Picosec Micromegas detector for precise muon timing in the Muon Collider detector

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On behalf of the Muon Collider Physics and Detector working group

FAST2023 Workshop, Biodola 28 May-1 Jun 23

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1. Introduction to the Muon Collider

- Requirement for Muon timing in Muon collider

2. Picosec concept and issues

3. Picosec development towards Muon Collider detector

- Timing with different photocathodes
- Timing with eco-friendly gases
- Electronics

4. Future perspective

Muon Collider facility

International Design Study facility

International MUON Collider Collaboration

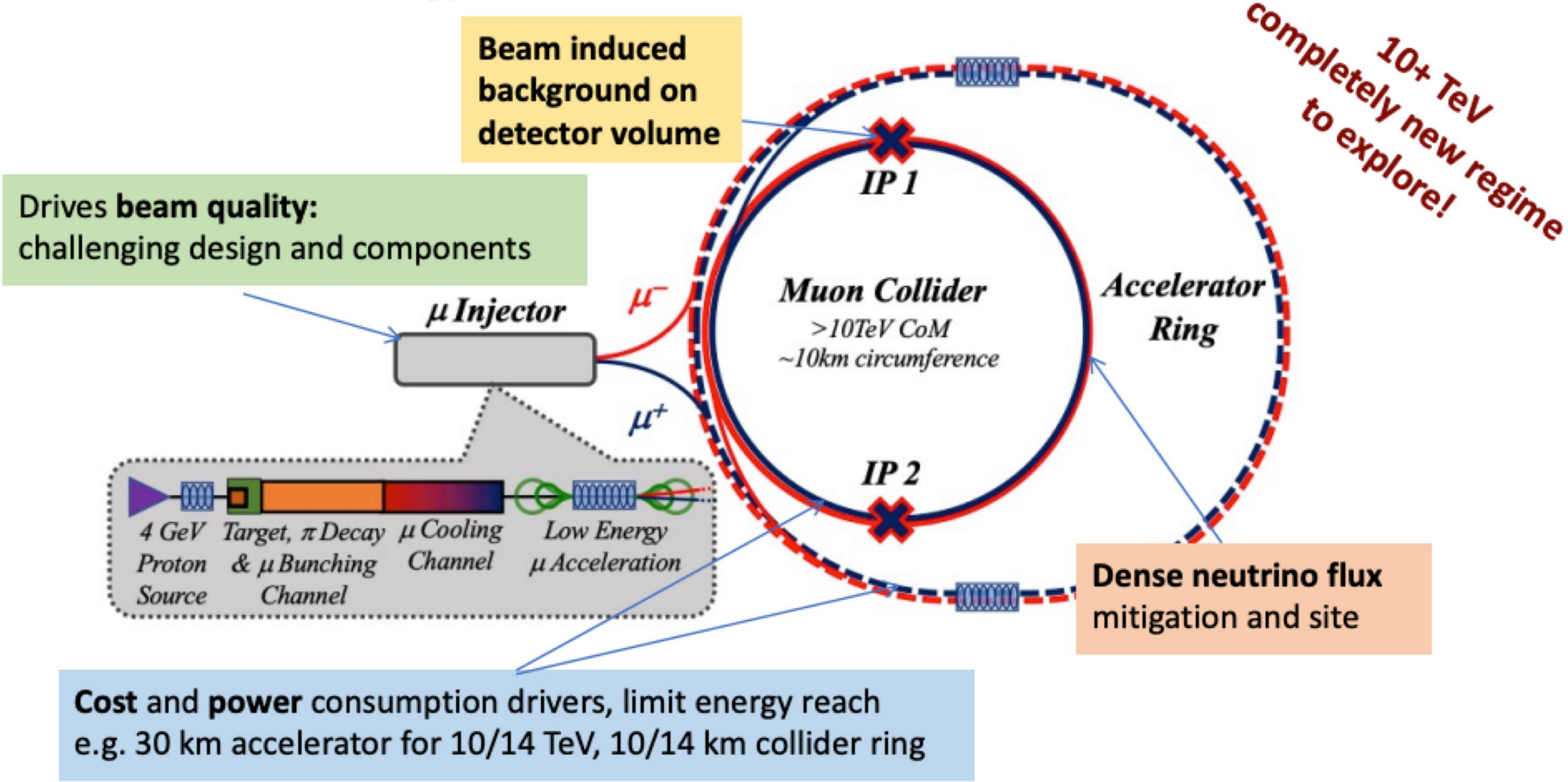
- **Focus on two energy ranges:**

3 TeV technology ready for construction in 10-20 years

10+ TeV with more advanced technology

Proton driver production as baseline

- **Simulations available for $\sqrt{s}$=1.5TeV**
- **Production ongoing for $\sqrt{s}$= 3TeV**

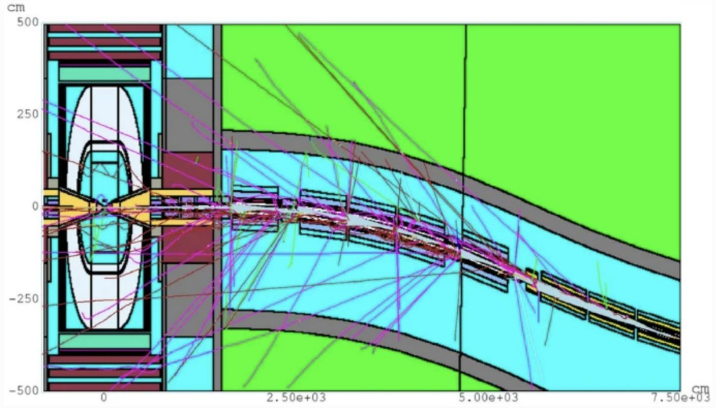


Muon Collider Detector

Design phase of the Muon Collider Detector

For the muon endcaps, a **Muon tracking and timing station** based on **Picosec+MPGD has been proposed**

Shielding from Beam Induced background (from decaying muons) limits the coverage in eta (θ>8°, η<2.7 available)



hadronic calorimeter

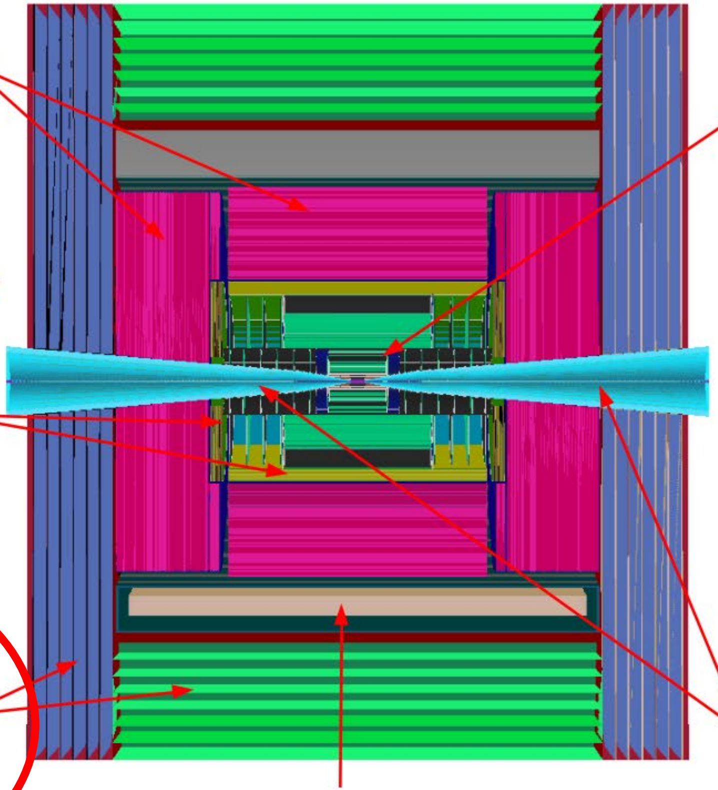
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

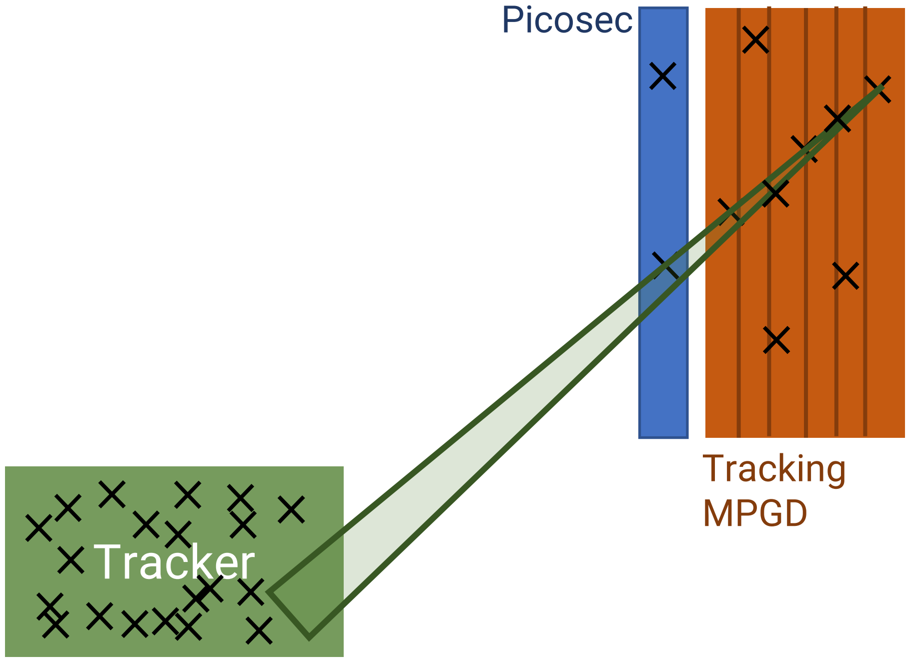
- Tungsten cones + borated polyethylene cladding.

Muon endcap

<u>Out-to-In</u> muon tracking approach currently under study

Resolve muon in the muon system to close the track in the tracker system reducing the combinatory background

Time resolution ~100ps

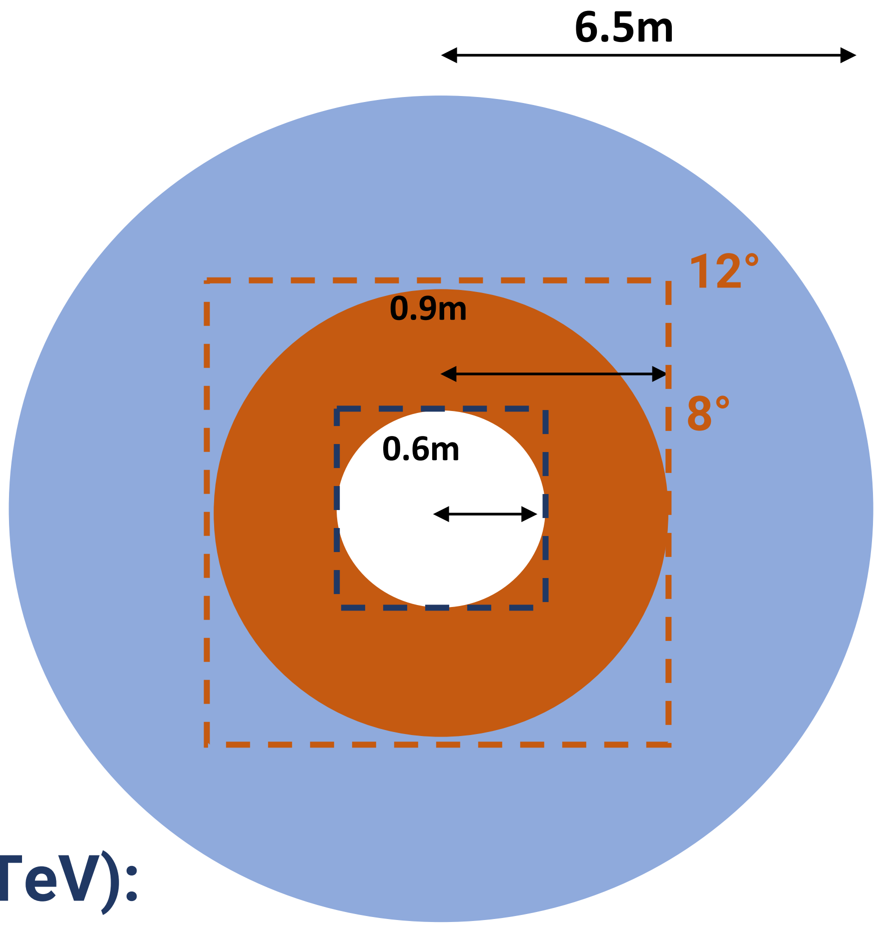


Operation in a heavily ionising particle environment

<u>≈1.5 m^2</u> per endcap

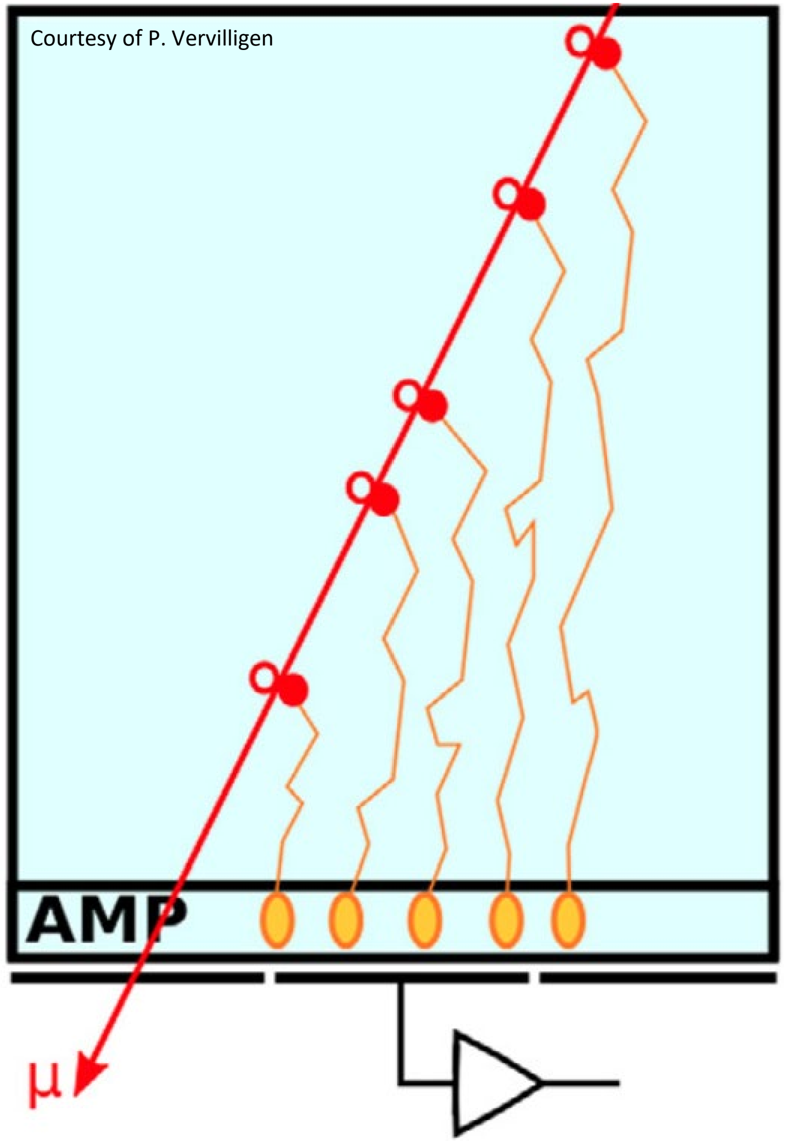
Rate capability ($\sqrt{s}$=1.5TeV):

- **60 kHz/cm^2 8°<θ<12°**
- 2 kHz/cm^2 θ>12°



Endcap – not in scale

Timing in MPGDs



Time resolution is dominated by the fluctuation in the position of the primary ionisation cluster created closest to the amplification region.

$$\sigma_t \propto \frac{1}{\lambda v_d}$$

λ ionization density (cluster/μm^{-1})
$\mathbf{v_d}$ electron drift velocity (μm/ns)

MPGD time resolution > several ns

Limitations

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

PRINCIPLES OF OPERATION OF MULTIWIRE
PROPORTIONAL AND DRIFT CHAMBERS

F. Sauli

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

GENEVA

1977

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

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.

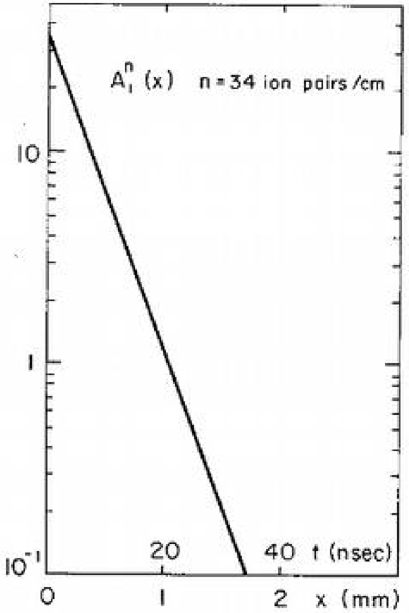


Fig. 8

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

Slide from Christos Lampoudis An overview of the PICOSEC detector and potential precise timing applications

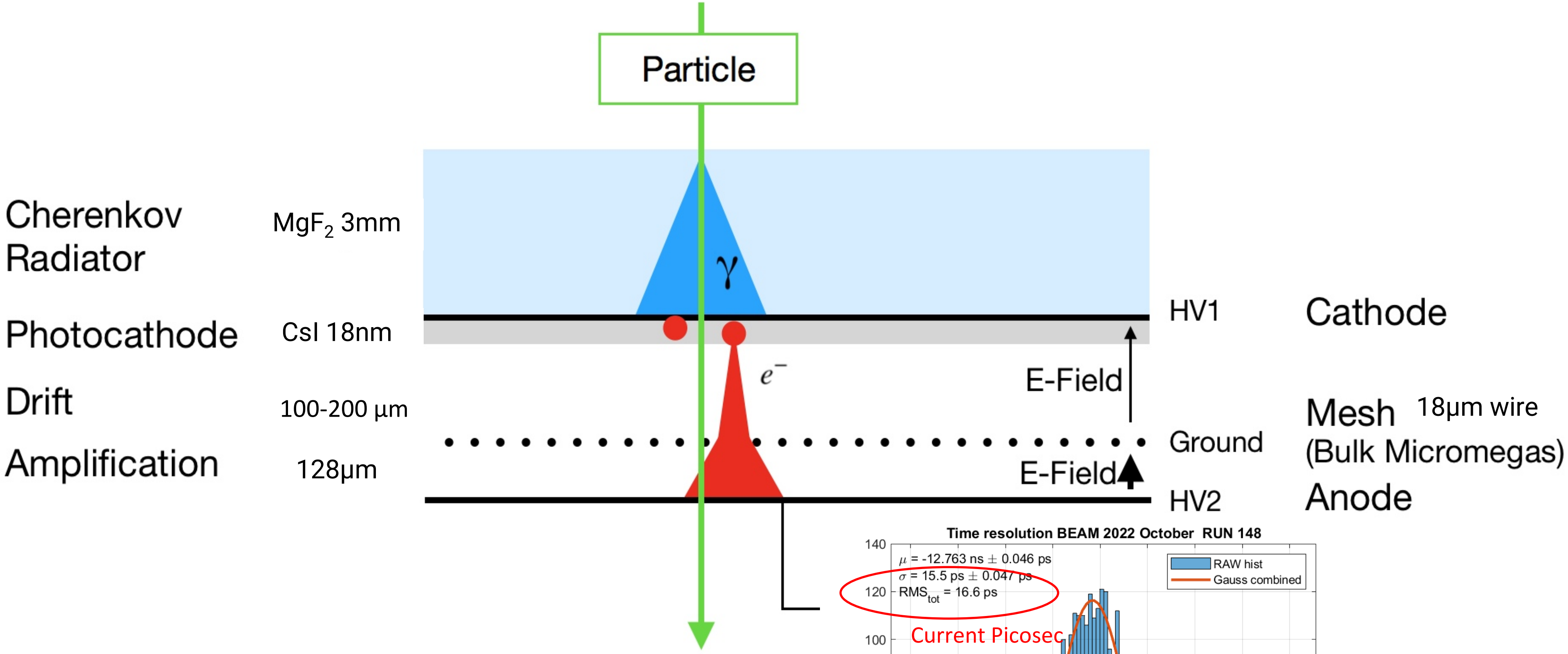
Picosec Concept

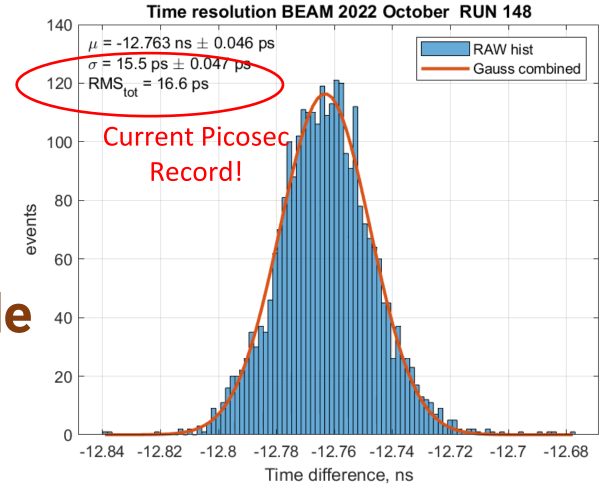
Gas Mixture:

$Ne/C_2H_6/CF_4$

80/10/10

Field(kV/cm)	Gain
~40	$\sim 10^3$
~20	$\sim 10^2$





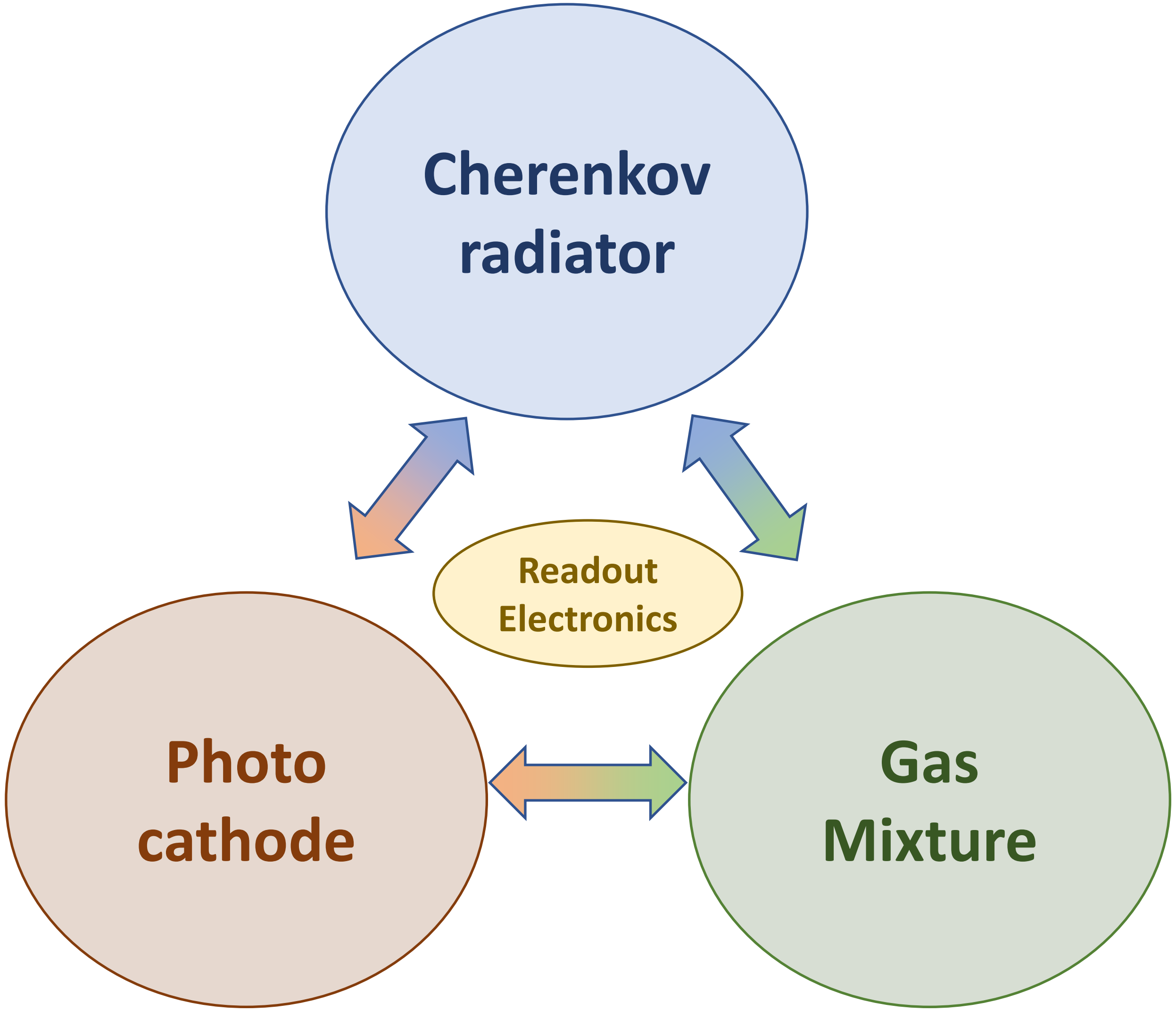
1. **Look at Cherenkov, not the ionisation**
   Photo-electrons created promptly with the MIP passage
2. **Remove the drift gap and start the avalanche as soon as possible**
   Avalanche propagate faster

1 readout pad over 100
Detector average
≈20ps

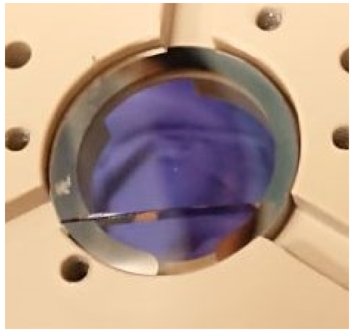
A. Utrobicic, A large area 100 channel PICOSEC Micromegas detector with sub 20 ps time resolution, MPGD2022

Bortfeldt, J., et al. "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector."*Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*903 (2018): 317-325.

Towards a robust and scalable detector



Cherenkov Radiator



Broken MgF_2 crystal

Cherenkov cross section

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

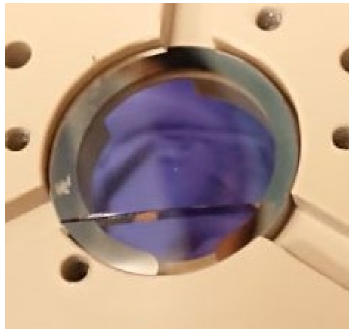
Transparency in the UV÷VUV region is fundamental!

Cherenkov radiator – Baseline MgF_2

- High UV transparency (>120nm)
- Fragile
- High cost (≈12€/cm²)
- No technology for large areas (100cm² max)

Quartz (≈5€/cm², >180nm)
Sapphire (≈6€/cm², hard, large area, >170nm)
other F-based crystals must be studied!

Cherenkov Radiator



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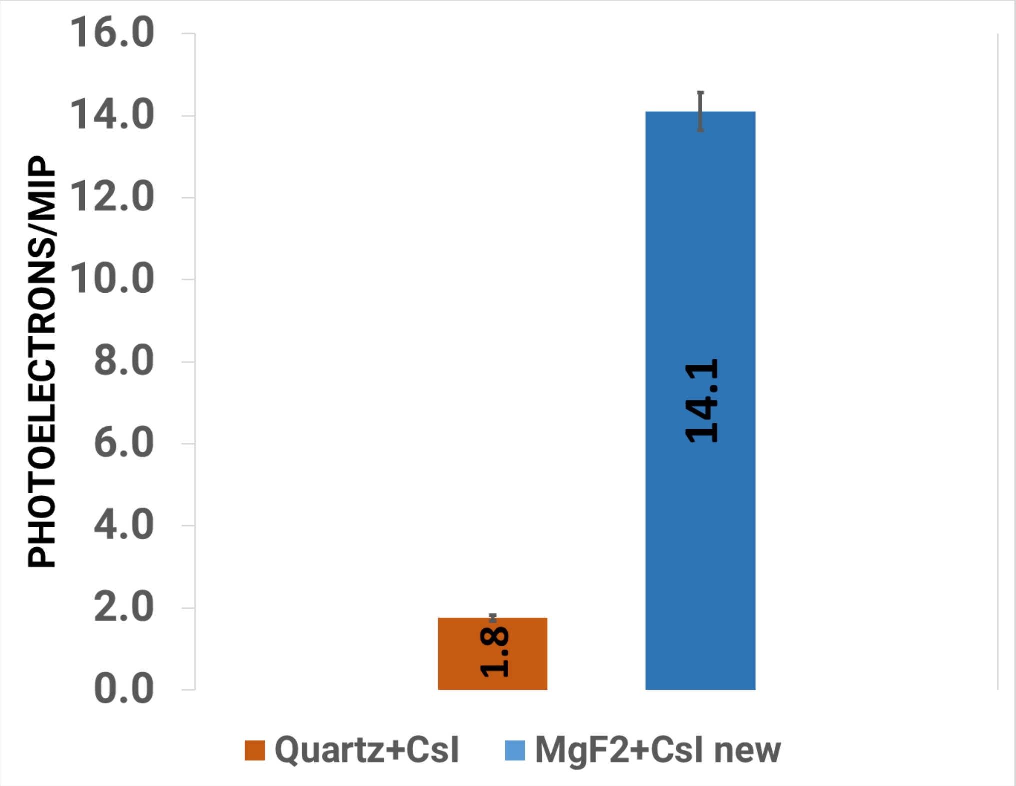
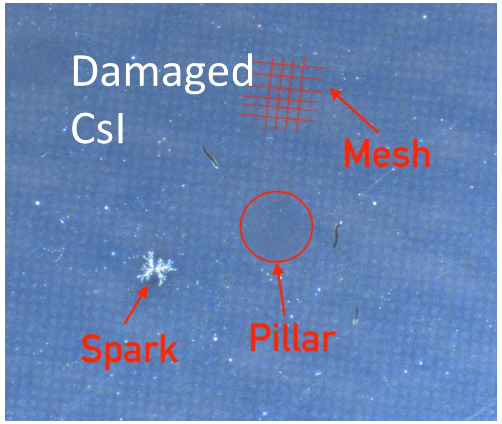
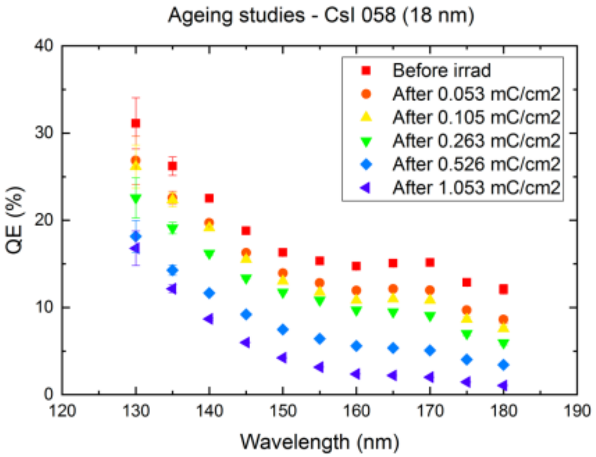
October 2022 test beam:

- Tested a **UV rated Quartz** crystal as a radiator
- Same photocathode wrt to MgF_2 (3nm Cromium + 18nm CsI)
- Photoelectrons yield **one order of magnitude lower**



Photocathode



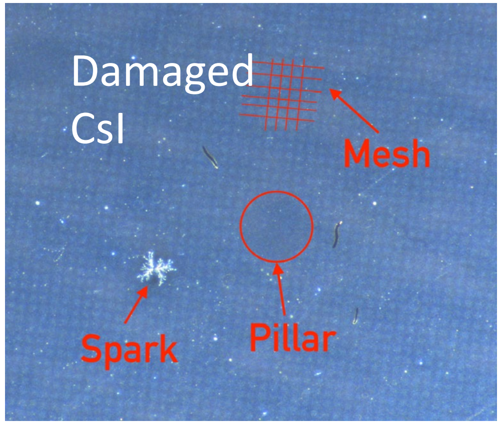


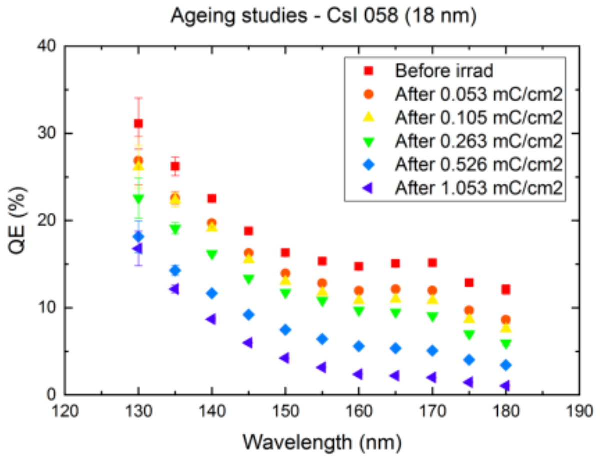
Photocathode – Baseline CsI

- High quantum efficiency to UV (≈10p.e./MIP)
- Easy to coat by Chemical Vapour Deposition
- Hygroscopic (sealed operation, dry gas)
- Damage by ion bombardment

- Metallic (Al, Cr, Au…) → easy to coat, non-resistive (pro and cons), lower QE (1-2 p.e./MIP)
- Carbon-based (DLC, B4C) → dedicated sputtering machine, resistive (pro and cons), lower QE (factor 3-4 p.e./MIP)

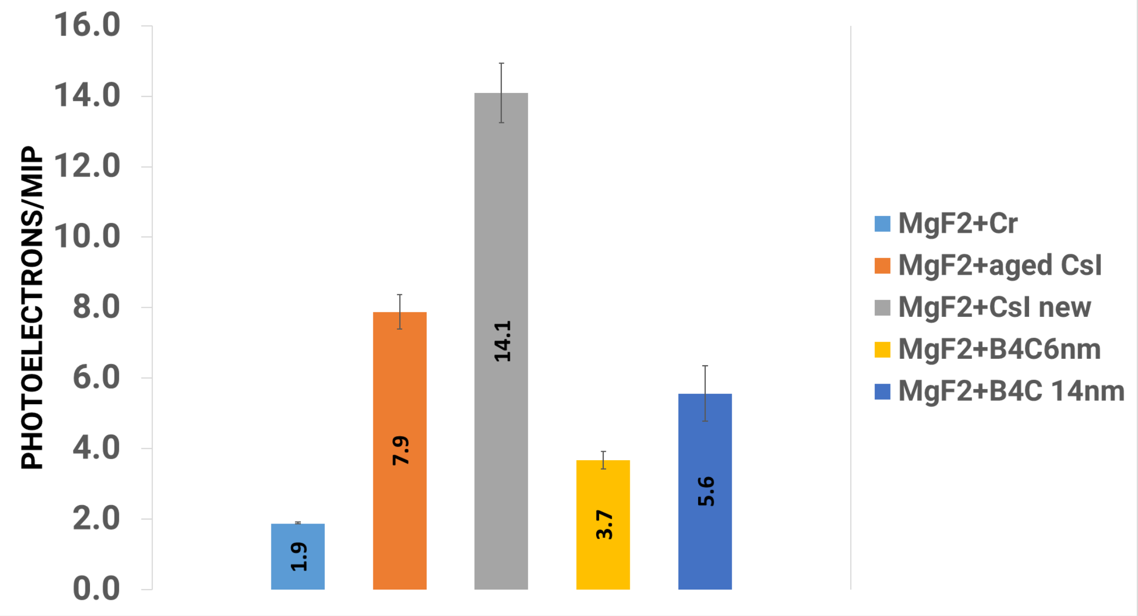
Photocathode





October 2022 & April 2023 test beams:

- Tested pure Chromium photocathode
- Tested B_4C photocathode (6 and 14nm)
- Other preliminary measurements made on DLC (here) and B4C (here) were made by other groups in the collaboration



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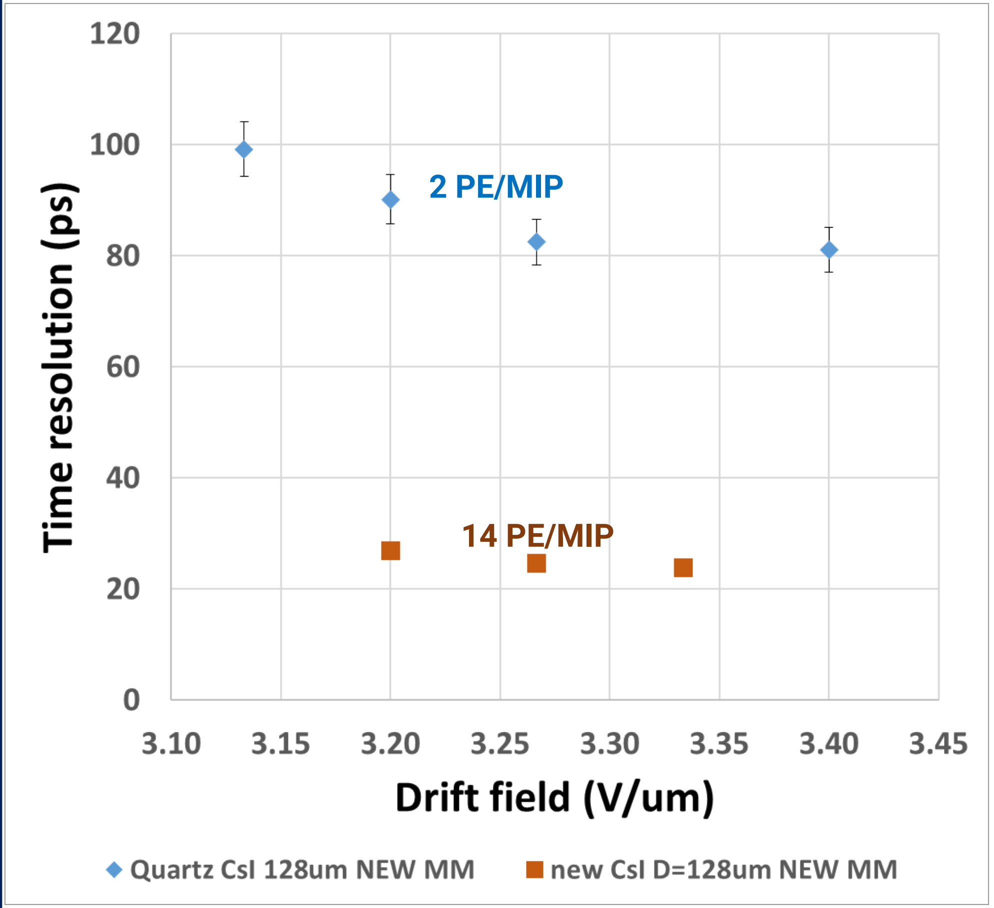
- **CsI aging** may undermine the detector performance
- **Pure Chromium** is not a good photocathode

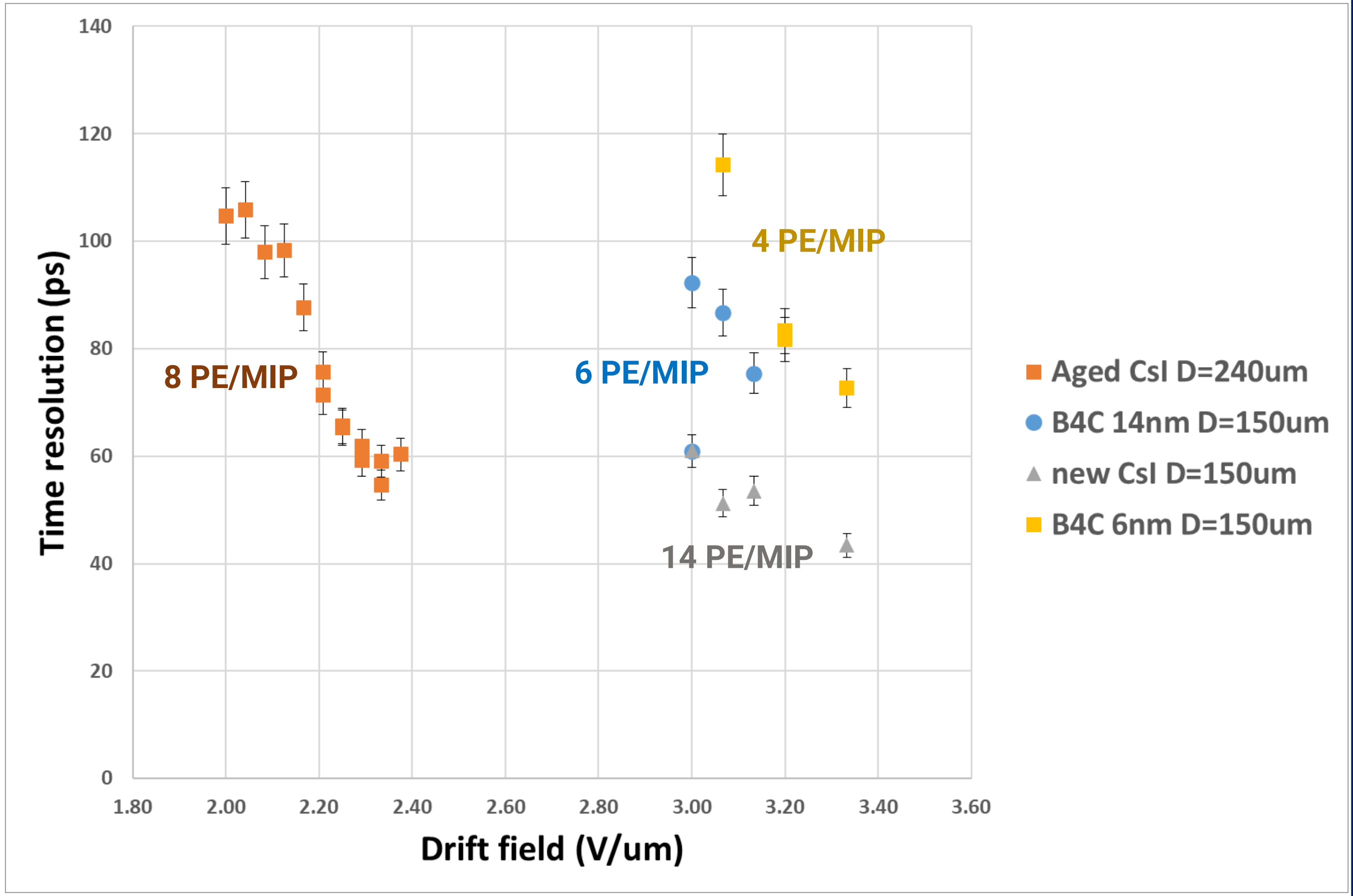
- **Carbon-based** material may be a suitable solution (confirmed by other groups)
- **Robust and resistive**

Effect of photoelectrons on timing

Radiator Comparison



Photocathode Comparison



NB → the top right plot shows data taken with a **Micromegas from a faulty batch** (large gap, way too high capacitance between mesh and ground)

Gas Mixture

Gas Mixture– Baseline Ne/C_2H_6/CF_4

- High gain and discharge quenching (up to 2-3x10^5)
- High drift velocity (10÷15 cm/μs)
- Very costly (Ukraine was the main producer of Ne, CF4 is heavily taxed for its GWP)
- Not eco-friendly (GWP≈740)

C_2H_6 (3k€ bottle, GWP=10.2) can be substituted with other quenchers :

- CO_2 (0.7k€ bottle, GWP=1, small quenching)
- iC_4H_{10} (1.5k€ bottle, GWP=3, good quenching)

CF_4 (5k€ bottle, GWP=7390) is difficult to replace:

- drop it
- R1234ze (1.5k€ bottle, GWP=7, candidate substitute for fluorinated gas in RPC and CMS-CSC)

New mixtures with new gases

- ALICE TPC GEM Ne-N_2-CO_2 (relatively high drift velocity, negligible GWP)

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April 2023 test beam:

- First test with non-standard gas mixtures

Gas mixture used	Global Warming Potential 100-years (normalized to CO_2)
$Ne/C_2H_6/CF_4$ (80/10/10)	**740**
Ne/iC_4H_{10} (94/6)	0.2
Ar/CO_2 (93/7)	0.07
$Ar/CO_2/iC_4H_{10}$ (93/5/2)	0.11

‘Standard’ and **ATLAS Micromegas** gas mixtures

Eco-friendly gas operation
-Ar based mixtures-

Gas mixture used	Global Warming Potential 100-years (normalized to CO_2)
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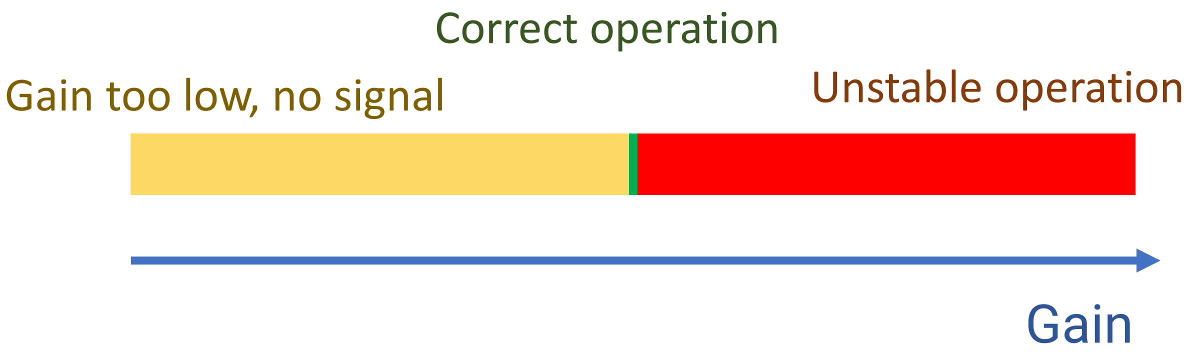
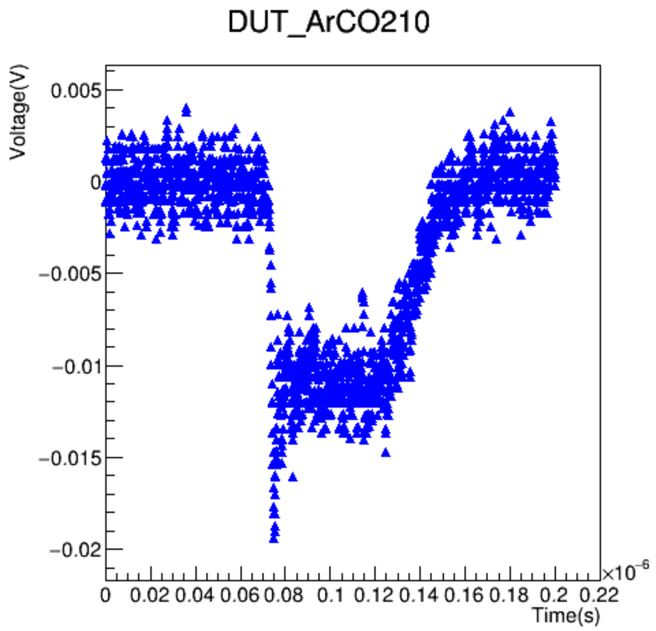
$Ar/CO_2/iC_4H_{10}$ (93/5/2)	**0.11**

- MIPs signal is on the order of several photoelectrons (depending on photocathode)
- We failed to find a suitable working point for such mixtures
- Immediate passage between np-signal region to spark region
- Such mixtures are not quenched enough to control the avalanche
- (more quencher needed





- We can see single-photoelectron signals in the lab
- Unstable detector (Sparks)
- Amplifier killed ☹

Eco-friendly gas operation

-Ne based mixtures-

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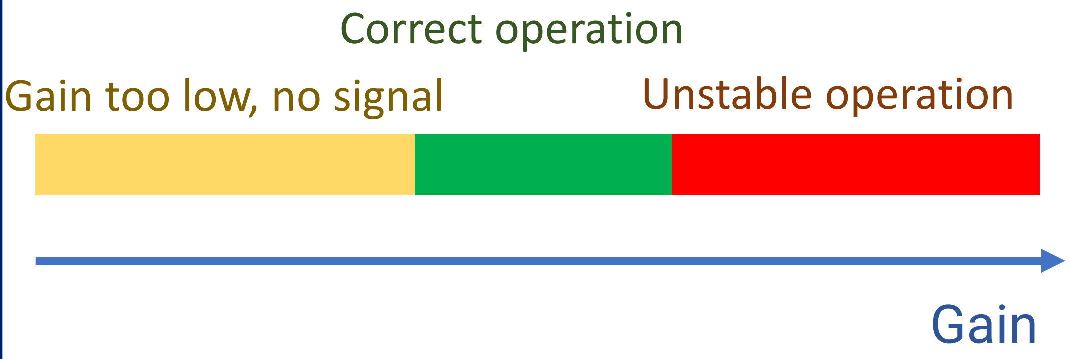
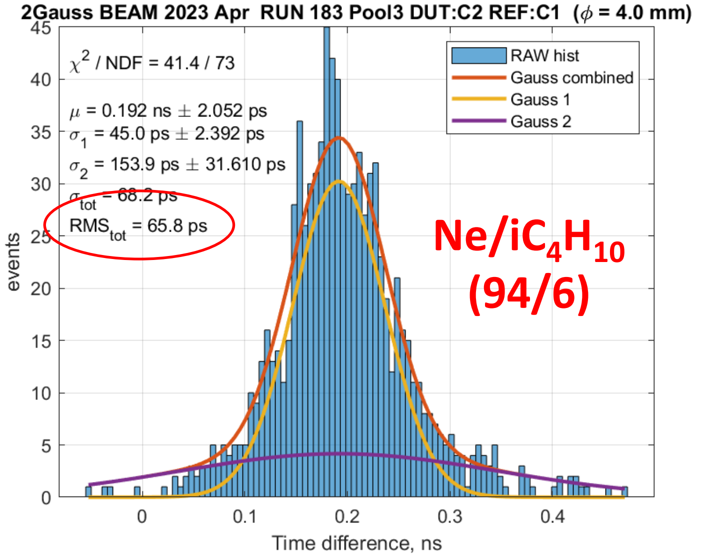
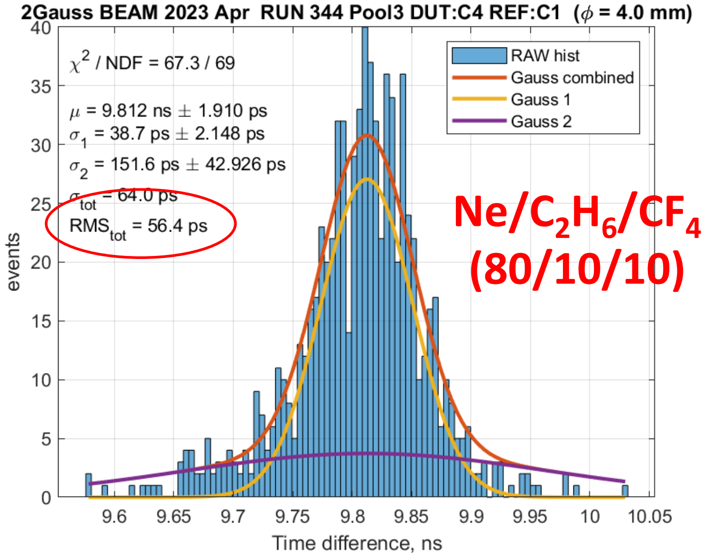


- Photocathode used was **B4C 6nm (<u>3 PE/MIP</u>)**
  - Photoelectron yield is around Lower time resolution wrt CsI is expected (**with CsI ≈25ps**)
- The two distributions are measured at **similar gains** for the two mixture
- The impact of CF_4 in timing is **visible but not drastic (≈15%)**
- Still, the 3-component gas mixture has a wider operational range because it is more quenched





Readout Electronics

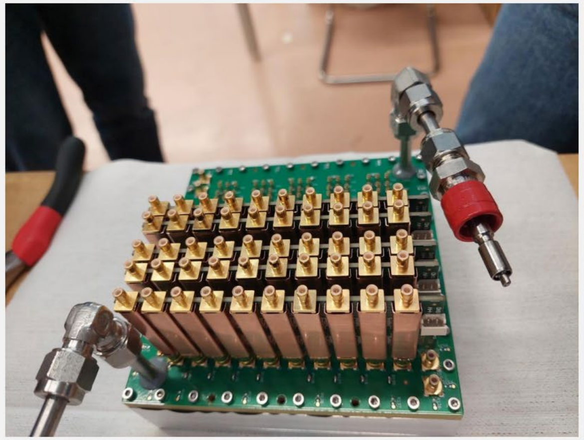
Amplifier

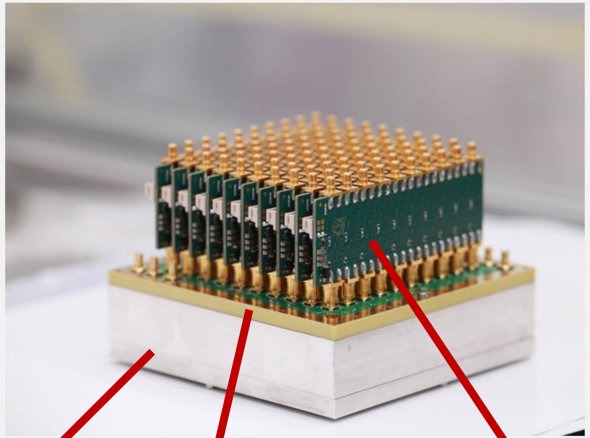
A. Utrobicic, A large area 100 channel PICOSEC Micromegasdetector with sub 20 ps time resolution, MPGD2022

Custom made 10 channel preamplifier board for PICOSEC MM detector

- Gain 38.5dB @100MHz
- HF -3dB cut-off ~~650 MHz~~, LF -3dB cut-off 4 MHz
- Input impedance 44 Ohm
- Negative pulses linear up to -1 V.
- Tested to sparks by shorting the input at 350 V bias.
- Power dissipation 75 mW per ch., Single supply 4 V.

No degradation of signal wrt other commercial linear amplifiers





100 pad detector

Readout board

10ch amplfier board

Readout Electronics

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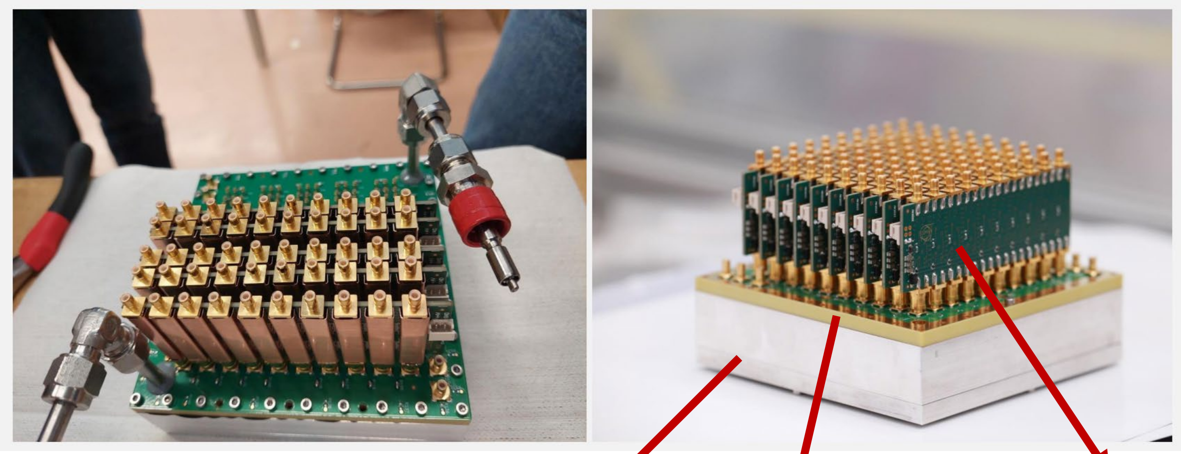
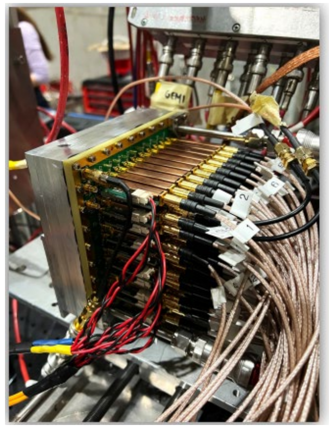
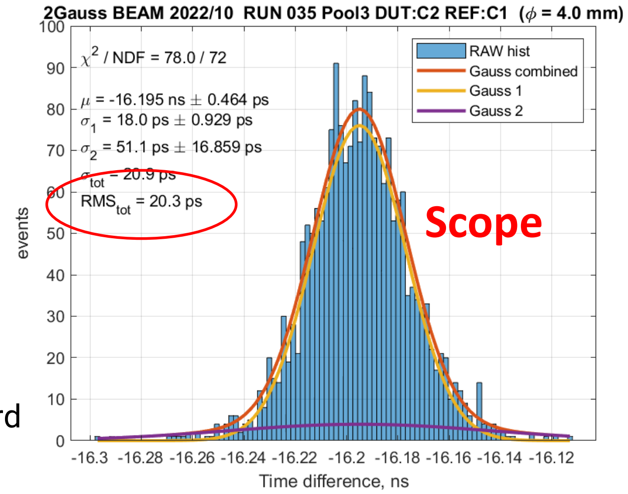


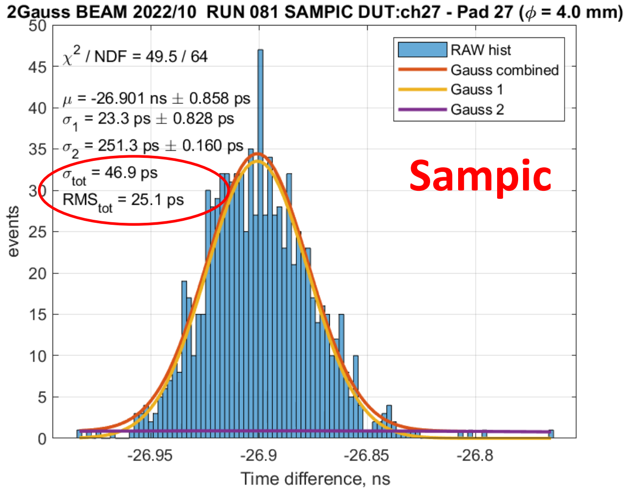
Fast ADC

1GHz 10Gs/s Scope was used for all previously shown measurement

SAMPIC 128-channel digitiser under test
→ 8.5 GS/s sampling frequency
→ 64 samples maximum digitalisation







Conclusions

Picosec Micromegas demonstrated sub-20ps time resolution on a 10x10 cm^2 detector.

20ps detector → <100ps detector
- Scalable
- Rad-hard

Development for Muon Collider detector → robust and scalable detector

- **Cherenkov radiator** (baseline *3mm* MgF_2)
  - → MgF_2 still is the most transparent crystal
  - → No evident options
- **Photocatode** (baseline *18nm CsI*)
  - → Resistive carbon-based photocathodes are very promising
  - → Lower yield than CsI but radiation harder and resistive (spark quenching)
- **Gas mixture** (baseline $Ne/C_2H_6/CF_4$)
  - → Heavily quenched mixture without CF_4 showed good performance (Ne/iC_4H_{10})
  - → Substitutes for CF_4 to be tested
- **Electronics**
  - → Scalability may be ensured by custom amplifiers and SAMPIC readout
  - → Integration of such a system on a large scale is still to be verified

RD51 PICOSEC Micromegas Collaboration

Y. Angelis[2], J. Bortfeldt[3], F. Brunbauer[4], E. Chatzianagnostou[2], K. Dehmelt[5], G. Fanourakis[6], K. J. Floethner[4,7], M. Gallinaro[8], F. Garcia[9], P. Garg[5], I. Giomataris[10], K. Gnanvo[11], T. Gustavsson[12], F.J. Iguaz[13], D. Janssens[4,14,15], A. Kallitsopoulou[10], M. Kovacic[16], P. Legou[10], M. Lisowska[4,25] J. Liu[17], M. Lupberger[7,18], S. Malace[11], I. Maniatis[4,2], Y. Meng[17], H. Muller[4,18], E. Oliveri[4], G. Orlandini[4,19], T. Papaevangelou[10], M. Pomorski[20], L. Ropelewski[4], D. Sampsonidis[2,21], L. Scharenberg[4,18], T. Schneider[4], L. Sohl[10], M. van Stenis[4], A. Tsiamis[2], Y. Tsipolitis[22], S.E. Tzamarias[2,21], A. Utrobicic[1], R. Veenhof[4,23], X. Wang[17], S. White[4,24], Z. Zhang[17], Y. Zhou[17]

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[24]University of Virginia, USA,
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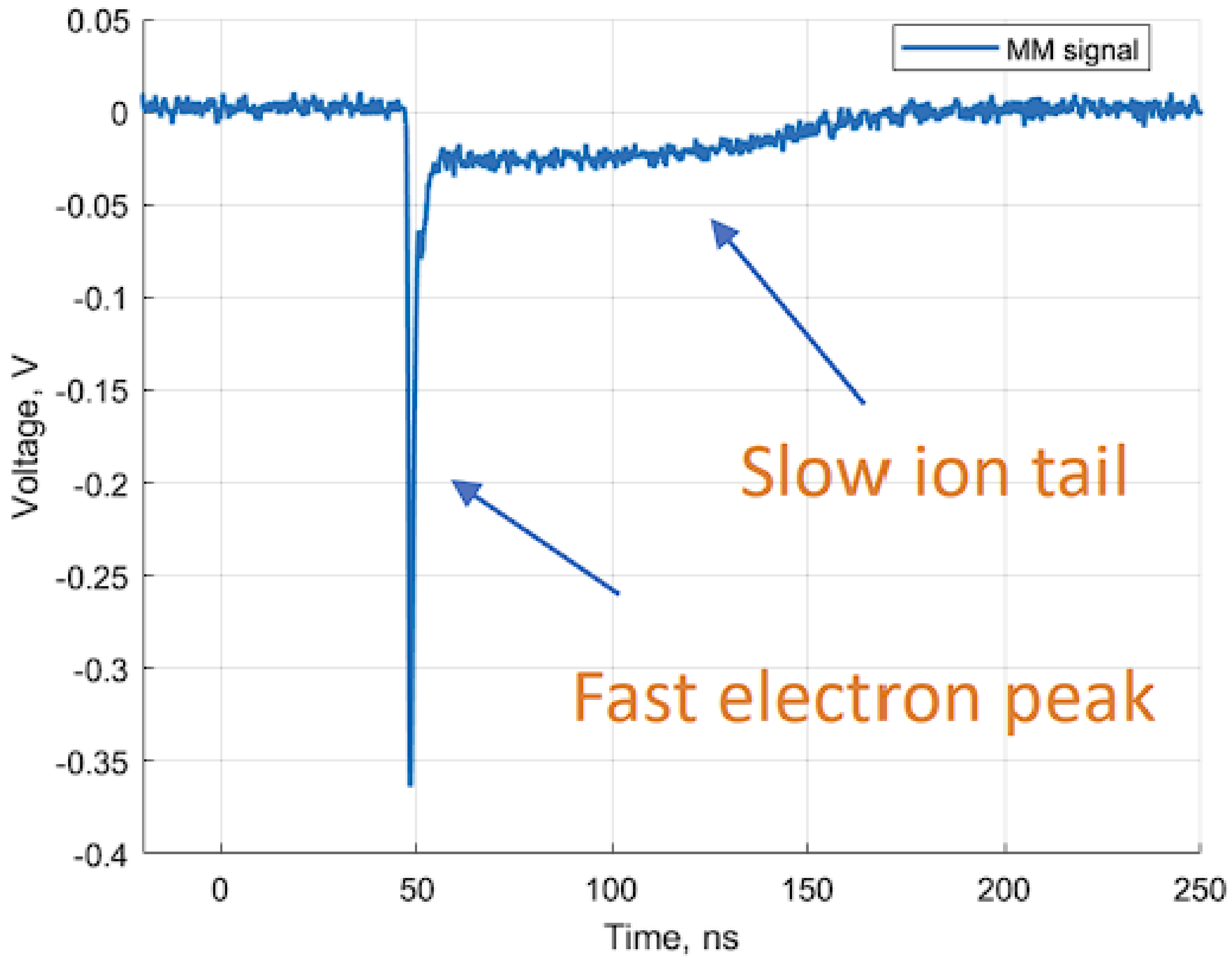
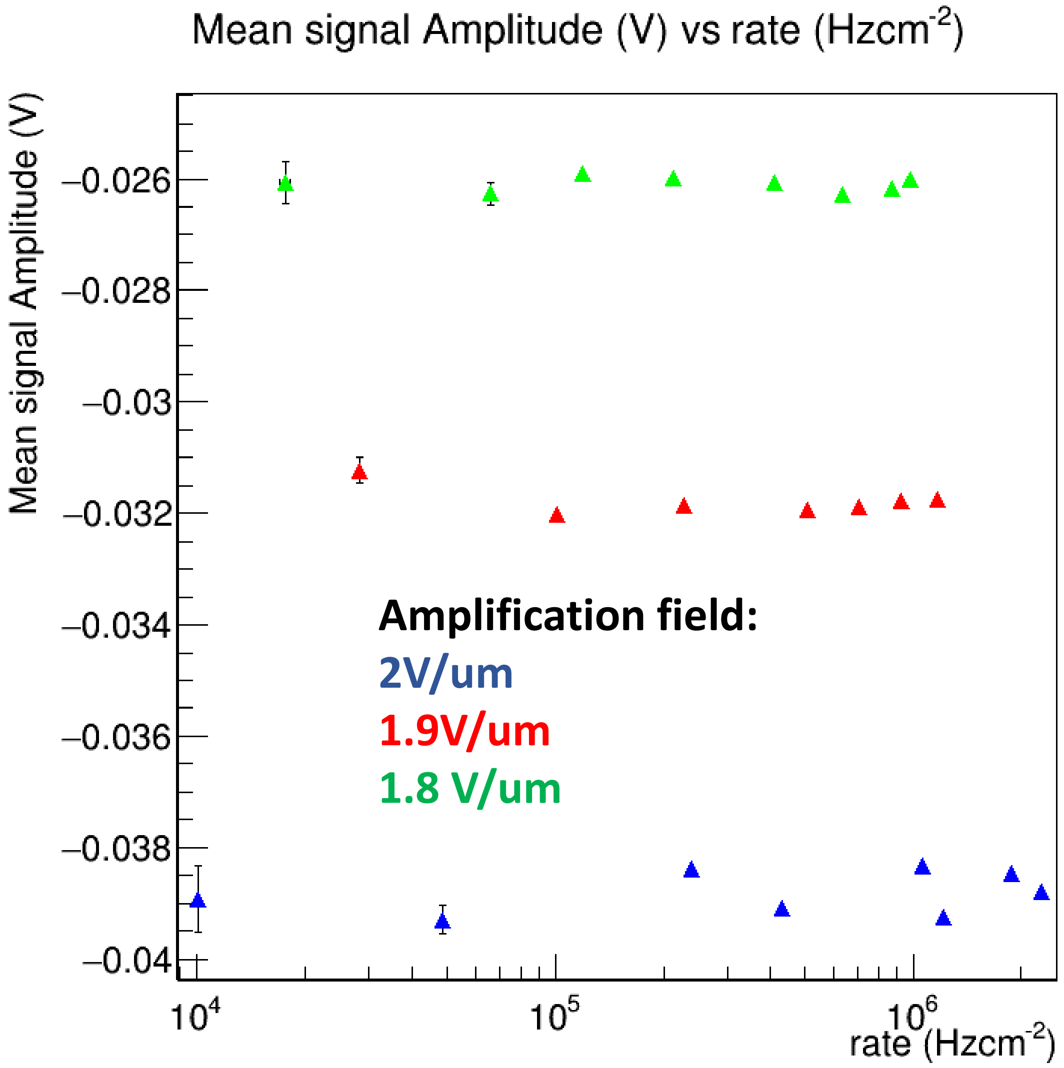
BACKUP

Picosec detector signal



Rate capability to single PEs -work in progress-

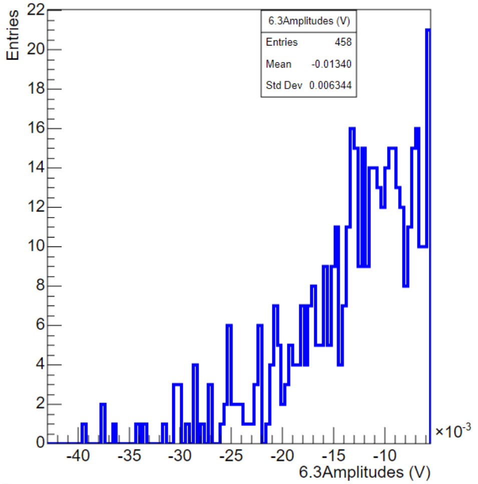


Irradiation with UV LED to generate **single-photoelectrons** signals

- CsI photocathode
- Counts signals and measures the average amplitudes
- Drift field: 3.13 V/um

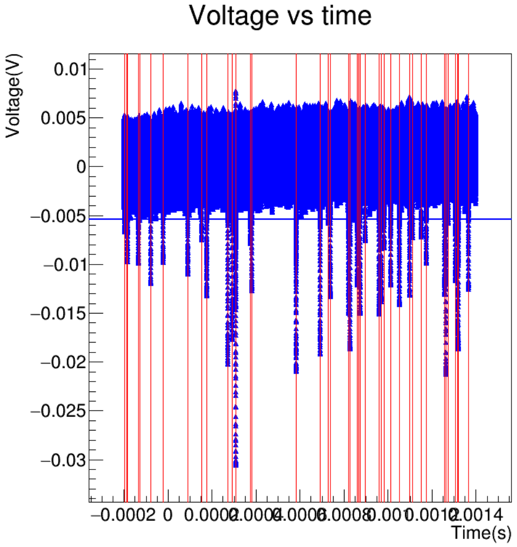
Detector performance stays **stable up to 2MHz/cm^2** for single-photoelectron

- One can roughly scale a factor of 10 for Muons
- We can go higher with the rate, but we have to fight against CsI degradation

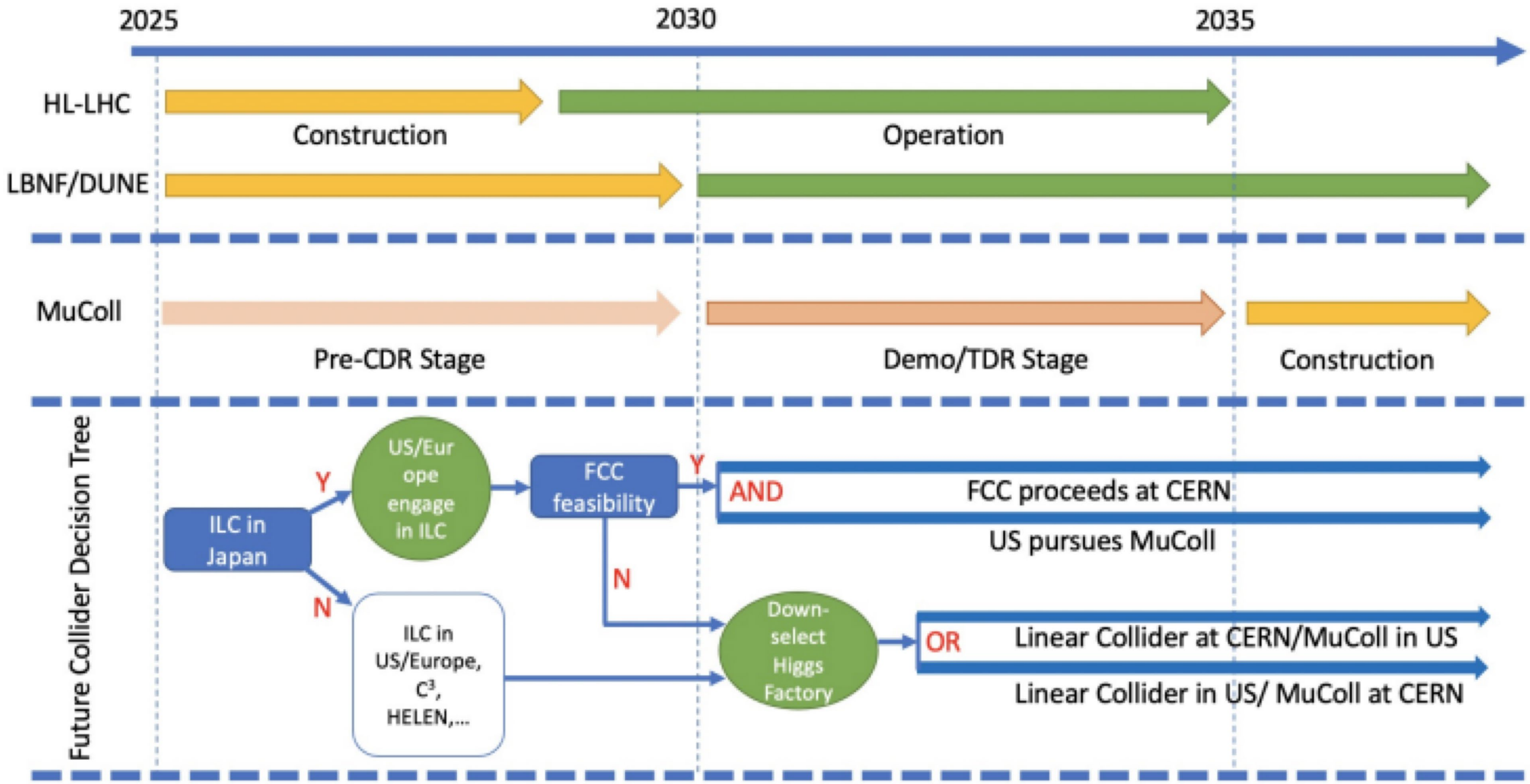


←Example of an amplitude spectrum

Example of 1.6ms of acquisition →

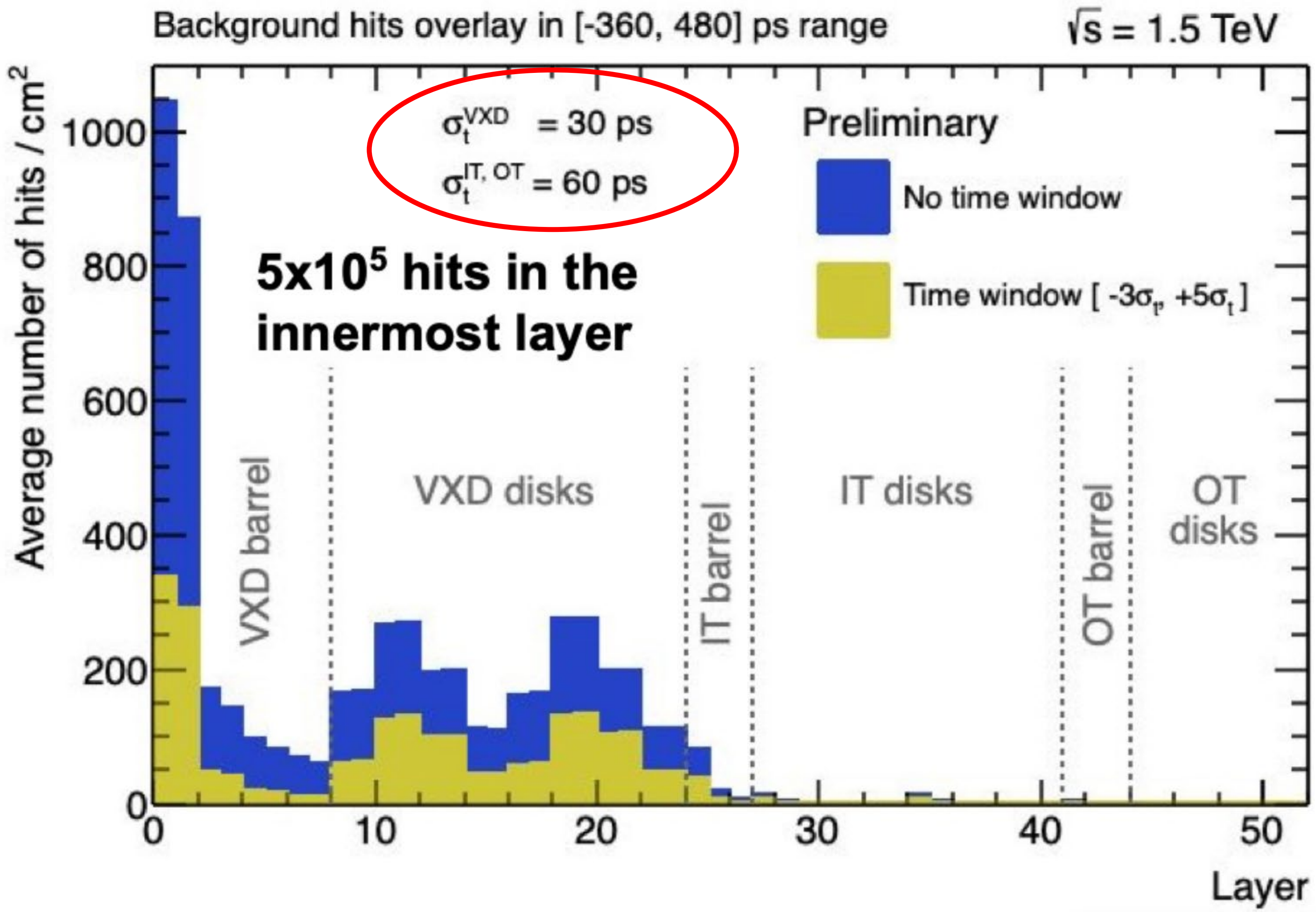


Timeline

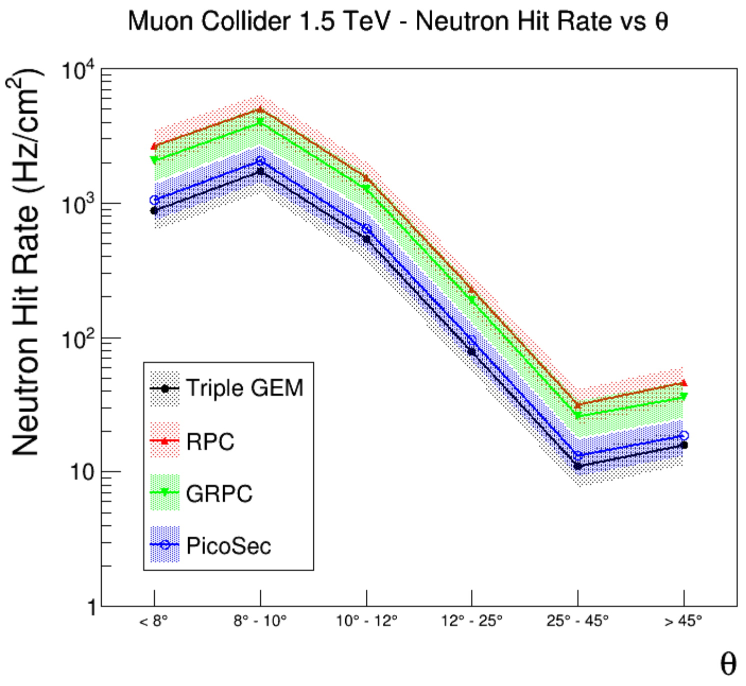


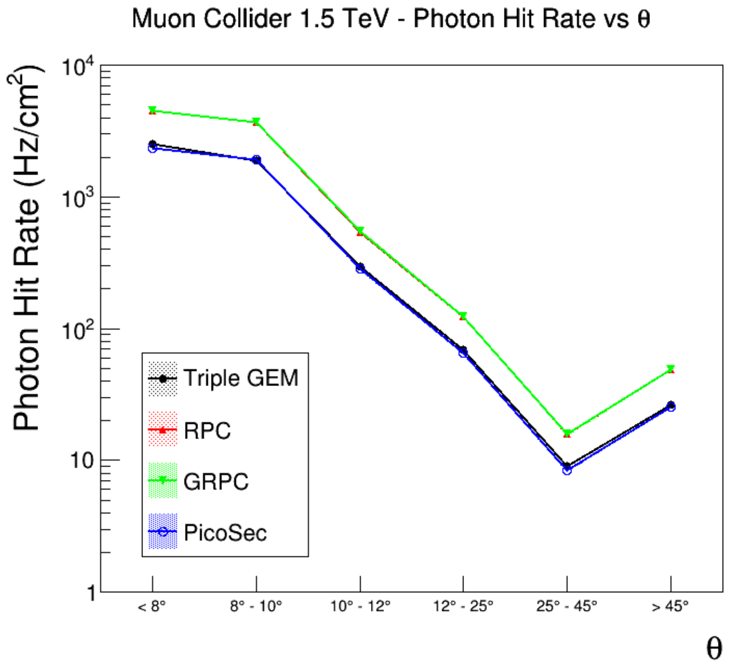
2025
2030
2035
HL-LHC
Construction
Operation
LBNF/DUNE
MuColl
Pre-CDR Stage
Demo/TDR Stage
Construction
Future Collider Decision Tree
ILC in Japan
Y
N
US/Europe engage in ILC
FCC feasibility
Y
AND
FCC proceeds at CERN
US pursues MuColl
N
ILC in US/Europe, C³, HELEN,...
Down-select Higgs Factory
OR
Linear Collider at CERN/MuColl in US
Linear Collider in US/ MuColl at CERN

BIB hit tracker



Simulation background



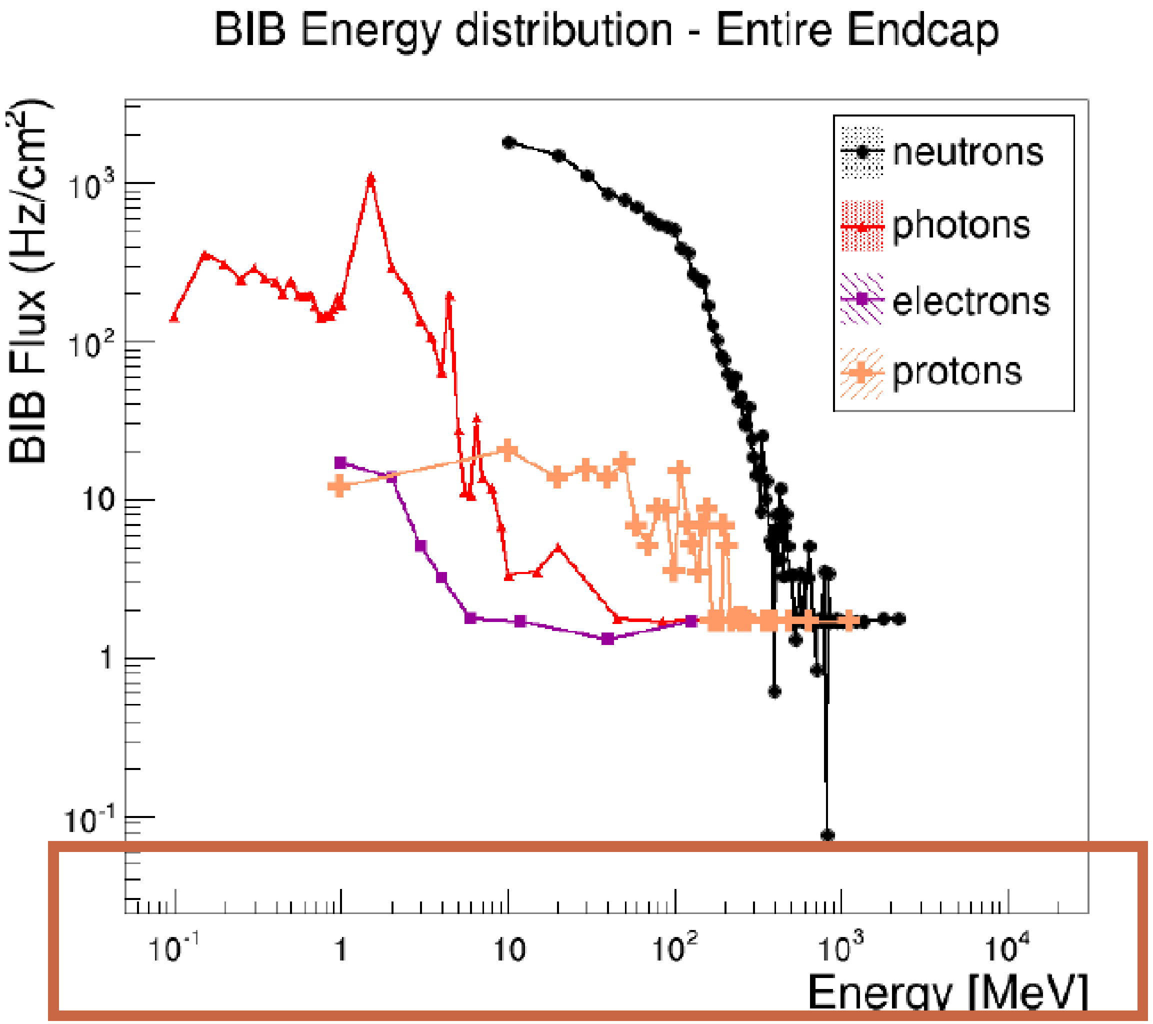


BIB particles flux [Hz/cm^2] in different regions (bunch crossing time 10 μs):

Particle	Endcap ($\theta > 12°$)	Endcap ($8° < \theta < 12°$)	Endcap ($\theta < 8°$)	Barrel
neutrons	$1.2 \cdot 10^3$	$5 \cdot 10^4$	$1.2 \cdot 10^6$	$1.4 \cdot 10^2$
protons	16	$3 \cdot 10^2$	$2.4 \cdot 10^4$	----
photons	$6.2 \cdot 10^2$	$1 \cdot 10^4$	$7.2 \cdot 10^5$	5
e+ e-	3	$3.3 \cdot 10^2$	$5 \cdot 10^3$	< 1
μ+ μ-	3	$3.7 \cdot 10^2$	$1.2 \cdot 10^4$	----
pions, kaons	< 1	70	$1 \cdot 10^3$	----
Total	≈ 2 kHz/cm^2	≈ 60 kHz/cm^2	≈ 2 MHz/cm^2	≈ 200 Hz/cm^2

- Background interaction with the detector was simulated in Geant4
- Convoluted with the response of different gaseous detector technologies (hit when a charged particle is found in the drift gap)
- Simulated Picosec: 3mm MgF_2 radiator, 18nm CsI photocathode, 200um drift gap
- **Picosec *can potentially* operate in high-rate environments and give timing information with higher precision wrt other technologies**

BIB spectrum



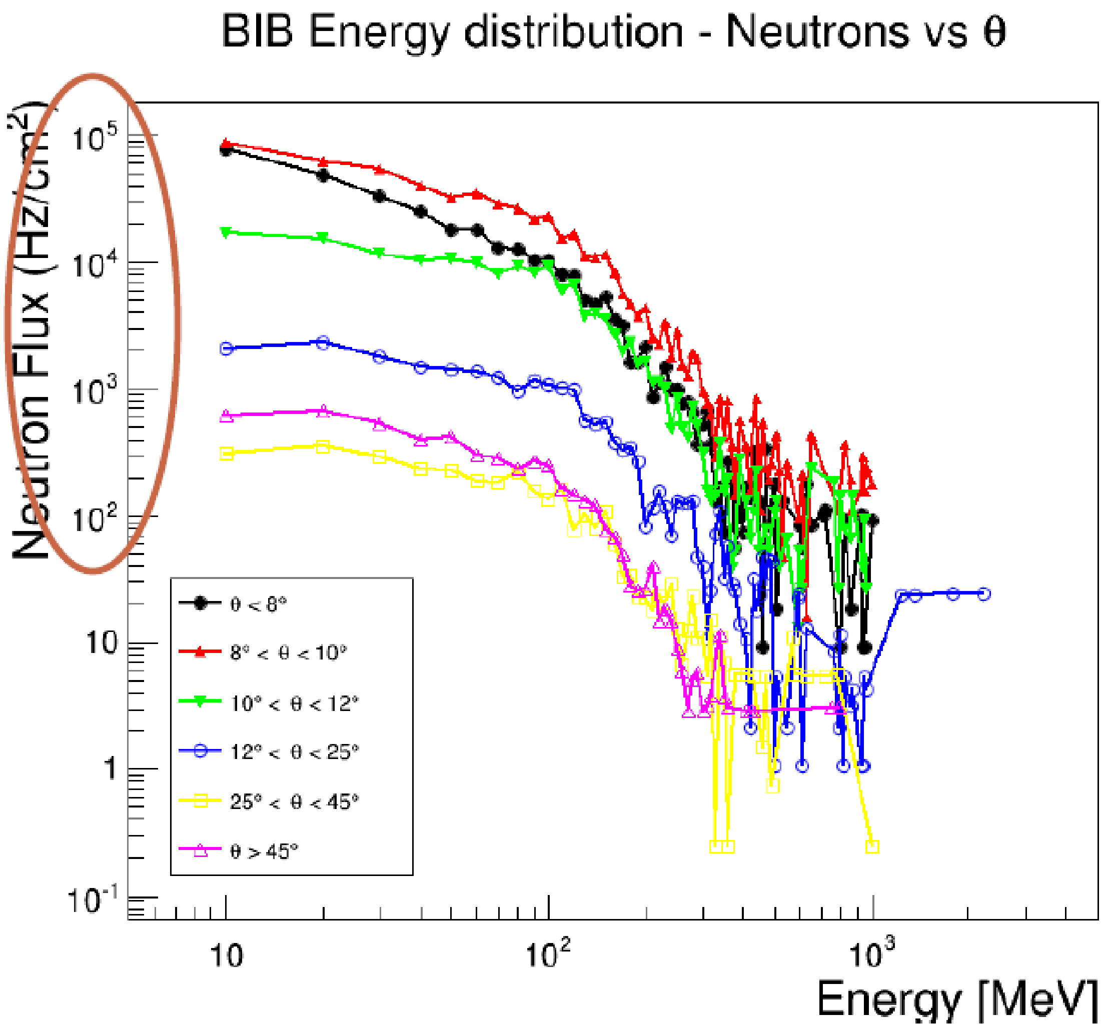
$$f(E) = \frac{p(E) \times BX^{-1}}{A}$$

where

- $p(E)$ = number of particles of a given type and energy reaching the muon system in a BX
- BX^{-1} = number of BX/s (10^5)
- A = considered area

This plot shows the flux on the entire endcap – not to be used to evaluate the actual fluxes on the detectors – but it gives us an overview of particle types and energy ranges.

BIB neutrons



We have divided the endcap region in six sub-regions based on θ (or r):

- In the inner regions, the neutron flux is almost 3 orders of magnitude higher than in the outer regions
- The energy goes from few MeV up to 2.5 GeV → *is there any cut on the lower energies?*
- The highest fluxes are for energies below 100 MeV

4

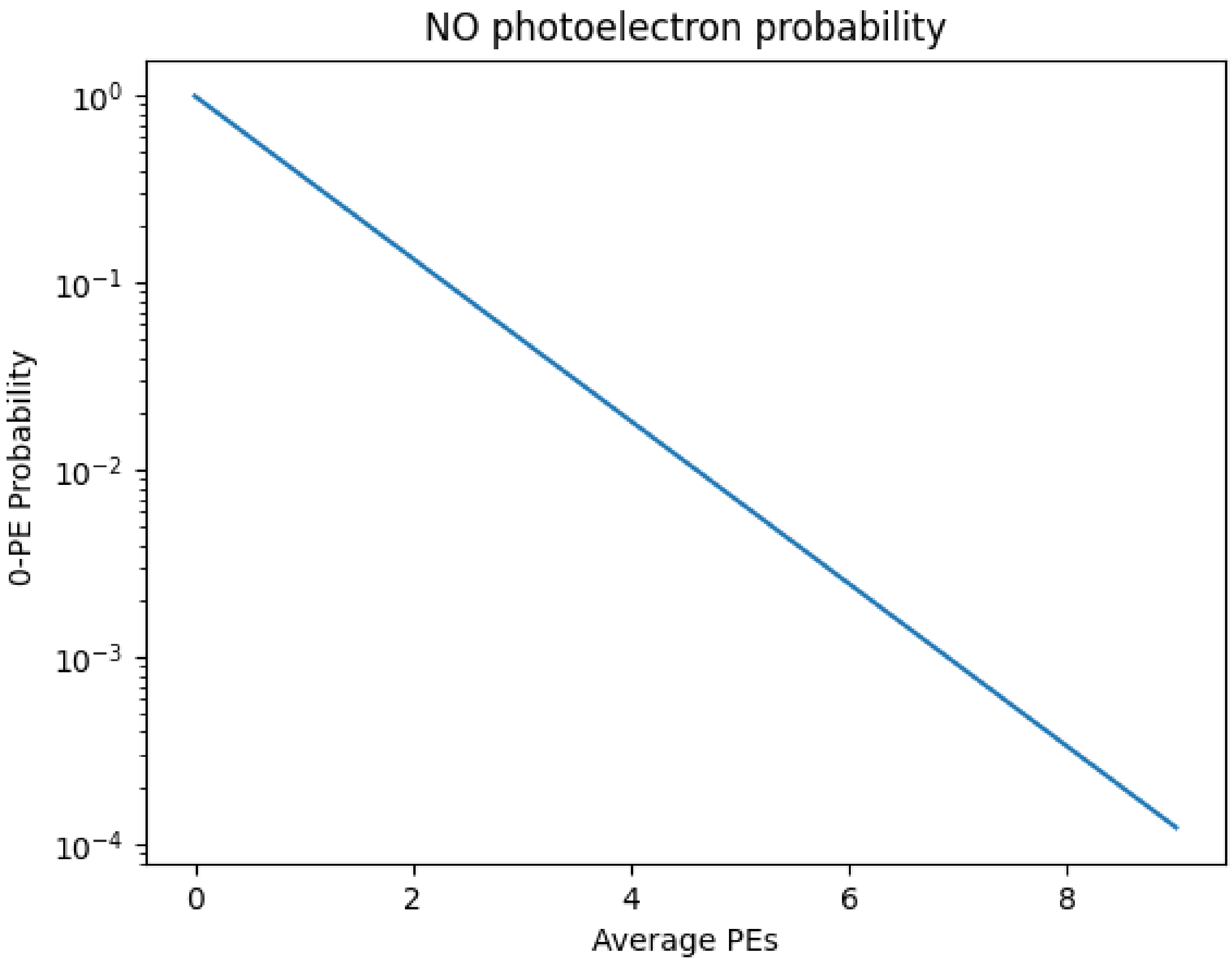
zero photoelectron probability

Poisson probability of having zero PE when the mean is:

- 2 → $P_2(0)=0.14$
- 5 → $P_5(0)=0.007$

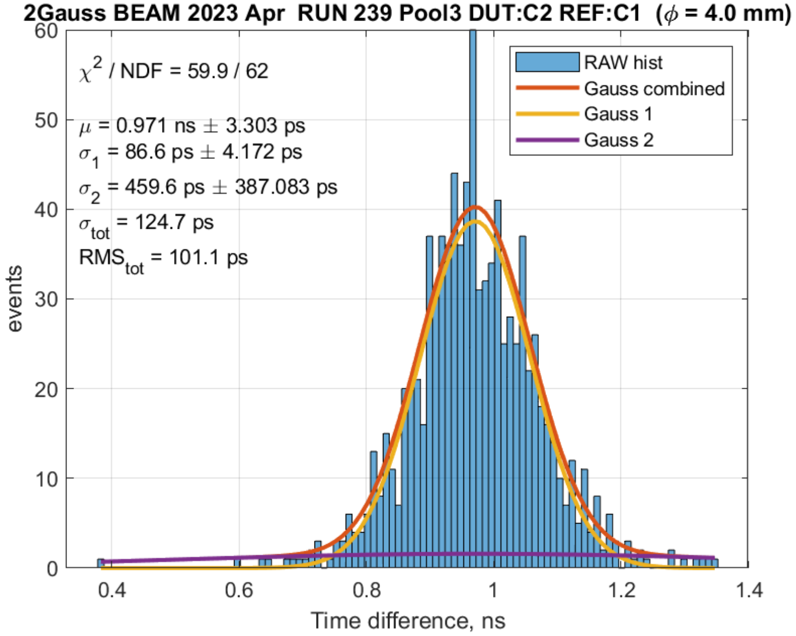
4.6 PE/MIP is considered the lowest acceptable value, i.e. 1% inefficiency

Comparison with test beam data not yet validated

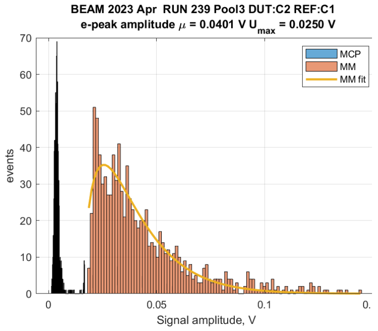


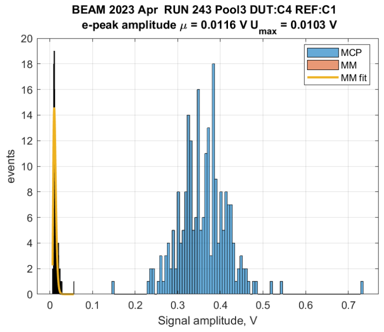
Pion/Muon comparison

PIONS (≈1MHz/cm2)
Ref: MCP1 2400V
DUT: MM2 Davide non-res 7nm B4C 275/430V

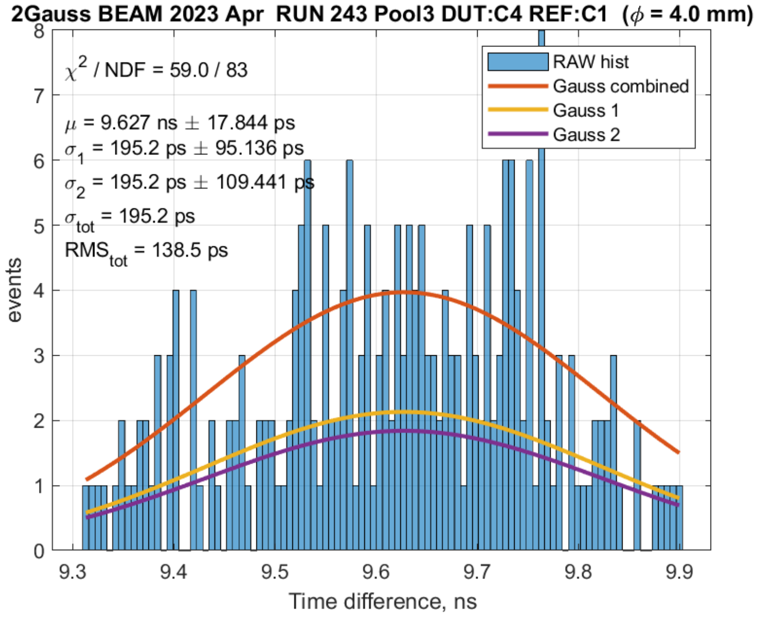


No tracking, trigger on MCP





MUONS
Ref: MCP2 3200V
DUT: MM2 Davide non-res 7nm B4C 275/430V

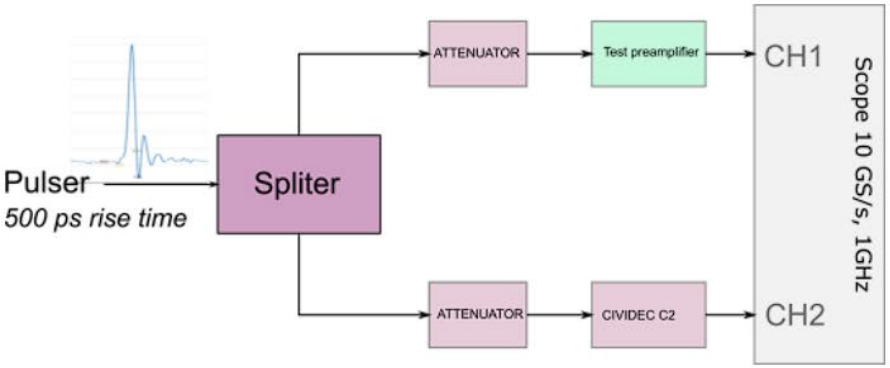


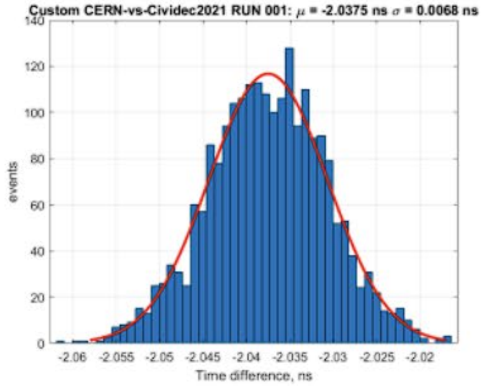
Tracking,
trigger on MCP

SAMPIC test

t 10 channel preamplifier boards
lered from LPSC.

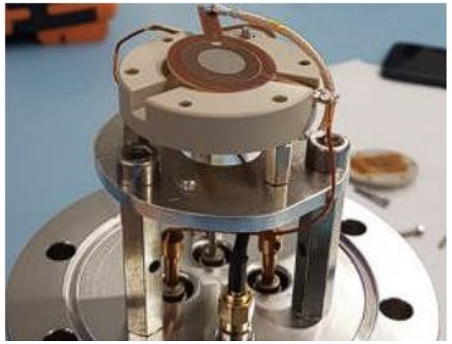
Timing test with pulser

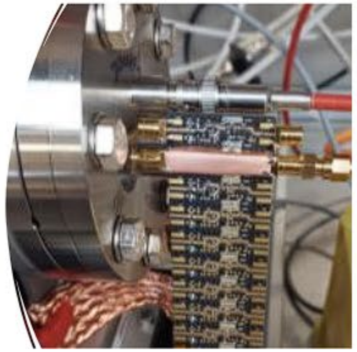


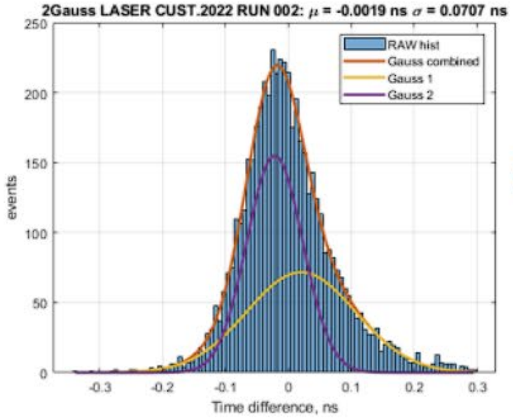


σ = 6.8 ps

Timing test with laser (connected on single channel detector): single photoelectron time response







σ_{SPE} = 70.7 ps

9

Non-resistive MM1 ThinGap CsI

Same CsI from May/July, 275A/465C
Analysed pad per pad, combined by nominal location per pad