International MUON Collider Collaboration

UNIVERSITÀ DI PAVIA
Dipartimento di Fisica

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Sezione di Pavia

Fast timing detectors for the muon system of a muon collider experiment: requirements from simulation and prototype performance

16th Topical Seminar on Innovative Particle and Radiation Detectors
25-29 September 2023
Siena, Italy

Ilaria Vai

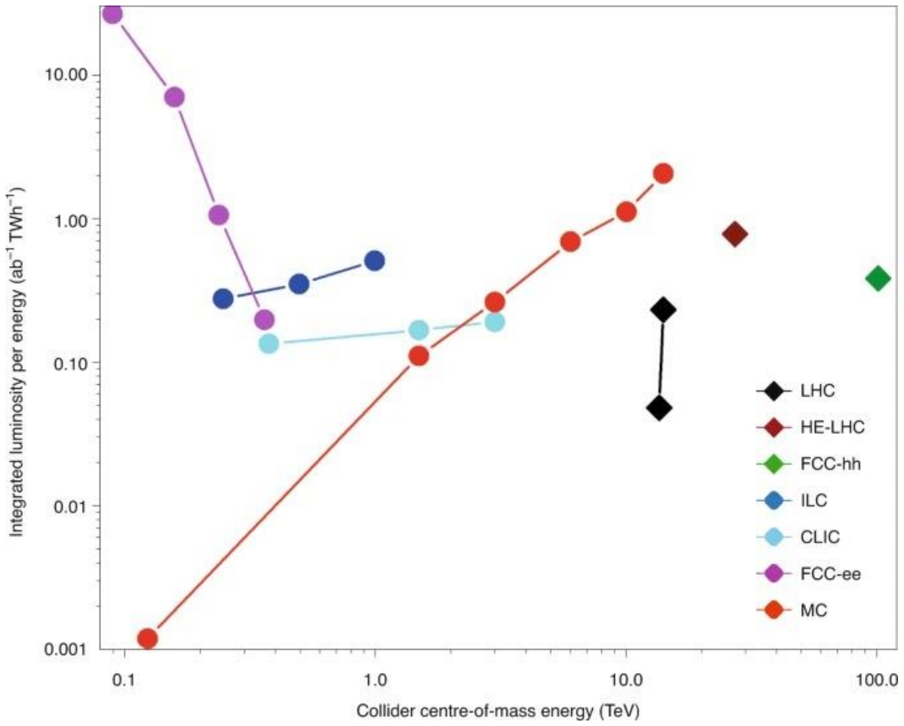
on behalf of the International Muon Collider Collaboration

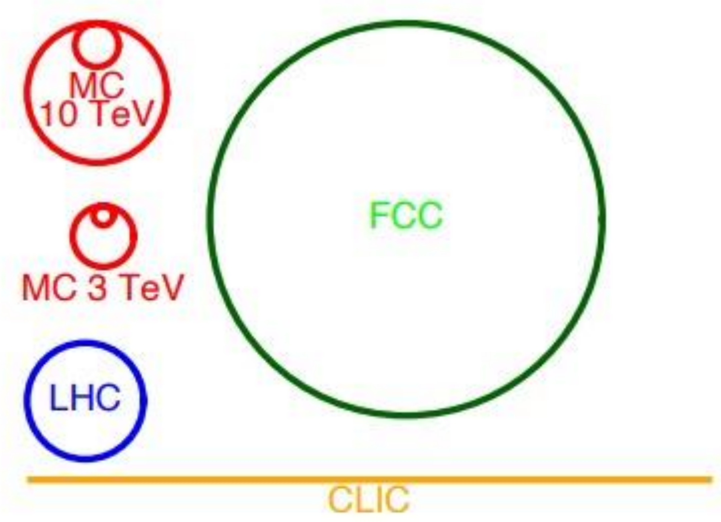
Why a muon collider?

A Muon Collider is a unique possibility of combining high energy with very precise measurements

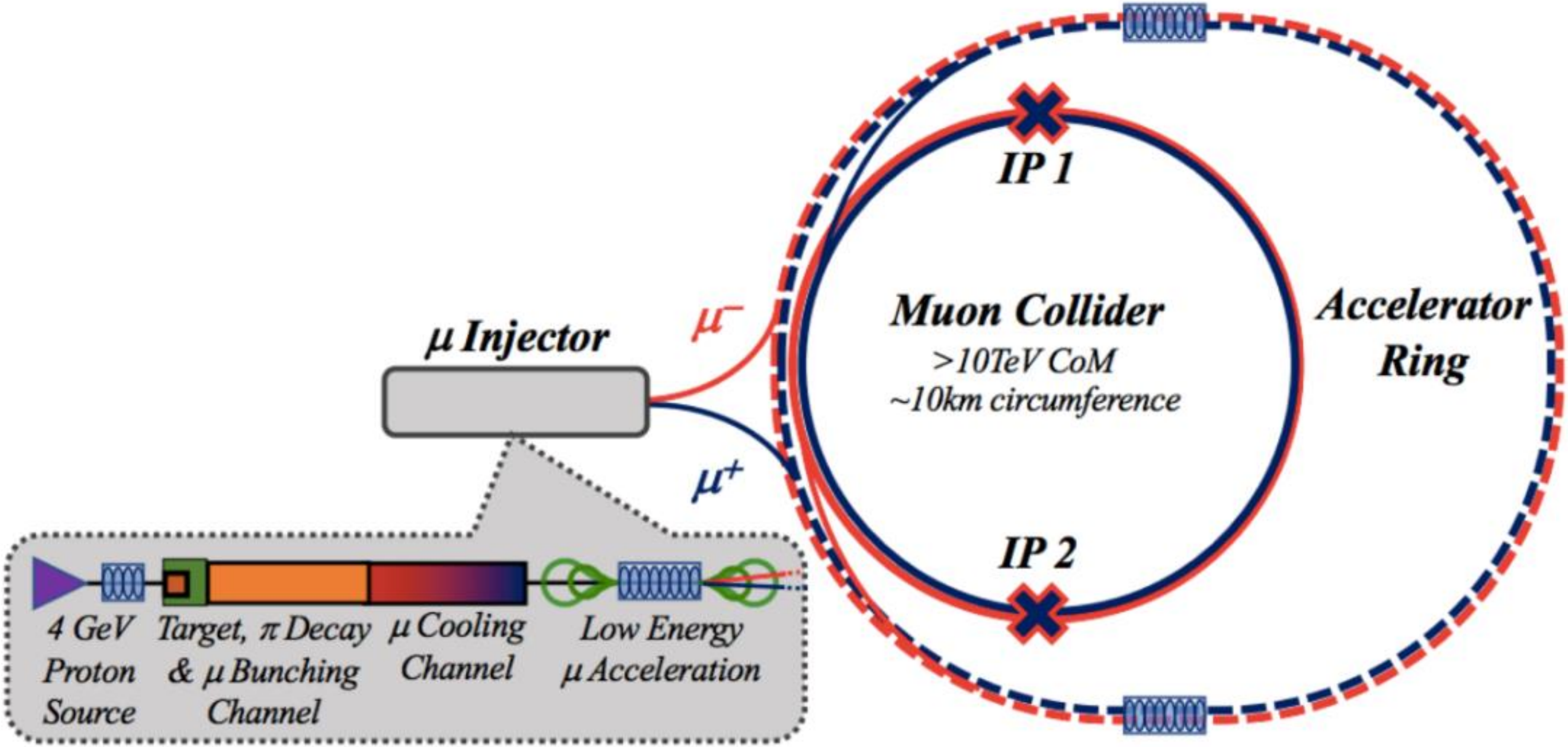
- pp machines → no limitations from synchrotron radiation
- e+e- machines → nominal E_{cm} entirely available

Long, K.R., Lucchesi, D., Palmer, M.A. *et al.* *Nat. Phys.* **17**, 289–292 (2021). https://doi.org/10.1038/s41567-020-01130-x



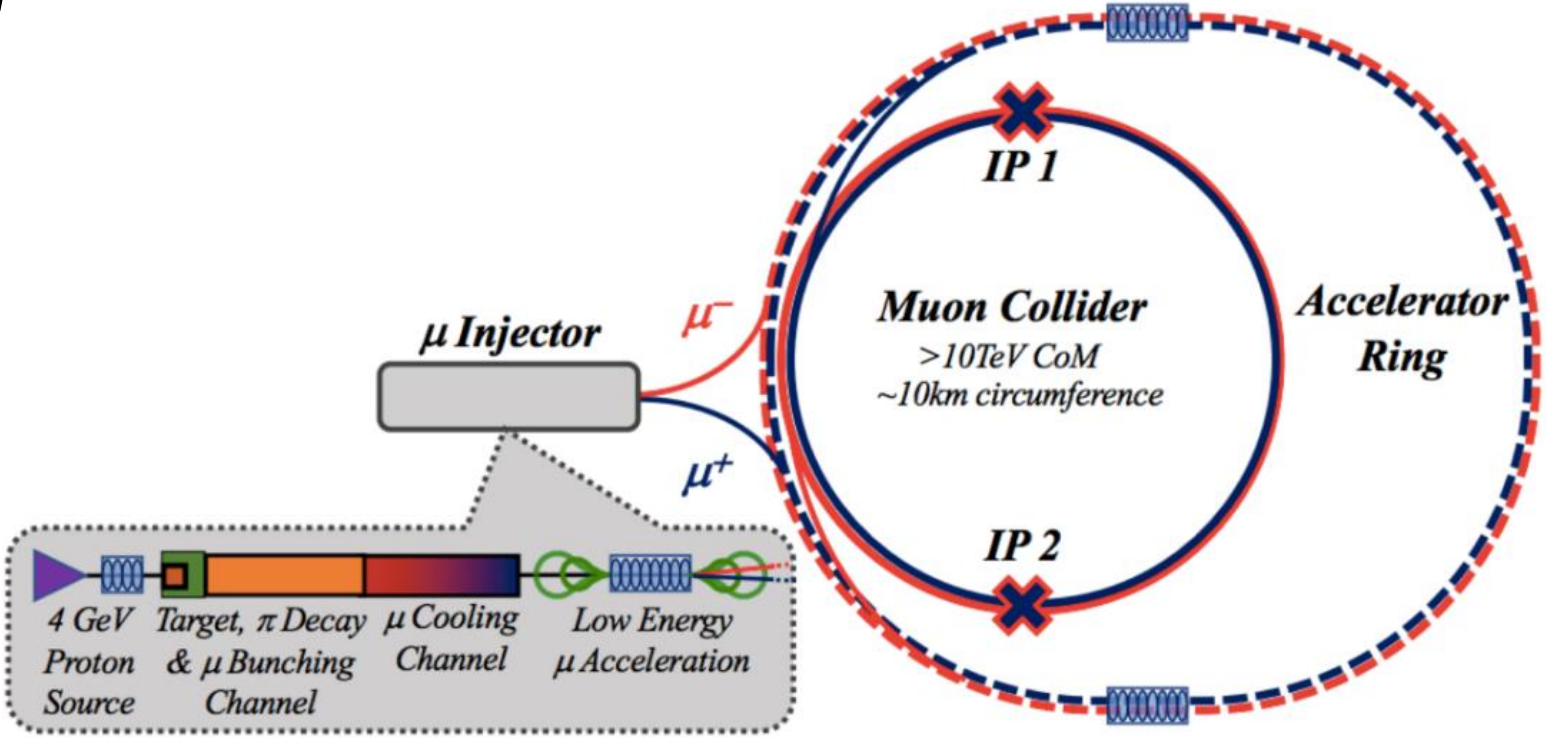


International design study facility



Main challenges

- ***Muon beams***: need to produce large numbers of muons in groups with small emittance
- ***Beam-Induced-Background***



Beam-Induced-Background

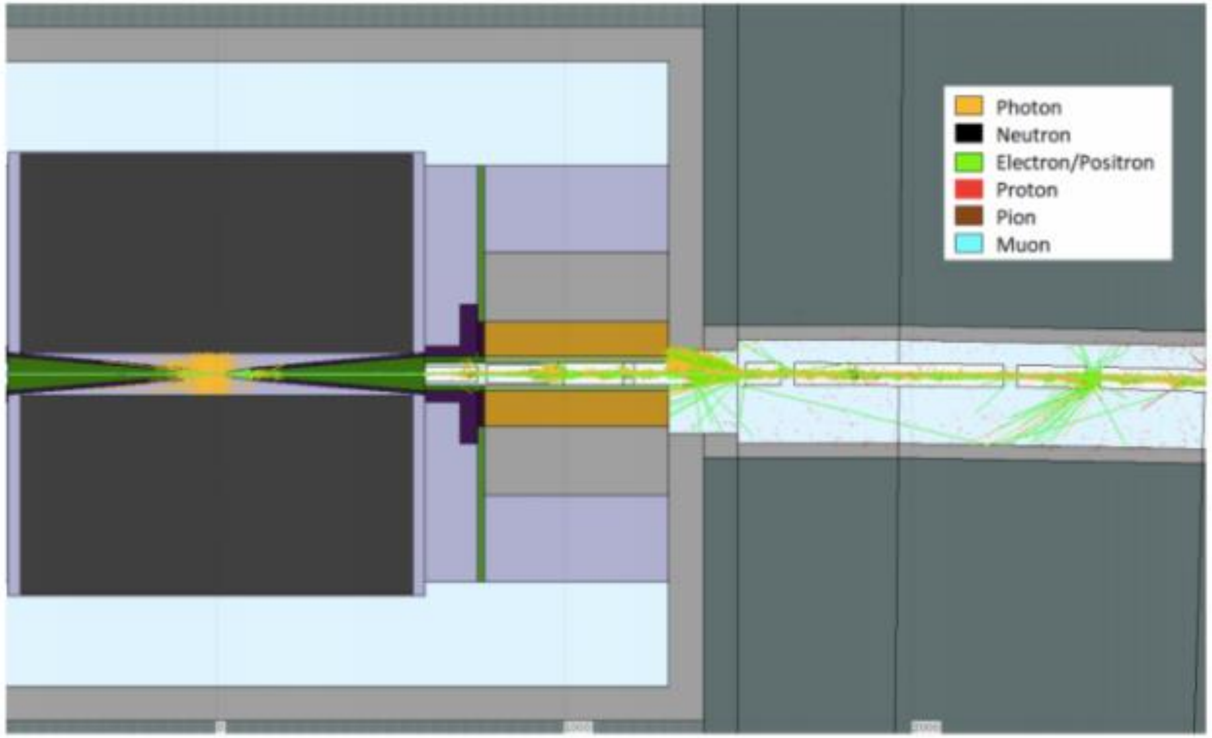
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

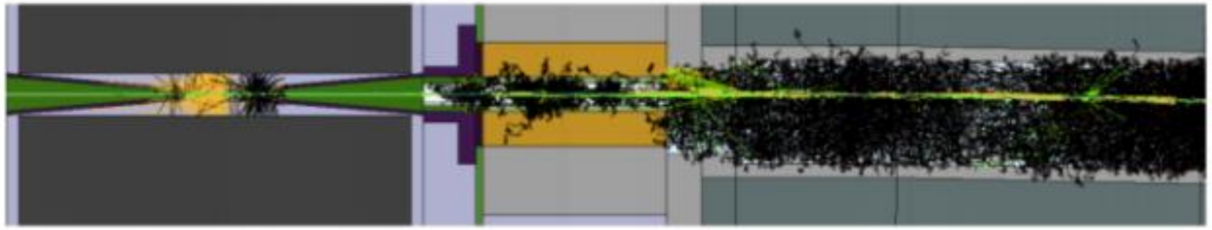
Secondary particles are produced from interaction with machine components:

- charged hadrons
- neutral hadrons
- Bethe-Heitler muons
- electrons
- photons

BIB may affect detector performance:

- shielding nozzles
- optimization of detector design





2021 JINST 15 P11009

Ilaria Vai

Initial detector design

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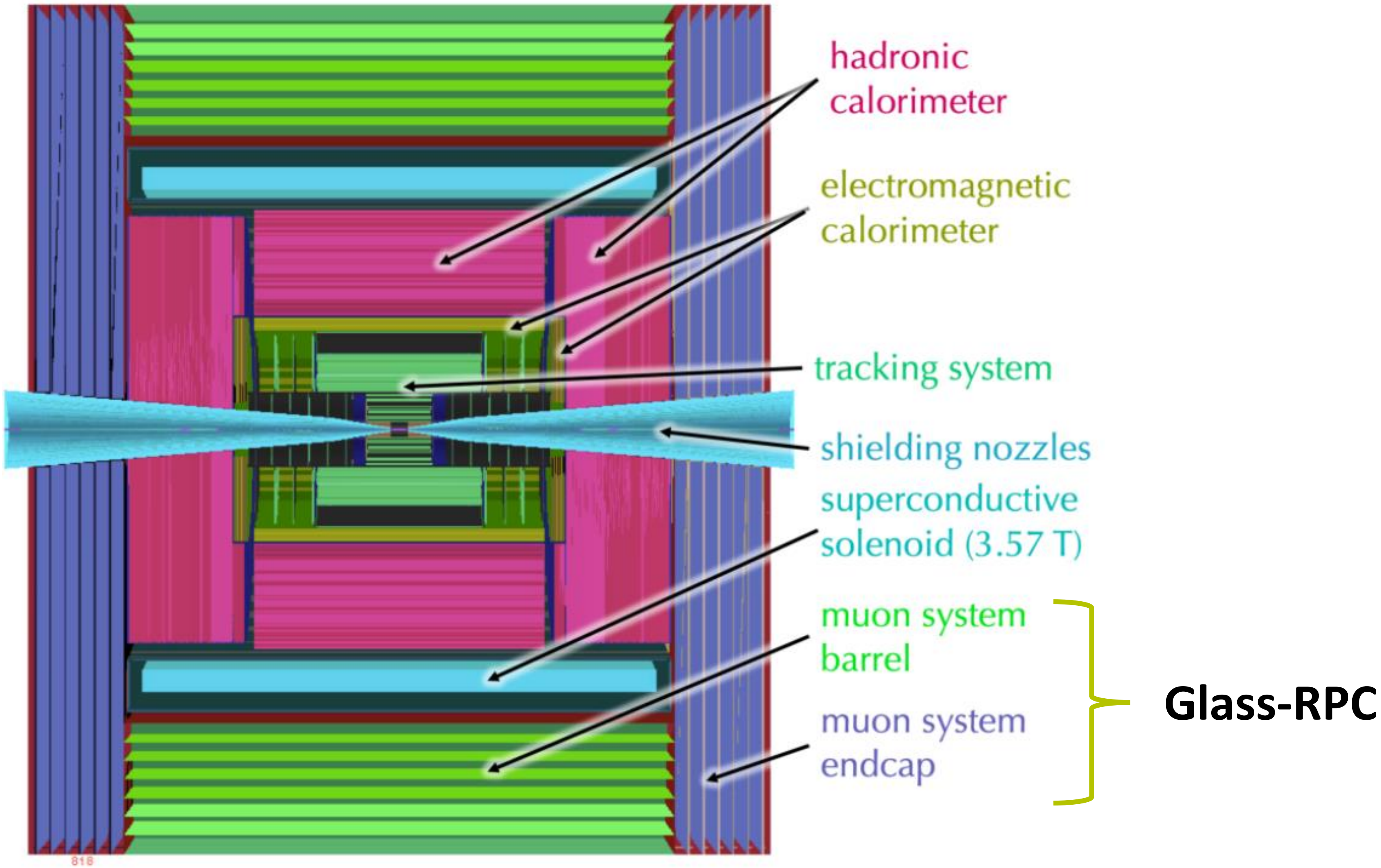
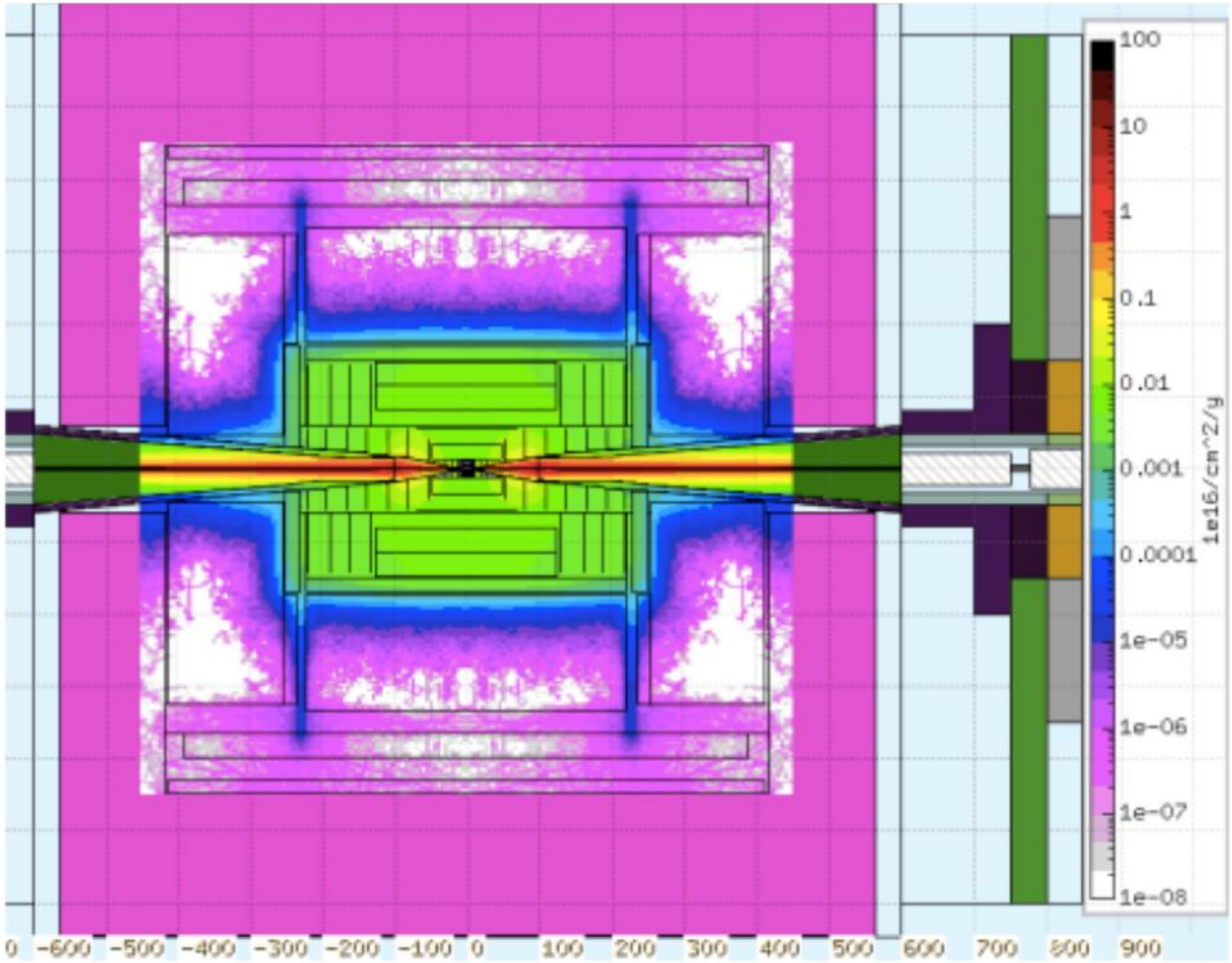


CLIC design: arXiv:1202.5940 [physics.ins-det]

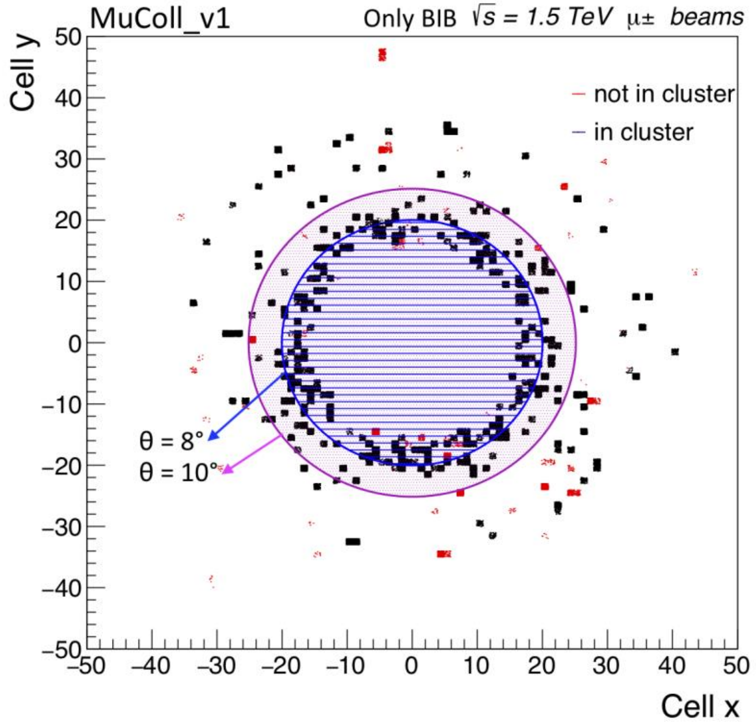
Beam-Induced-Background



FLUKA simulations

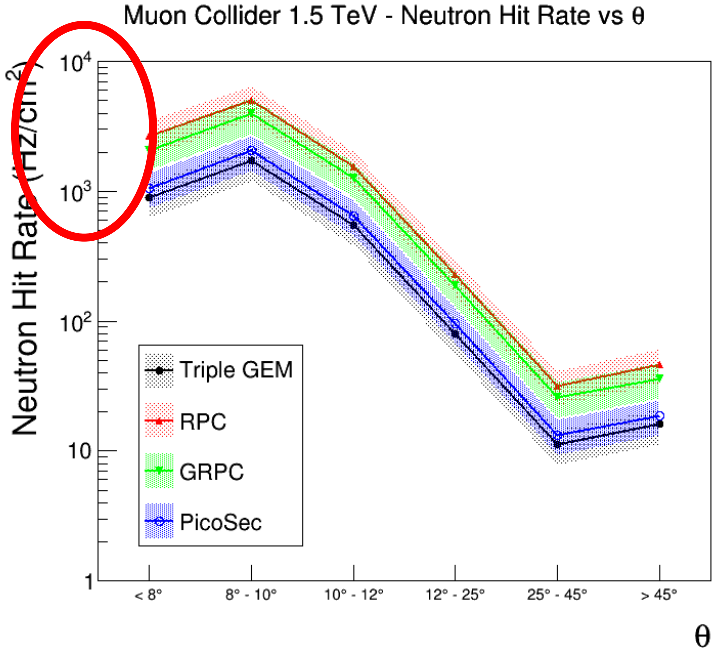
1 MeV neutron equivalent fluence

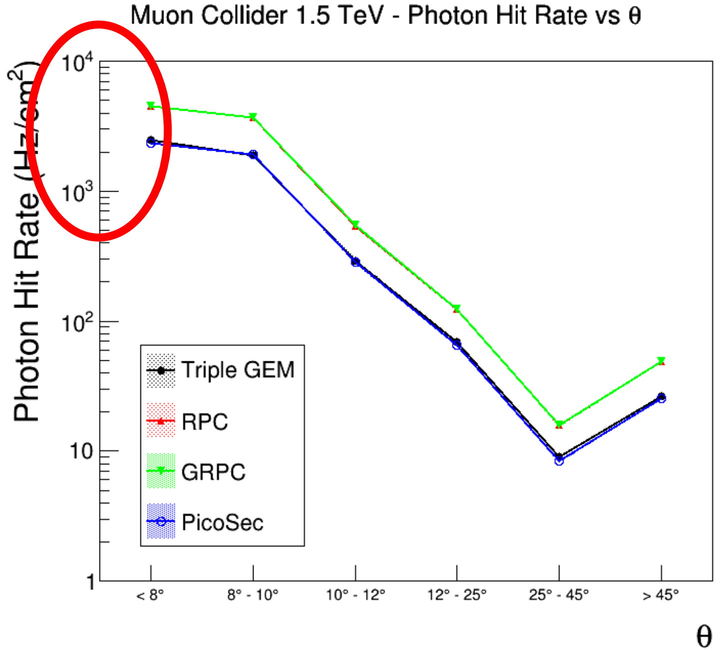
BIB in the muon system



BIB hits are localized in the regions closest to the beam line

$$\boldsymbol{Hit\ rate = sensitivity \times flux}$$



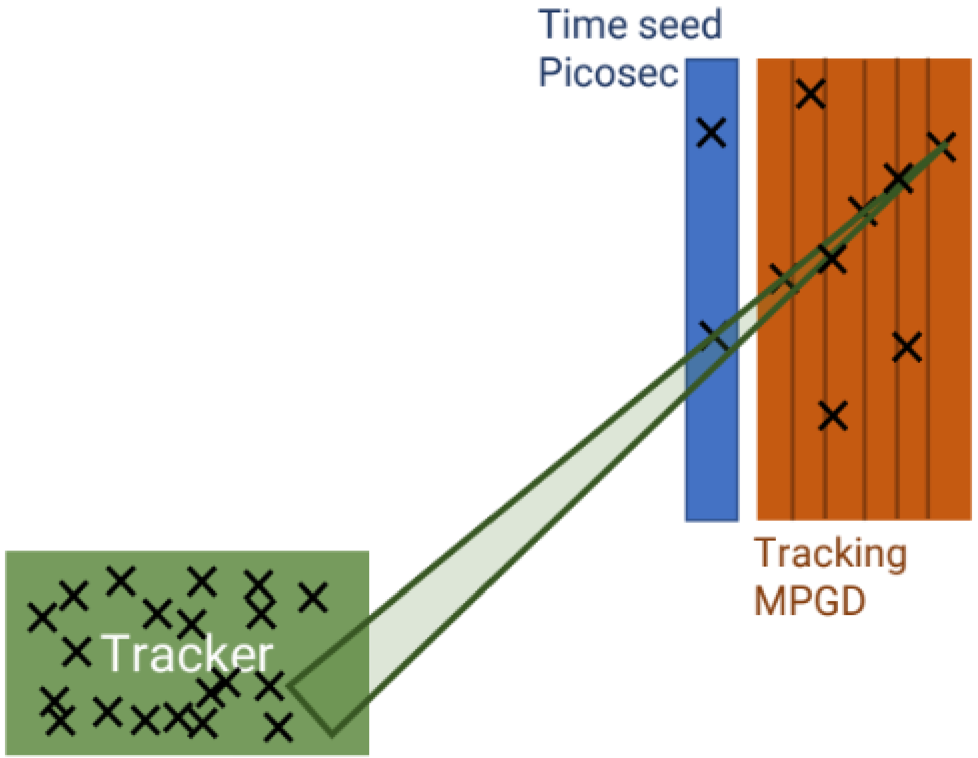


Estimated hit rate at the limit of the current Glass-RPC capability
→ Alternative design based on MPGD is being considered

Alternative muon system design

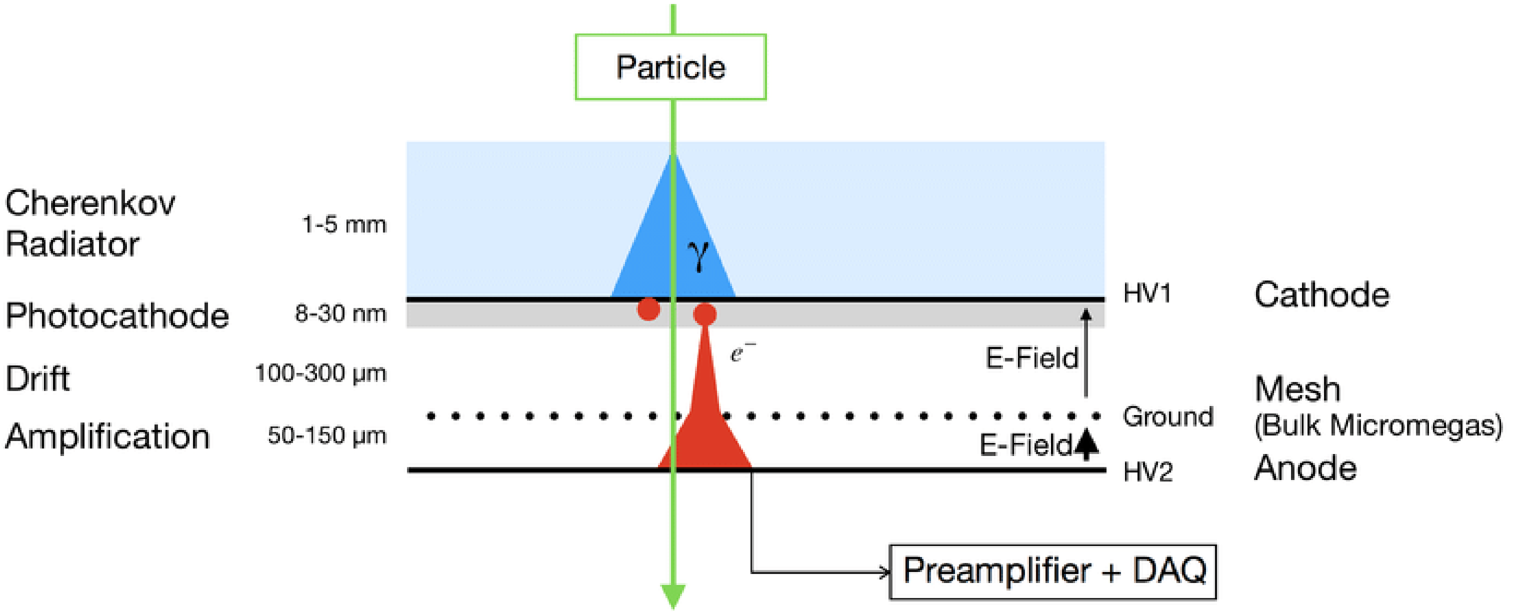
Out-to-In muon tracking approach is currently being considered: reconstruct muons in the muon system and then propagate back to the tracker → **reduce combinatorial background**

We need a time resolution comparable to the tracker one → ~100 ps



Alternative muon system design:
- **Timing layer** → *Picosec* detector
- **Tracking** based on classical MPGDs (eg. Triple-GEM)

Picosec Micromegas detector



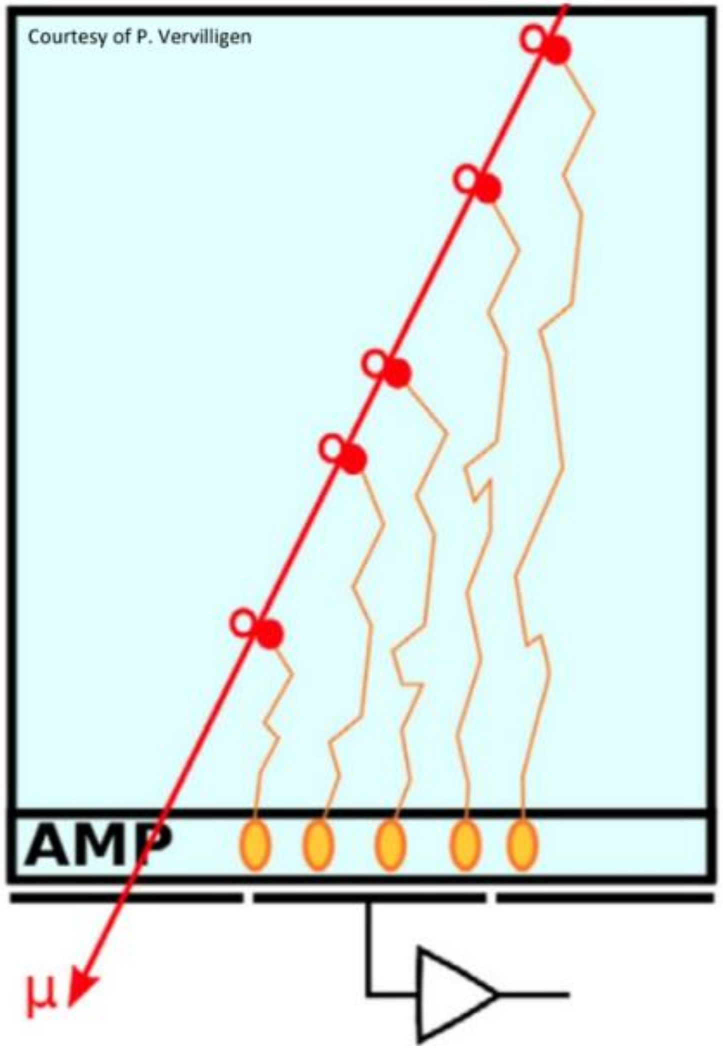
J. Bortfeldt et al, NIM A 903 (2018) 317–325, https://doi.org/10.1016/j.nima.2018.04.033

Working principle

- Highly energy particles cross the Cherenkov radiator and produce **Cherenkov photons**
- Photons are converted by the **photocatode**
- **Electrons** enter the micromegas and are amplified

Why this idea?

Timing in MPGD

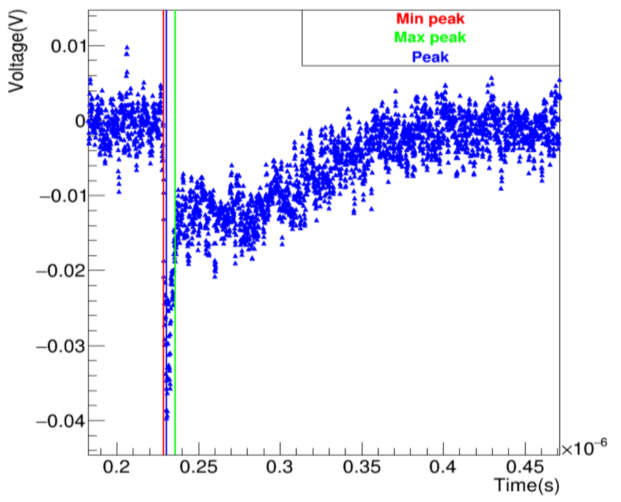


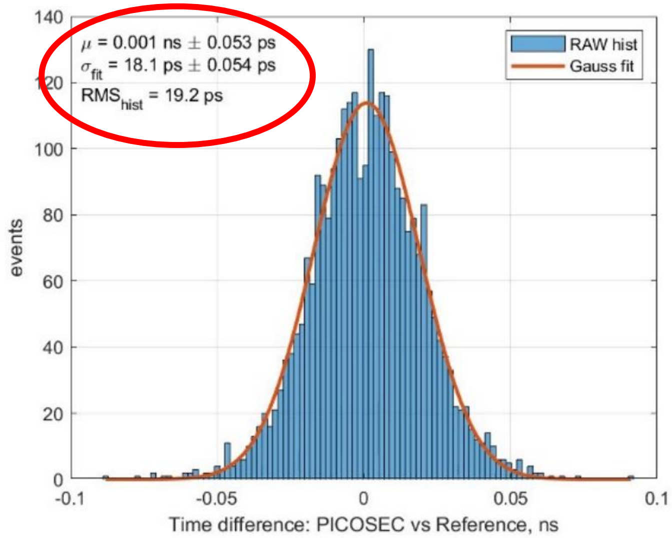
Time resolution is dominated by the position of the ionization cluster in the drift gap → ***large drift gap = large fluctuation = worse time resolution***

Classical MPGDs usually have $\sigma_t \sim few\ ns$

Picosec advantages:

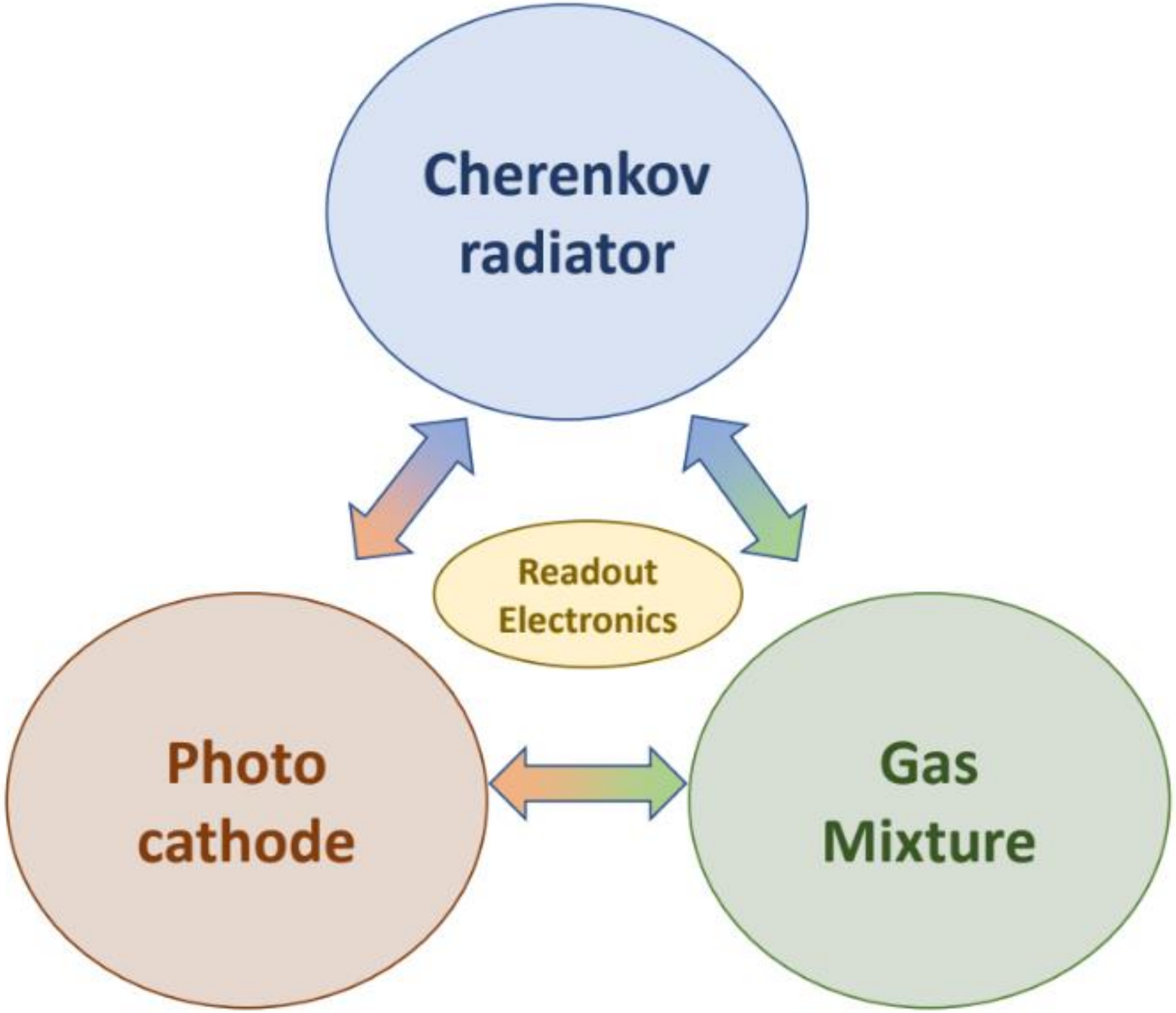
all electrons produced in the same position + very thin drift gap = ***fluctuation greatly reduced***





arXiv:2303.18141 [physics.ins-det]

Which R&D?


Cherenkov radiator
Readout Electronics
Photo cathode
Gas Mixture

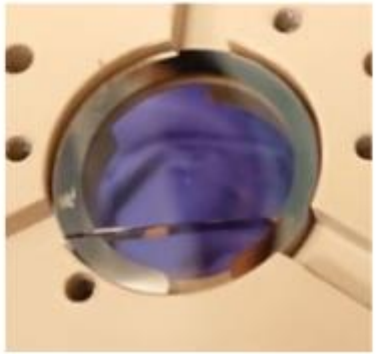
Cherenkov radiator

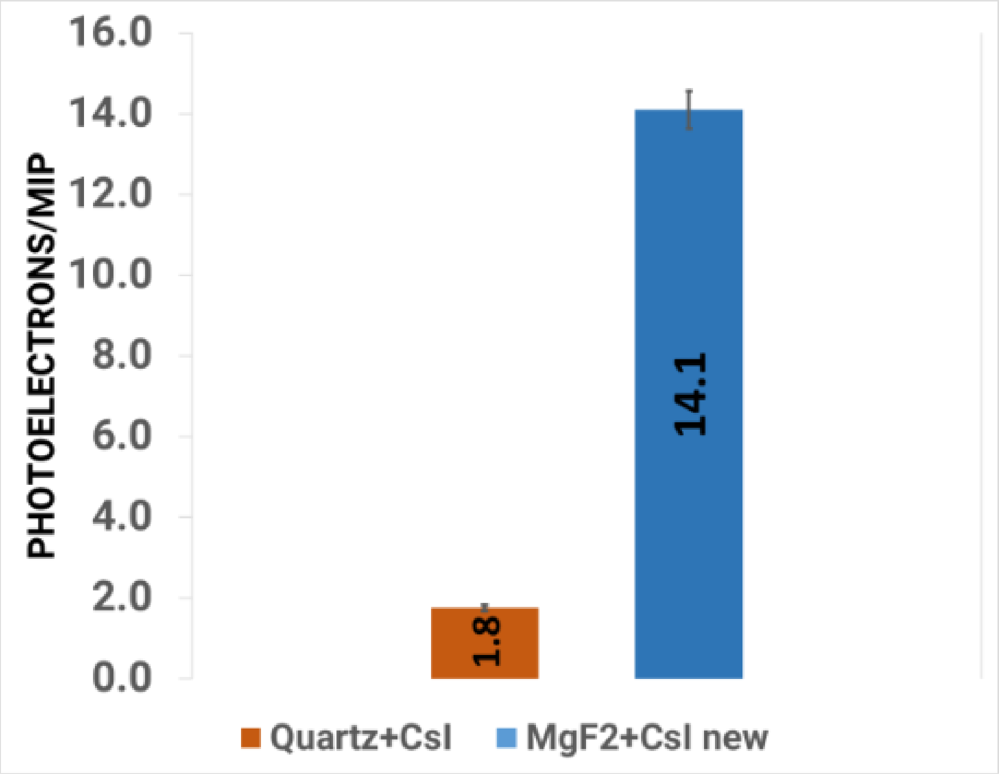
Baseline: MgF_2

Alternatives:
- Quartz
- Sapphire

Pro:
- High UV transparency

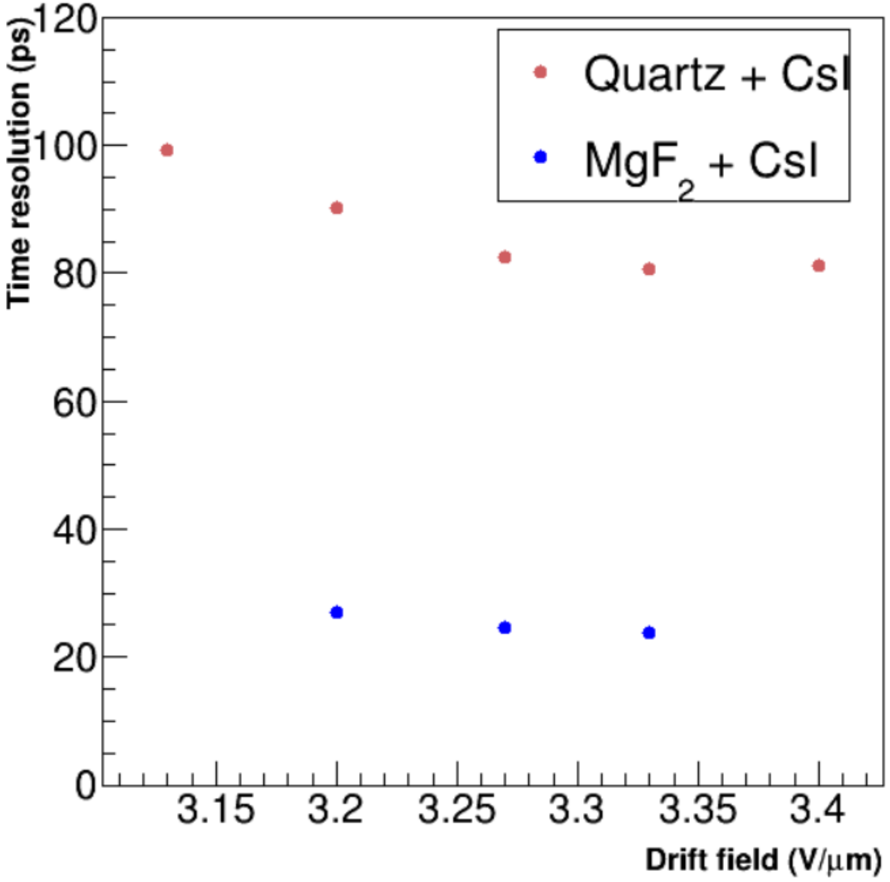
Cons:
- Fragile
- High cost
- Max 100 cm^2

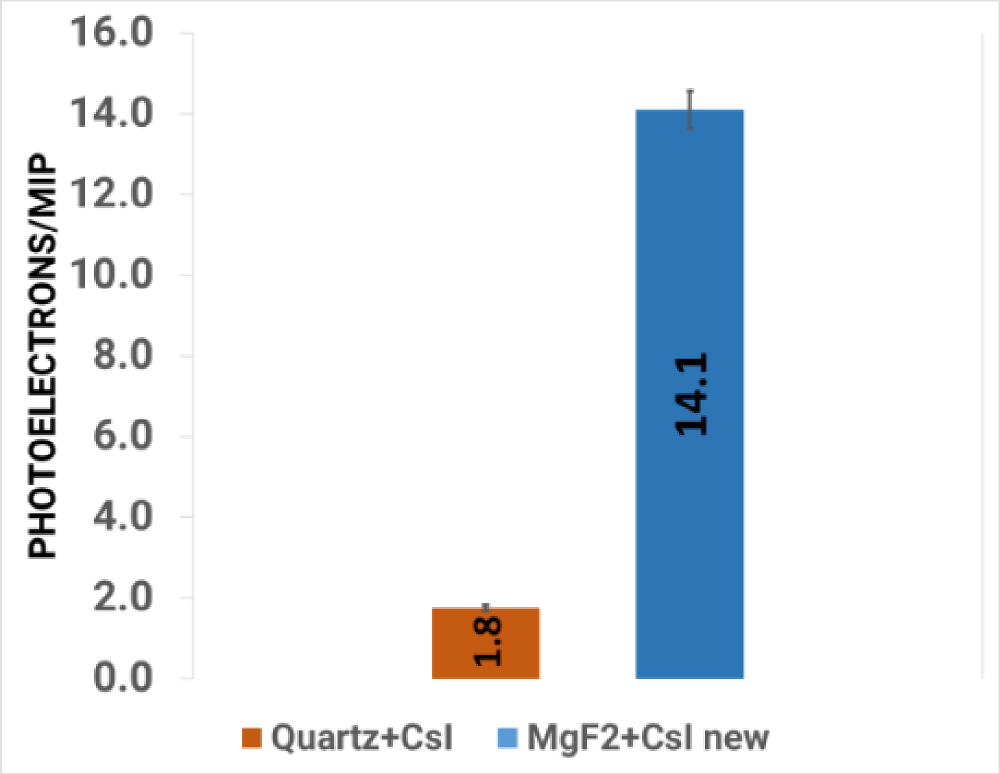




Cherenkov radiator

Alternatives:
- Quartz
- Sapphire





Photocathode

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PICOSEC Micromegas

Baseline: CsI

Alternatives:

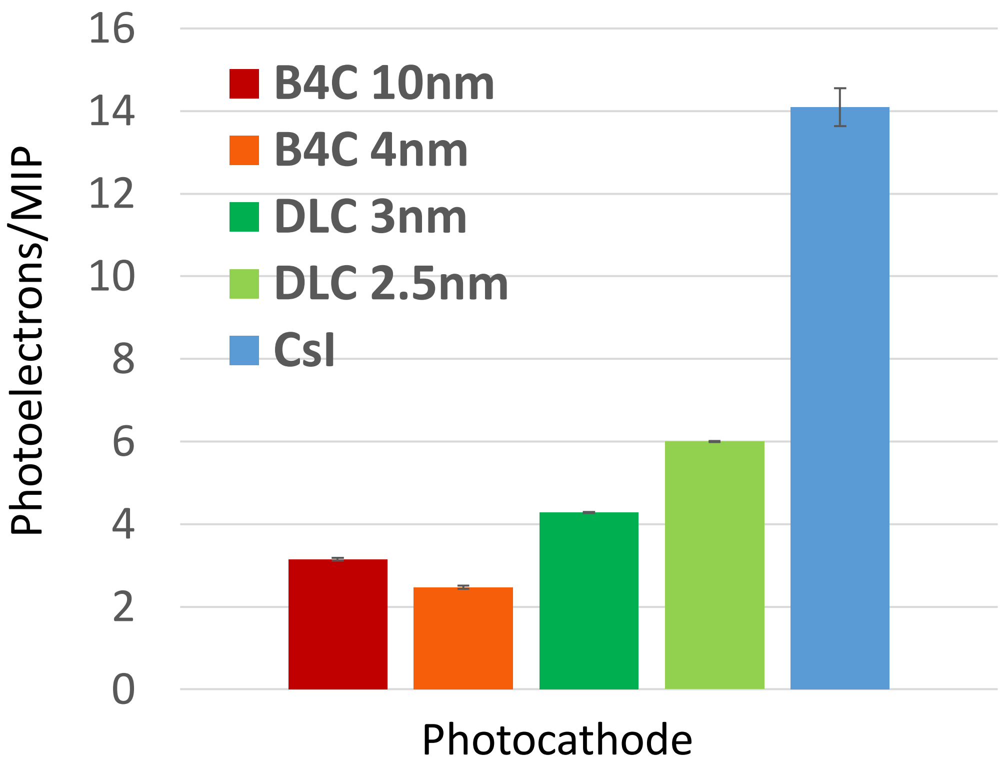
- Metallic (Al, Cr, Au...)
- Carbon-based (DLC, B4C)

Pro:

- High quantum efficiency to UV (≈10p.e./MIP)
- Easy to coat by Chemical Vapour Deposition

Cons:

- Hygroscopic (sealed operation, dry gas)
- Damage by ion bombardment



Photocathode

Alternatives:
- Metallic (Al, Cr, Au...)
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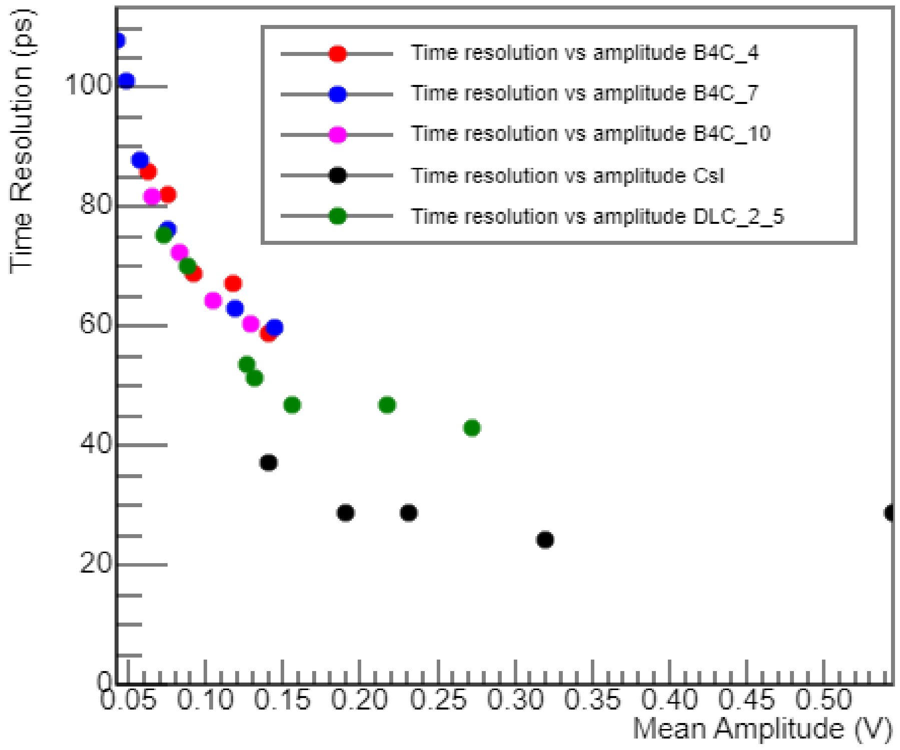

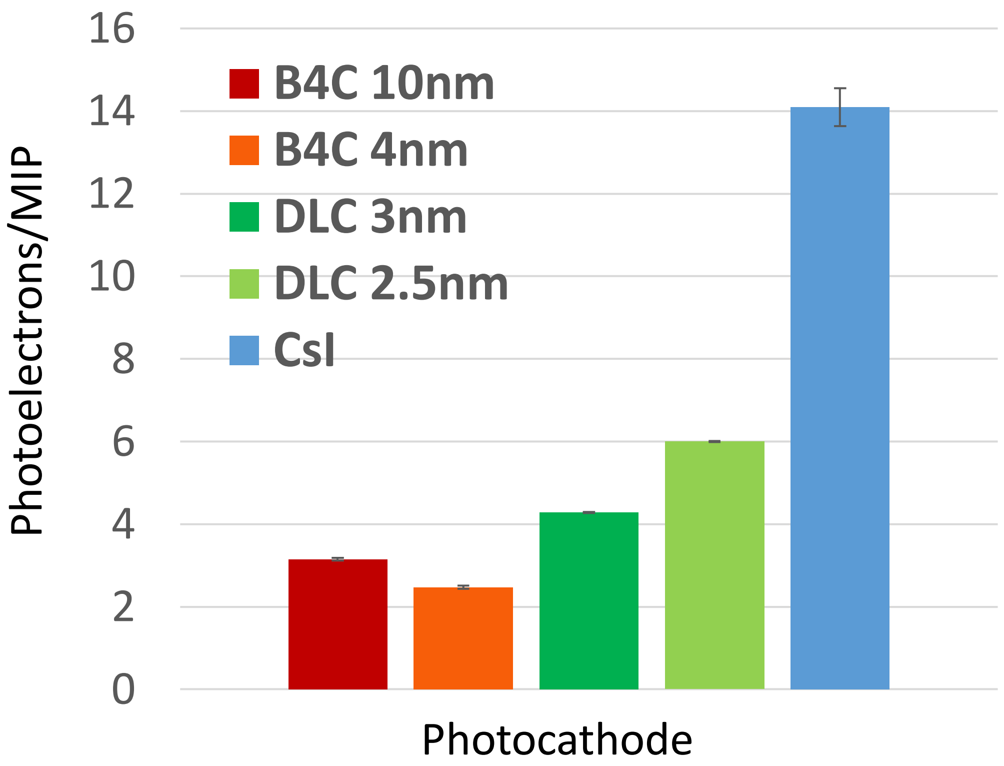

Gas mixture

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PICOSEC Micromegas

Baseline: $Ne/C_2H_6/CF_4$

Pro:

- High gain and discharge quenching (up to 2-3x10^5)
- High drift velocity (10÷15 cm/µs)

Cons:

- Very expensive
- Very high GWP (≈740)

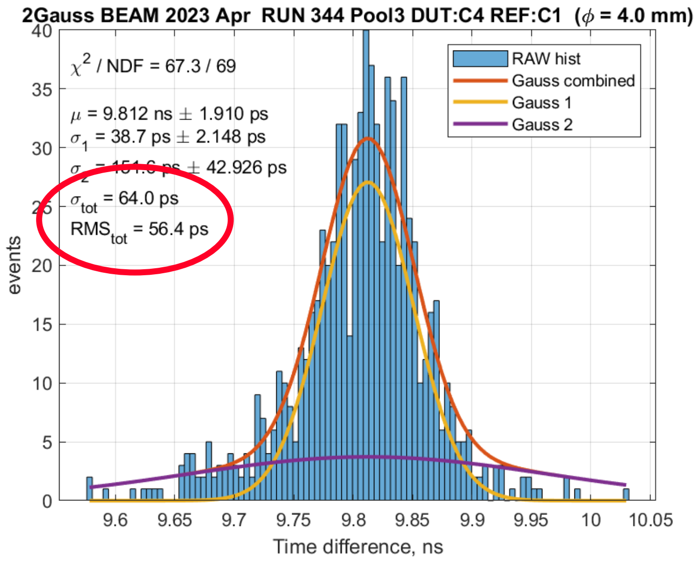
Alternatives:

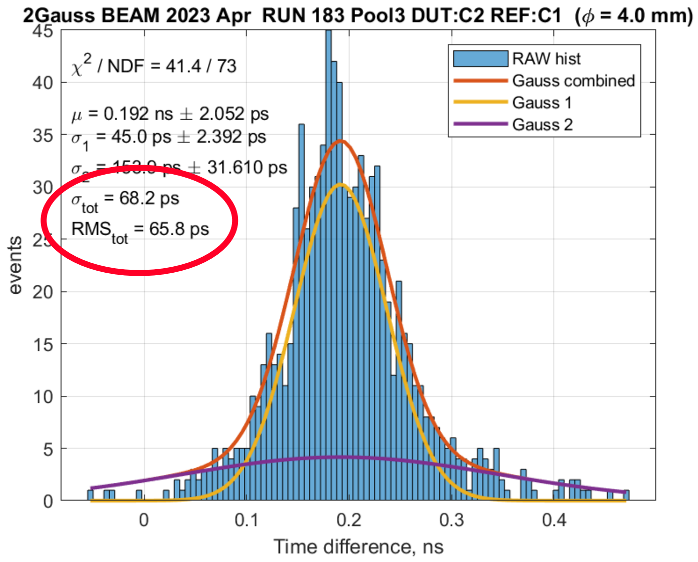
Gas mixture used	Global Warming Potential 100-years (normalized to CO_2)
$Ne/C_2H_6/CF_4$ (80/10/10)	**740**
Ne/iC_4H_{10} (94/6)	0.2
Ar/CO_2 (93/7)	0.07
$Ar/CO_2/iC_4H_{10}$ (93/5/2)	0.11

Results

Ar-based gas mixtures have too small operation range → extremely difficult to find an operational configuration in which the detector is stable & the signal is visible

Ne/iC_4H_{10} gives interesting performance:



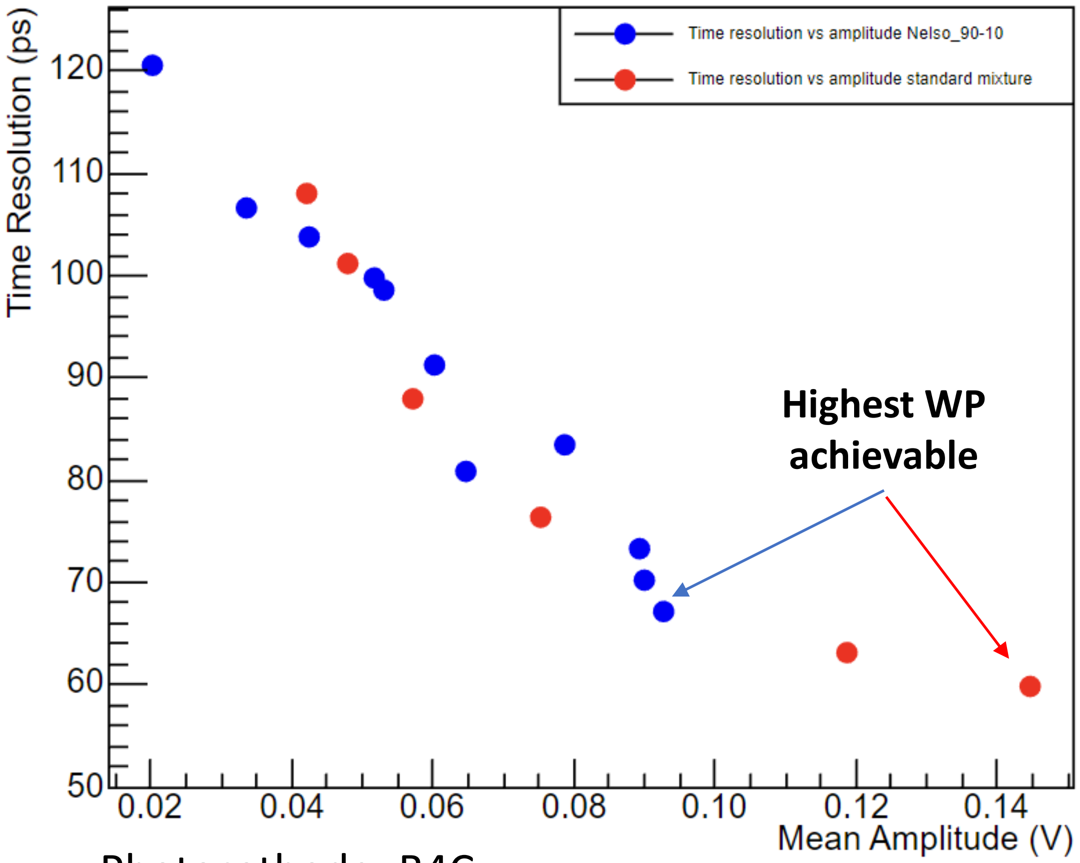


$Ne/C_2H_6/CF_4$ → **Ne/iC_4H_{10}**

Photocathode: B4C 6nm (3 PE/MIP) → Lower time resolution wrt CsI is expected

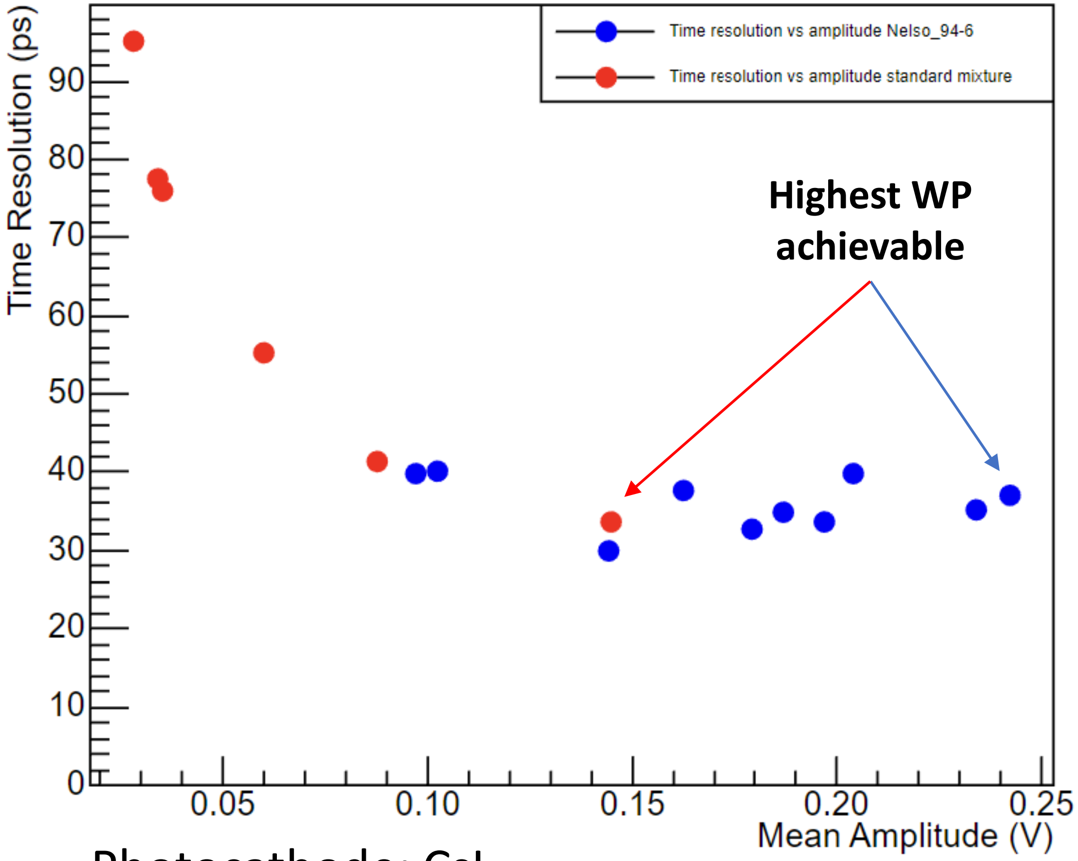
Results

Ne/iC_4H_{10} 90/10 vs standard mixture



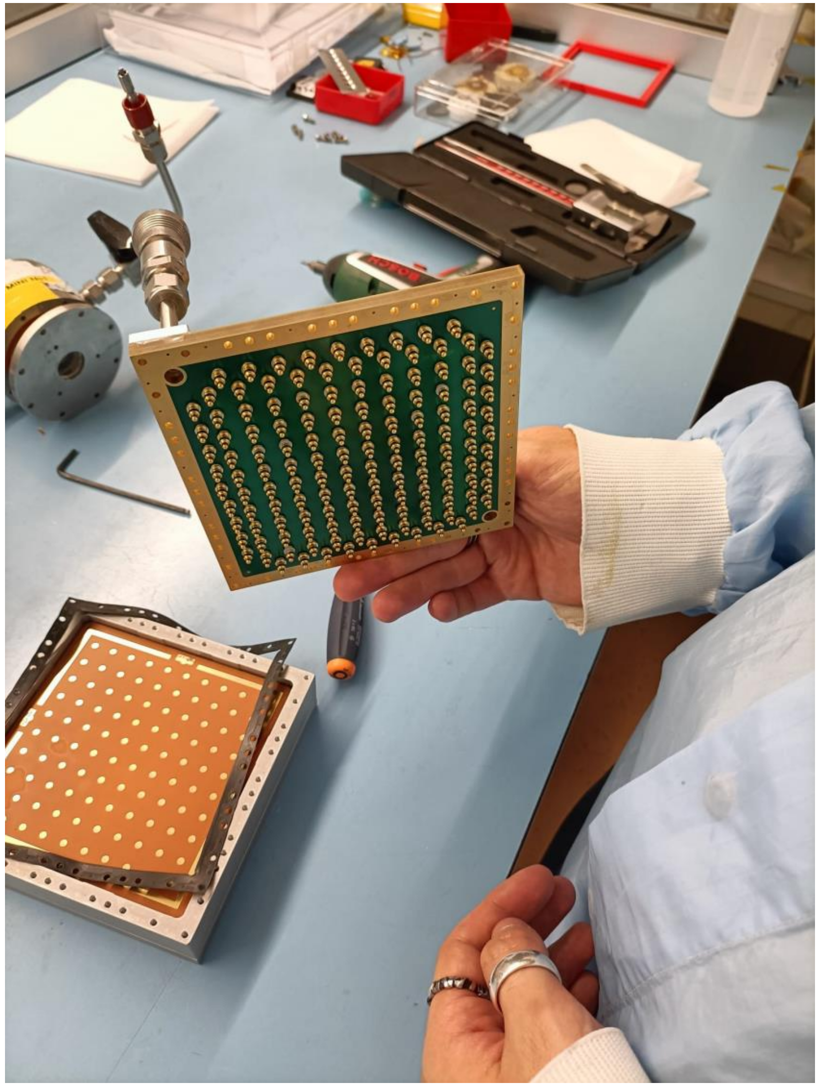
Photocathode: B4C
Resistive Micromegas 300 kΩ

Ne/iC_4H_{10} 94/6 vs standard mixture



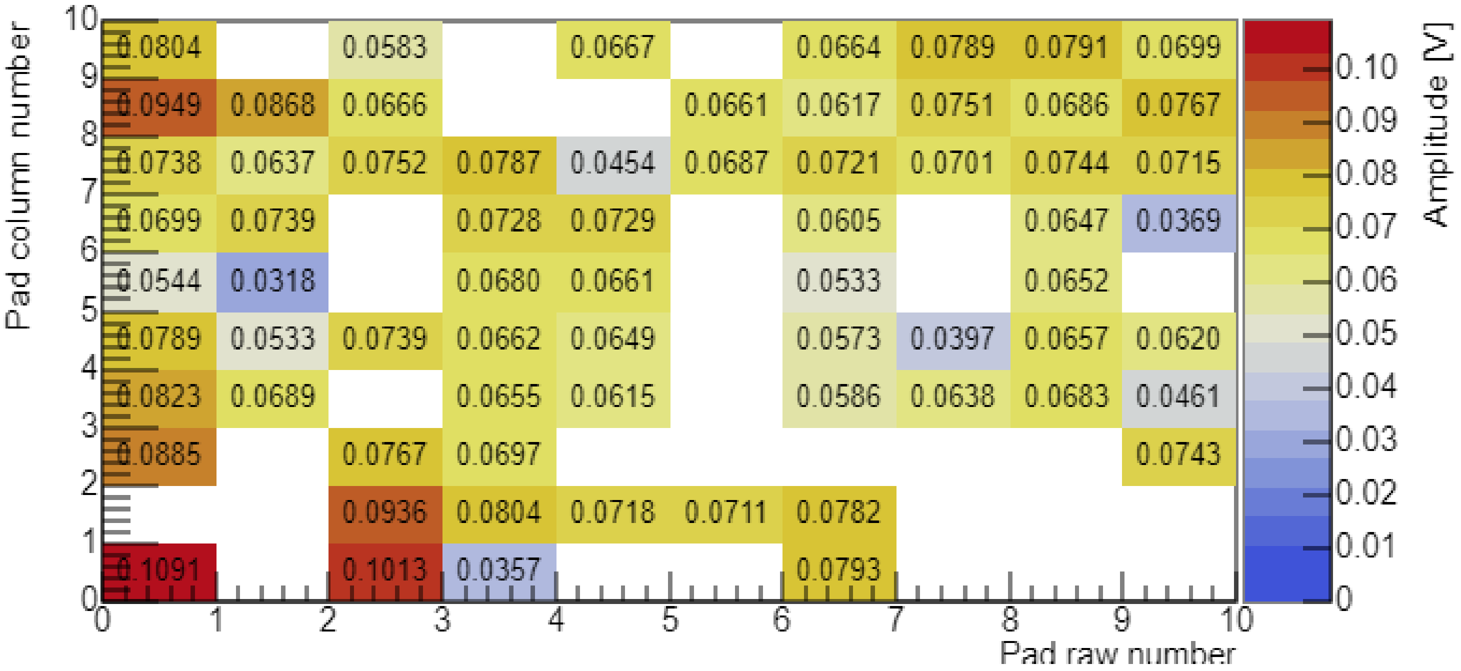
Photocathode: CsI
Resistive Micromegas 82 MΩ

10x10 cm² multipad prototype



10x10 cm2 multipad prototype assembled in spring 2023:

- 100 readout channels
- tested in July test beam with standard gas mxture
- readout with ORTEC preamp (lab test) and SAMPIC digitizer (test beam)



Summary

The **muon collider** is an interesting opportunity for the future of high energy physics. It poses however challenging operational conditions, mainly related to the presence of BIB.

The design of a **proper experiment** is ongoing: MPGDs are being considered as candidate detectors for the muon system.

Picosec is a candidate technology for a timing layer in the muon system: a dedicated R&D is ongoing, maily focused on optimization of the Cherenkov radiator, photocathode and gas mixture.

Thanks to the RD51 Picosec-Micromegas Collaboration for the precious support and help!

Next year R&D activities will focus on on the mechanics needed for the instrumentation of large surfaces and on the assessment of a environmental-friendly gas mixture.

Thanks for your attention!