Picosec Micromegas for the Muon Collider Detector

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On behalf of the Muon Collider Collaboration

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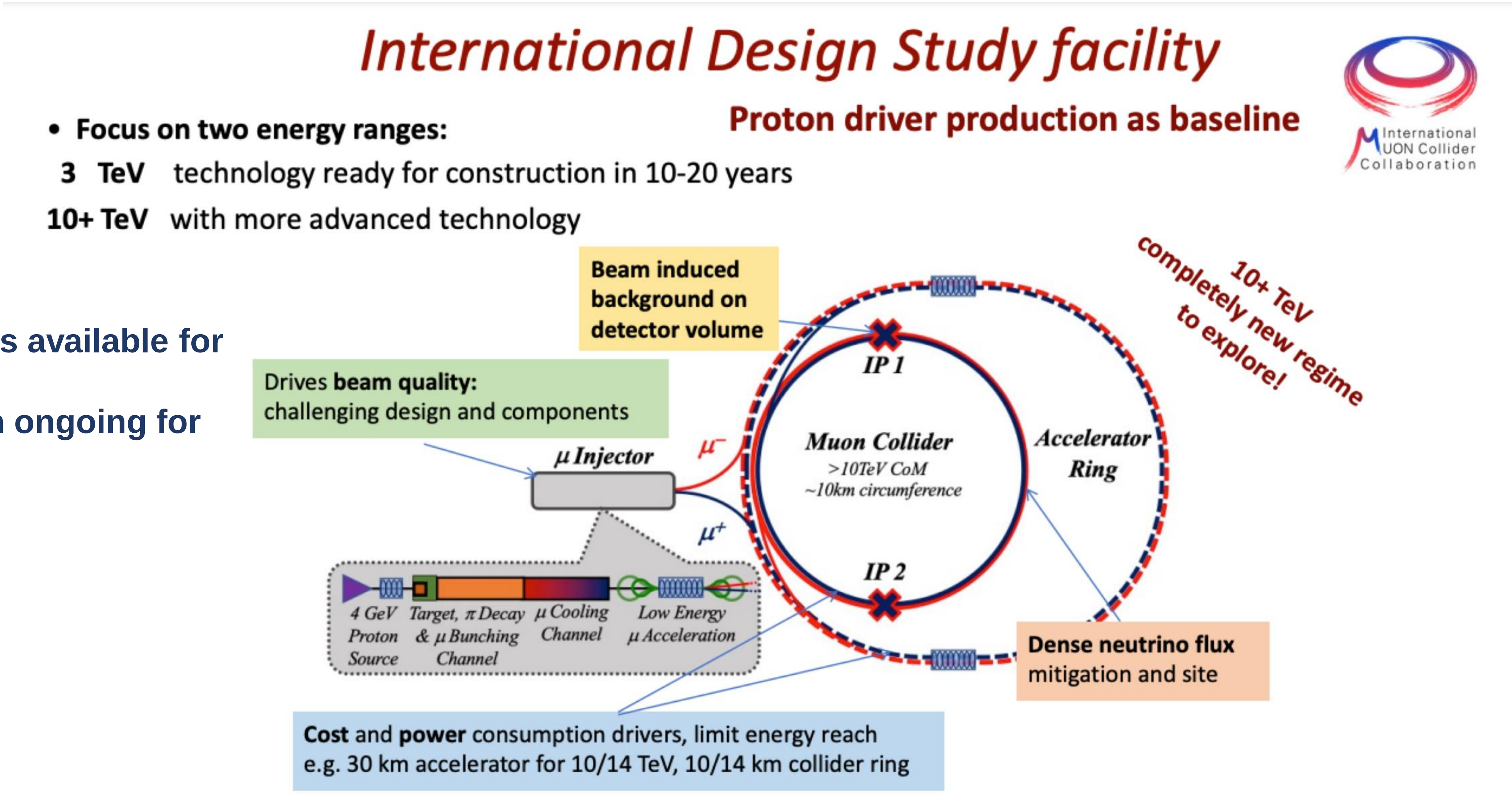
Muon Collider facility



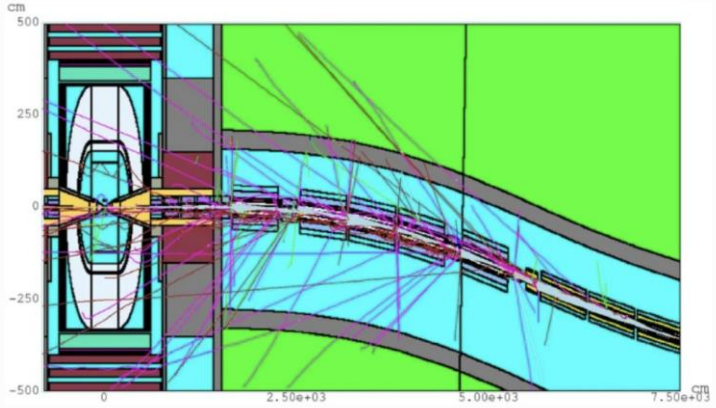
- **Simulations available for $\sqrt{s}$=1.5TeV**
- **Production ongoing for $\sqrt{s}$= 3TeV**

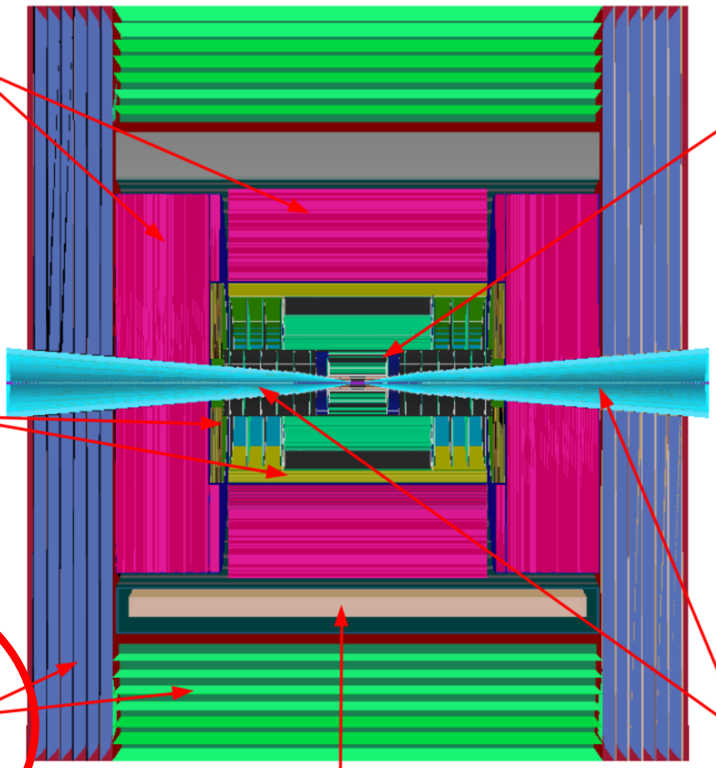
Muon Collider Detector

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)



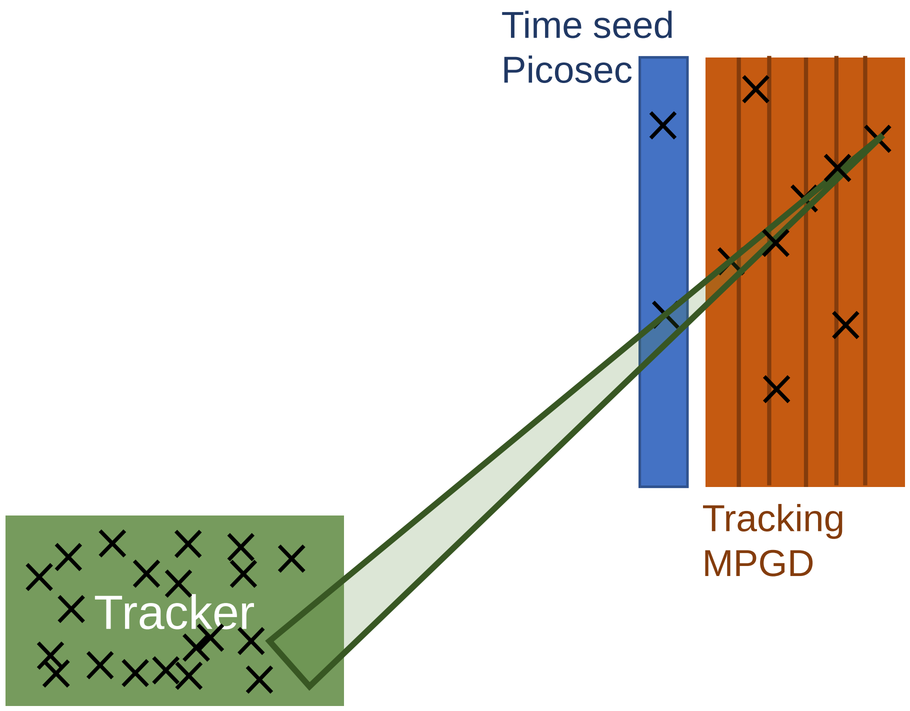


Muon endcap

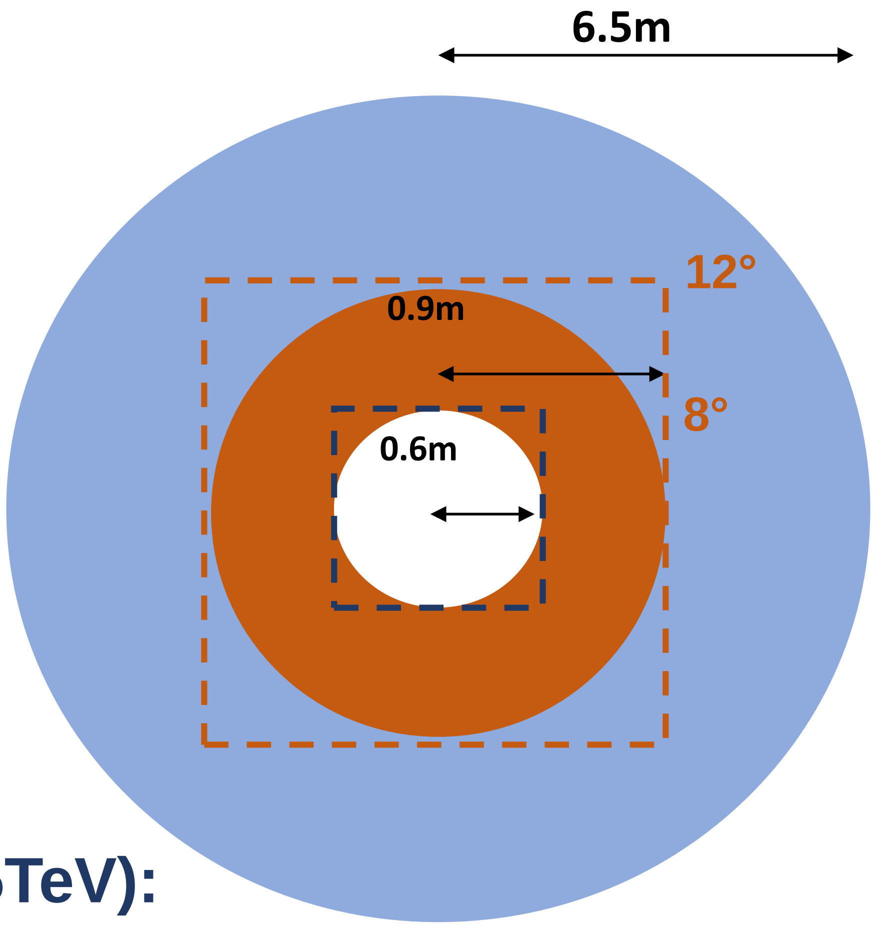
<u>Out-to-In</u> muon tracking approach currently under study

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



Endcap – not in scale

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

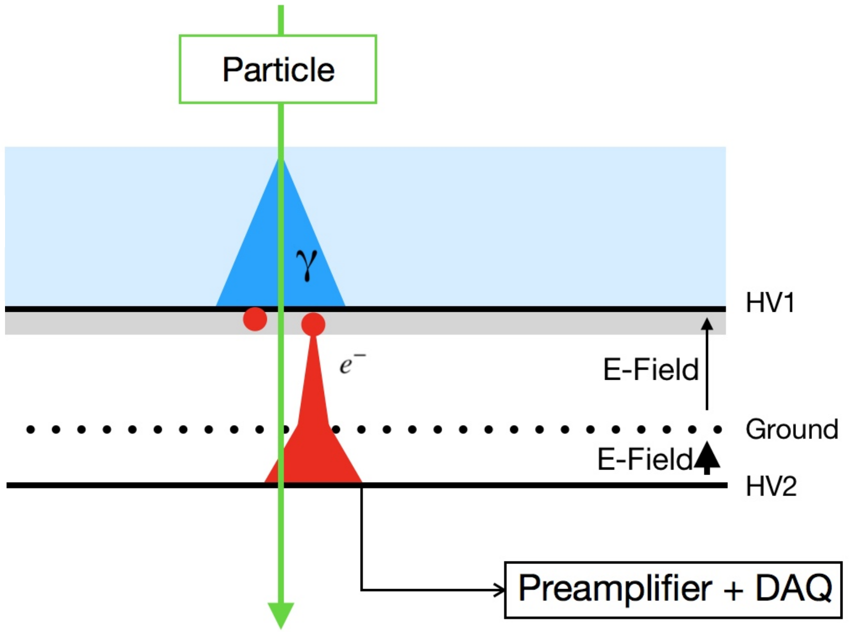
- **60 kHz/cm^2 8°<θ<12°**
- 2 kHz/cm^2 θ>12°

Picosec Micromegas

Gas Mixture:

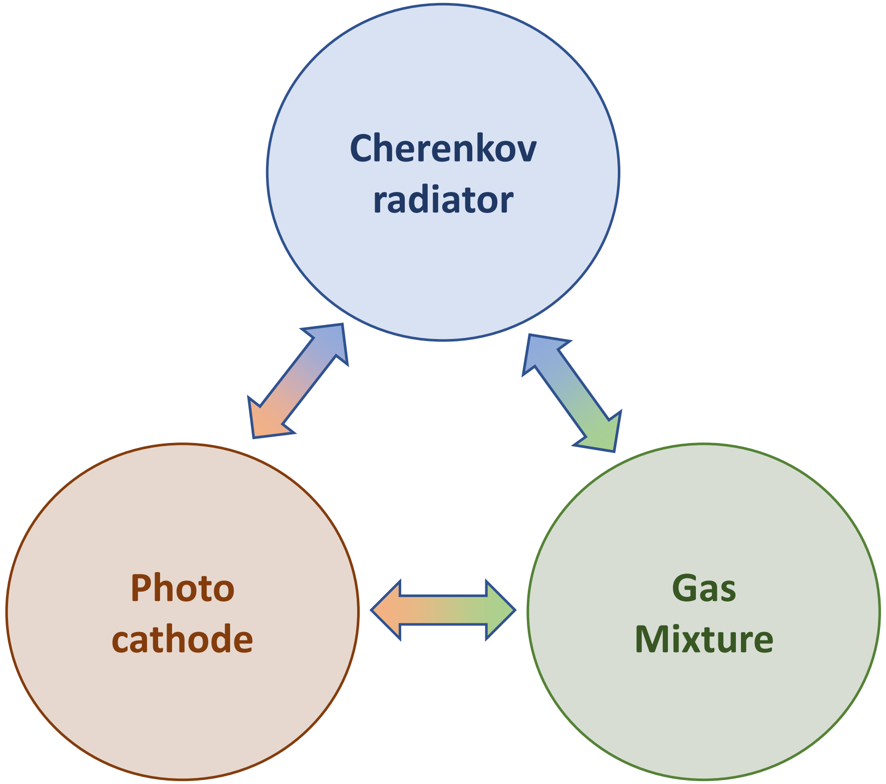
$Ne/C_2H_6/CF_4$
80/10/10

Cherenkov Radiator	MgF_2 3mm
Photocathode	CsI 18nm
Drift	200µm
Amplification	128µm



Cathode
Mesh 18µm wire
(Bulk Micromegas)
Anode

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



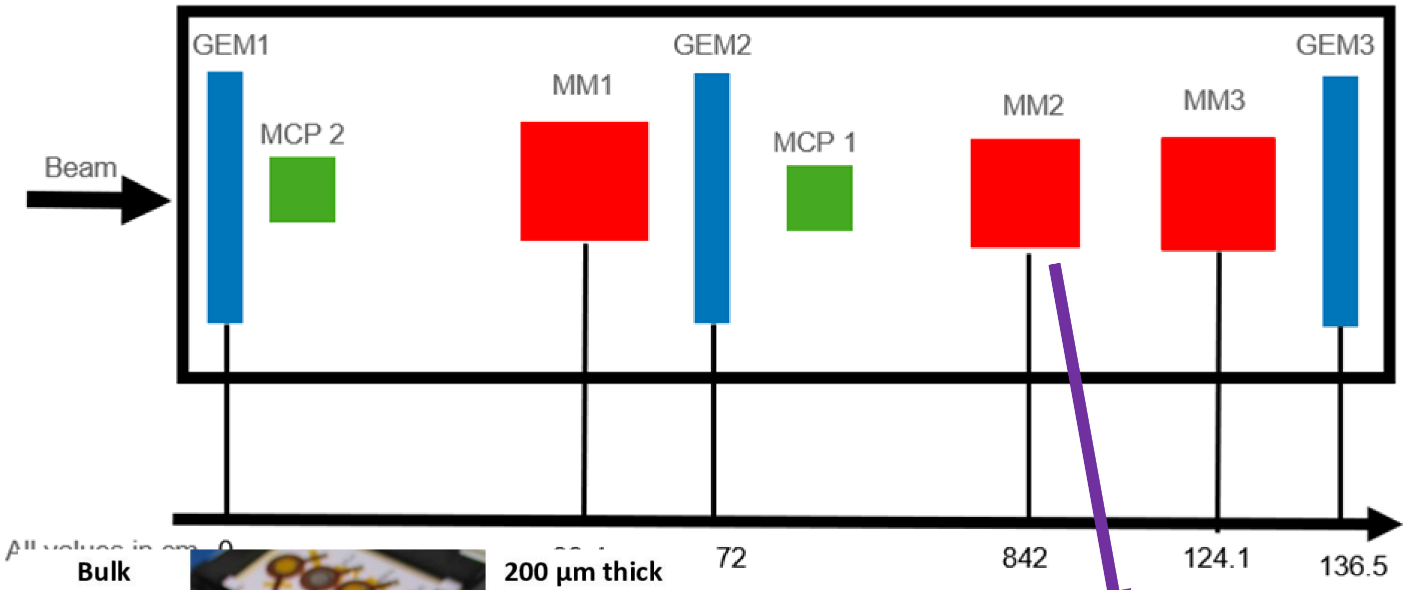
Cherenkov radiator MgF2:
- Optimal UV transparency, high cost, no technology for large windows, fragile

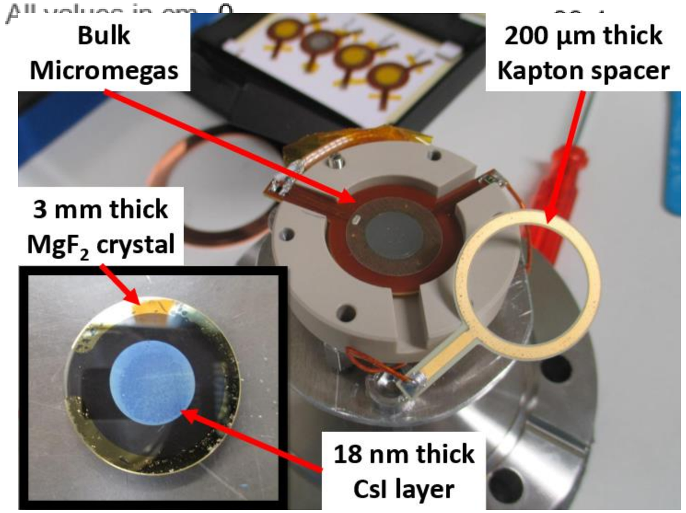
Photocathode CsI:
- Best UV QE, radiation damage, Hygroscopic

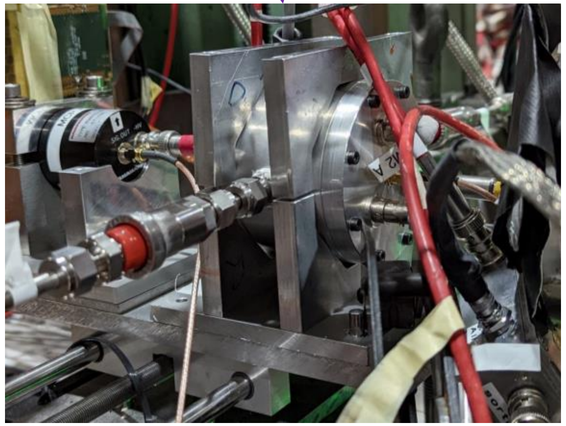
Gas Ne/C2H6/CF4:
- High quenching, high-cost, non-eco-friendly

Test Beam Setup

MCP for time reference $\sigma_t \approx 5ps$







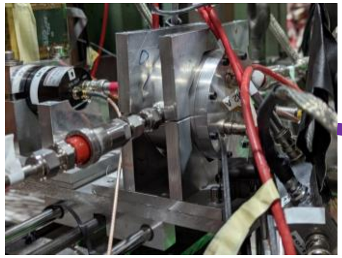
Test beam, 19Oct-1Nov 2022

- Profited of the RD51 GEM-based tracker
- Participated to full RD51 R&D campaign
  - First beam time with a **dedicated detector for muon collider R&D**

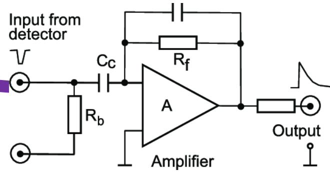
Single-channel:

- Test the detector operation on the beam
- Measure different **radiator+photocathode combination yield** (photoelectrons/MIP) and compare
- Measure **time resolutions** with different **radiator+photocathode** combination
- Comparison between **non-resistive** MM (amplification 150um) and **resistive** MM (amplification 128um)

Single-channel setup
- Photoelectrons/MIP measurement-



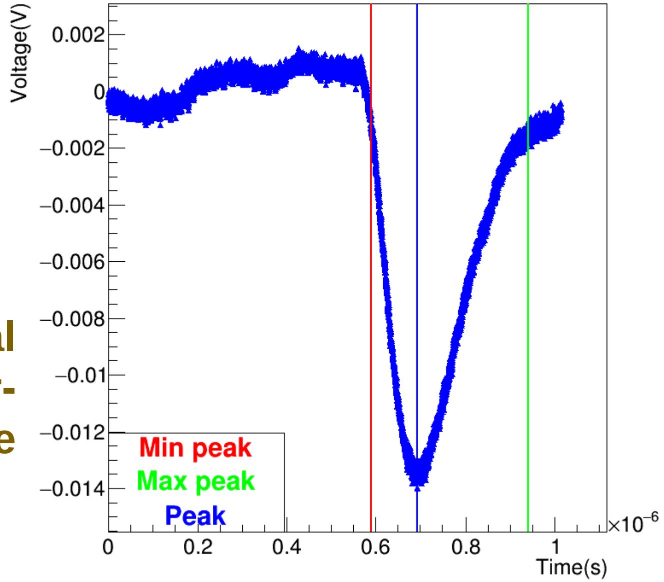
Charge amplifier

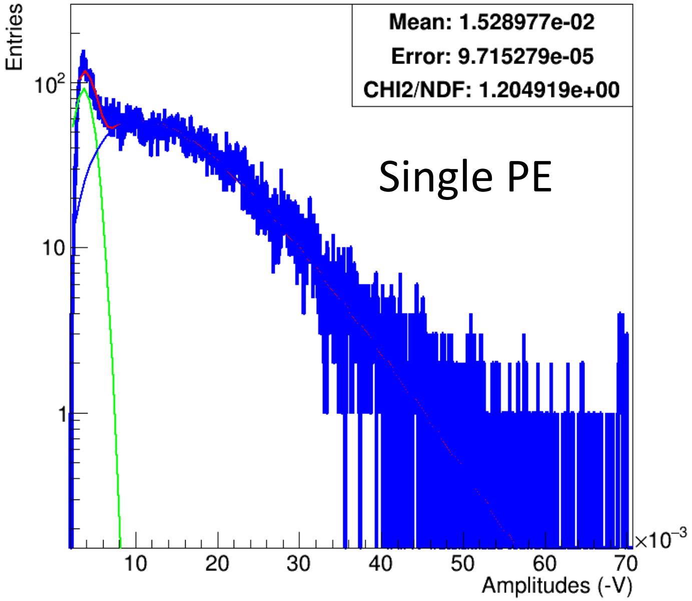


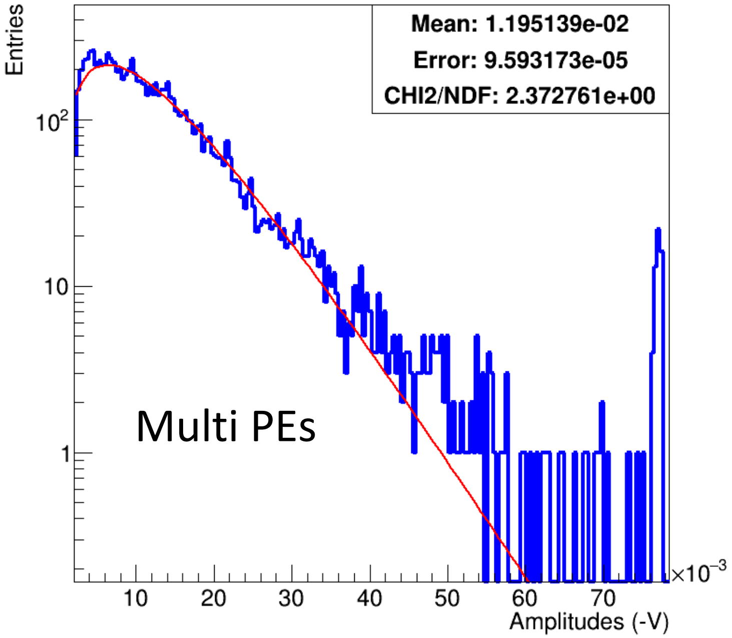
Waveform saved for processing

- Charge spectrum with UV LED → single photoelectron spectrum
- Charge spectrum with beam → photoelectrons from beam spectrum
  - Geometrical cut essential to select only fully contained Cherenkov cones

Integral of the signal
-or-
Just the amplitude



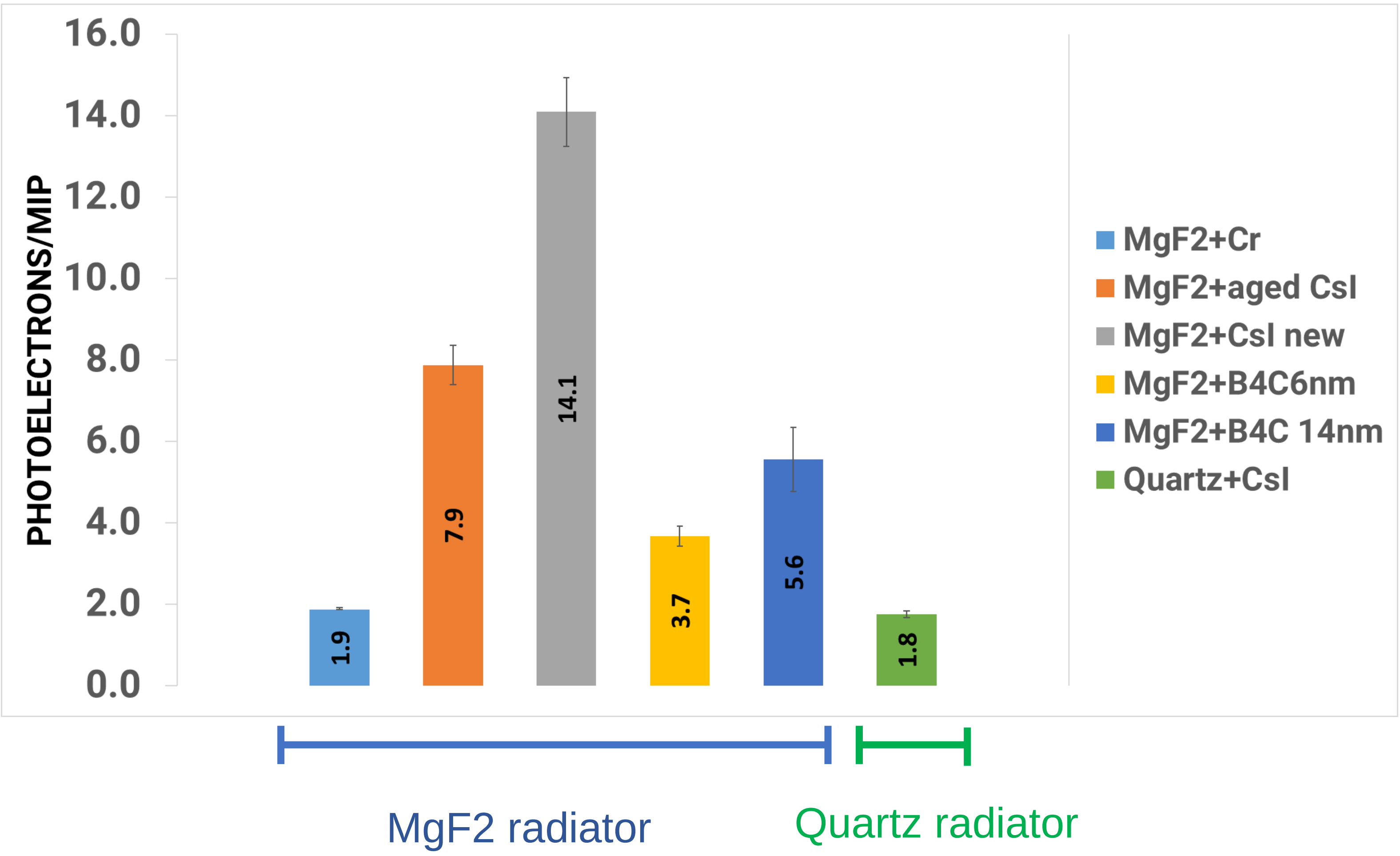




Polya function (negative binomial)
Describe well the gain fluctuation when the primary charges are low

$$p(x) = \frac{(1+\theta)^{1+\theta}}{\Gamma(1+\theta)} \frac{x}{\bar{x}}^{\theta} e^{-\frac{(1+\theta)x}{\bar{x}}}$$

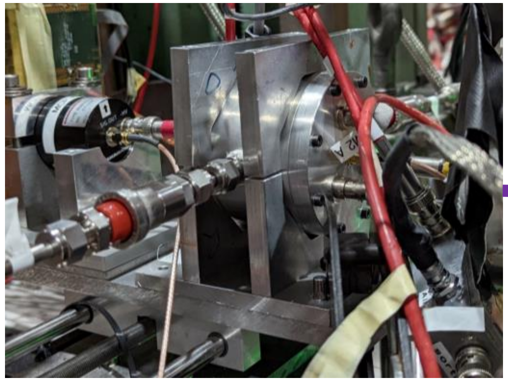
Photoelectrons per Muon

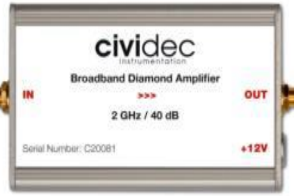


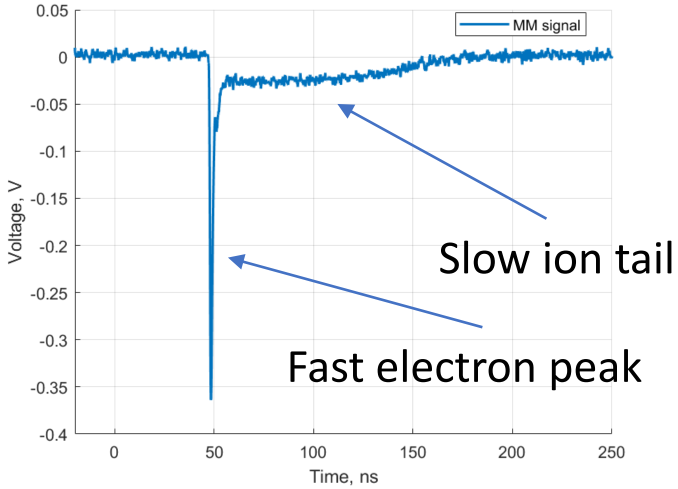
The ratio among the mean amplitudes gives the average number of photoelectrons per incoming muon.

- We don't know precisely the amount of aging of the CsI photocathode in orange, but it was handled in the air multiple times (collected humidity damage). **CsI is prone to degradation if exposed to humidity and heavy ion bombardment**
- **Quartz is not a good radiator**. Its yield is an order of magnitude lower than MgF2. May create some inefficiencies
- **B4C is very promising** (12nm demonstrated the best performance https://indico.cern.ch/event/1219224/contributions/5130512/attachments/2565710/4423222/Marta Lisowska - PICOSEC Micromegas - MPGD2022.pdf). Moreover is resistive (spark protection) and easy to handle.

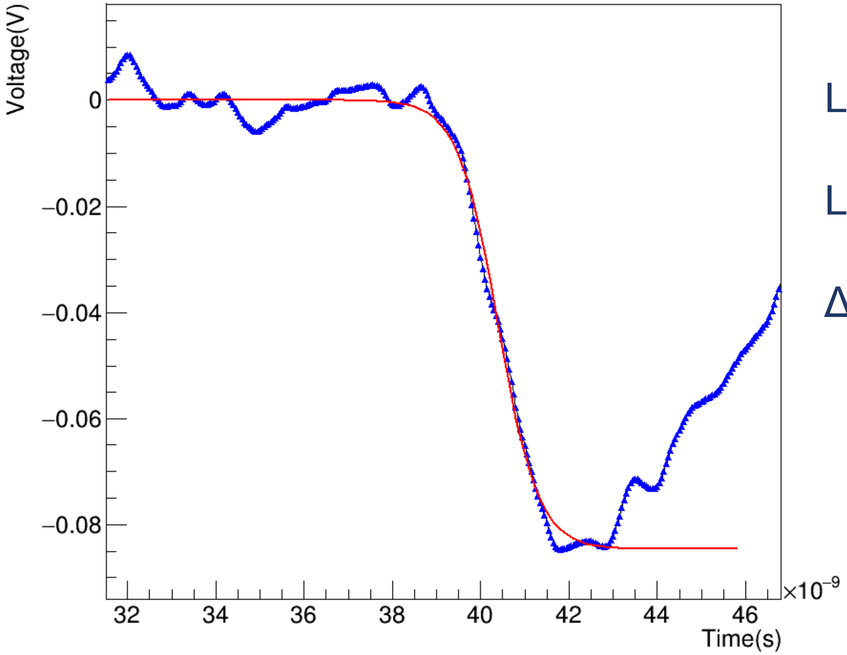
Single-channel setup
-Timing measurement-





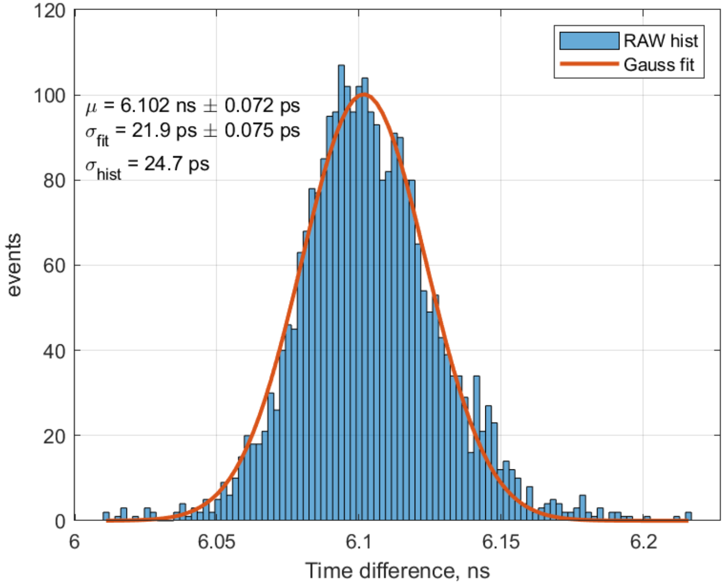


Current amplifier To preserve the rising edge!

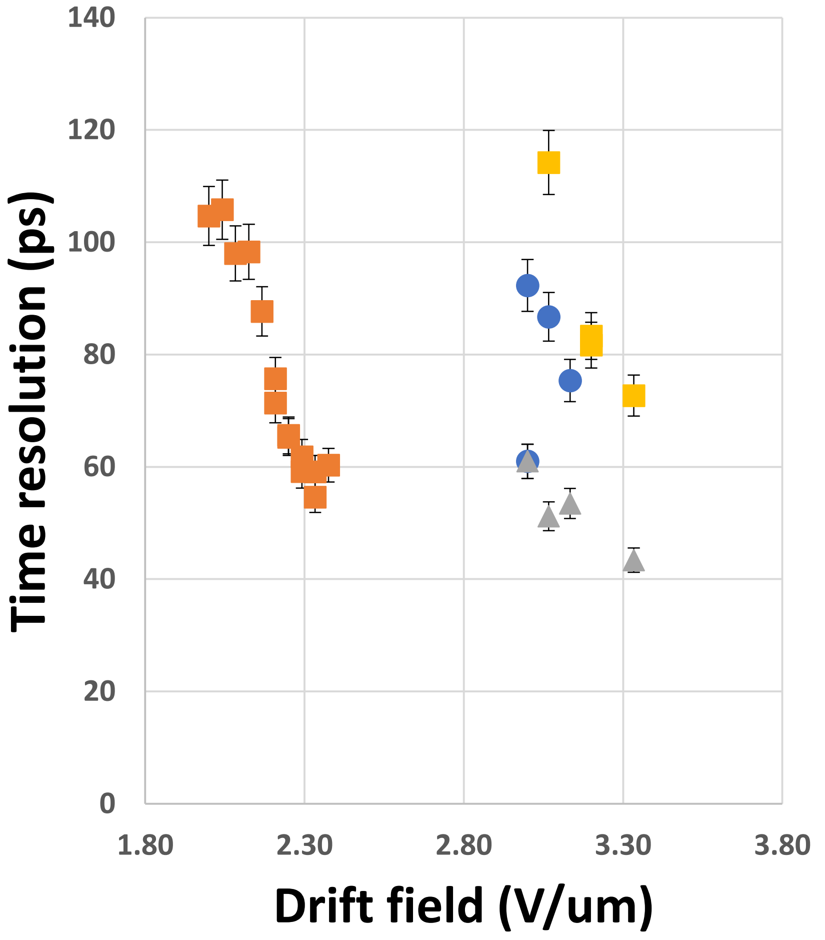


Logistic function fit on Picosec signal
→ CFD on fit → Signal Arrival Time
Logistic function fit on MCP signal
→ CFD on fit → Signal Arrival Time
Δt between the SATs gives the time resolution!

The geometrical cut on the fully contained cones is fundamental also in timing.

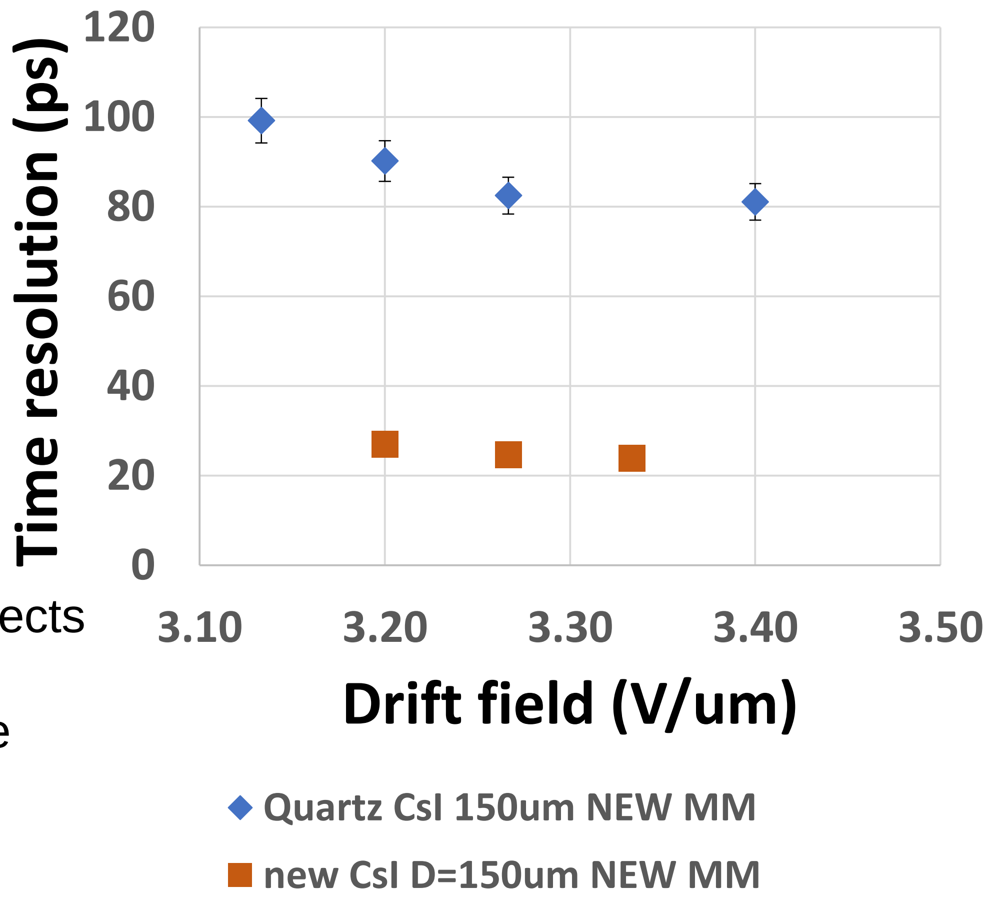


Timing Results



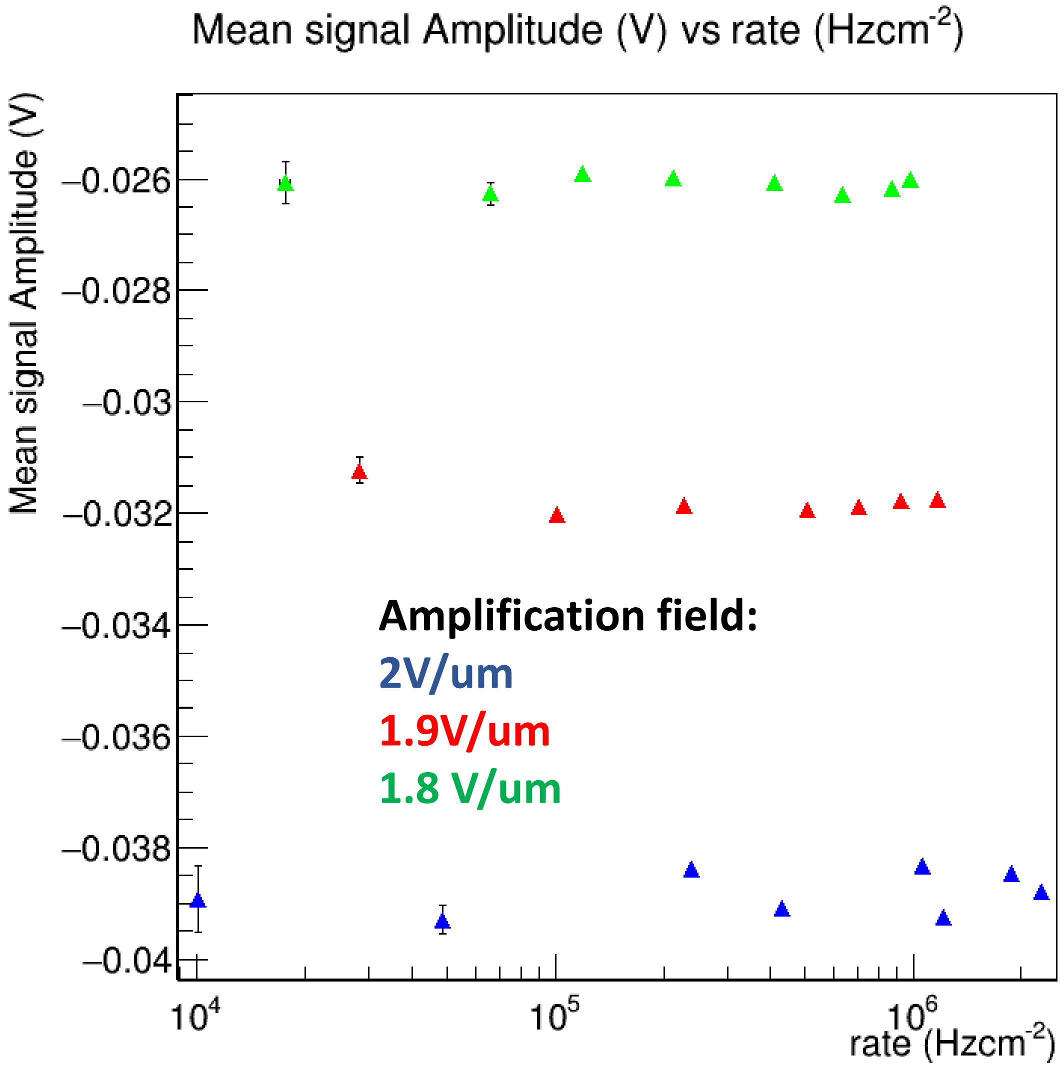
←non-resistive MM 150um 1.84 V/um

Resistive MM 128um 2.15kV/um→



- The timing performance reflects the number of PEs/MIP
- All the combinations may be suitable for Muon Collider application (<100ps)

Rate capability to single PEs
-work in progress-

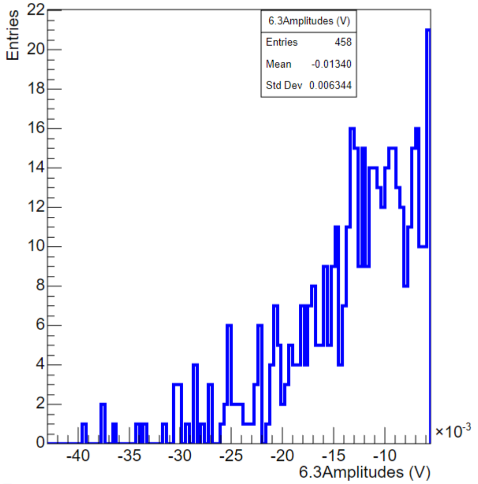


Irradiation with UV LED to generate **single-photoelectrons** signals

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

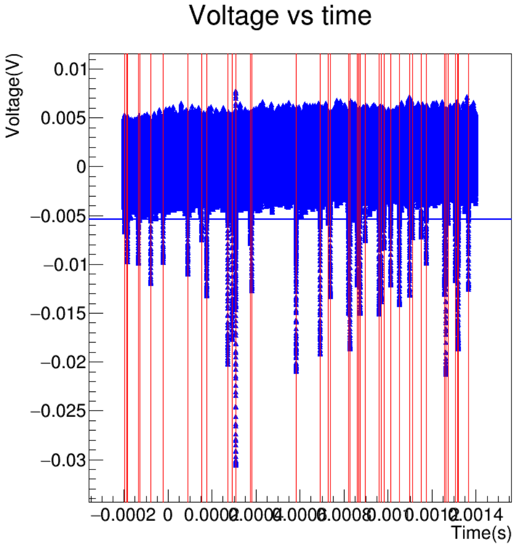
Detector performance stays **stable up to 2MHz/cm²** for single-photoelectron

- 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

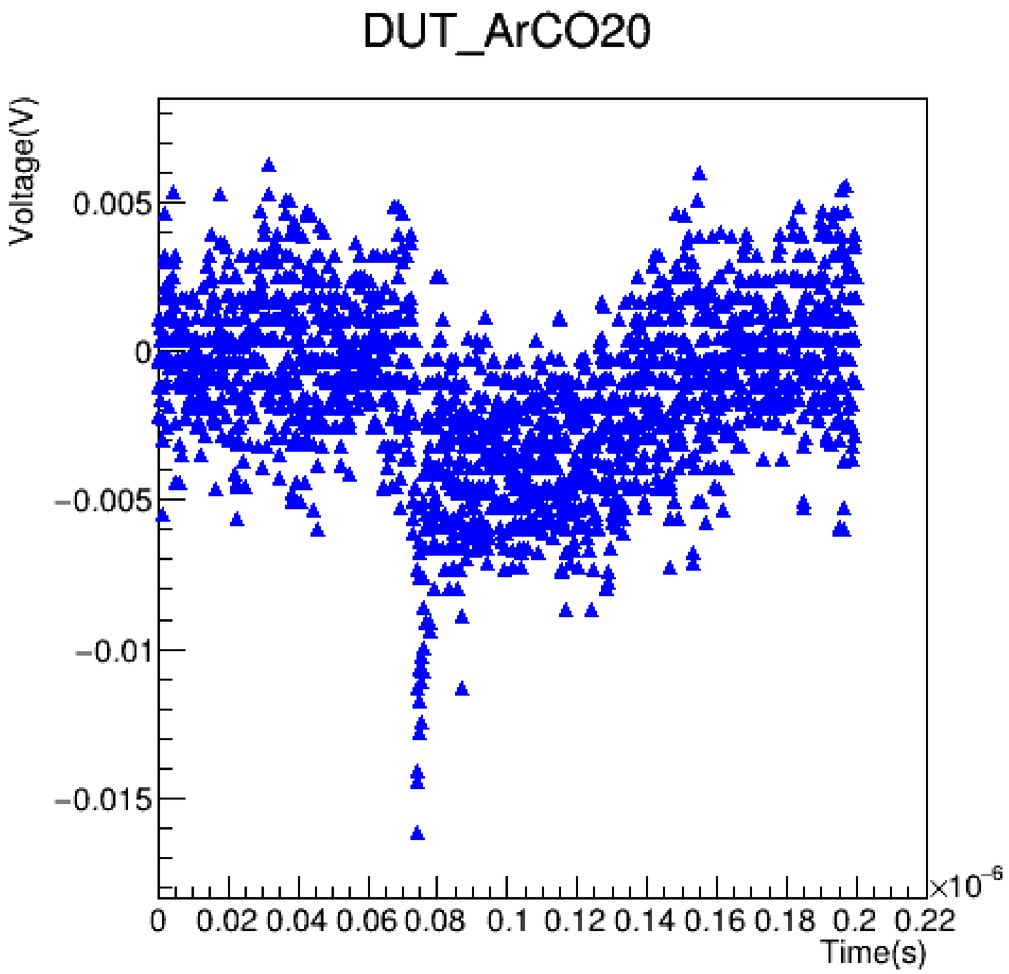


←Example of an amplitude spectrum

Example of 1.6ms of acquisition →



Eco-friendly gases
-work in progress-



- LED irradiation → single Photoelectrons signals
- **Gas: Ar/CO_2 93/7**
- Drift: 150um, Amplification: 150um
- Drift: 380V, Amplification 480V (max voltages achievable with such mixture)

Many of the signals do not present the expected electron-peak/ion-tail ratio

- Multiple signals on the same rising edge
- Probably caused by some feedback process because of the low quenching gas?
- Any suggestion on that is very welcomed ☺

Conclusions

Muon Collider requirement

- **~100ps** time resolution
- **60kHz/cm^2** rate capability
- **Spark** and **radiation hard** detector
- Scalable technology up to **~m^2** (baseline option is to tile a large surface with small detectors)

Test Beam results

- All configurations **satisfied the ~100ps** time resolution
- **Quartz+CsI and MgF2+Chromium may lead to inefficiencies** because of the low number of photoelectrons
- **CsI** is the best photocathode but can be **easily damaged** by ion bombardment and humidity
- **B4C** is a very **promising** candidate (resistive and easy to handle)
  - Not suitable for Muon Collider because of neutrons, but **DLC** should have a similar performance

Rate capability

- Detector response to single photoelectrons stable **up to 2MHz/cm^2**
- Operational limit will be tested soon!

Eco-friendly gas

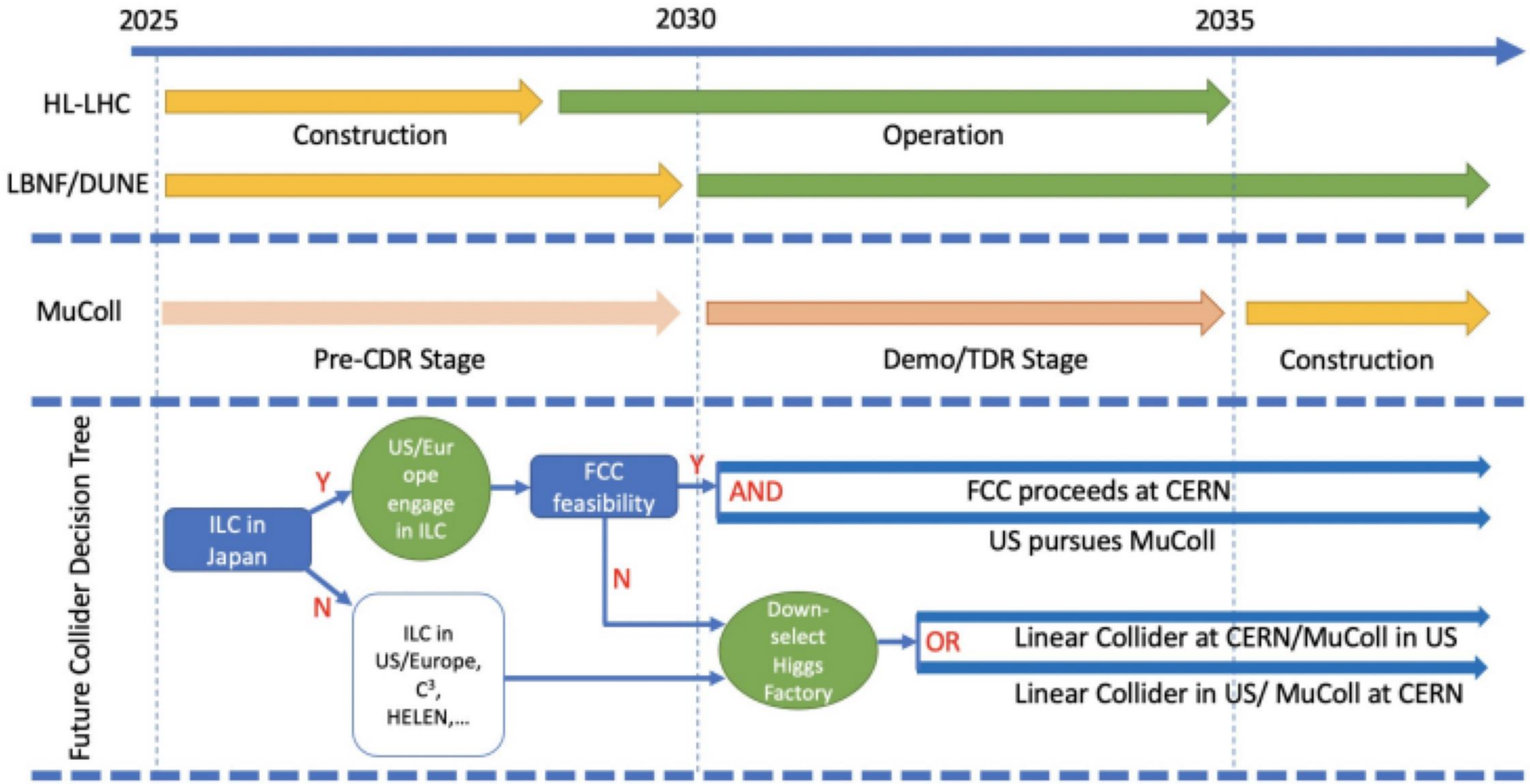
- Ar/CO2 (93/7) seems to have a too-small quenching factor for good performance in a single photoelectron case
- New gases will be tested in Pavia (Ne, Ar, C2H6, C4H10, R1234ze…)

DRD1 transition:

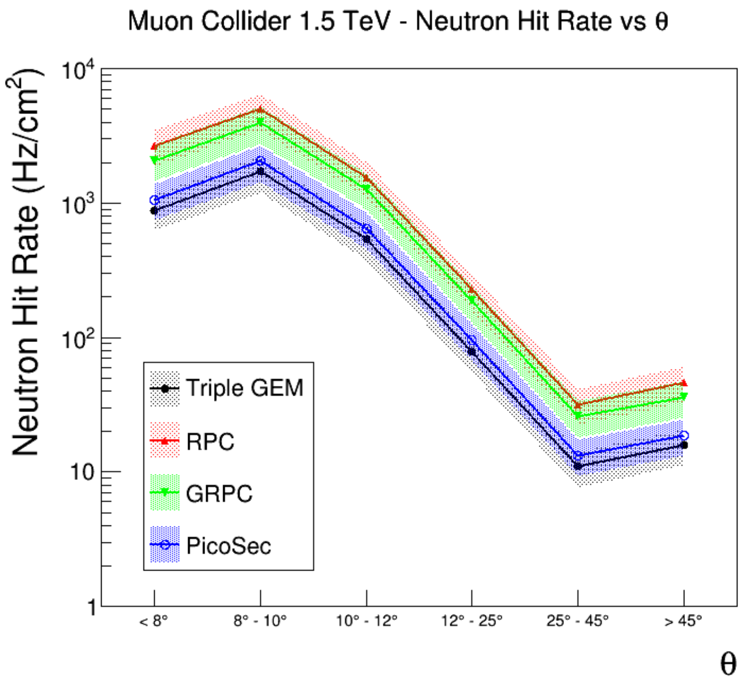
- Pavia group is the ‘watcher’ in the Muon Collider Collaboration for the new DRD1
- Expression of interest in RPC, straw tubes and MPGDs (Picosec but not only)

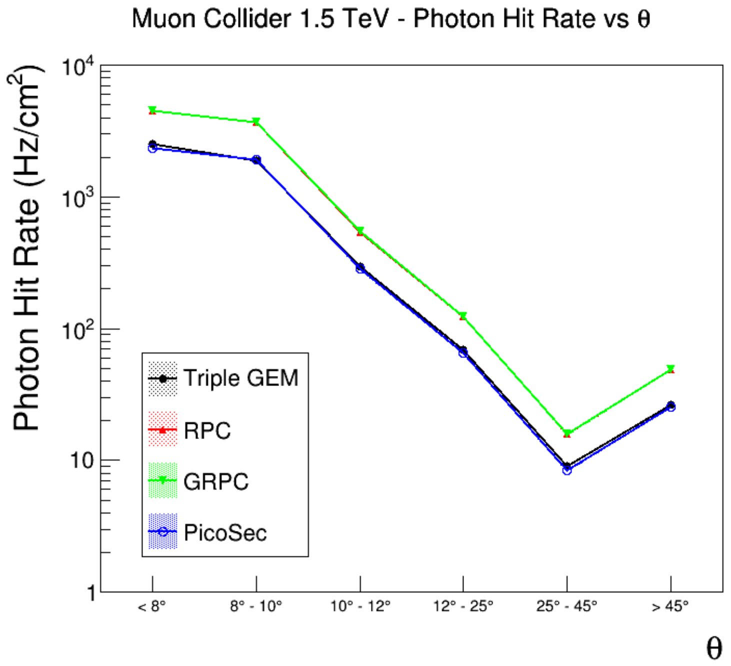
BACKUP

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
N
AND
FCC proceeds at CERN
US pursues MuColl
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

Simulation background



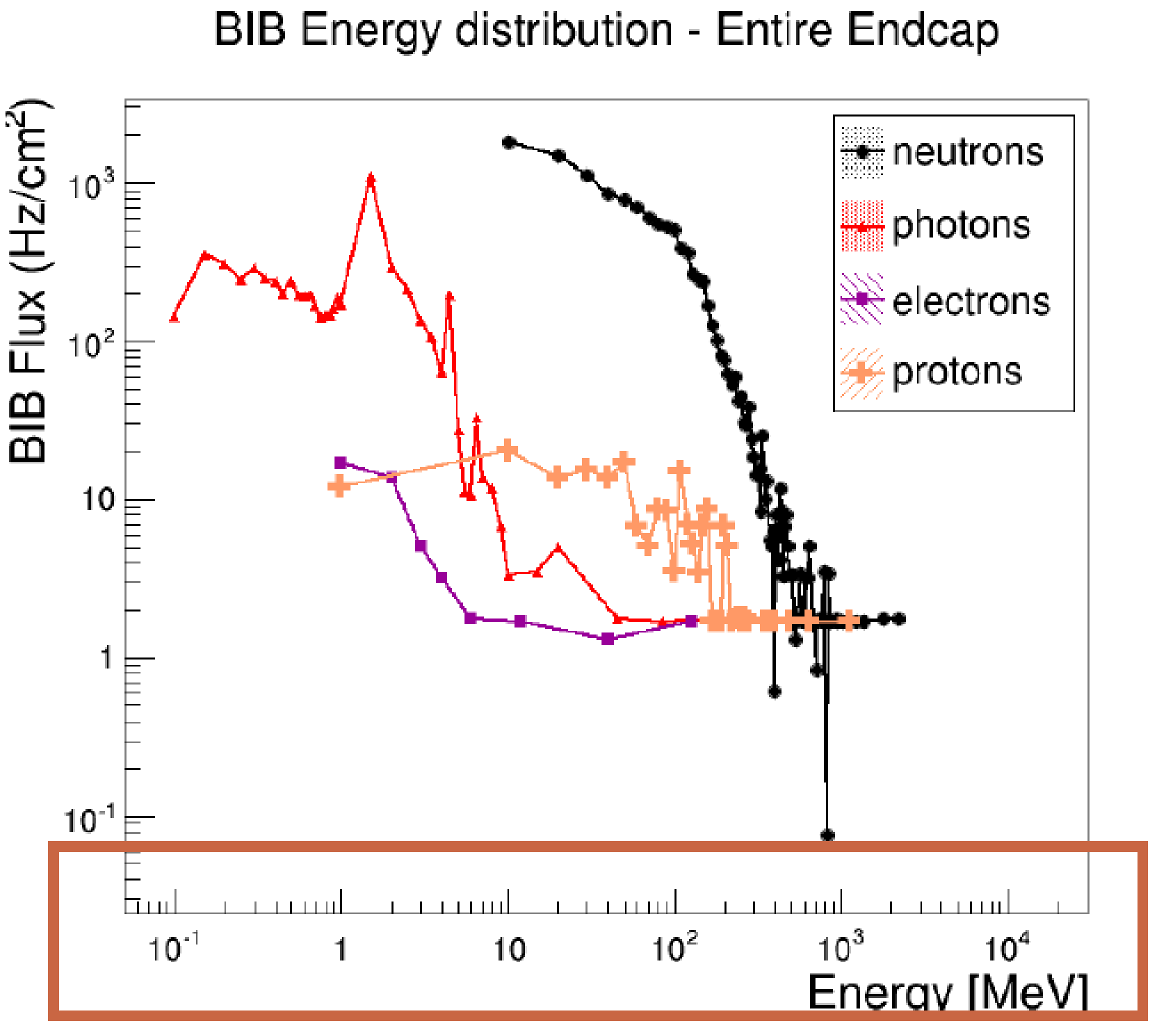


BIB particles flux [Hz/cm^2] in different regions (bunch crossing time 10 μs):

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 MgF2 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



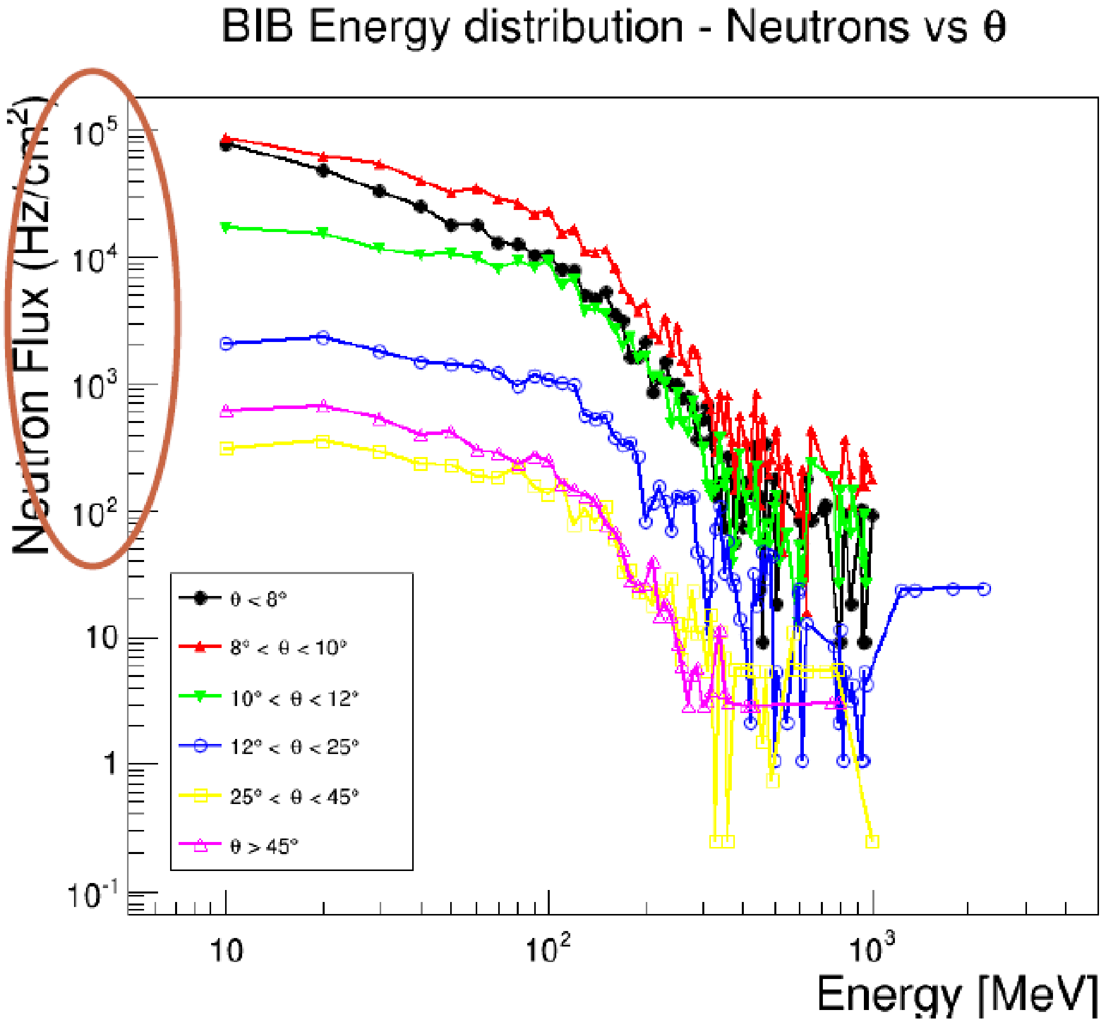
$$f(E) = \frac{p(E) \times BX^{-1}}{A}$$

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

Selection of detectors for MIP timing

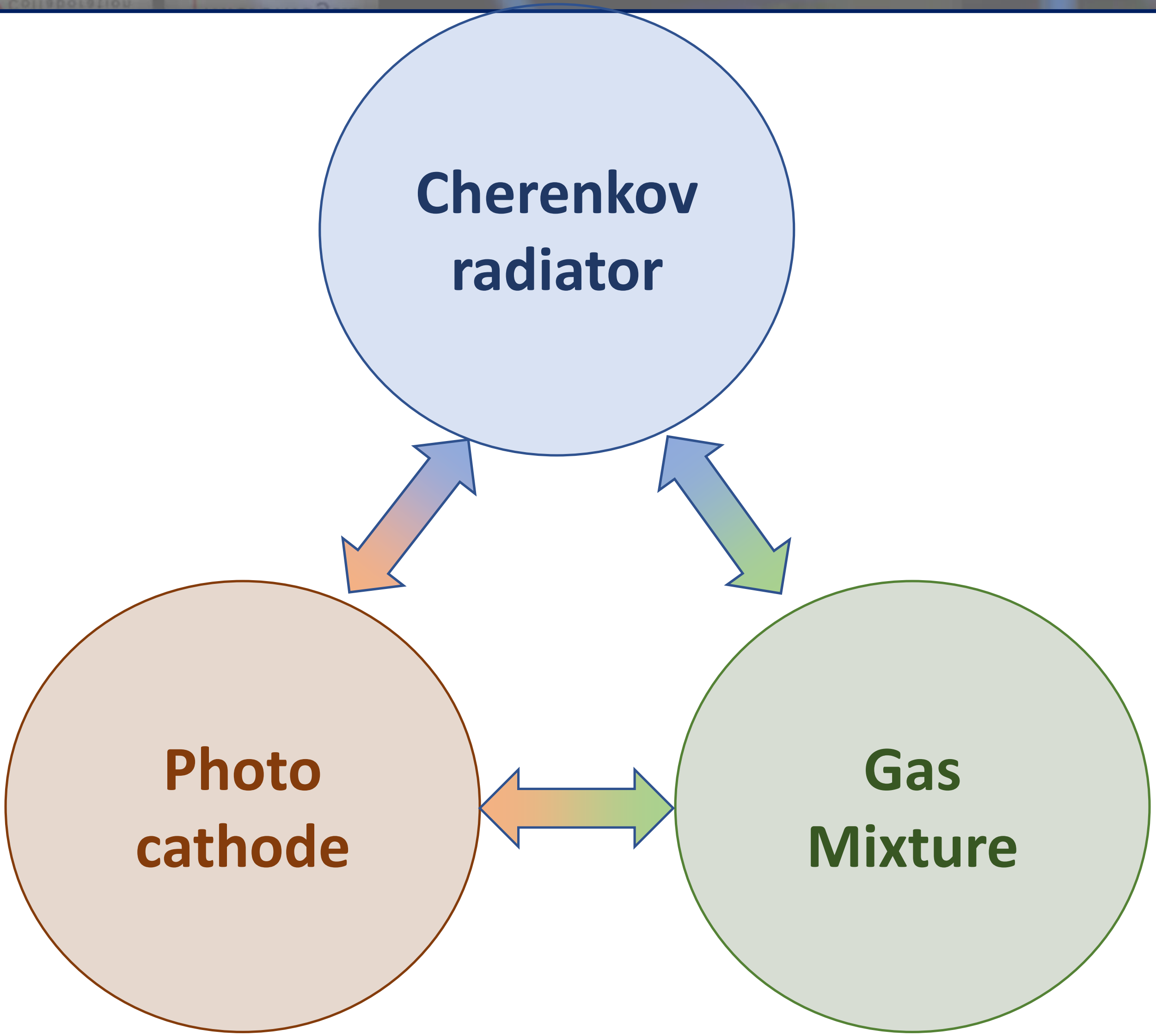
Detector	Space resolution	Time resolution	Rate capablity	Longevity	Cost (CHF/cm²)	Reference
MRPC ALICE ToF	≈3cm*	≈60ps**	500Hz/cm²**	No issue after 20 years operation**	≈1	• alice_toftdr.pdf (cern.ch) • 1806.03825.pdf (arxiv.org)
LGAD ATLAS HGTD	≈1mm*	≈30ps →≈70ps end of life	-	$2.5x10^{15}n_{eq}/cm^2$	≈38	HGTD TDR (cern.ch)
LGAD CMS MTD endcap	≈1mm*	≈30-40ps →50-60ps end of life	-	$1.5x10^{15}n_{eq}/cm^2$	≈62	CMS Technical Design Report for the Phase-2 Timing Upgrade (cern.ch)
Picosec 10x10cm² prototype	≈1cm*	≈24ps	Tested on ≈50kHz/cm² laser beam and ≈100Hz/cm² muon beam NO LIMIT REACHED	-	≈70 **Cost of one 100cm² prototype**	
Micromegas ATLAS NSW	<100µm	≈7ns	>15kHz/cm² required ≈1MHz/cm² max	>230mC/cm²	≈1	• ATLAS-TDR-020.pdf (cern.ch) • pdf (iop.org) • 47d84fb8700bff3c5787574218f71972 (inspirehep.net)

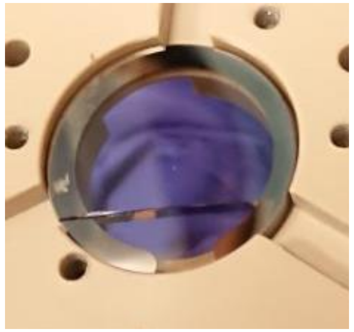
*estimated from pad size
**from real operation

Picosec potential:

- **High rate capability wrt MRPC**
- **Low cost wrt to LGAD**

R&D Plan: Cherenkov Radiator





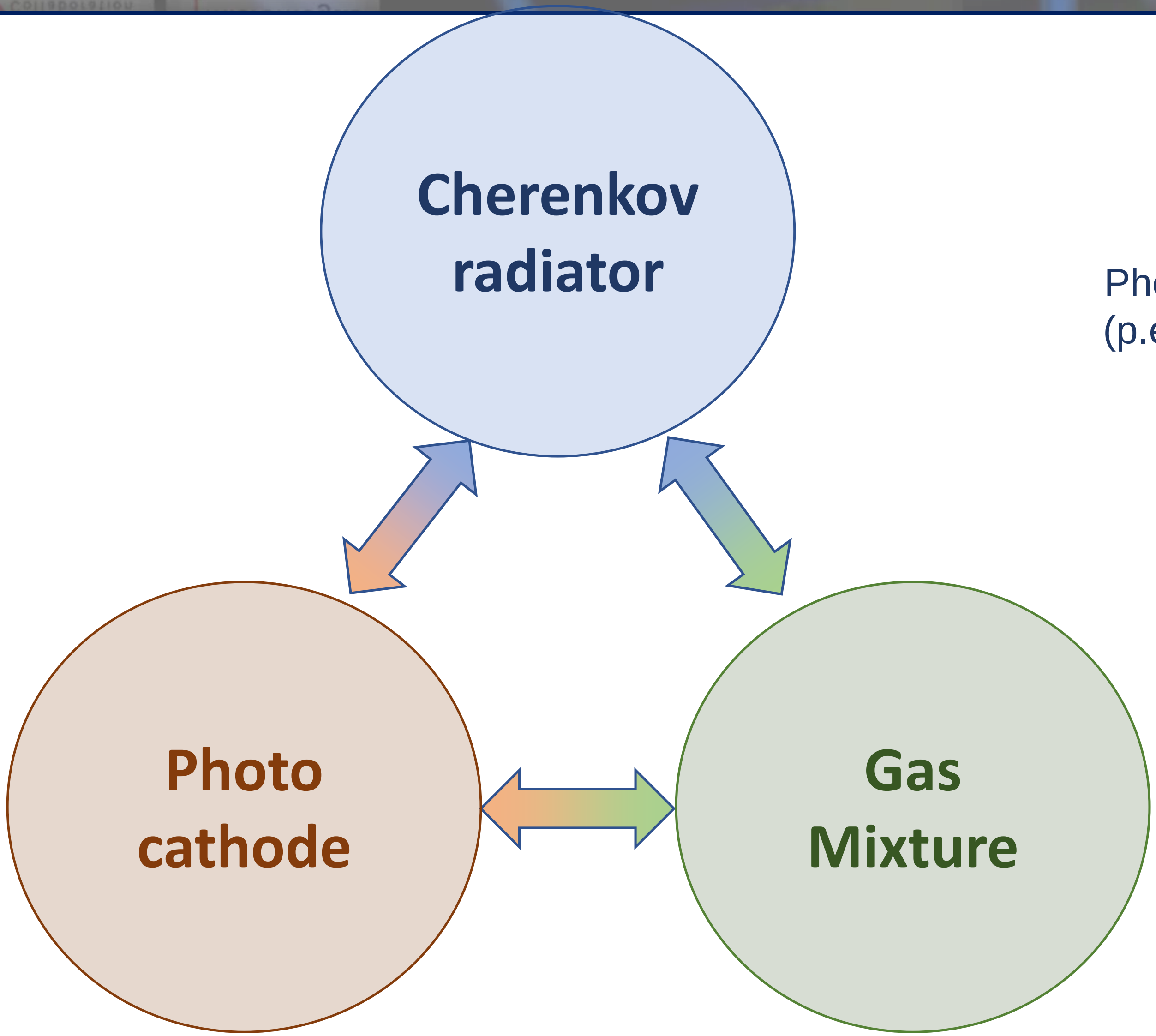
Broken MgF_2 crystal

Cherenkov radiator – Baseline MgF_2

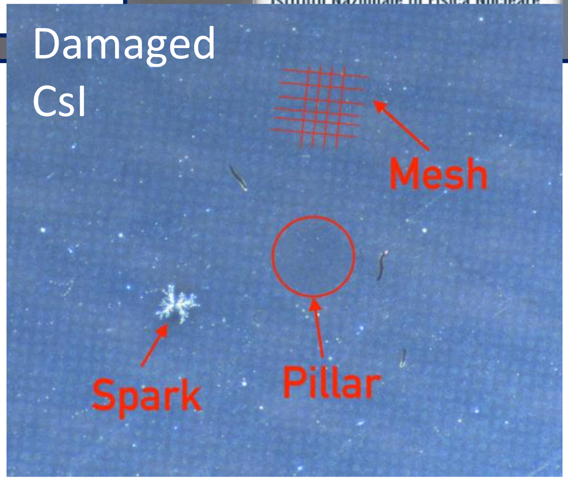
- High UV transparency (>120nm)
- Fragile
- High cost (12€/cm^2)
- No technology for large areas (100cm^2 max)

Quartz (5€/cm^2, >180um)
Sapphire (6€/cm^2, hard, large area, >170um)
other F-based crystals have to be studied!

R&D Plan: Photocathode



Photoelectrons generated per MIP (p.e./MIP) with 3mm MgF_2 radiator

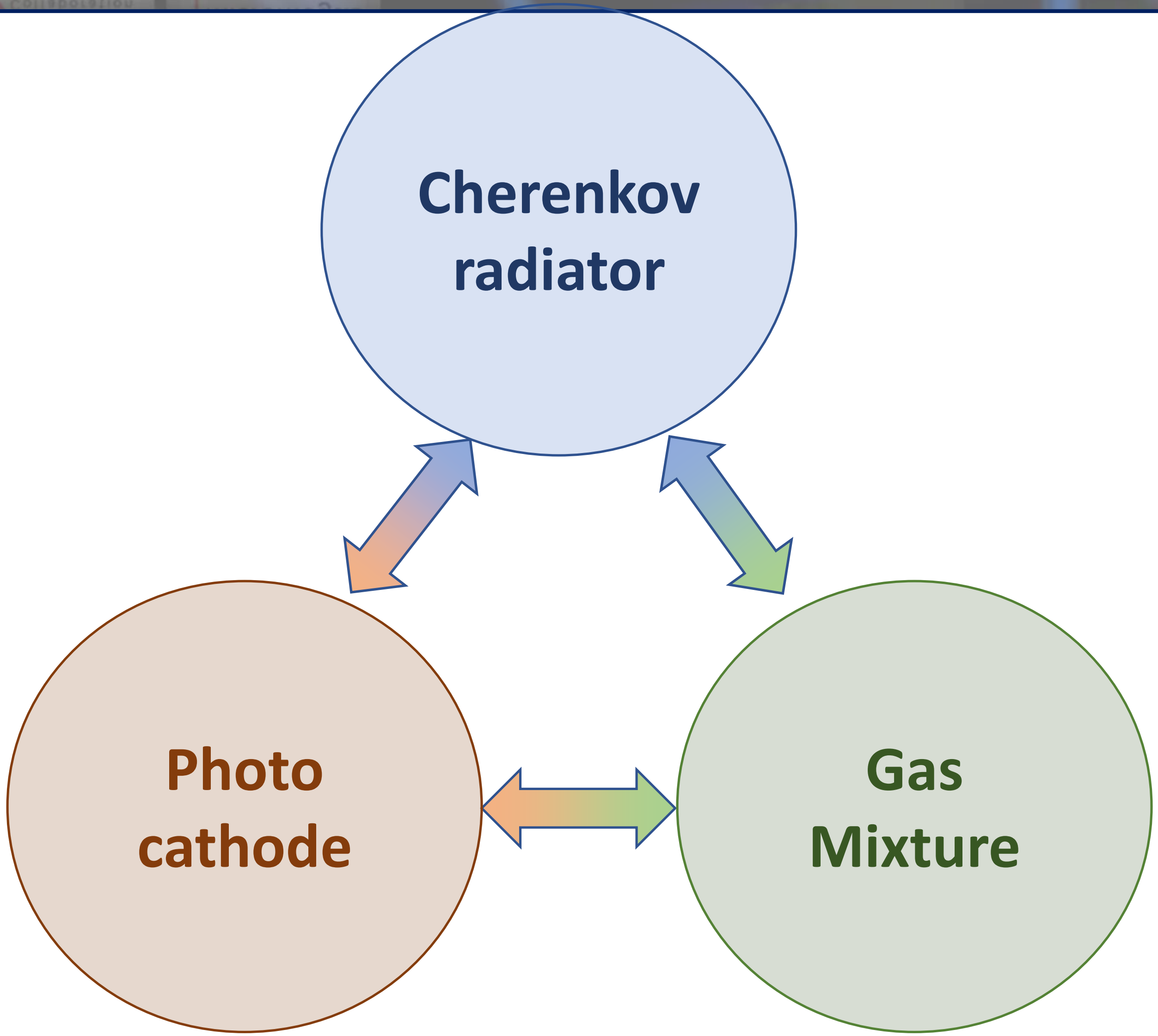


Photocathode – Baseline CsI

- 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)

R&D Plan: Gas Mixture



Gas Mixture– Baseline $Ne/C_2H_6/CF_4$

- High gain and discharge quenching (up to 2-3x10^5)
- High drift velocity (>5 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 (4k€ 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)