloscopes

(*** for multi-channel: have to move to chip solutions. Tried SAMPIC, no results yet)

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

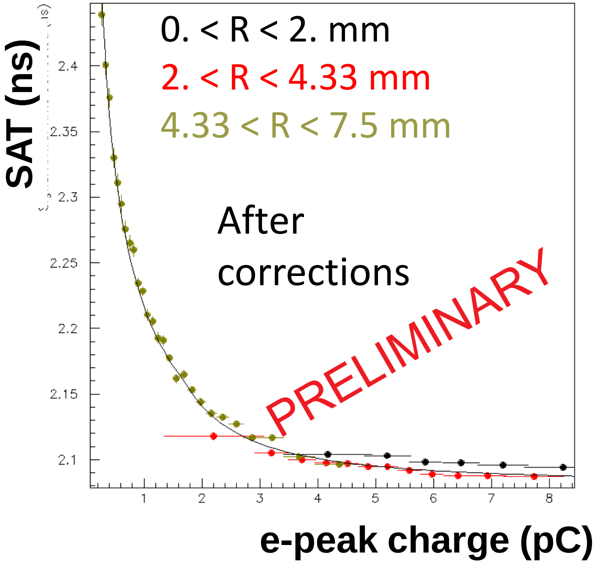


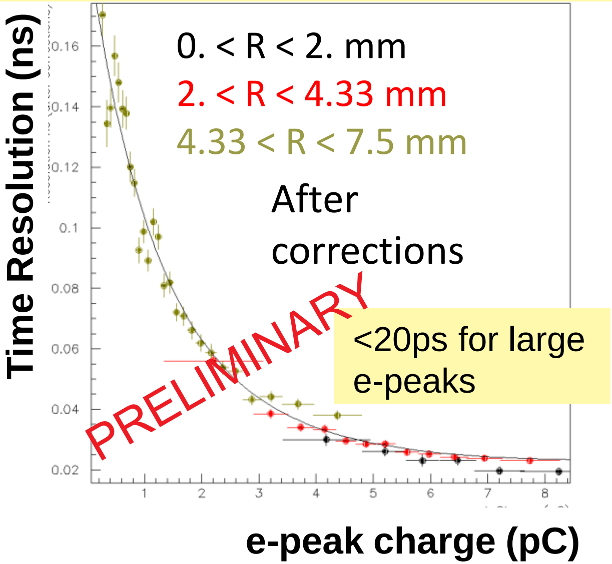
Hexagonal pads 5mm side

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:





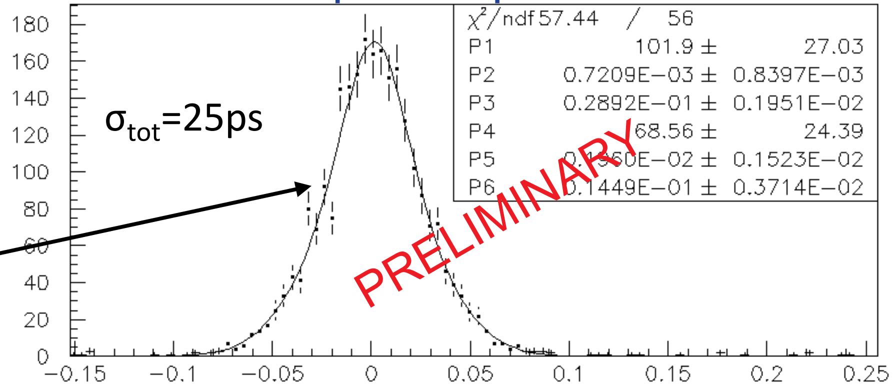
Multi-pad: Same resolution as single-pad

<u>**At center of each pad (0<R<2mm):**</u>

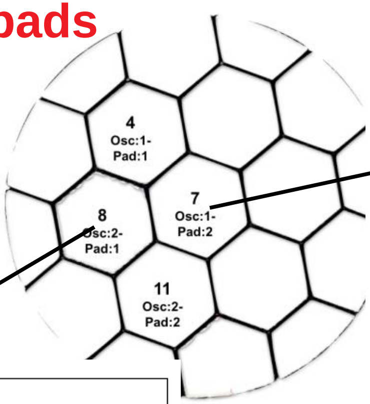
a time resolution of 25ps for all pads

E.g.:

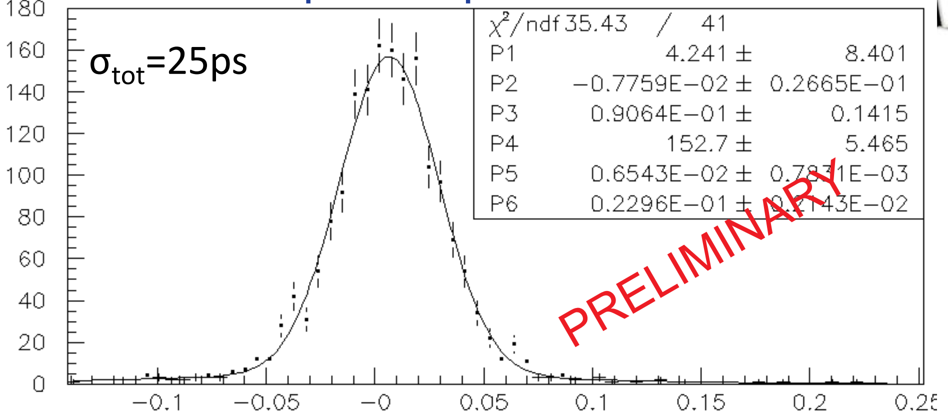
Individual pad response



ΔT = Time after all corrections (ns)



Individual pad response

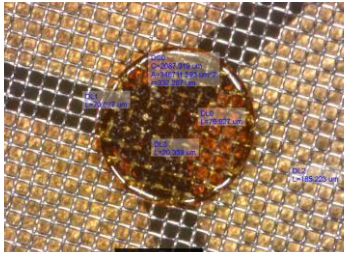


ΔT = Time after all corrections (ns)

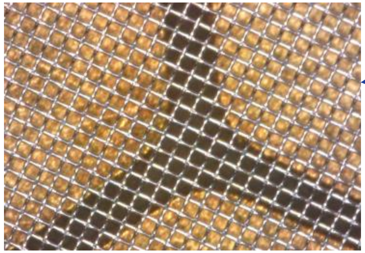
Multi-pad: pad responses for any impact point

These are not the easiest regions

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



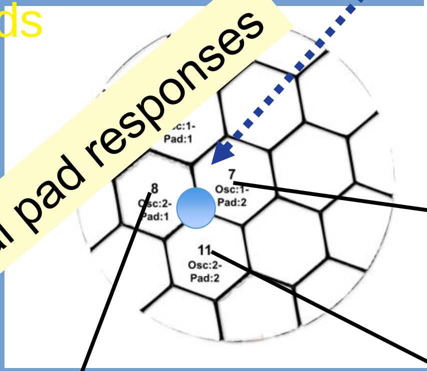
Pilars of ~650µm diameter

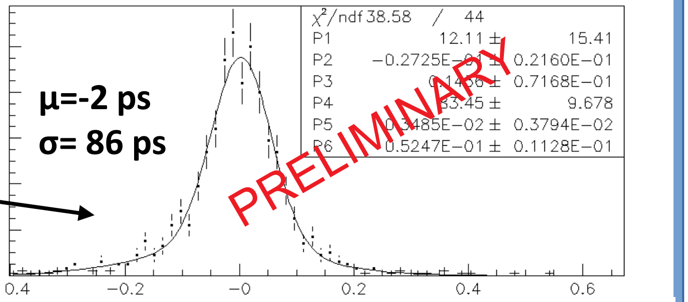


200µm inter-pad space

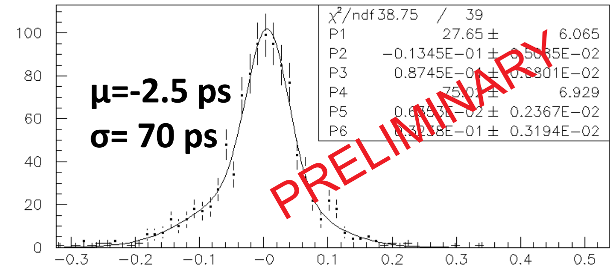
Each individual pad: resolution worsens moving outwards

Individual pad responses

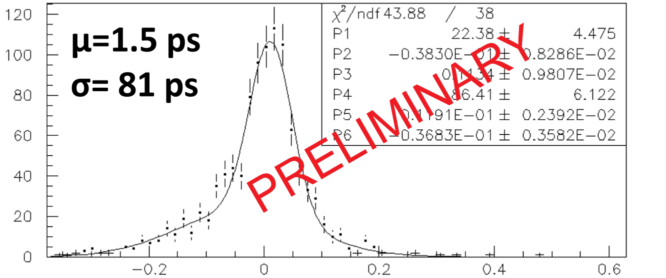




ΔT = Time after all corrections (ns)

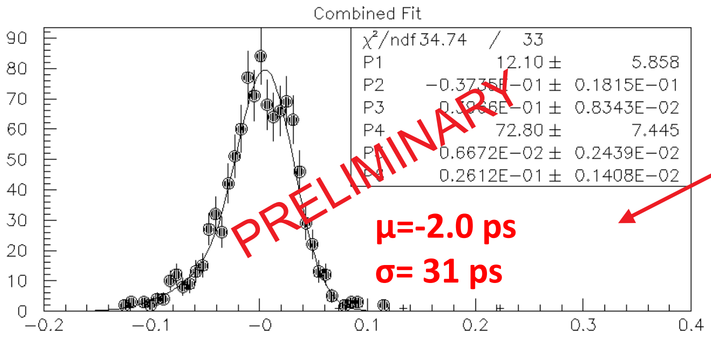


ΔT = Time after all corrections (ns)

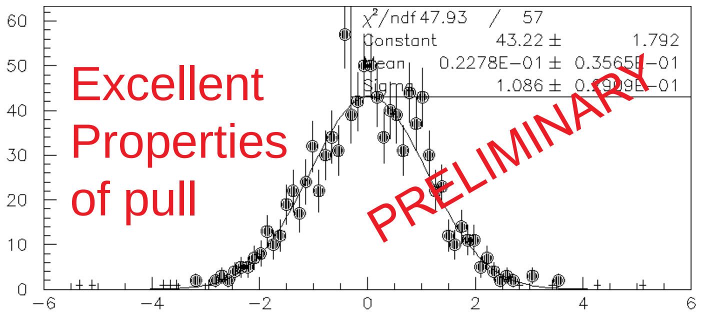


ΔT = Time after all corrections (ns)

Multi-pad: Combining pads



ΔT = Time after all corrections (ns)



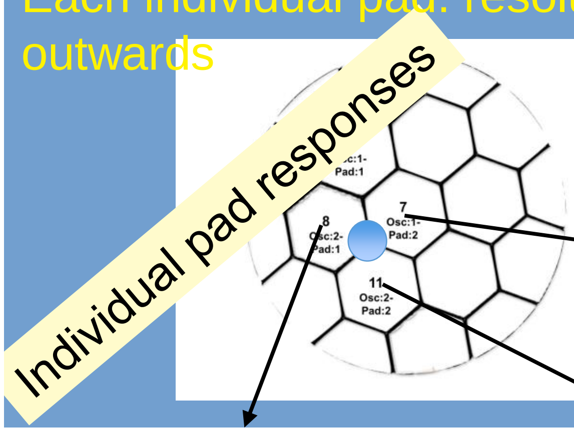
$\Delta T / \sigma_t$

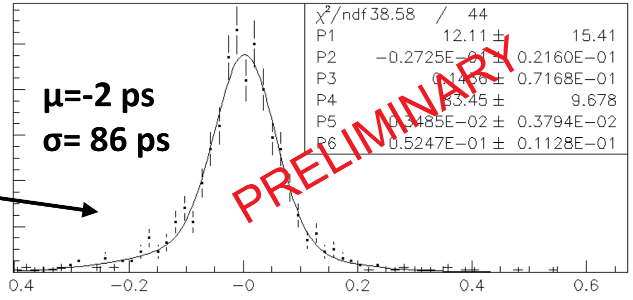
Similar results all across the area covered by the 4 pads

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

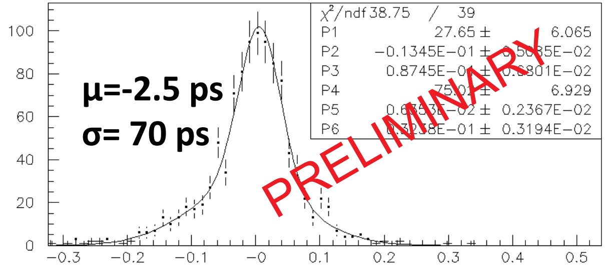
Combining pads event-by-event → Excellent time resolution

Each individual pad: resolution worsens moving outwards

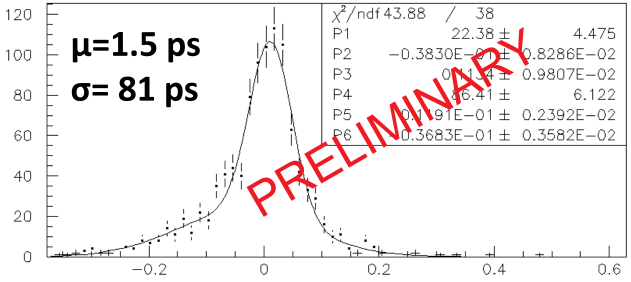




ΔT = Time after all corrections (ns)



ΔT = Time after all corrections (ns)



ΔT = Time after all corrections (ns)

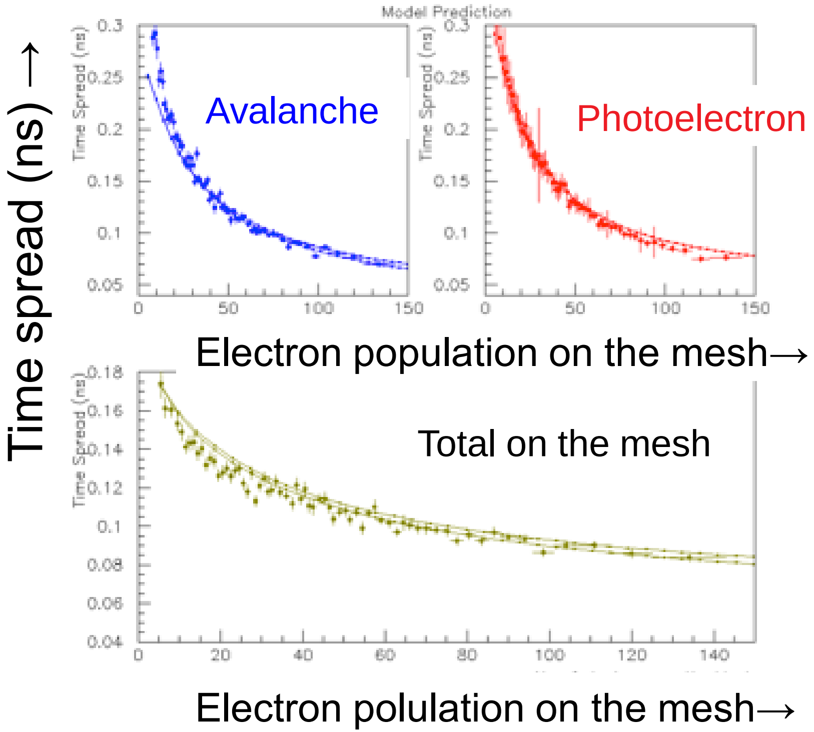
Conclusions

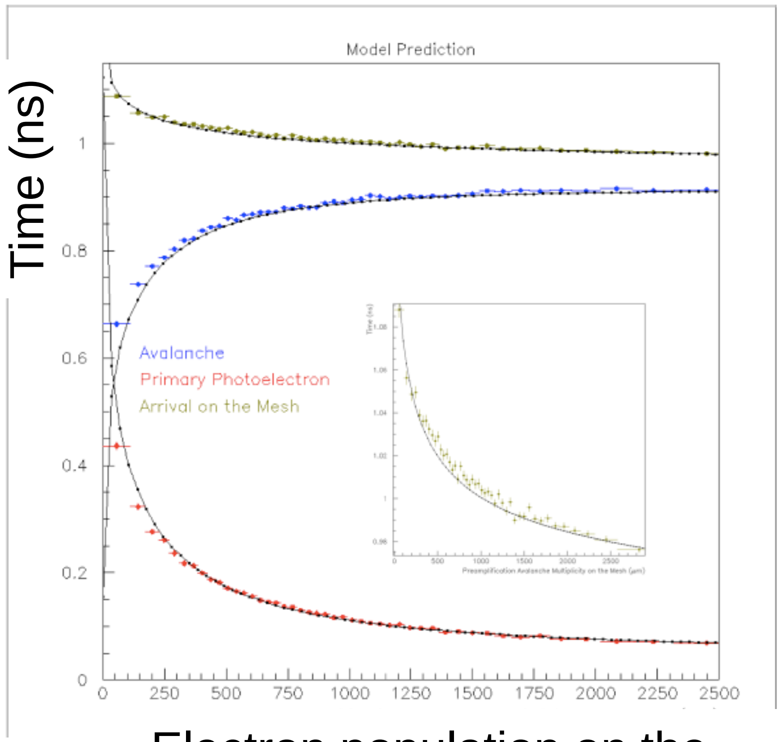
- PICOSEC MicroMegas: a detector with precise timing:
  - Single-channel prototype in Laser and Particle beams
  - 76ps for single photoelectrons, 24ps resolution for timing MIPs
- A well-understood detector:
  - reproduce observed behavior with detailed simulations and a phenomenological model: valuable tool for parameter-space exploration
- Efficient photocathode
  - consistent and unbiased procedure to estimate the number of photoelectrons per MIP
- Towards a large-scale detector: multi-channel
  - response of multi-channel PICOSEC prototype: similar precision as the single-channel prototype, for any impact point of a MIP

Thank you

Understood in terms of phenomenological model

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



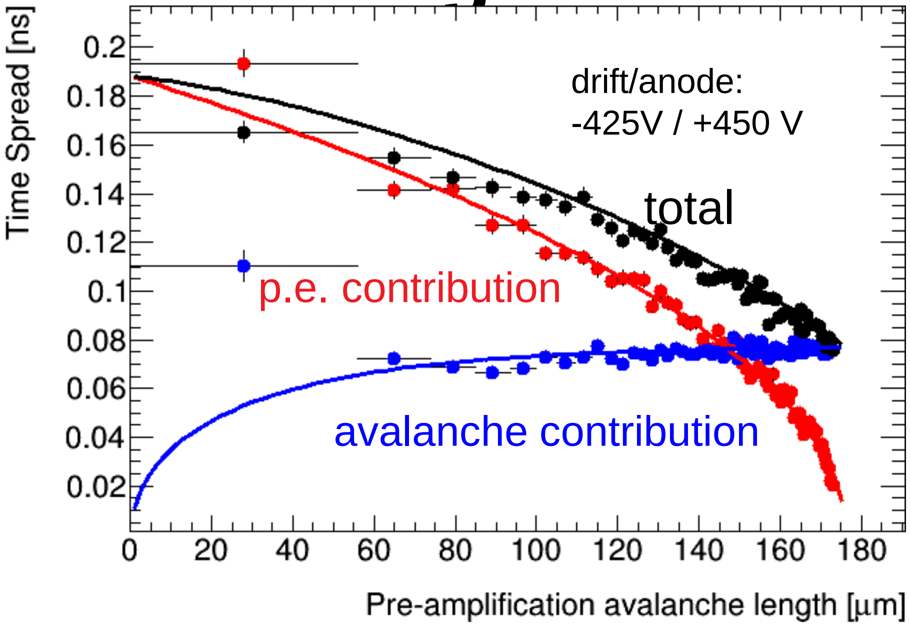


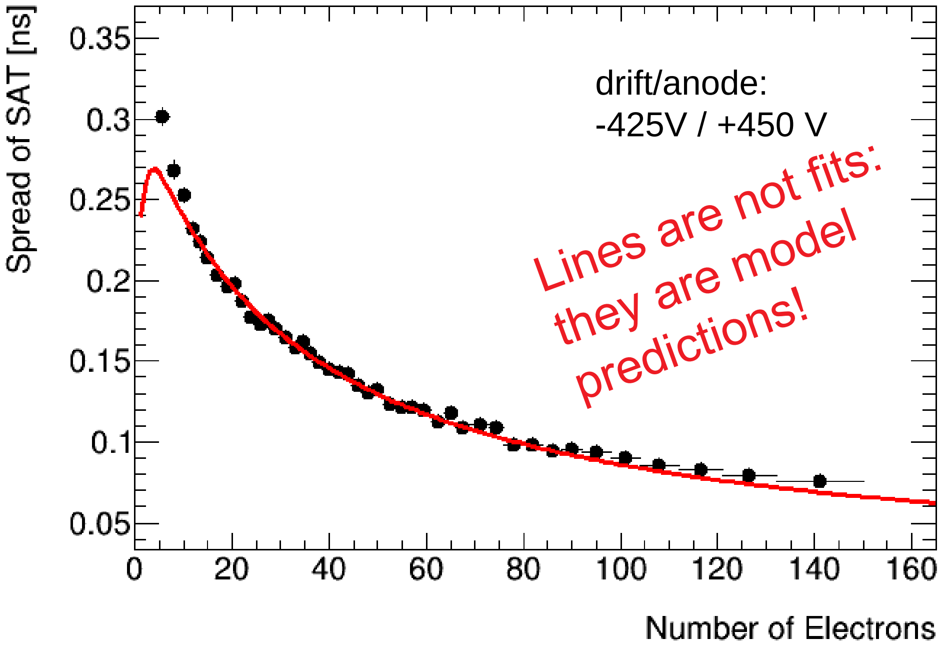
Electron population on the mesh

arXiv:1901.10779v1 [physics.ins-det]

Understood in terms of phenomenological model

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

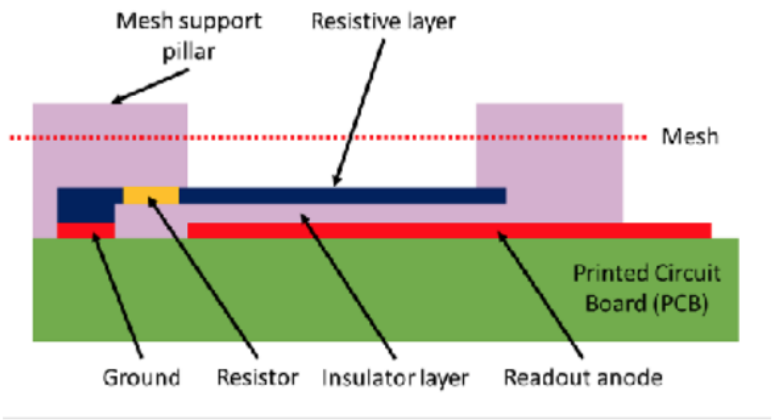


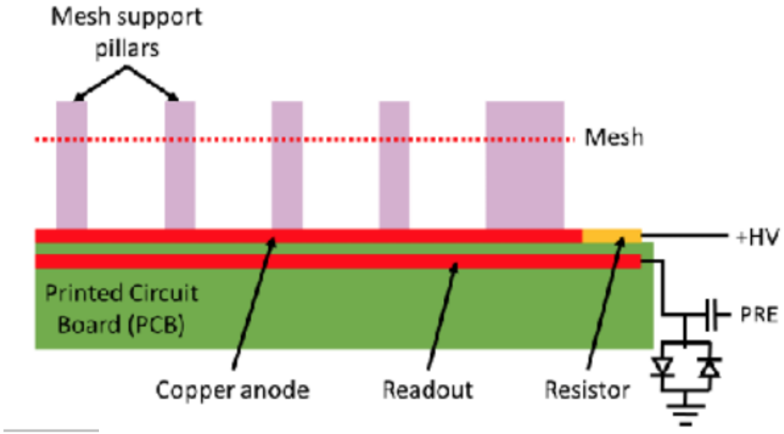


Describe SAT and Resolution
a) vs. avalanche length &
b) **vs. number of electrons in avalanche (i.e, vs. e-peak charge)**
→ Before and after the mesh
Not only averages and RMS, but full distributions, vs. values of operational parameters (e.g., drift voltage)

arXiv:1901.10779v1 [physics.ins-det]

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





Readout beneath resistive layer: picks up signal from above

Copper Layer to HV via resistor; Readout "floating"

Resistive strip grounded

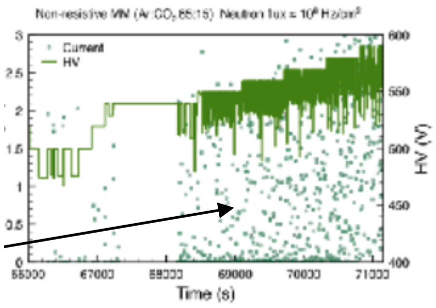
Non resistive ← MAMA results → With resistive strip

Developed in the MAMA project

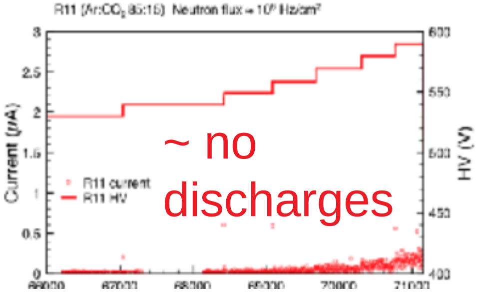
Resistive readouts operate stably at high gain in neutron fluxes of 10^6 Hz/cm^2.

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

Current →



discharges



~ no discharges

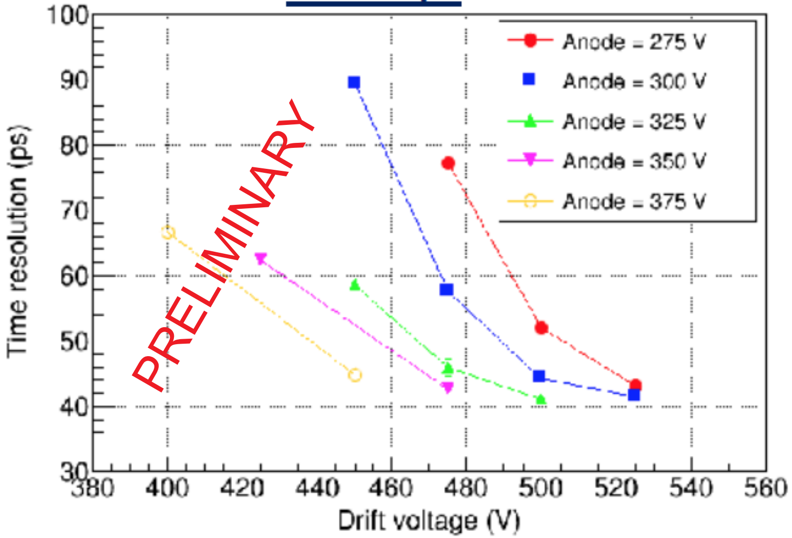
Irradiation time →

Beam results with protected anodes

Time resolution

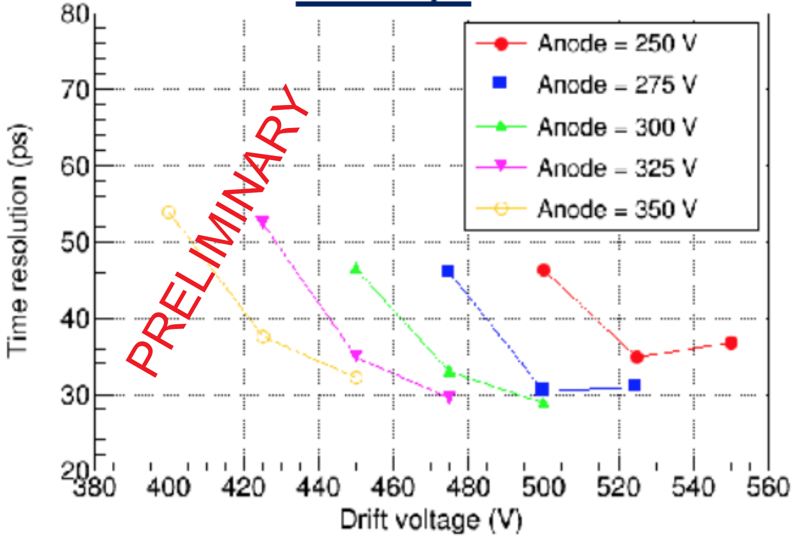
Resistive strips

σ = 41 ps



Floating strips

σ = 28 ps

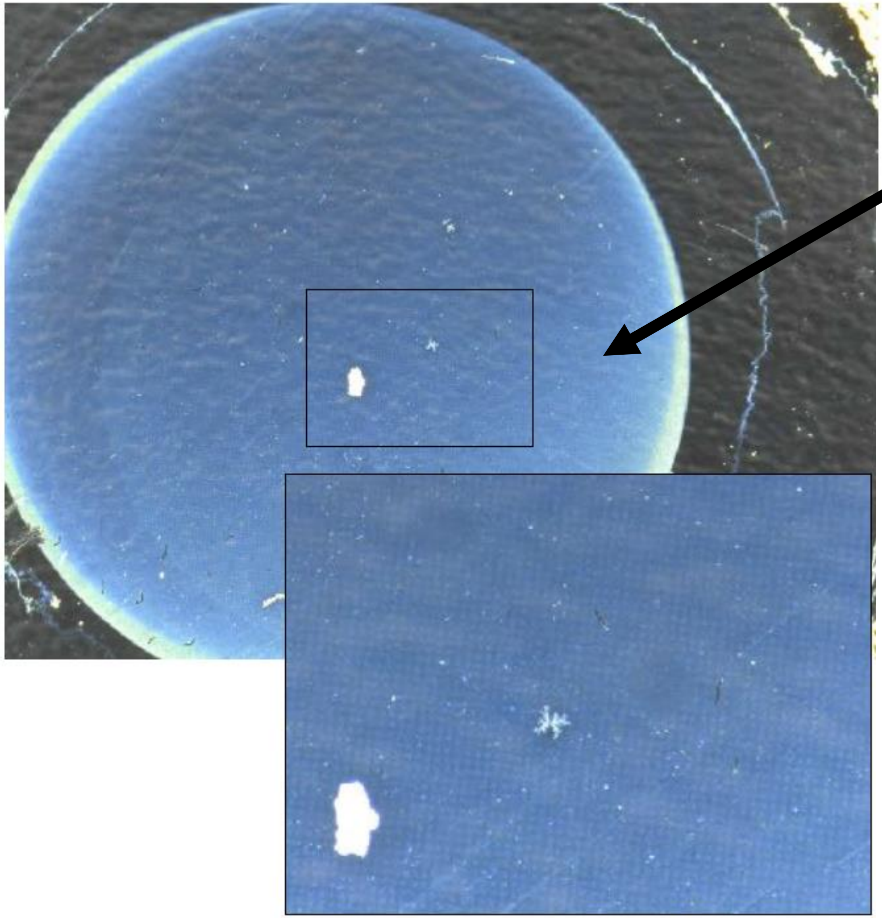


PRELIMINARY

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

Best resolution was at voltages which give high ion backflow? robust photocathode

Best time resolution (24ps for MIPs) for CsI photocathode, but not robust



- Ion back flow damages CsI photocathode

Robust photocathodes needed.

Investigating Photocathodes

- For each photocathode material the working point with the best time resolution has to be determined
- The time resolution, quantum efficiency and efficiency are compared
- Reference single photon measurements and tracking data are necessary

And they have to be robust.

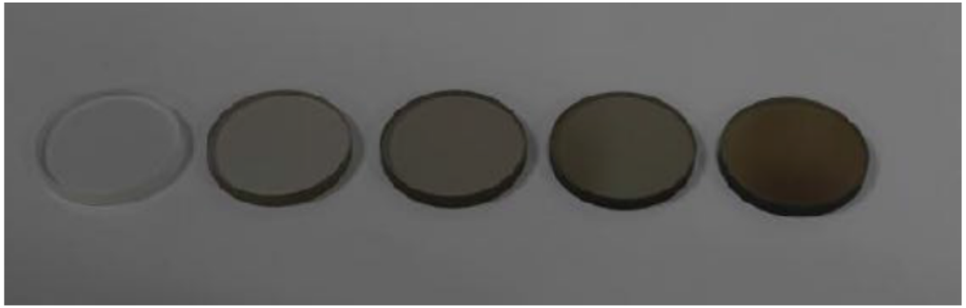
Most promising performance results for non-CsI are from Diamond-Like Carbon (DLC), which also seems robust:

- atmospheric conditions for a few months
- irradiated with pions, in a resistive MM prototye →minimal reduction of Npe/MIP

Different Materials tested like:

- Metallic Photocathodes
- CsI with protection layer
- Nano Diamond Seeding
- Diamond secondairy emitter
- Diamond-like Carbon

3mm MgF_2 + DLC of different thicknesses :



See talk by Xu Wang

Promising: Diamond Like Carbon (DLC) photocathodes

- **2.5 nm DLC time resolution up to 34 ps observed**
- **Results repeatable in independent samples and Measurements**
- **Addtitional tests with heating treatment under N2 and H2**
- **Additional aging tests under pions**
- **Samples survived rough transport from China**

Thickness of DLC film (nm)	Npe/per muon	Detection efficiency for muons
1	Bad	Bad
2.5	3.7	97%
5	3.4	94%
7.5	2.2	70%
10	1.7	68%
5 nm Cr + 18 nm CsI	7.4	100%

PRELIMINARY

2.5 nm DLC in Bulk MM

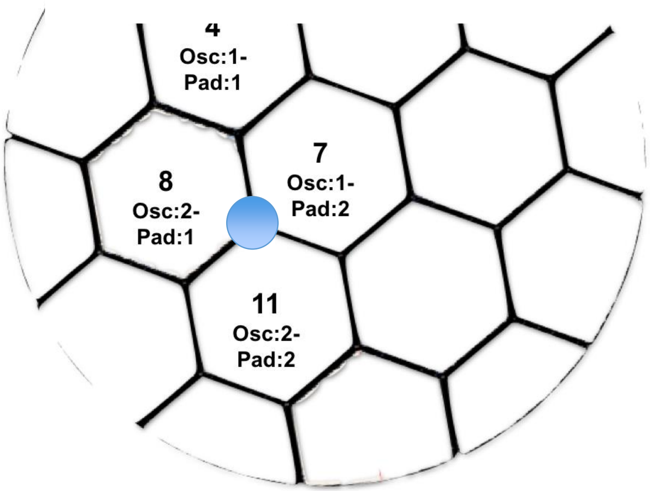
A/D Voltage	Time Res. (ps)
250/550	37
250/575	34
275/525	38
275/550	34
300/500	39
300/525	34

PRELIMINARY

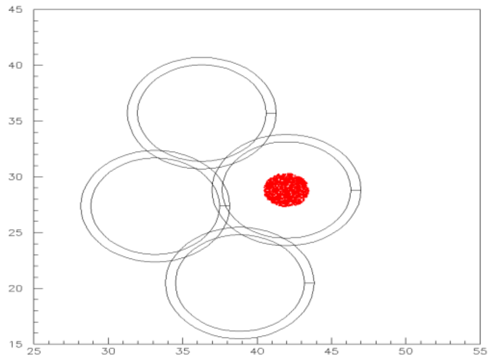
See talk by Xu Wang

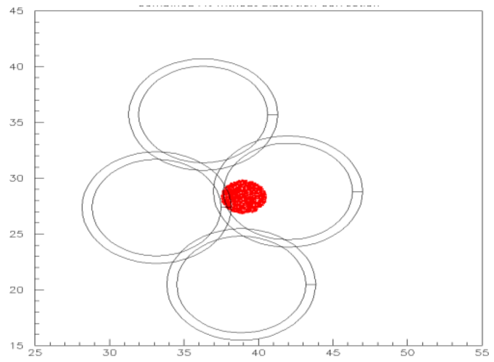
Multi-pad PICOSEC: Combining multiple pads

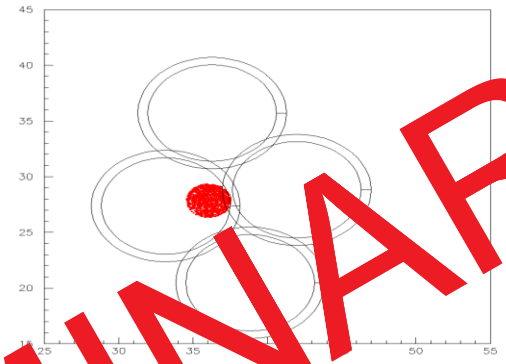
$$\chi^2 = \sum_{i=1,4} \frac{\left(\left[t_i - \left\{\langle SAT\rangle(R_i,\theta_i) - \langle SAT\rangle(R_i,90^o)\right\} - \left\{SL(Q)\right\} - \hat{t}\,\right]\right)^2}{\left(\mathrm{Res}\,(Q_i)\right)^2}$$

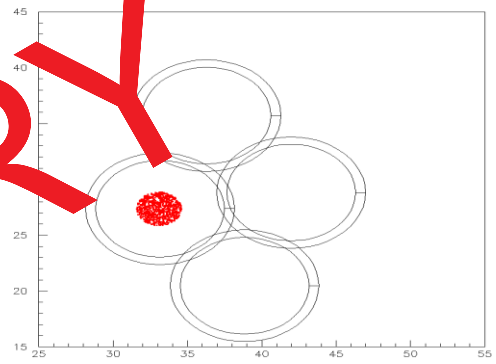


Multi- pad: Tracks are selected within a circle of 1.5 mm radious

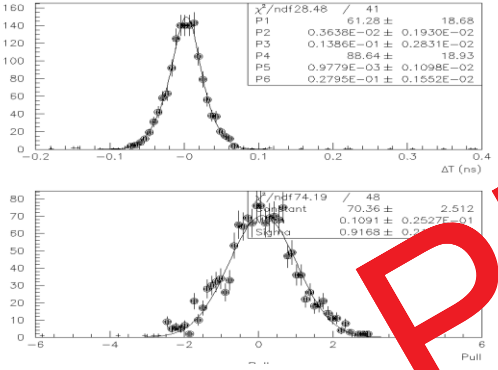




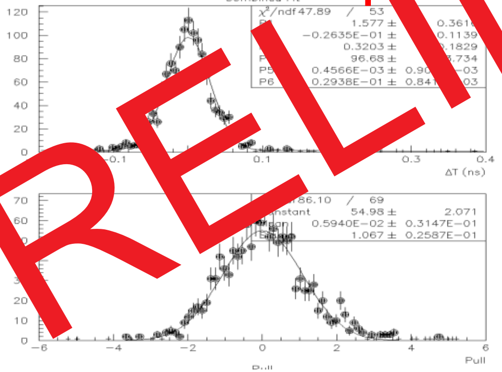




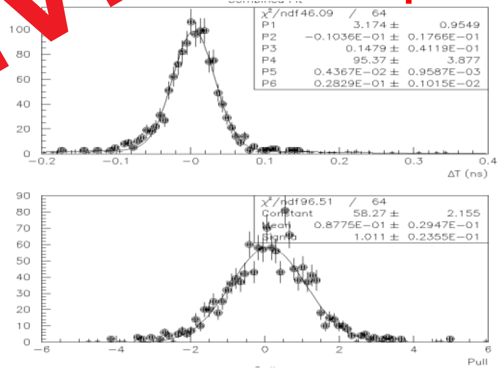
μ=1.6 ± 2ps
σ= 25± 1.5 ps



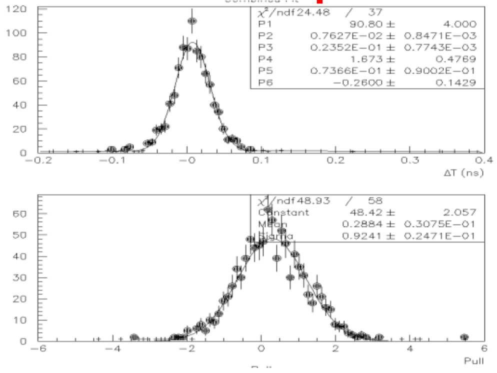
μ=0 ± 2ps
σ= 31± 1.5 ps



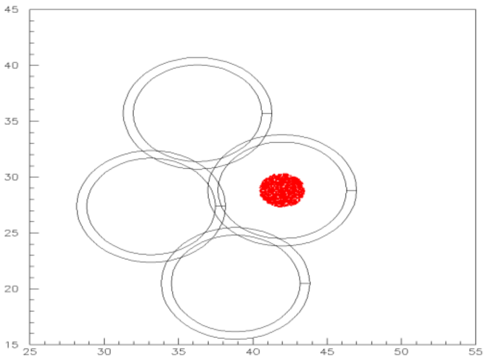
μ=2 ± 2ps
σ= 31± 1.5 ps

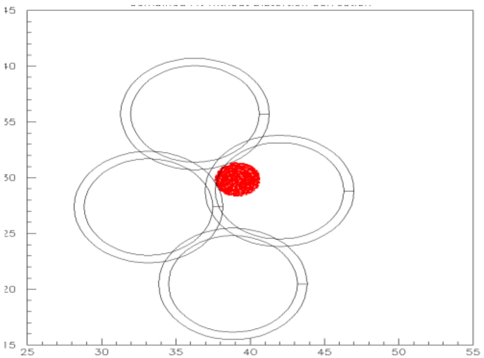


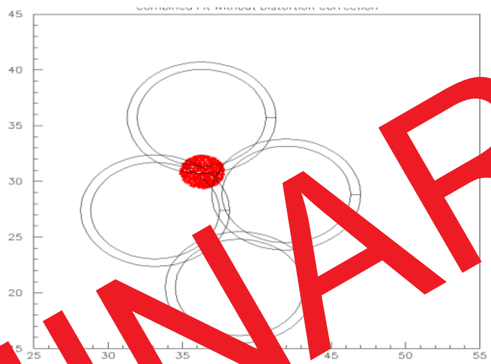
μ=5 ± 2ps
σ= 25± 1.5 ps

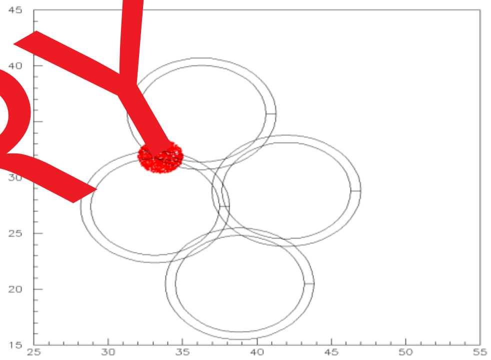


Multi- pad: Tracks are selected within a circle of 1.5 mm radious

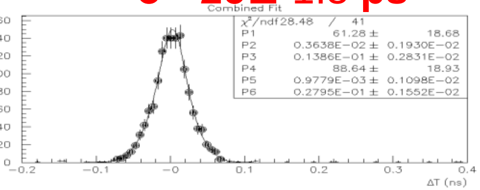


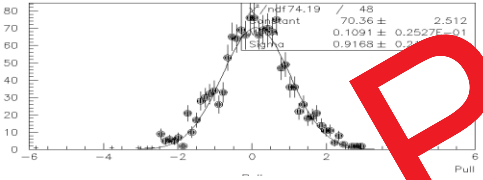




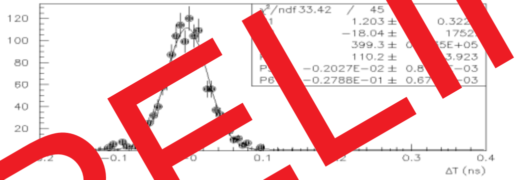


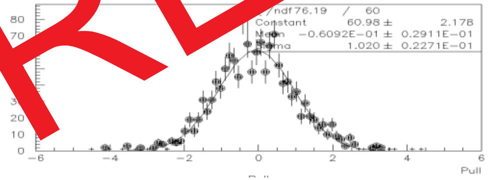
μ=1.6 ± 2ps
σ= 25± 1.5 **ps**



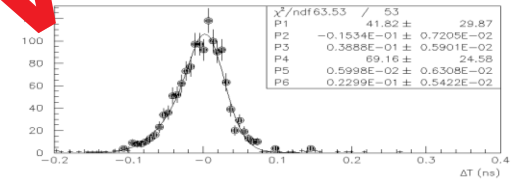


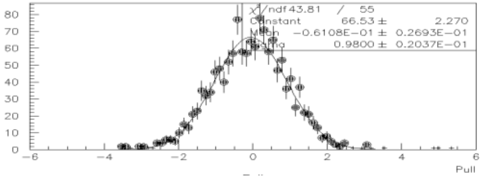
μ=-2 ± 2ps
σ= 29± 1.5 **ps**



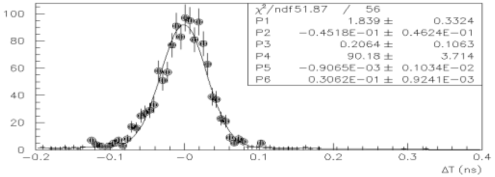


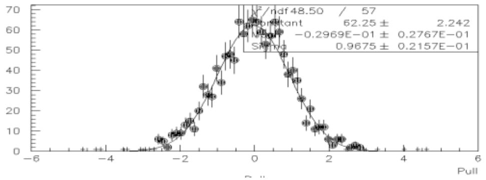
μ=-4 ± 2ps
σ= 32± 1.5 **ps**





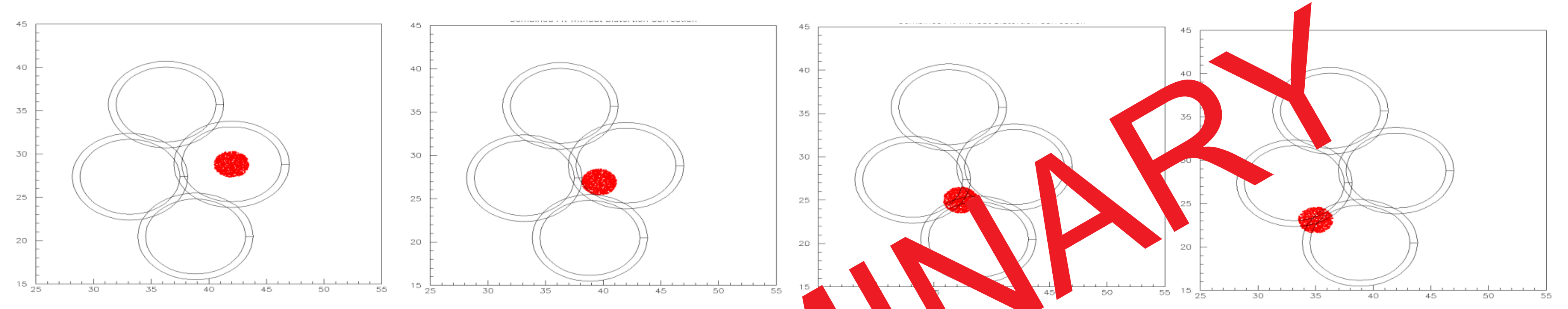
μ=-1.5 ± 2ps
σ= 33± 1.5 **ps**





PRELIMINARY

Multi- pad: Tracks are selected within a circle of 1.5 mm radious



μ=1.6 ± 2ps
σ= 25± 1.5 ps

μ= 3 ± 2ps
σ= 32 ± 1.5 ps

μ= 1 ± 2ps
σ= 33± 1.5 ps

μ= 4 ± 2ps
σ= 31± 1.5 ps