

Towards High-Performance Thin-Glass RPCs for the Next Generation of Collider Experiments

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Outline

1. Motivation

FCC-ee,
muon requirements,
R&D roadmap

2. Prototype and GIF++ campaign: setup

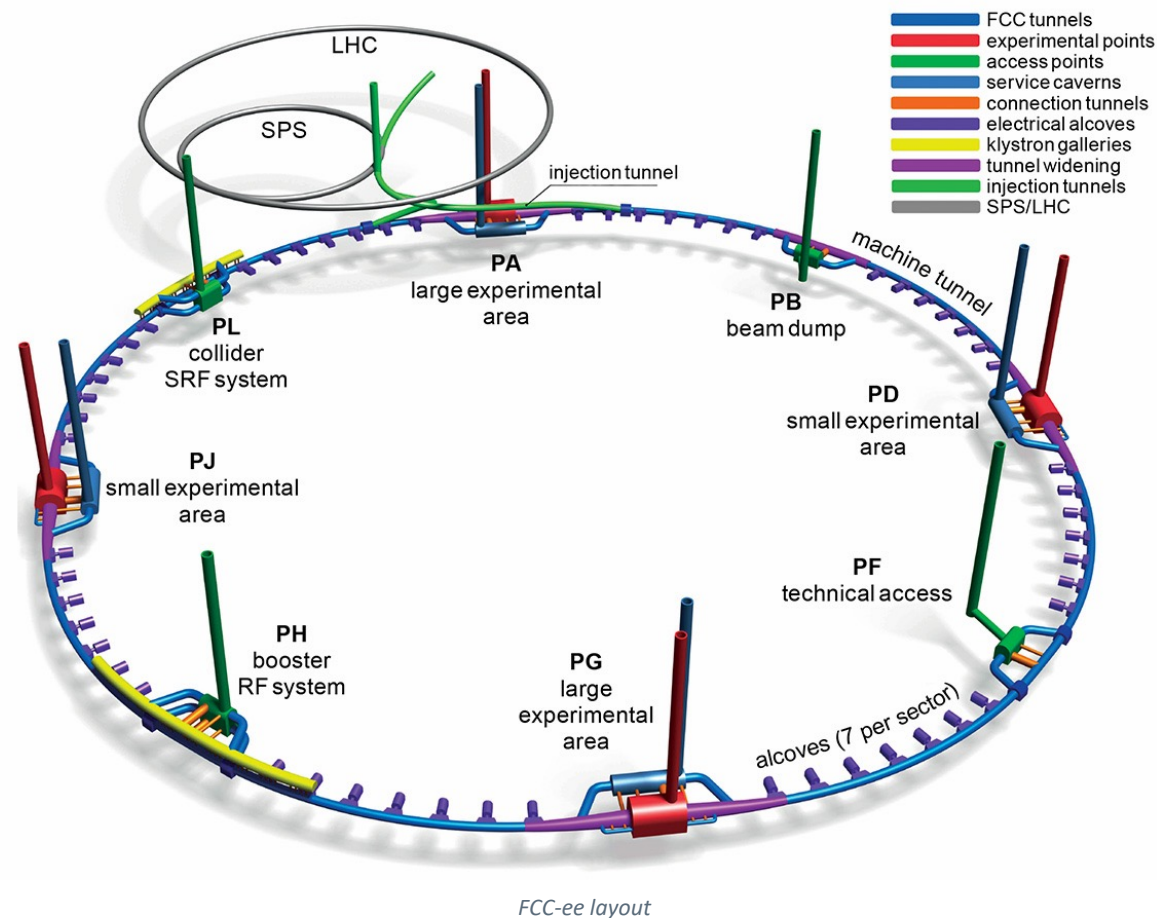
3. Waveform analysis and 2D methods

4. Results

5. Summary and outlook

FCC-ee

- FCC-ee [1] will operate at 4 different center-of-mass energies:
 - Z pole (90 GeV)
 - WW pairs production (160 GeV)
 - HZ events production (240 GeV)
 - $t\bar{t}$ events production threshold (365 GeV)
- High Luminosity ($\sim 10^{34}\text{--}10^{35} \text{ cm}^{-2}\text{s}^{-1}$) while lower rate environment than HL-LHC
- Maximum muon momentum roughly 180 GeV/c
- Isolated muons detection similar to LEP. Identification of non-isolated muons from hadron decays inside jets needs more stringent measures for precision flavor physics [2]
- High statistic of inelastic electron-positron collisions $\rightarrow$ rare processes production of feebly-interacting and slow particles



[1] Christoph Paus, FCC-ee: Physics & Detectors

[2] S. Monteil and G. Wilkinson, Heavy-quark opportunities and challenges at FCC-ee, Eur. Phys. J. Plus 136, 837 (2021), 2106.01259

Muon detector requirements and where RPCs sit

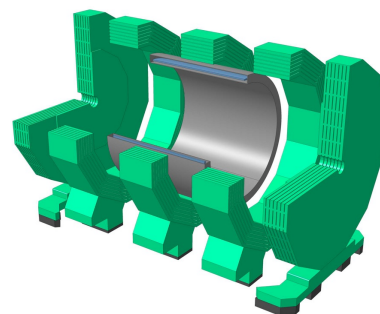
Only educated guesses from simulations and LEP experience

Working requirements for FCC-ee muon detection

- Low particle rate: $O(100 \text{ Hz/cm}^2)$
- High muon identification efficiency ($>98\%$), complementing tracking-based momentum measurement
- Standalone capability for muon trigger and long-lived particles discrimination: sub-mm spatial resolution + timing $O(200 \text{ ps})$
- Bunch-crossing timing still under discussion (20 ns, possibly down to 5 ns)
- Robustness, long-term stability, large coverage at low cost/channel
- Environmentally sustainable operation — a new requirement absent at LEP/LHC

RPC technology is a strong candidate to address most of these requirements simultaneously

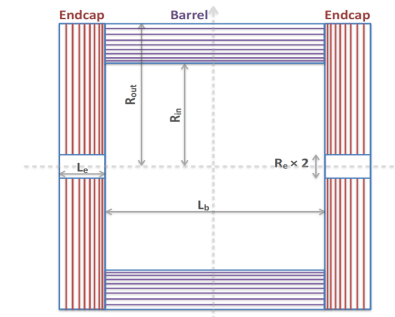
Concepts considering RPCs



CLD



ALLEGRO



CEPC

- CLD — 6 muon-identification layers, RPCs with $30 \times 30 \text{ mm}^2$ readout cells
- ALLEGRO — muon tagger on the instrumented yoke; RPCs, MPGDs, drift tubes and scintillators all still under consideration
- CEPC (synergy) — RPC is the baseline: 8 sensitive layers, $\sim 8600 \text{ m}^2$, $\sigma_{r\phi} = 2.0 \text{ cm}$, $\sigma_z = 1.5 \text{ cm}$, few-ns timing, $50\text{--}100 \text{ Hz/cm}^2$

→ Large area at low cost per channel, with timing: the classic RPC argument, now with a few-hundred-ps target.

R&D roadmap

DRD1-WP7b: High-performance thin glass RPCs for timing applications— INFN Bari & KODEL (Hanyang University)

Task 1

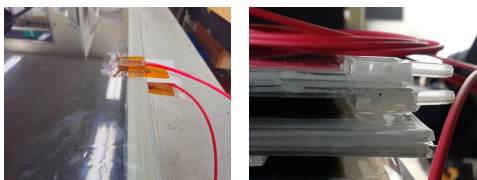
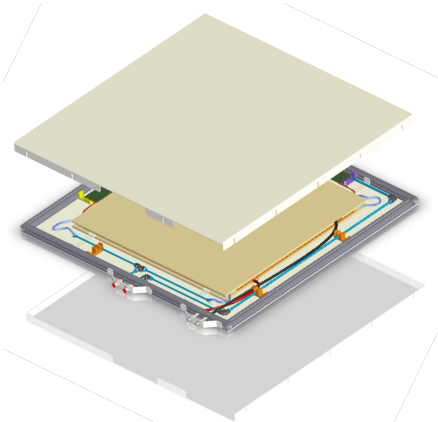
Develop and characterise a small RPC prototype with time resolution of $O(200 \text{ ps})$

Task 2

Produce a large-area RPC while preserving time performance

WP1 (synergy)

Search for eco-friendly gaseous mixtures for sustainable operation



First Small Prototype:
cosmic performance

- Performance study with several gaseous mixtures

- Double gap (CMS-like) – 500 μm each glass built in KODEL
- Strip panel - pitch 6.25 mm

First Small Prototype:
beam test study

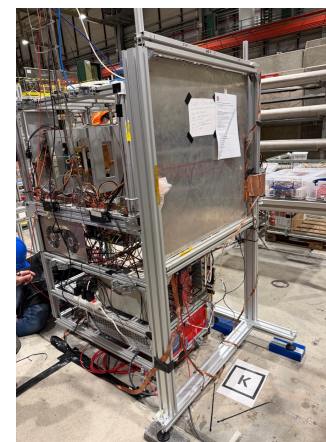
- efficiency, ..., time and spatial resolution

Spatial resolution algorithm :

- RPC integration in GDD triple GEM telescope
- VMM-3a read-out

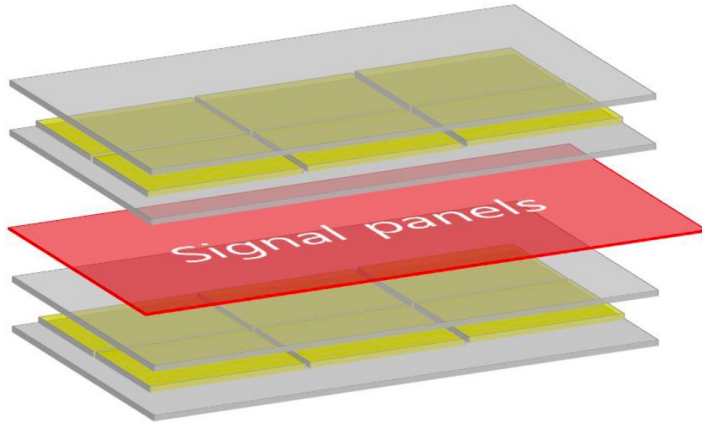
Second Prototype (bi-gaps):
performance study

talk HERE



First prototype @DRD1
test beam (2025)

Double bi-gap thin-glass RPC



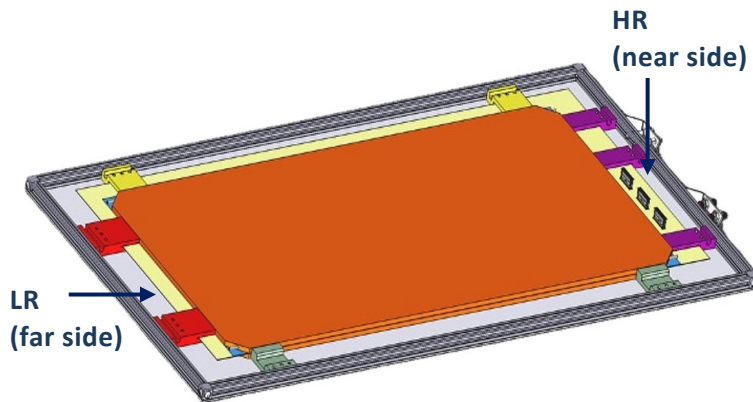
Double bi-gap concept: two 0.5 mm gaps per gas volume

Detector

- Double bi-gap: 2 gaps per gas volume, 2 gas volumes
- Gap area $50 \times 100 \text{ cm}^2$
- Single-gap thickness $500 \text{ }\mu\text{m}$
- Glass 2 mm throughout the bi-gap stack

bi-gap advantage

- Two thin gaps recover the primary-ionisation efficiency lost
- Timing is set by the fastest gap, so the jitter advantage of a thin gap survives



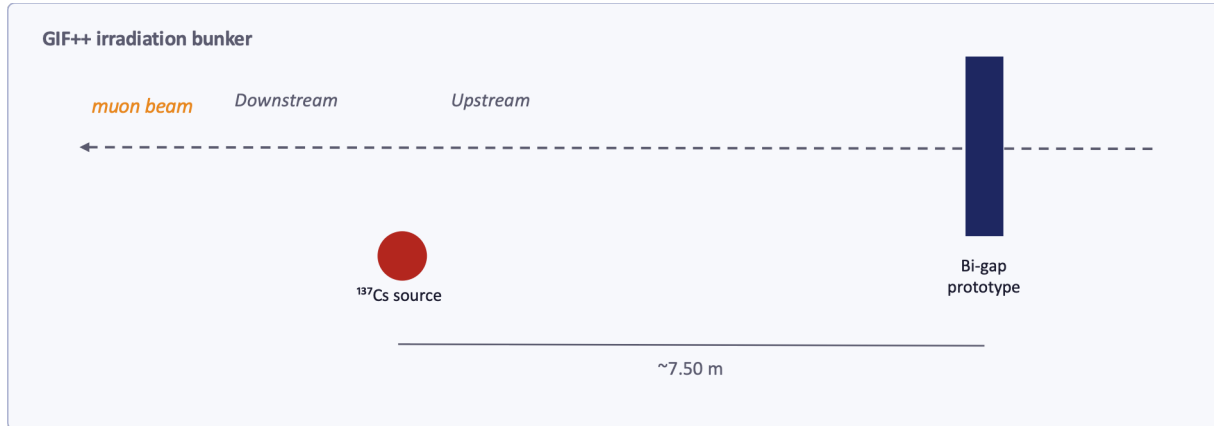
Readout PCB

- 48 strips, 9.66 mm wide, pitch 10.411 mm
- Strip copper length 99.975 cm ; 96 cm covered by the gas gap
- Both ends routed — dual-end readout available (*CMS-like*)

Signal readout

- Analog: CAEN Digitizer DT5742
16 channels + fast trigger @ 5 GS/s
- Digital: CAEN FERS DT5203 picoTDC
Leading edge $\rightarrow$ ToA, LSB 6.25 ps
Trailing edge $\rightarrow$ ToT, LSB 12.5 ps

GIF++ campaign: setup



GIF++ irradiation bunker — chamber ~7.5 m from the source

- ^{137}Cs source, ~11 TBq, attenuated by a combination of filters
- Chamber ~7.5 m from the source; muon beam through the bunker
- Gas: CMS standard dry mixture, $\text{TFE}/\text{iC}_4\text{H}_{10}/\text{SF}_6 = 95.3/4.5/0.3$

Working-point definition

$$\varepsilon(\text{HV}) = \varepsilon_{\text{max}} / \{ 1 + \exp[\lambda (\text{HV}_{50} - \text{HV})] \}$$

$$\text{WP} = \ln(19)/\lambda + \text{HV}_{50} + 150 \text{ V}$$

$\ln(19)/\lambda + \text{HV}_{50}$ is the 95% point of the plateau; the 150 V margin puts the chamber safely on it (CMS legacy).

Five readout configurations

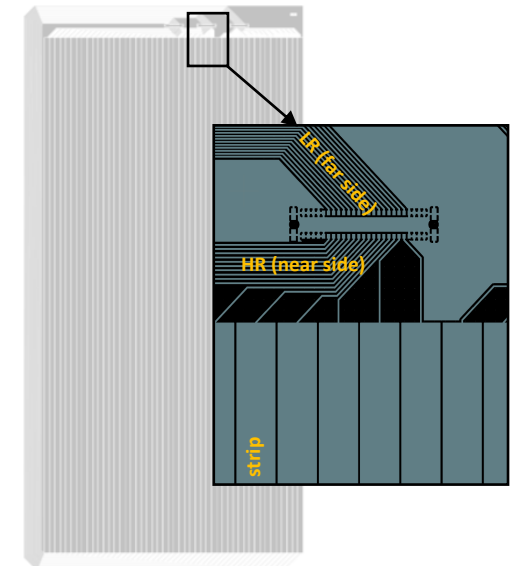
HR only LR terminated 50 Ω

LR only HR terminated 50 Ω

HR only LR open, no termination

LR only HR open, no termination

DUAL both ends read out



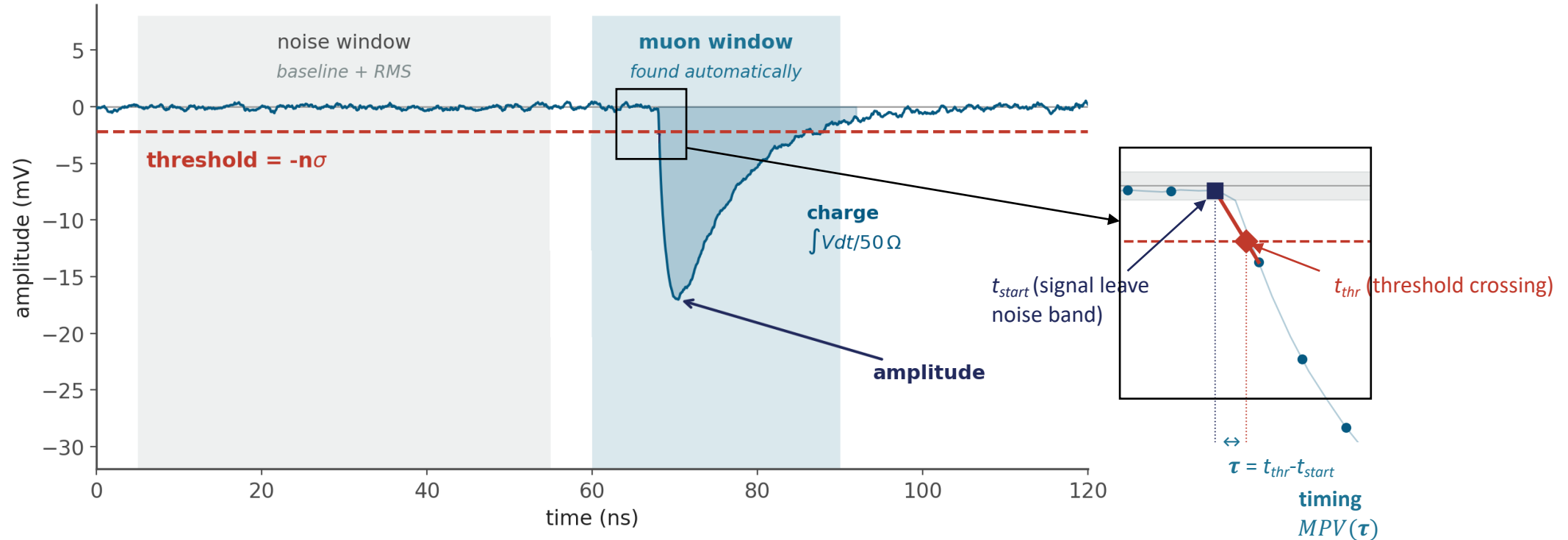
What is measured on a single channel

Noise window

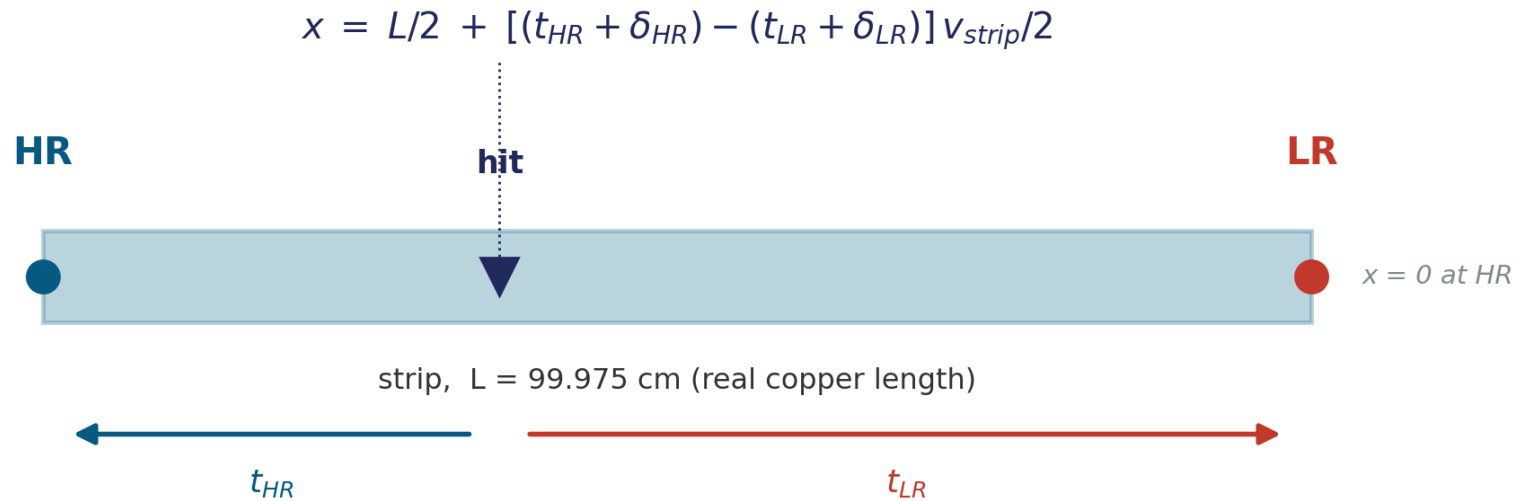
Fixed, signal-free. Gives the baseline to subtract and the RMS that sets the threshold, event by event and channel by channel.

Muon window

Where a signal is accepted. Found automatically from the data - and separately for each readout side.



Position along the strip from the time difference



- $x = 0$ at the HR end, $x = L$ at the LR end
- L is the real copper length, not the active area
- delta terms carry the line-length and offset calibration
- The half-sum of the two times is independent of x , so it is the right quantity for the time measurement

Calibration steps

A · Readout-line lengths

The per-strip routing lengths are extracted from the board Gerber (48 strips, 3 to 205 cm). Converted to delays, they remove the part of the bias that grows with the strip index.

B · Propagation speed

With the correction off, the measured position of each strip is plotted against its length difference. The slope gives the speed in the line, the intercept the true hit position.

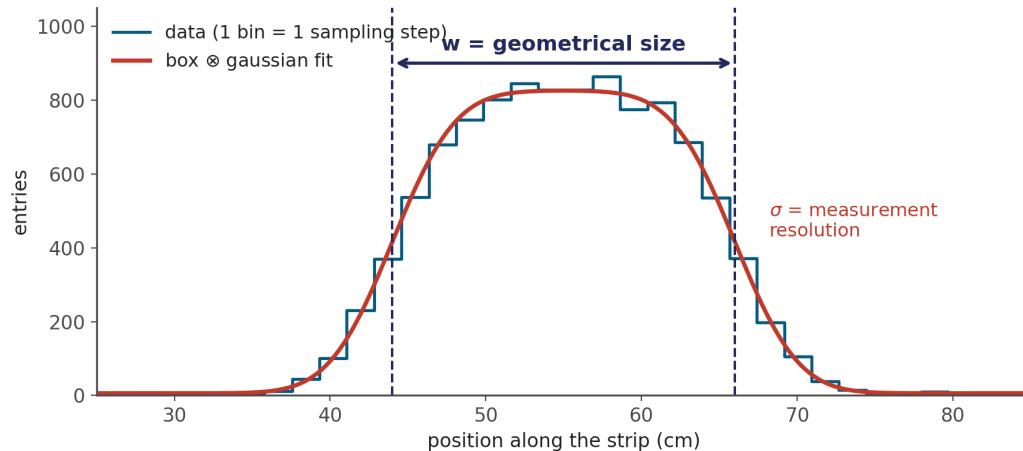
C · Per-strip offsets

What is left - cables, connector pins, channel-to-channel delays - is absorbed into one offset per strip, aligning all strips to a common position.

Beam size: a box convolved with a gaussian

The trigger coincidence is a rectangle of width w ; the measurement smears each edge by σ . Fitting with *Box-Gaussian function* separates the geometry and the measurement resolution

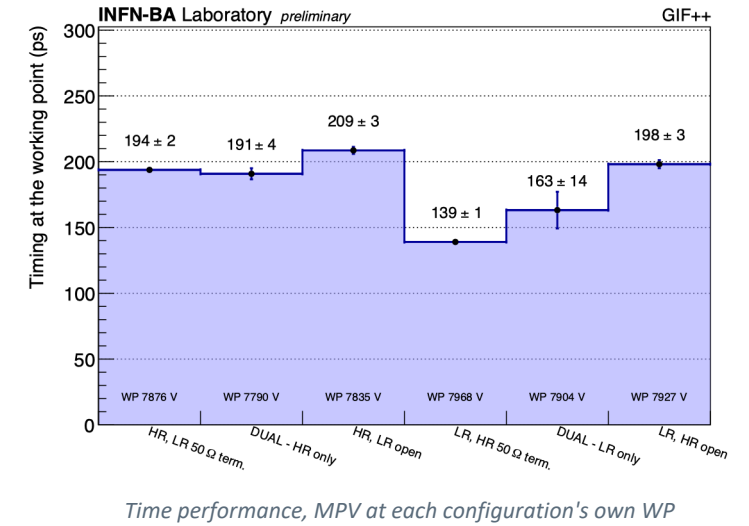
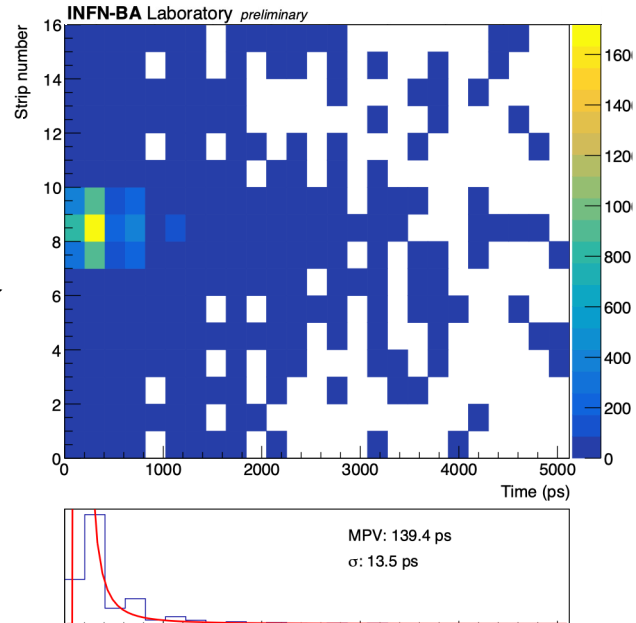
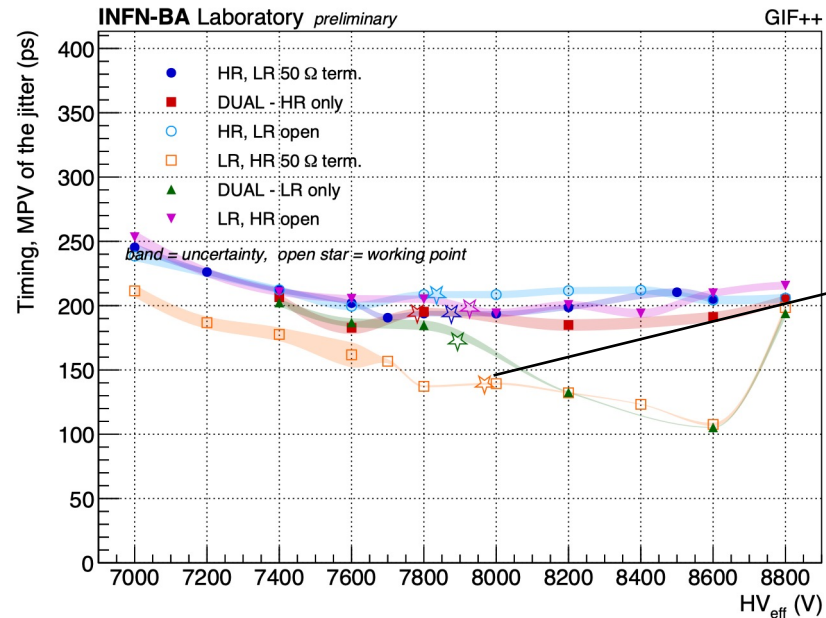
$$f(x) = \frac{A}{2} \cdot \left[\operatorname{erf}\left(\frac{x - c + \frac{w}{2}}{\sqrt{2}\sigma}\right) - \operatorname{erf}\left(\frac{x - c - \frac{w}{2}}{\sqrt{2}\sigma}\right) \right] + b, \quad \operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$



Fit parameters

A plateau height	→ seeded from the 90th percentile of the bins
c centre	→ beam position
w width	→ the GEOMETRICAL beam size
σ gaussian sigma	→ the measurement resolution
b flat background	→ spurious hits

Timing performance

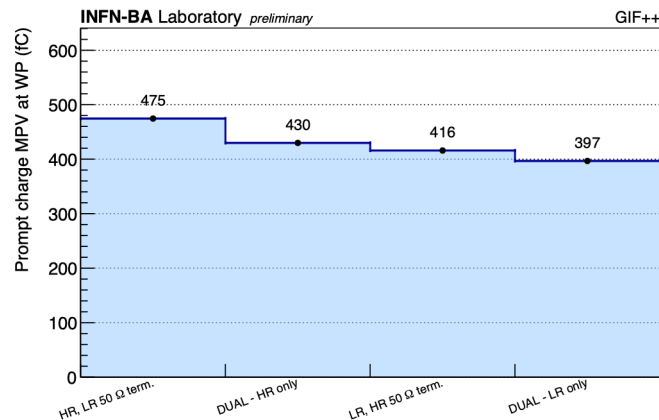
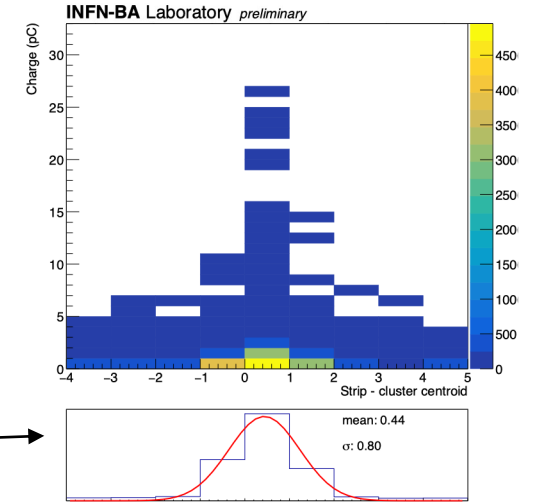
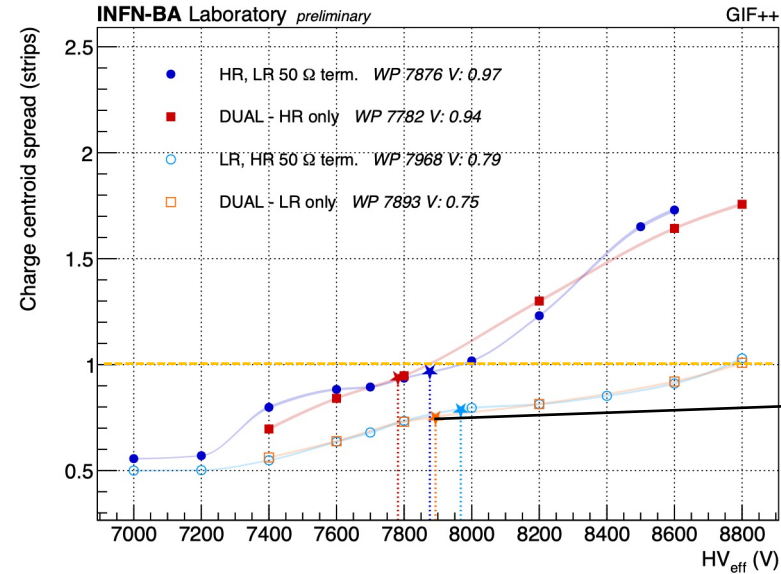
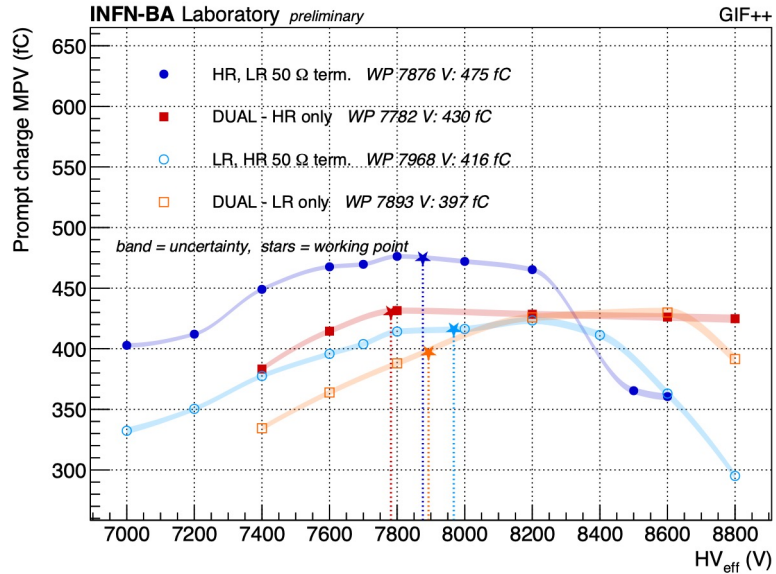


DOWN TO

139–209 ps

- Best configuration obtained by reading from LR while HR is terminated (139 ps)
- Impedance coupling and signal attenuation impacts between readout configurations still under investigation

Signal charge



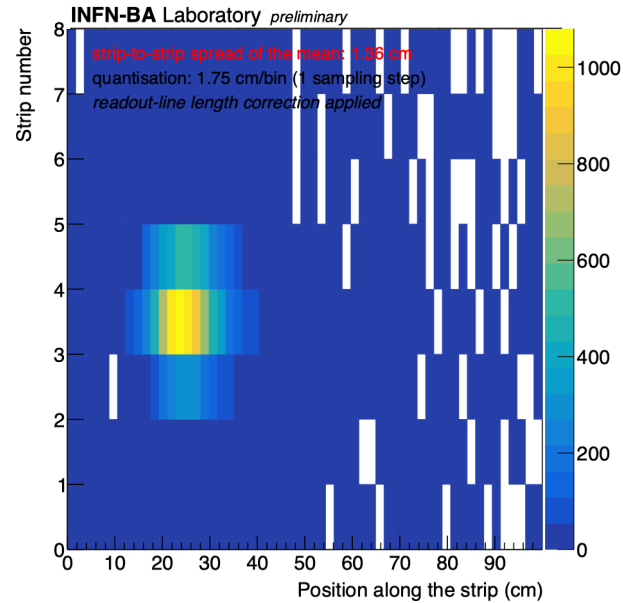
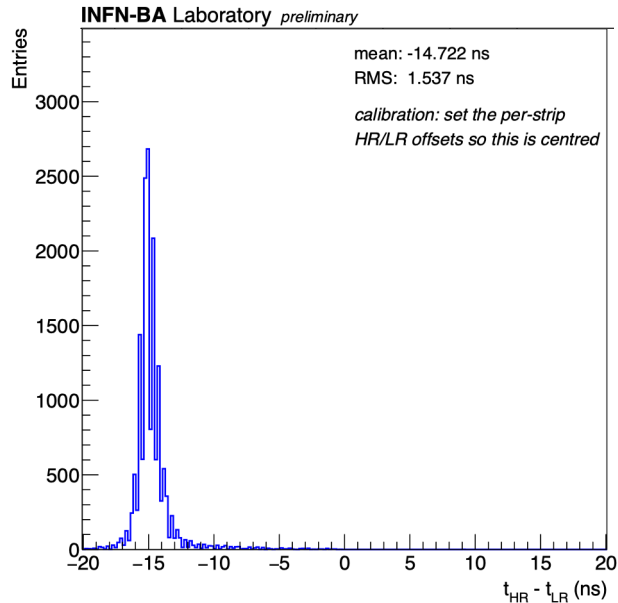
- Charge found maximum values around WP: charge saturation effect
- Distributions differ mainly in the collected fraction, not in the shape of the spectrum
- Lowest charge at WP found for the best time performance readout settings (LR, HR 50 ohm term.)
- Charge centroid spread stays below 1 $\rightarrow$ space resolution improvement could be reached

2D capability

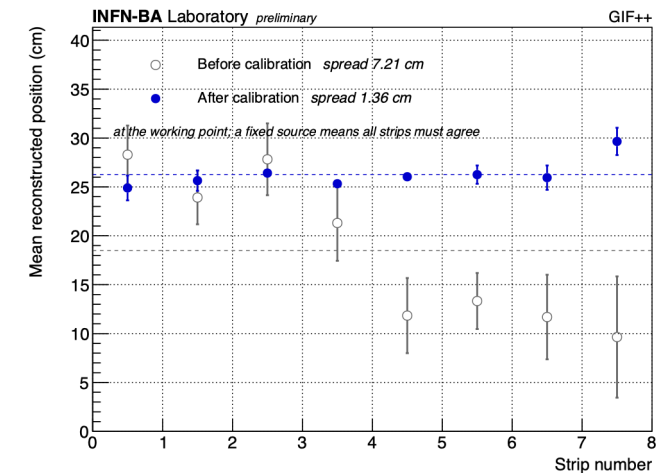
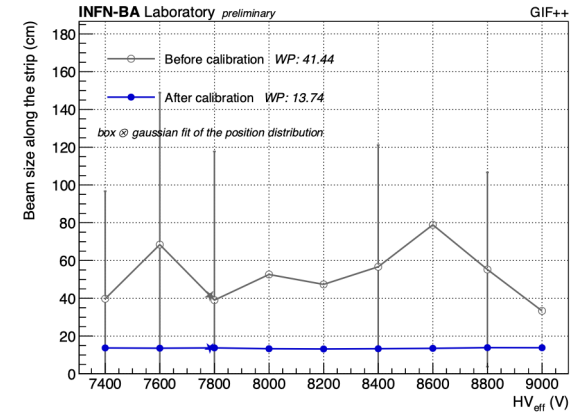
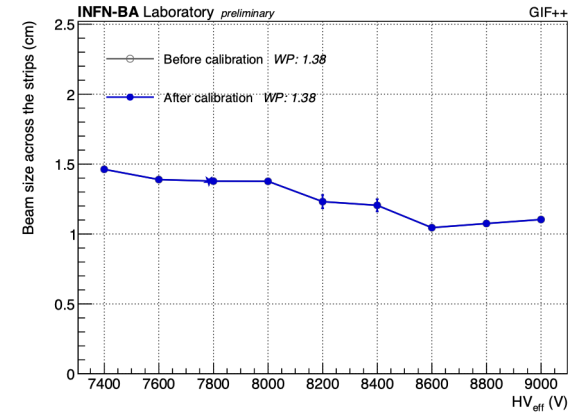
Position available only in dual readout

Beam position found around 26 cm from HR side, in agreement with physical scintillator position

Spread average position along the strips 1.36 cm

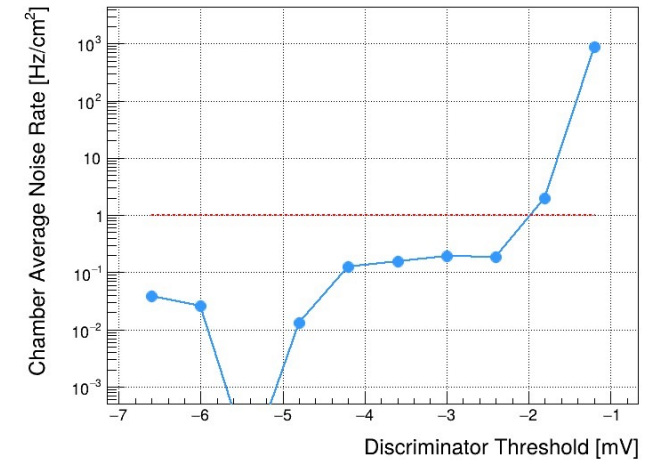
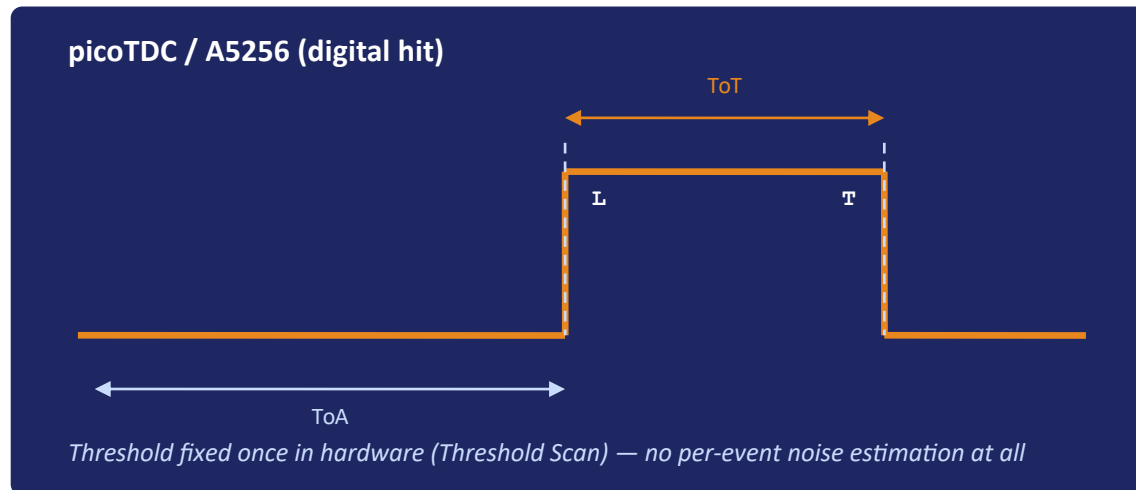
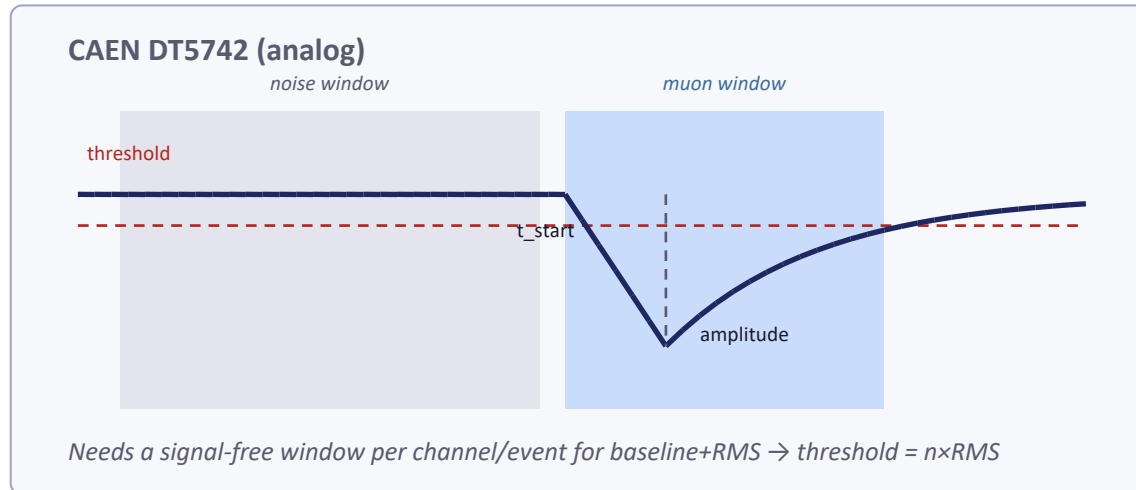


2D beam profile at WP



From waveforms to a digital hit list: CAEN picoTDC

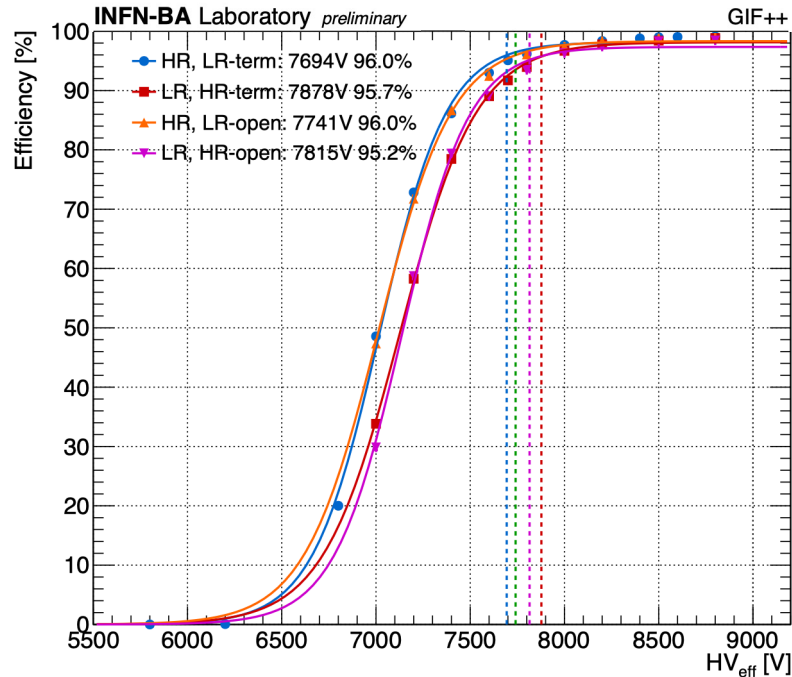
No waveform, no baseline/RMS: threshold crossing is already digital, set once via the Threshold Scan



Chamber-average noise rate vs discriminator threshold

- The A5256 only allows 0.6 mV steps — -1.8 mV is the finest step past the noise knee, not a free choice

Efficiency, working point and cluster size

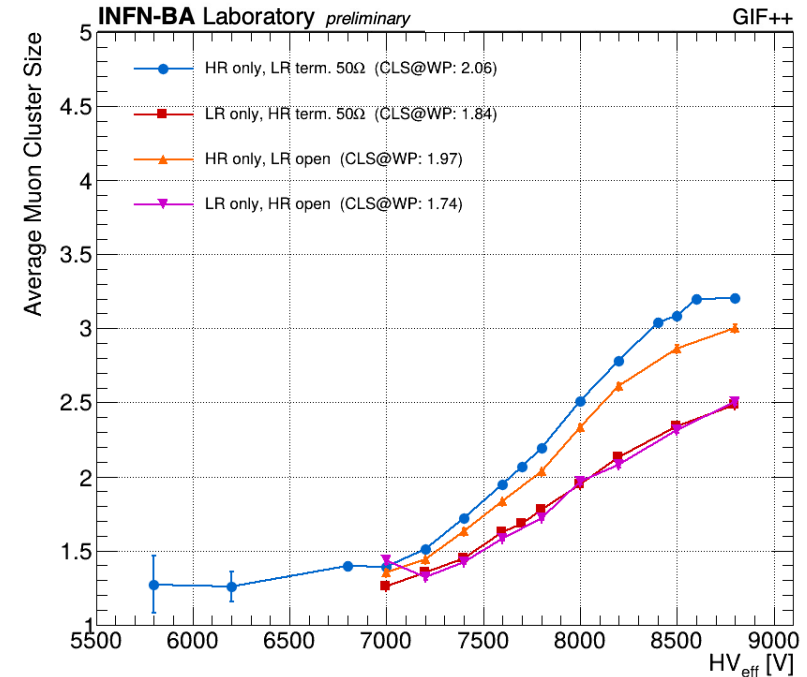


95.2–96.0%

efficiency at the working point

7694–7878 V

working-point range, four configurations

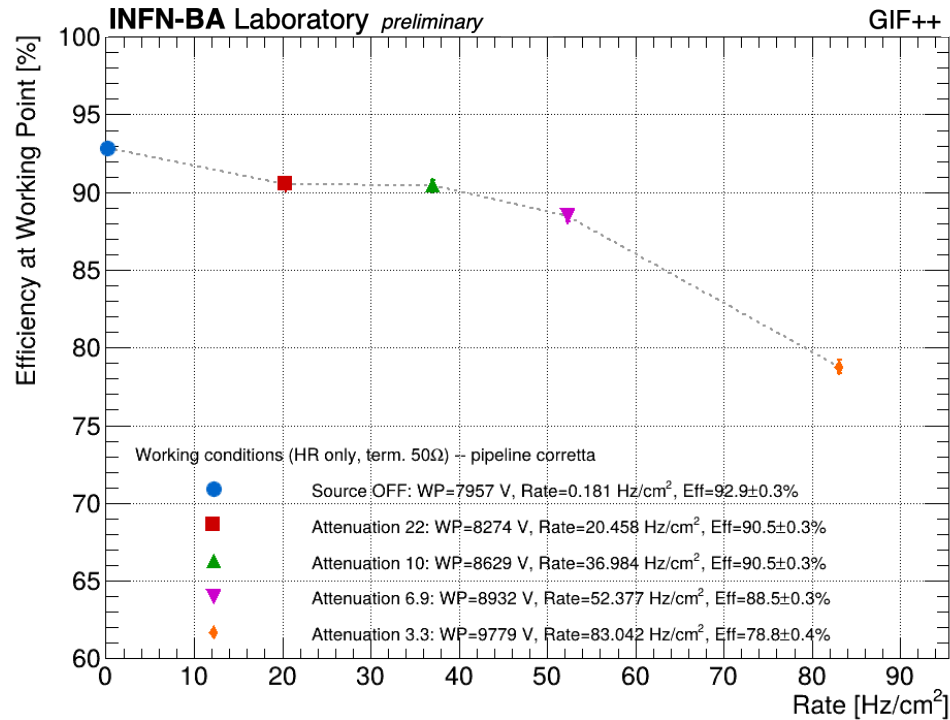


1.7–2.1

cluster size at the working point

Four single-ended configurations agree to within a percent in efficiency and within ~260 V in working point

Rate capability



- Five GIF++ attenuation filters (ABS): source OFF, 22, 10, 6.9, 3.3
- Rate scans taken with a random trigger and no beam; efficiency scans with beam + GIF trigger (2 + 2 scintillators)

Hit rate up to **83 Hz/cm²**

with efficiency drop **$\Delta\text{Eff} = 14.1\%$**

- WP compensates upward by ~1.8 kV (7959 → 9797 V)
- Low-rate capability driven by high resistivity of glass (preliminary measure points to $O(10^{13} \Omega \cdot \text{cm})$) and high digitalization threshold (without FEE amplification).

RPCs technology is a credible option for FCC-ee muon systems

Timing The second prototype with 500 μm gaps — double bi-gap — reach less than 200 ps. At GIF++ the timing performance sits at 139–209 ps

Efficiency Up to 95.2–96.0% at GIF++, consistent across both readout configurations, an improvement w.r.t. the first prototype

Rate capability Measured for the first time with the digital readout up to $\sim 80 \text{ Hz/cm}^2$ — not far from $O(100 \text{ Hz/cm}^2)$ scale FCC-ee asks for.

- Next**
- Petiroc-based front-end in the chain and ToF setup
 - Alternative mixtures
 - Low resistivity electrodes

Backup

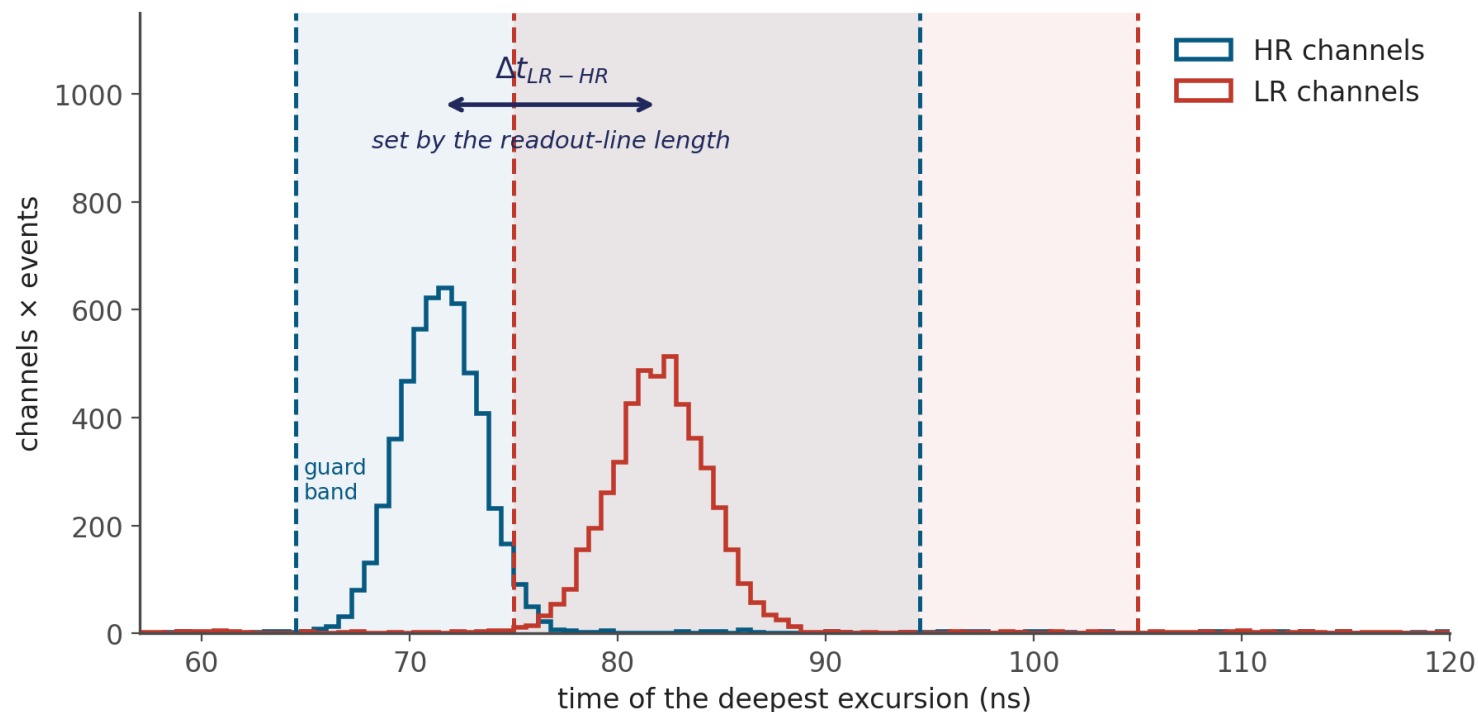


CEPC muon detector — baseline parameters

Parameter	Baseline
$L_b/2$ [m]	4.14
R_{in} [m]	4.40
R_{out} [m]	6.08
L_e [m]	1.72
R_e [m]	0.50
Segmentation in ϕ	12
Number of layers	8
Total thickness of iron ($\lambda = 16.77$ cm)	6.7 λ (112 cm) (8/8/12/12/16/16/20/20) cm
Solid angle coverage	0.98 $\times 4\pi$
Position resolution [cm]	$\sigma_{r\phi}$: 2 σ_z : 1.5
Time resolution [ns]	1 – 2
Detection efficiency ($P_\mu > 5$ GeV)	> 95%
Fake($\pi \rightarrow \mu$)@30GeV	< 1%
Rate capability [Hz/cm ²]	~60
Technology	RPC (super module, 1 layer readout, 2 layers of RPC)
Total area [m ²]	Barrel: ~4450
	Endcap: ~4150
	Total: ~8600

CEPC CDR baseline: RPC super-modules, ~8600 m² total sensitive area

The muon window is found from the data



DQM example: arrival-time distribution per side with the selected windows.

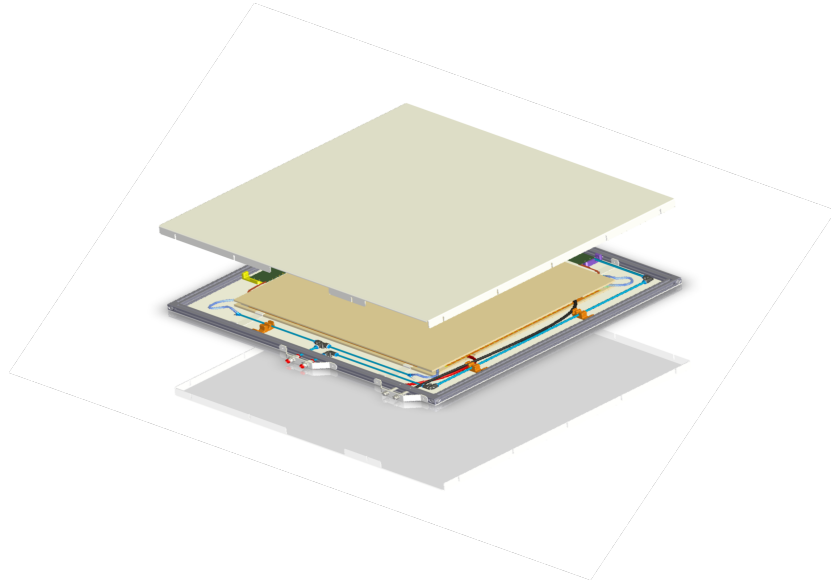
- **Only the WIDTH is chosen by hand.**
- The position of the window comes from the arrival times of the signals above n sigma.
- The window kept is the one containing the largest number of them.
- A guard band keeps the earliest pulses away from the boundary.
- Determined once on the highest HV point, then applied to the whole scan.

Why two windows

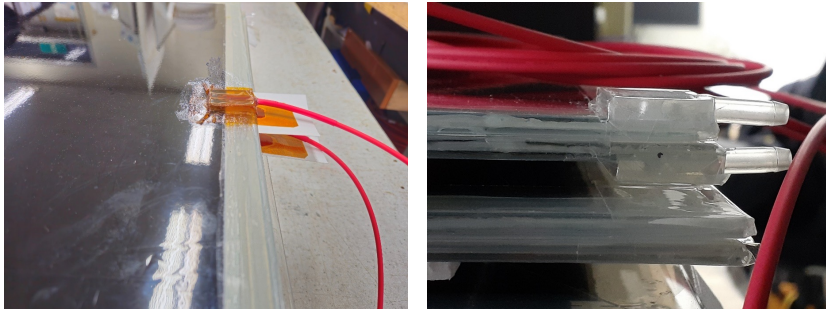
The two ends of a strip reach the digitizer through very different line lengths, so their pulses do not arrive together.

Small double-gap thin-glass RPC

Built at the KODEL laboratory, Hanyang University



Double gap with the strip readout panel in between



Detector

- Envelope $80 \times 80 \times 2 \text{ cm}^3$
- Double gap, readout panel in between
- Soda-lime glass electrodes, 1.1 mm
- Gas gap $500 \mu\text{m}$
- Bulk resistivity $\sim 10^{12} \Omega \cdot \text{cm}$ at 20°C
- Active area $\sim 10 \times 50 \text{ cm}^2$

Readout

- Strip pitch 6.25 mm, single-ended, far end terminated at 50Ω
- CAEN DT5742 digitiser, 16 ch + fast trigger at 5 GS/s
- Full waveform stored per channel per event

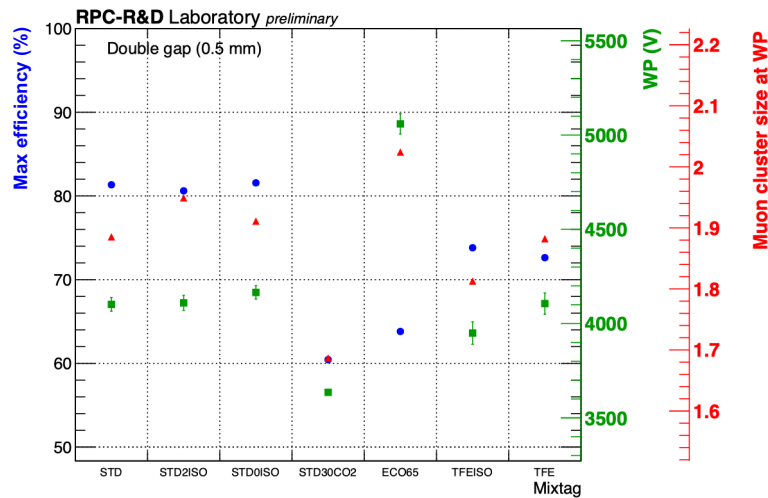
Why 500 μm gaps

- Shorter avalanche development $\rightarrow$ smaller time jitter
- Timing improves as the gap narrows — the route that took timing RPCs below 100 ps
- Glass electrodes keep the construction simple and cheap over large areas
- Trade-off: less primary ionisation per gap, so a multi-gap stack is needed to recover efficiency

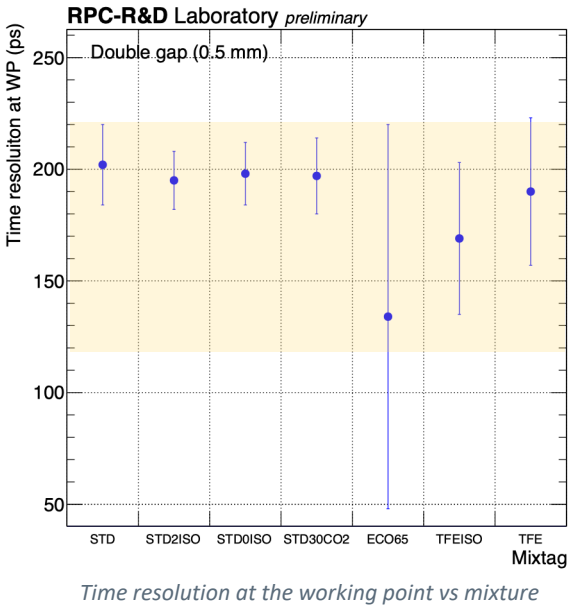
Efficiency and timing

Mixtag	TFE	HFO-1234ze	CO ₂	iC ₄ H ₁₀	SF ₆
STD	95.2	—	—	4.5	0.3
STD2ISO	97.7	—	—	2	0.3
STD0ISO	99.7	—	—	—	0.3
STD30CO2	65	—	30	4	1
ECO65	—	65	30	4	1
TFEISO	95	—	—	5	—
TFE	100	—	—	—	—
GWP	1430	7	1	3	22800

Mixtures explored at the INFN-Torino laboratory (concentrations in %)



Summary, all mixtures



Time resolution at the working point vs mixture

70–80%

efficiency at WP
(no front-end amplification)

~4 kV

working point
(+1 kV for ECO65)

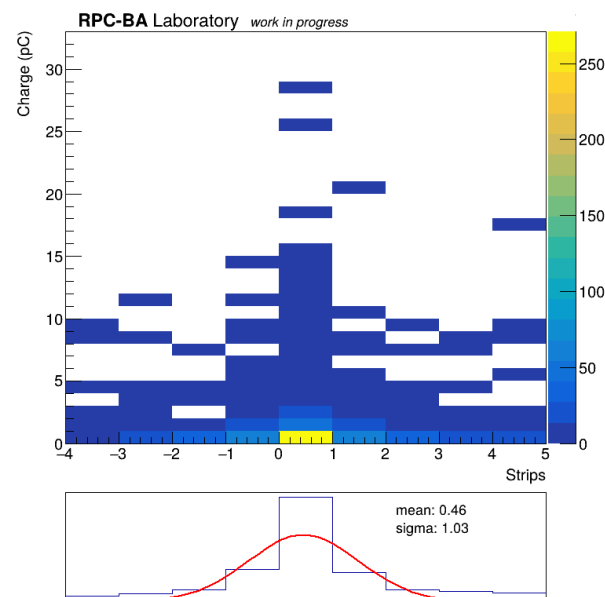
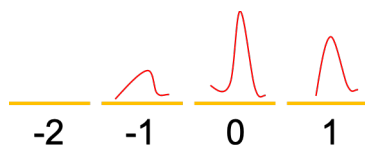
~200 ps

chamber time resolution
for every mixture tested

The eco-friendly mixtures — ECO65 (HFO-1234ze) and the CO₂-based blend — reach the same ~200 ps as the standard mixture. Timing is not what is lost when the GWP is reduced.

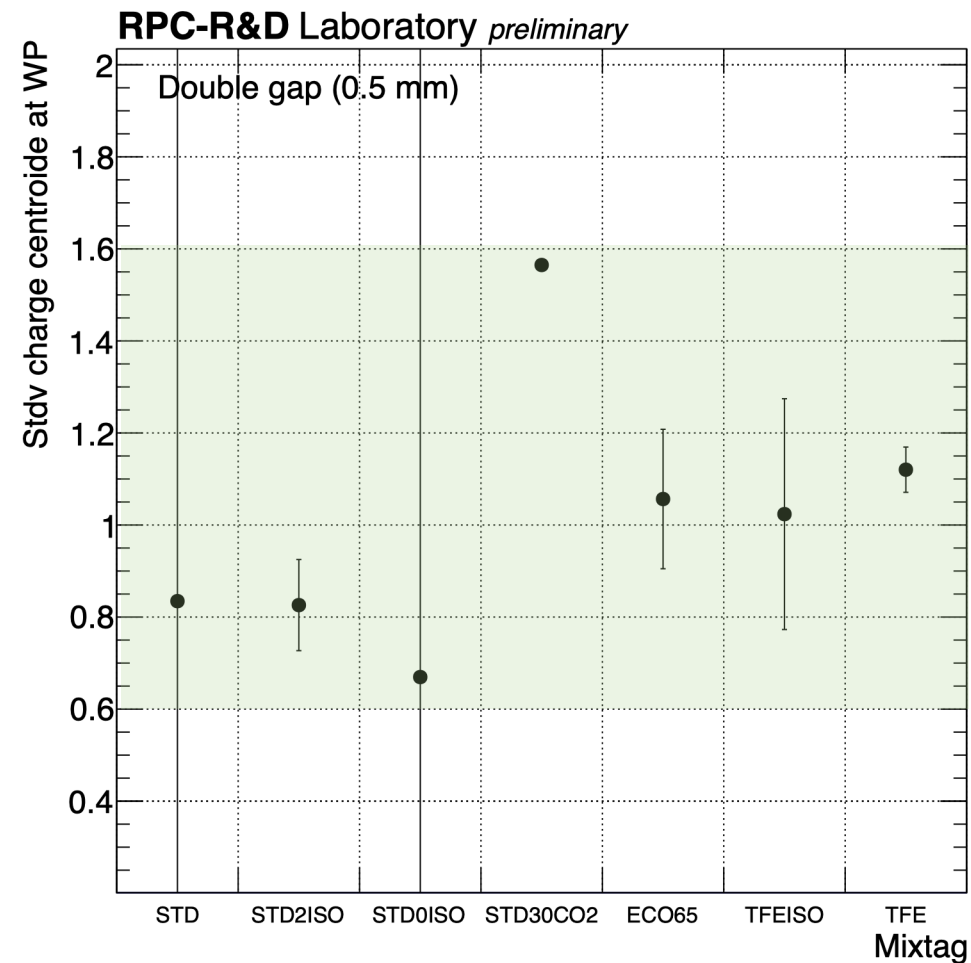
Cluster charge centroid

Cluster charge definition

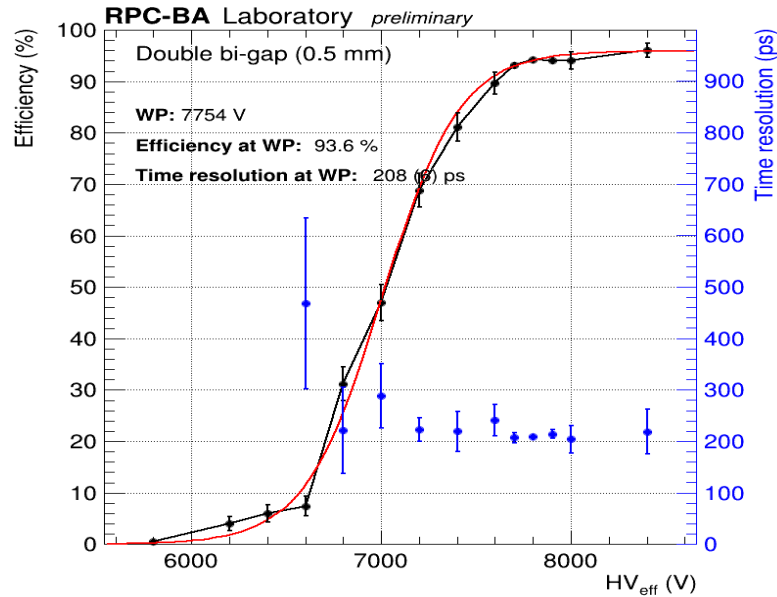


5mm strip pitch single side readout

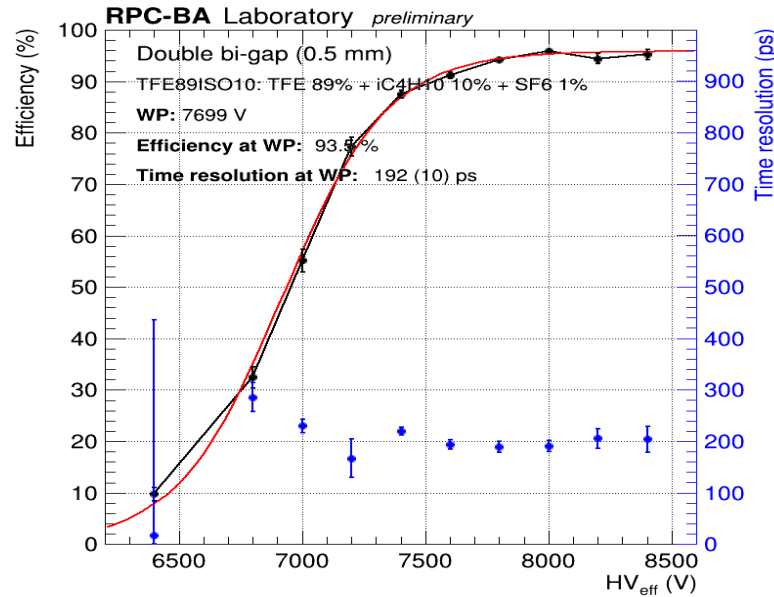
- σ clus. charge centroid ~ 1 strip $\rightarrow$ potentially improved space resolution



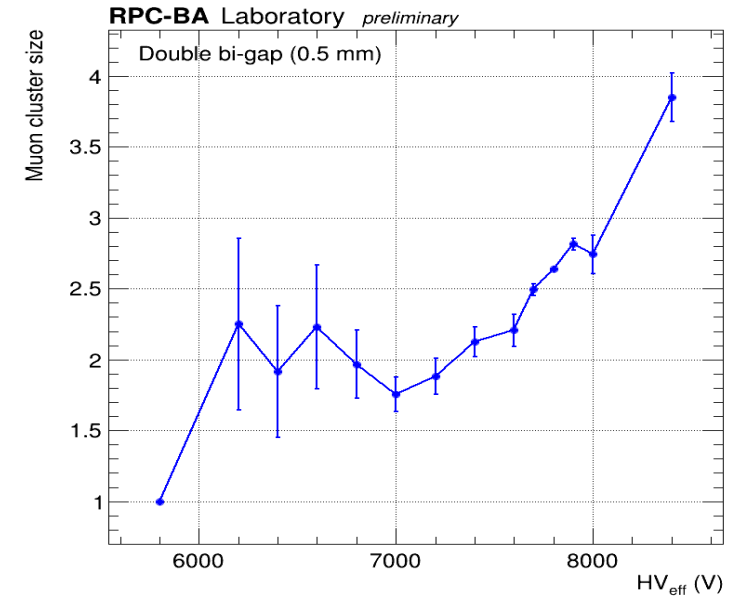
Cosmic-ray performance of the double bi-gap



STD: 95.2% TFE + 4.5% iC₄H₁₀ + 0.3% SF₆



TFE89ISO10: 89% TFE + 10% iC₄H₁₀ + 1% SF₆



Muon cluster size vs HV_{eff}

STD WP 7754 V · efficiency 93.6% · time resolution 208 ± 16 ps

TFE89ISO10 WP 7699 V · efficiency 93.0% · time resolution 192 ± 10 ps

Maximum efficiency up to 97% without any front-end amplification; cluster size ~2.5 strips at the working point.

The double bi-gap layout improves the timing modestly over the single double-gap — down to ~190 ps with the higher-isobutane mixture.

Efficiency, working point and cluster size

