110° Congresso Nazionale Società Italiana di Fisica (SIF 2024)

Performance in a high-rate environment of triple-GEM detectors for the ME0 system of the CMS Phase-2 Upgrade

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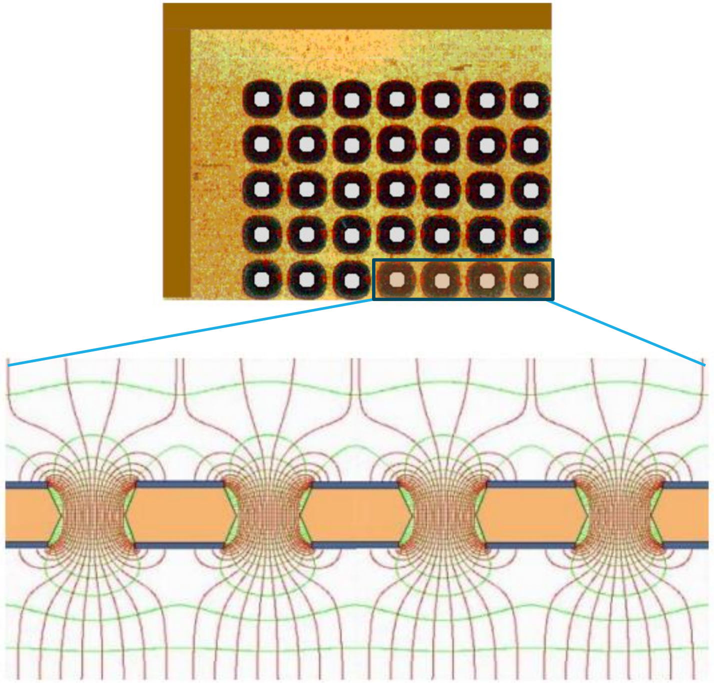
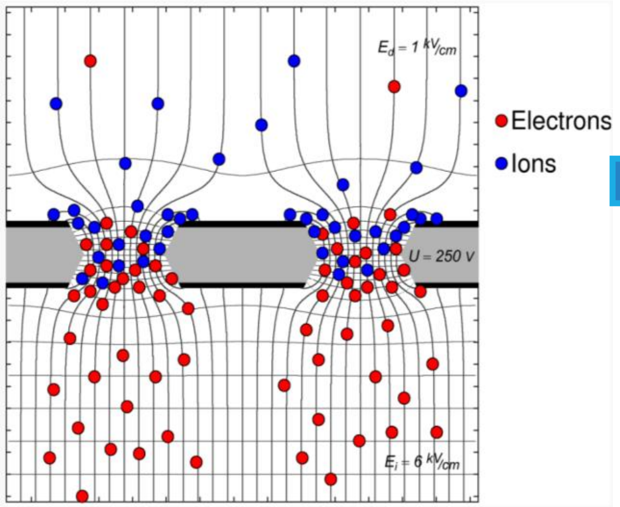
Triple-GEM detectors

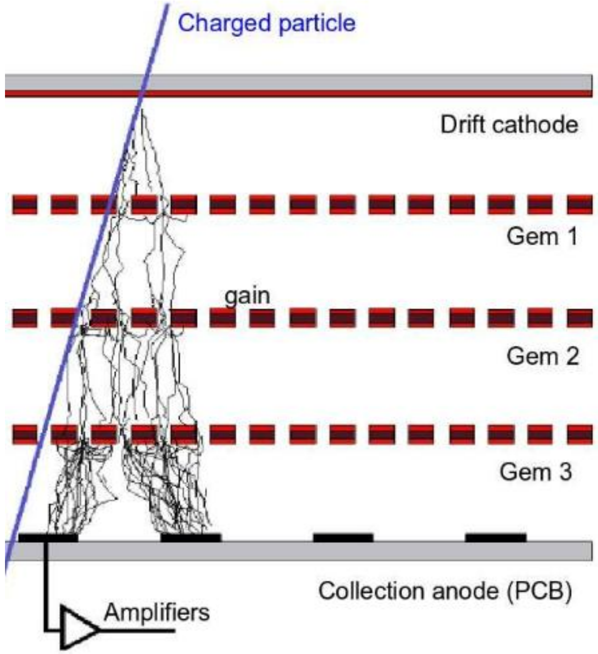
Based on the **GEM foils**:
thin polymer foils metal coated on both sides with a pattern of holes.
Both the diameter of the holes and the thickness of the foil $\sim 50\ \mu m$.



When a voltage is applied to the GEM foil an electric field develops within the holes.
The electric field can be high enough ($\sim 80\ kV/cm$) to make the **avalanche multiplication** develop.



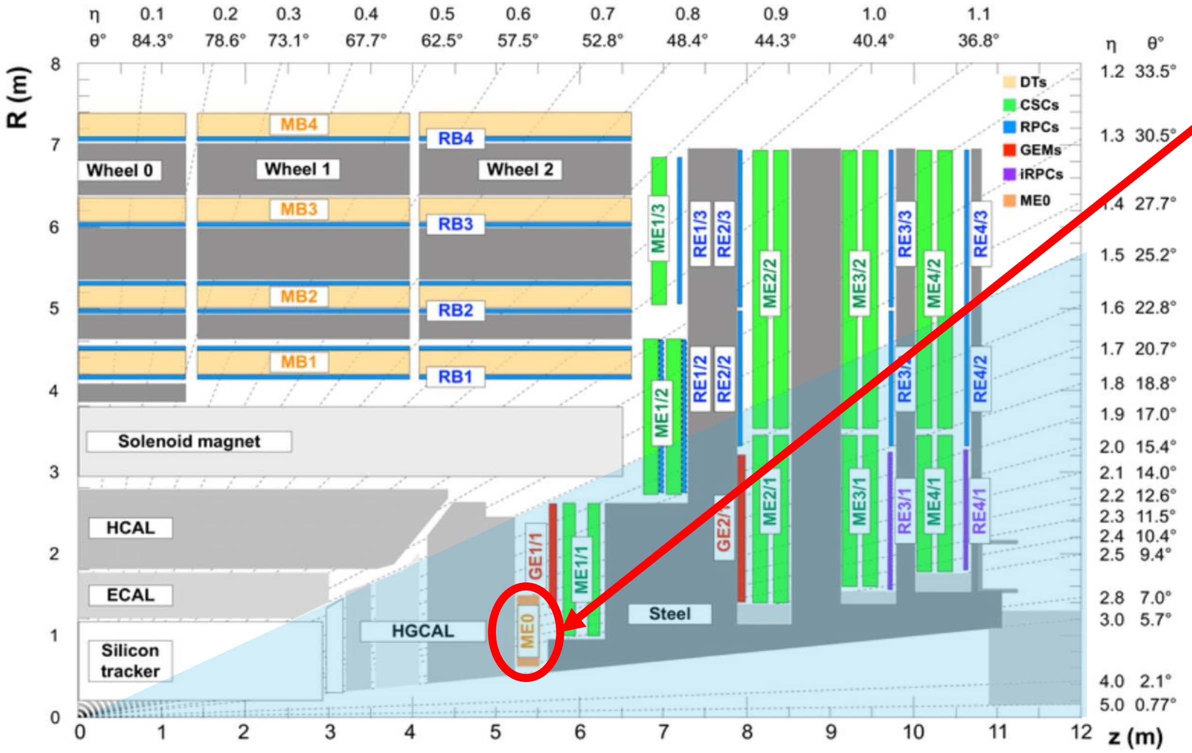
To enhance stability, GEM foils are often put in cascade.
A typical configuration is that of three GEM foils:
Triple-GEM detectors



GEM in the CMS Phase-2 Upgrade

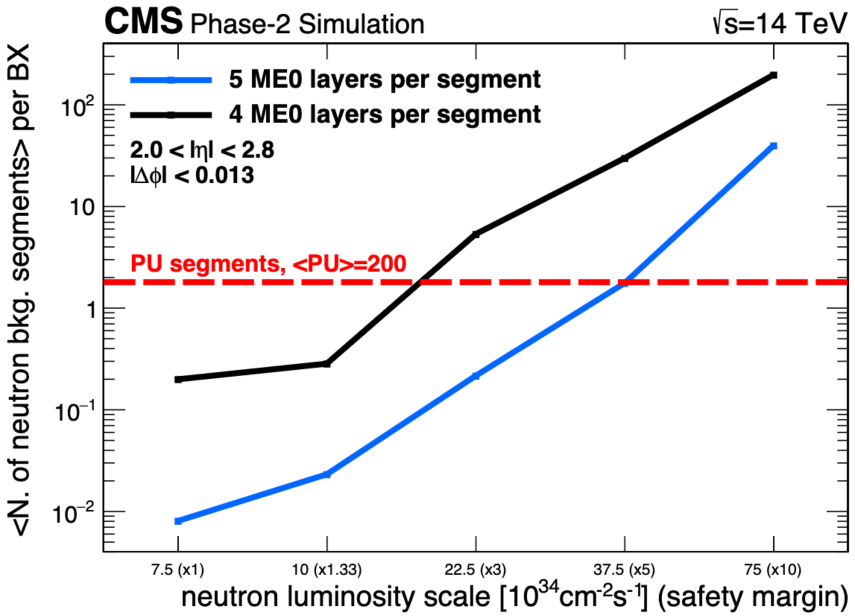
In 2029: High Luminosity LHC → luminosity up to $5 - 7.5$ times the nominal LHC luminosity ($10^{34}\ \text{cm}^{-2}\text{s}^{-1}$)
→ Higher rate of particles → **CMS Phase 2 Upgrade**

Three new GEM stations in the forward region of the endcaps
→ complement muon stations to reduce L1 trigger rate



ME0 station will

- complement muon stations in $2.1 < \eta < 2.4$
- extend muon trigger coverage $2.4 < \eta < 2.8$

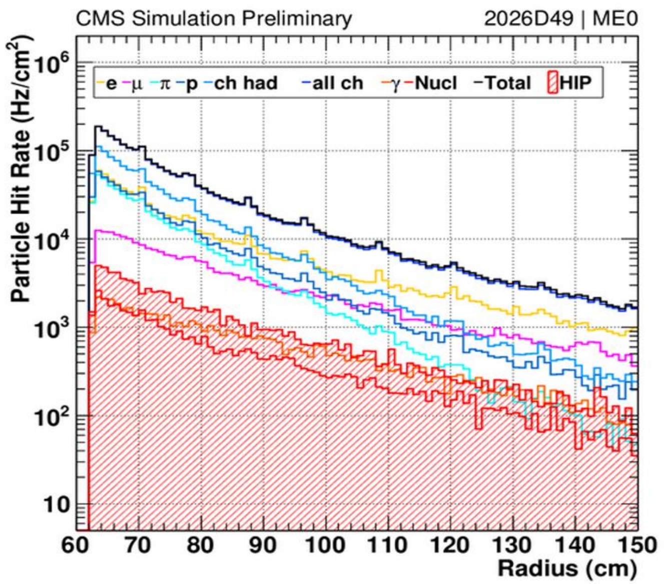


CMS Collaboration, "**The Phase-2 Upgrade of the CMS Muon Detectors**"

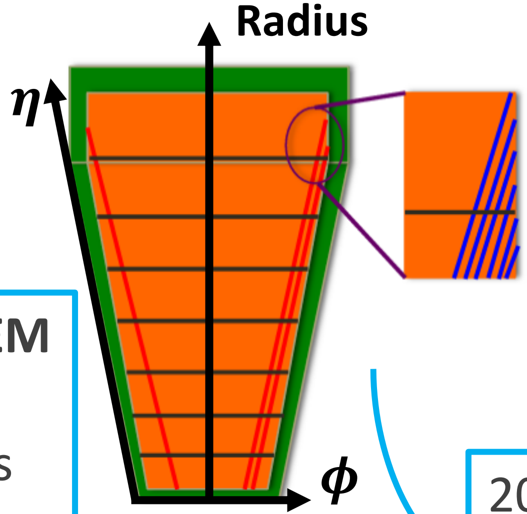
The ME0 station

Will be the closest detector of the muon system to the interaction point
→ highest rates (max $\sim 150\ \mathrm{kHz/cm^2}$)
The main requirements are:

- **Rate capability** → $\sim 150\ \mathrm{kHz/cm^2}$
  Measured with a test beam campaign at the GIF++
- **Time resolution** → $8-10$ ns per chamber
  Measured with cosmic rays

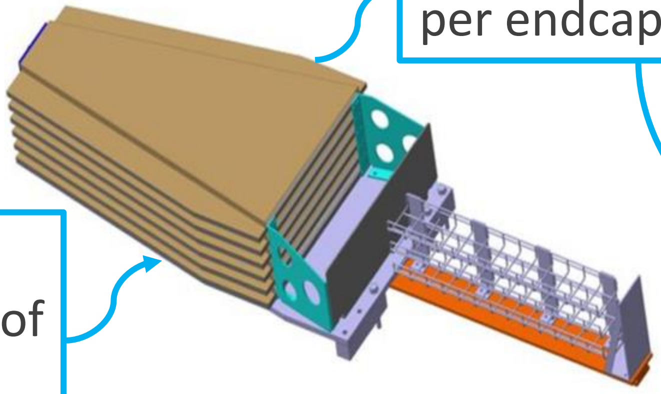


CMS Collaboration, "**Rate capability of large-area triple-GEM detectors and new foil design for the innermost station, ME0, of the CMS endcap muon system**"

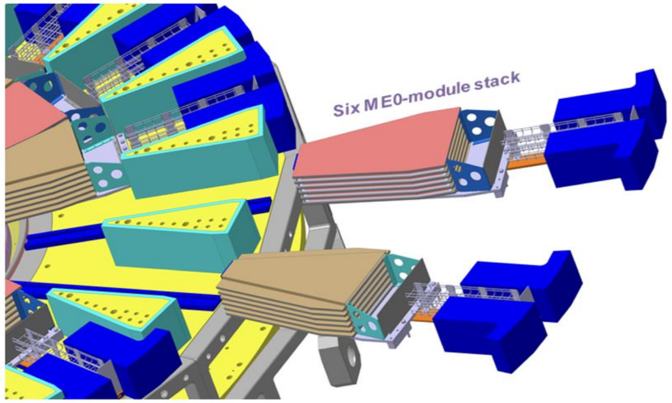


Triple-GEM
8 η partitions
384 strips along ϕ

20 degree stack made of 6 layers



18 stacks per endcap



ME0 production and installation plans

R&D

April 2024 | ME0 module production started:

- 245 modules to be assembled by the summer of 2026
- 32 modules produced up to now

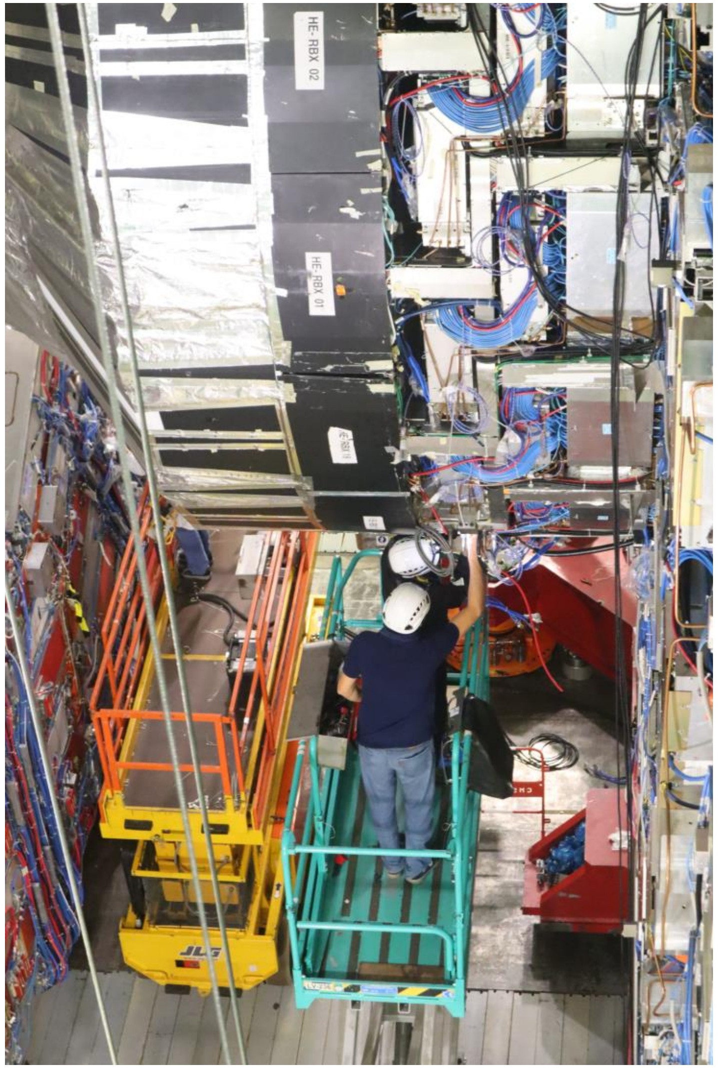
October 2024 | ME0 stack production scheduled to start

August 2025 | Expected delivery date for the 1st endcap

October 2026 | Expected delivery date for the 2nd endcap

February 2027 | Need-by dates for ME0 station installation

HL-LHC first run



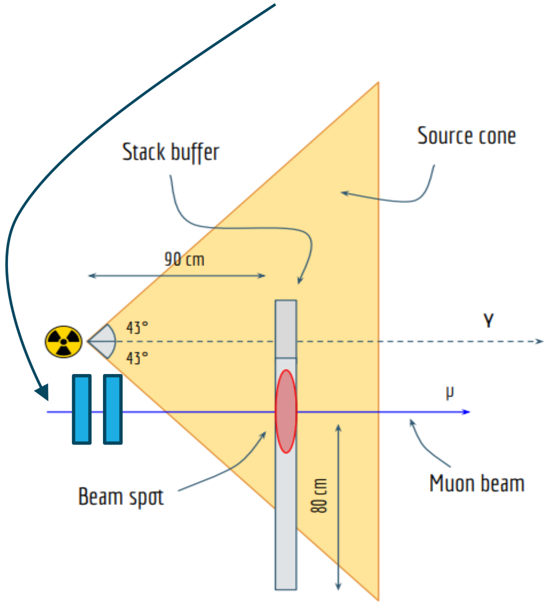
GIF++ test beam setup

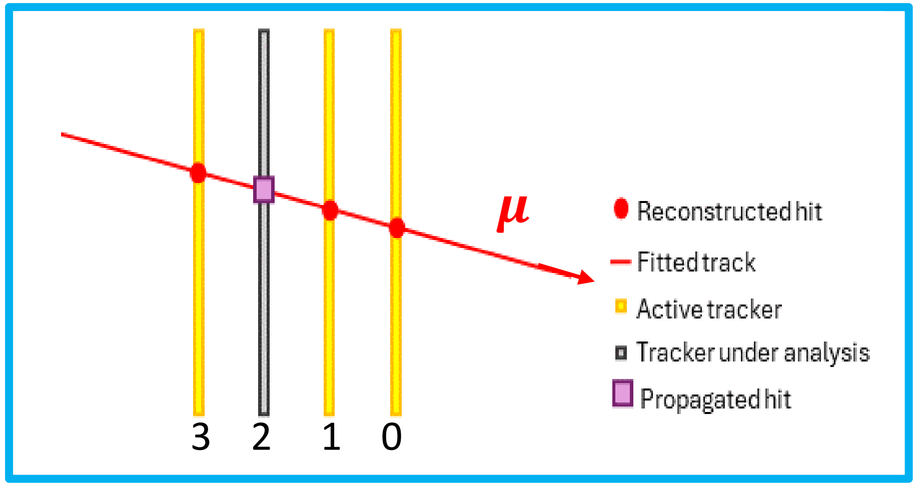
The Gamma Irradiation Facility (GIF++) provides:

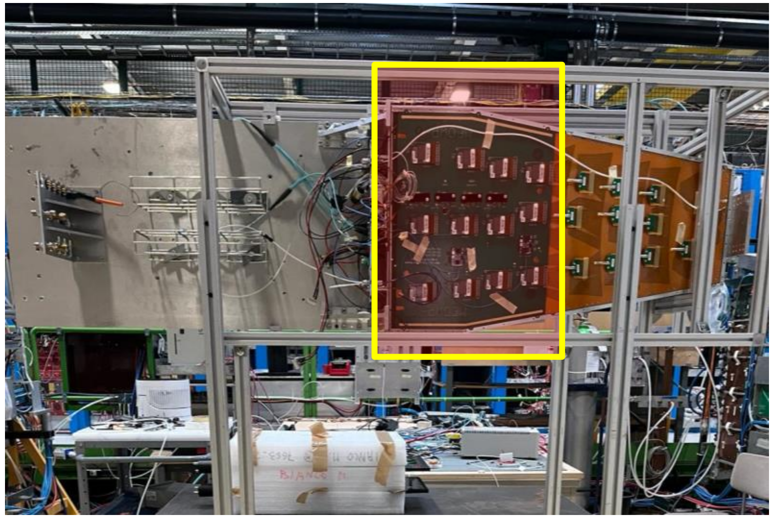
- A high energy **muon beam** (~ 80 GeV)
- A radioactive source: 14 TBq ^{137}Cs

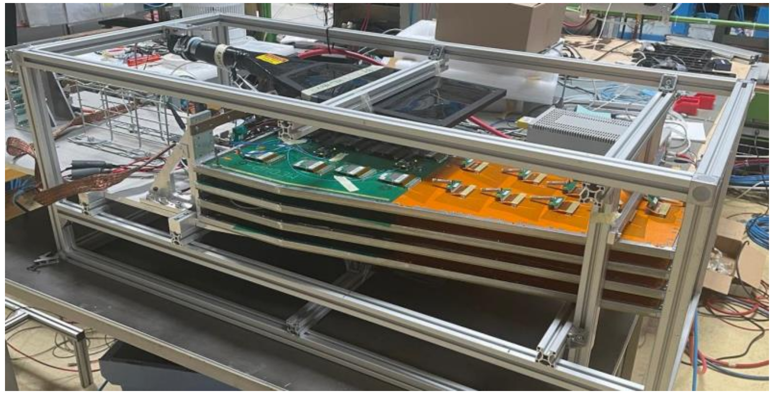
ME0 stack used standalone for reconstruction

2 GIF++ scintillators out of the irradiation field are used as trigger.









Rate capability measurement

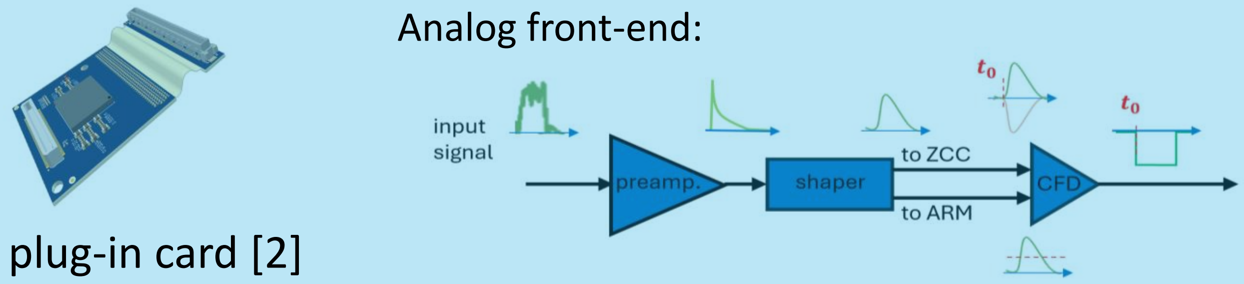
The efficiency for muons of the 4 chambers in the stack will be measured by varying **the photon background rate**

The drop of the efficiency for muons can be used to measure the **dead time** of the system.

MEASURED DEAD TIME = DETECTOR ⊕ ELECTRONICS ⊕ RECONSTRUCTION

Negligible contribution thanks to HV compensation [1]

The frontend readout chip is the **VFAT3** dead time $\sim 400 - 1000\ \mathrm{ns}$



VFAT3 plug-in card [2]

(important contribution from INFN Bari)

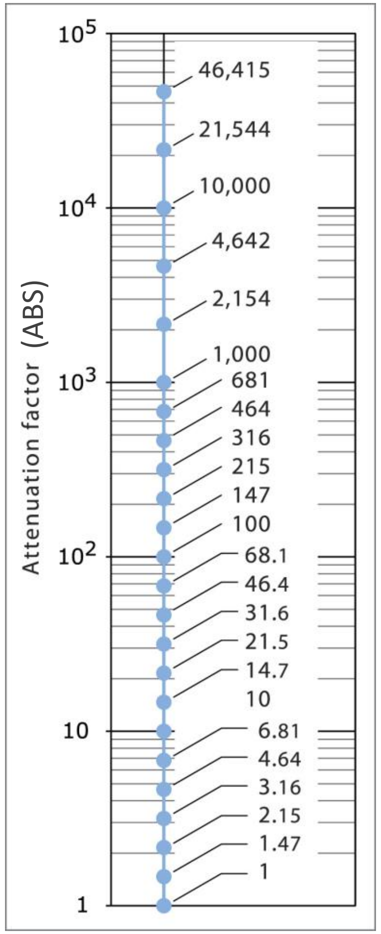
The data then split into two paths:

- Fixed latency → trigger
- Variable latency → send to the backend the «interesting» hits

[1] A. Pellecchia, «**Performance of micro-pattern gaseous detectors at the LHC and future collider experiments**»

[2] P. Aspell et al., «**VFAT3: A Trigger and Tracking Front-end ASIC for the Binary Readout of Gaseous and Silicon Sensors**»

Background rate in the GIF++



List of GIF++ attenuation factors

Set of absorbers around the Cs source

$$\rightarrow \mathbf{I(ABS) = I_0/ABS}$$

The measured rate VS ABS^{-1}:

- in absence of dead time → linear function
- Effect of dead time → saturating function

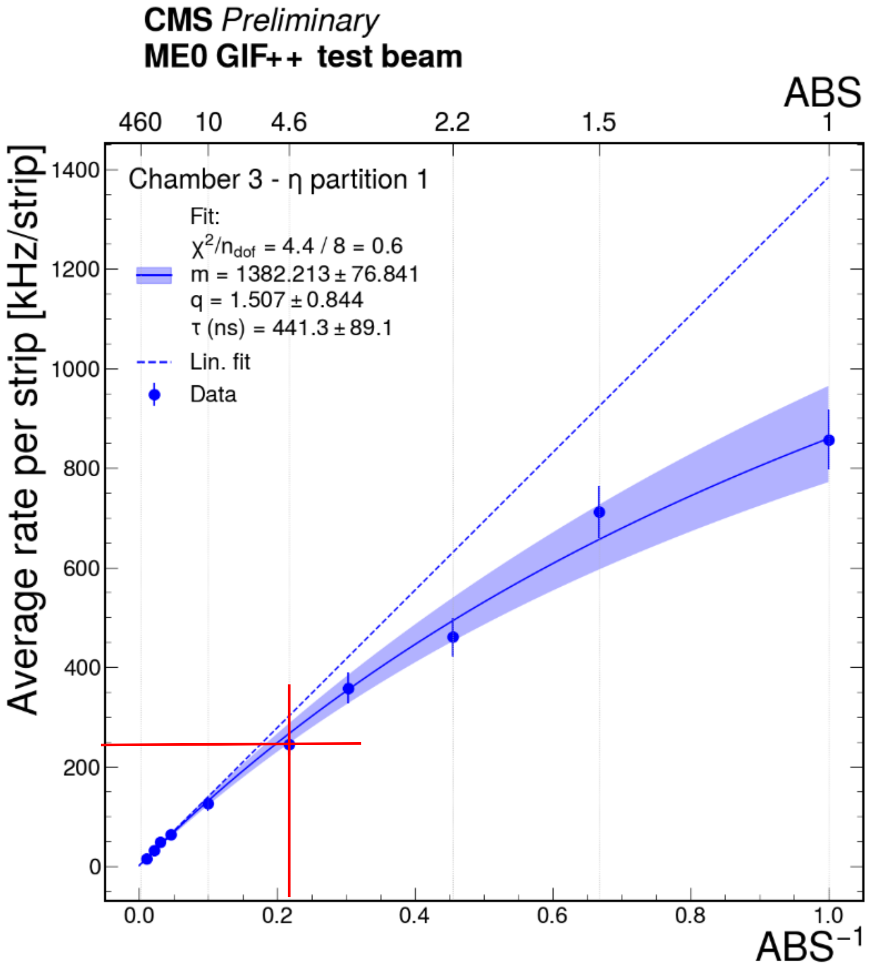
MEO rate ~ $\mathbf{150\ kHz/cm^2}$

~ $\mathbf{1\ cm^2}$ **per strip**

Interested in bkg rate ~ $\mathbf{150 - 200\ kHz/strip}$

$\boldsymbol{ABS^{-1} \sim 0.2}$

$\mathrm{ABS} \geq 4.6$

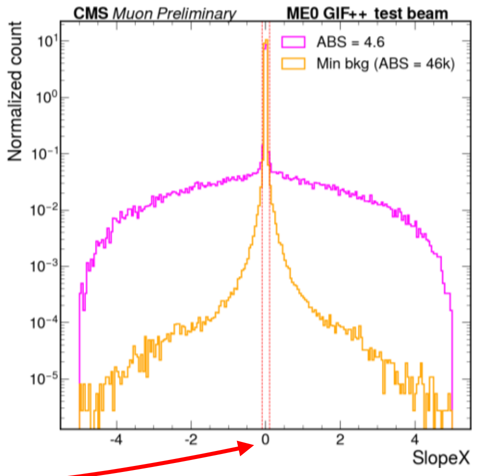


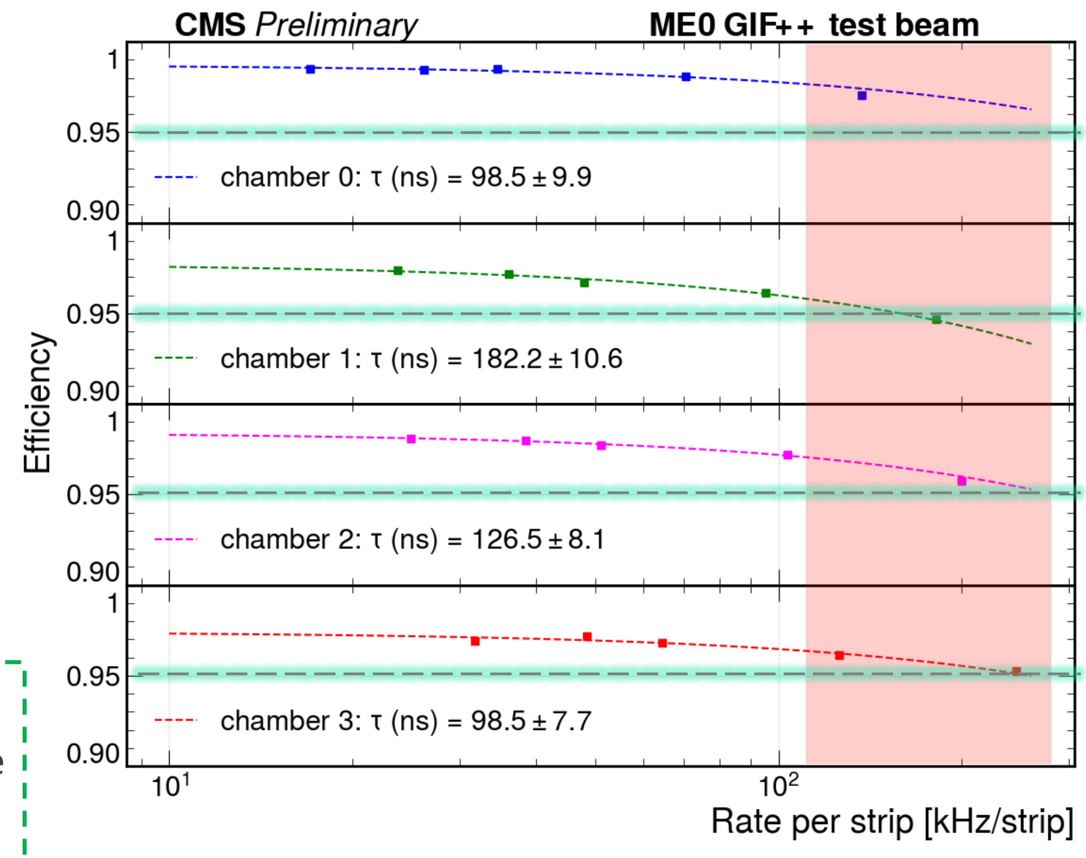
Rate capability

Muons + background hits complicate the combinatorial process
→ Higher slope **faulty tracks** enhancing the efficiency drop

To mitigate the efficiency drop quality selections on the tracks were applied:

- $\chi^2 < 10$
- $|\text{SlopeY}| < 0.01$
- $|\mathbf{SlopeX}| < \mathbf{0.1}$





Applying these cuts:

✓The efficiency drop is ~**1-2%**, and $\sim \mathbf{100-200\ ns}$ in terms of dead time of the system

✓The dead time is compatible with the expected VFAT3 dead time due to different cluster sizes of muons and bkg hits

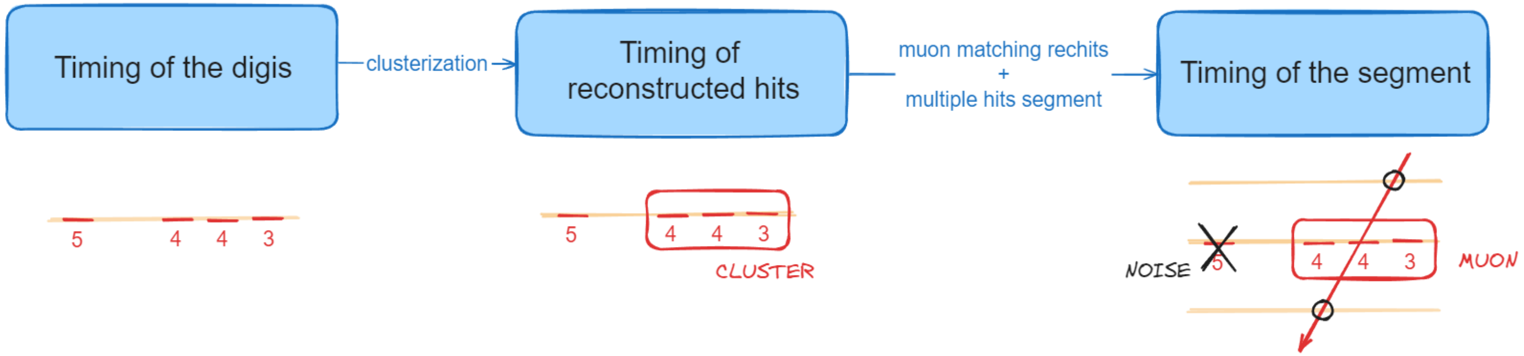
✓At the expected ME0 rate $\sim 150\ kHz/cm^2$ the chambers have an efficiency for muons of $\sim 95\%$.

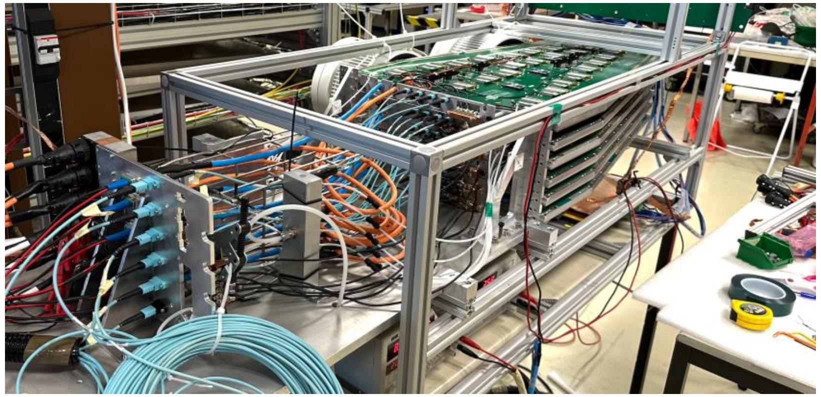
For the 6-layer stack, requiring **at least** 5 hits to reconstruct a segment:
$\mathbf{99\%}$ (no bkg) $\rightarrow$ $\mathbf{97\%}$
matching the Physics goals of ME0

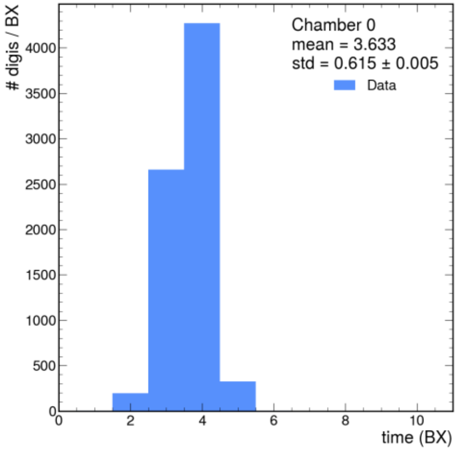
Time resolution

- ME0 prototype with six triple-GEM chambers
- Measurement of the time resolution with cosmic rays

REQUIREMENTS → $\sigma \sim 10$ ns

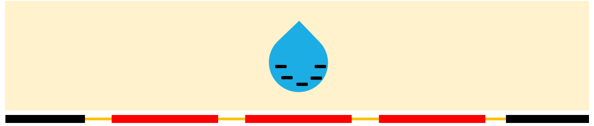






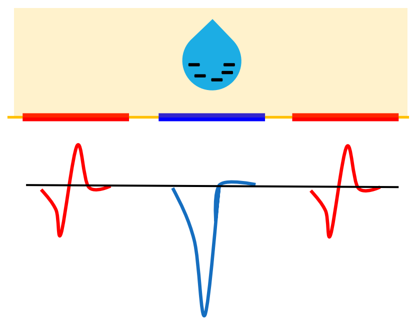
- Digi = readout strip
- $\sigma_{t,digi} = 15.5 \pm 0.3\ ns$
- Larger than requirements

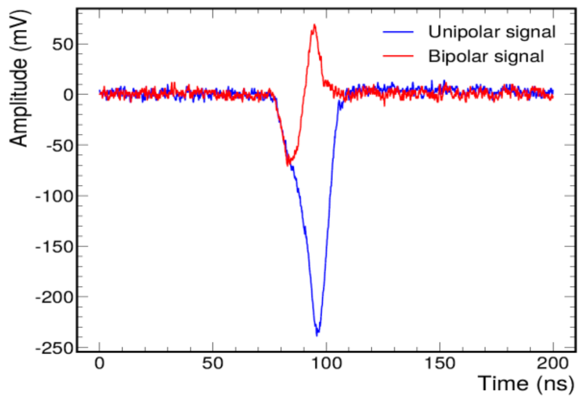
Look at the signal shape on strips within the cluster

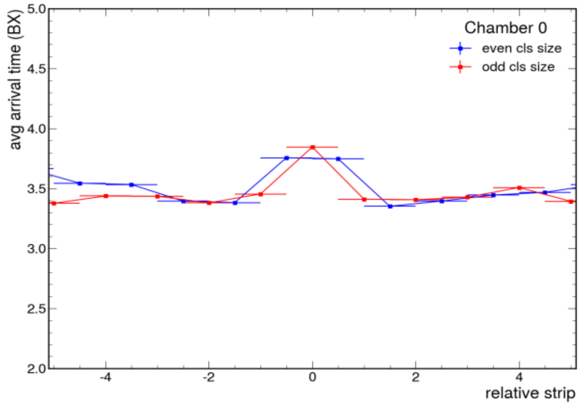


Rechit timing

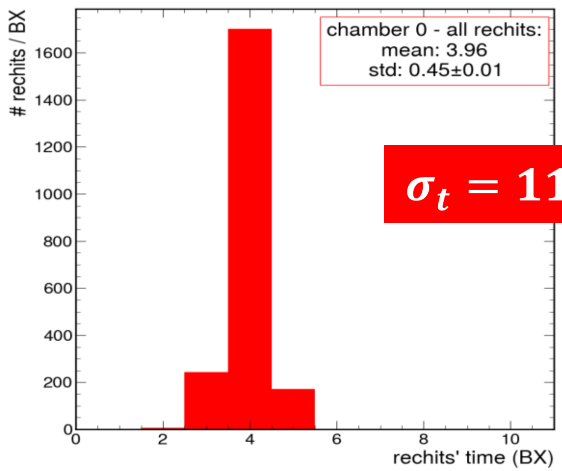
- The time resolution of the digis is affected by the different nature of the signals within a cluster:
  regular signals and **bipolar** signals





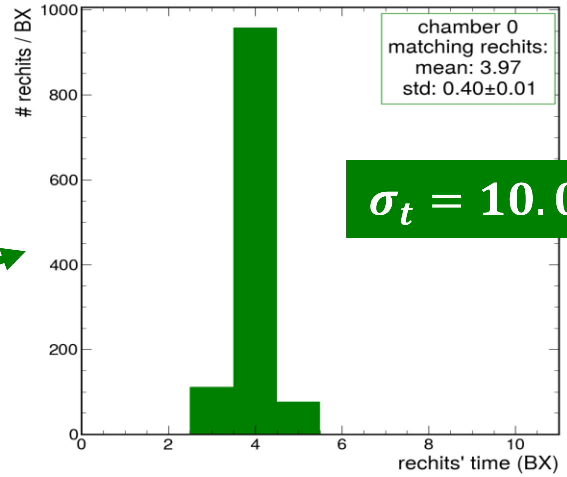


- After clustering, the time of the cluster is associated to the last firing strips



$\sigma_t = 11.3 \pm 0.3\ ns$

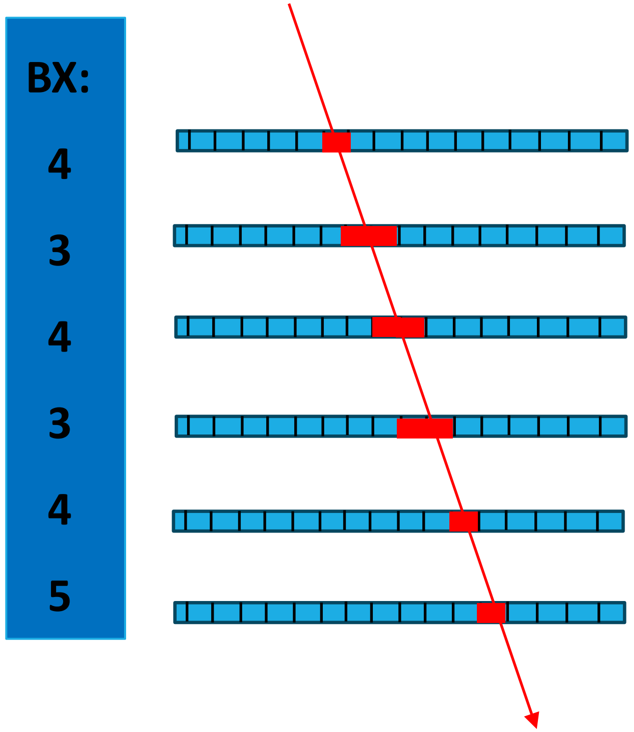
Considering only the timing of the matching rechits

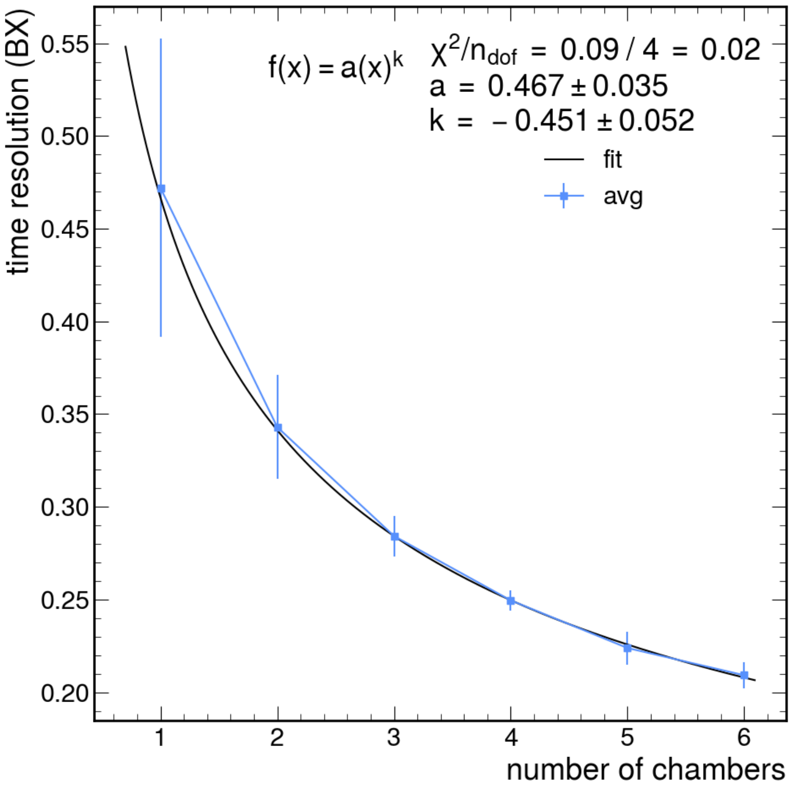


$\sigma_t = 10.0 \pm 0.3\ ns$

Segment timing

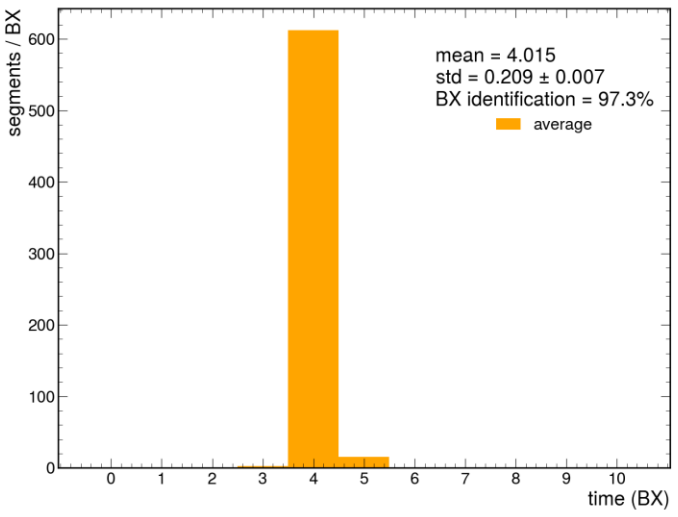
- Timing resolution of the stack takes advantage from the multi-layer segment reconstruction
- Once the segment is reconstructed, we have up to 6 hits → 6 timing information → averaging them





- $\sigma_t \propto 1/\sqrt{N}$, as expected
- For a six-layer segment:

$$\boldsymbol{\sigma_{t,6layers} = 5.25 \pm 0.18\ \mathbf{ns}}$$



→ Excellent BX identification of ~ 97%!

Conclusions

Validation of the performance of the triple-GEM detectors of the ME0 prototype

Performance of **4-layer** ME0 stack under a rate up to $250\ \mathrm{kHz/strip}$ at the GIF++:

- An **efficiency** drop of **1-2%** was observed, corresponding to a dead time of $\sim \mathbf{100-200\ ns}$, as expected from VFAT3 dead time

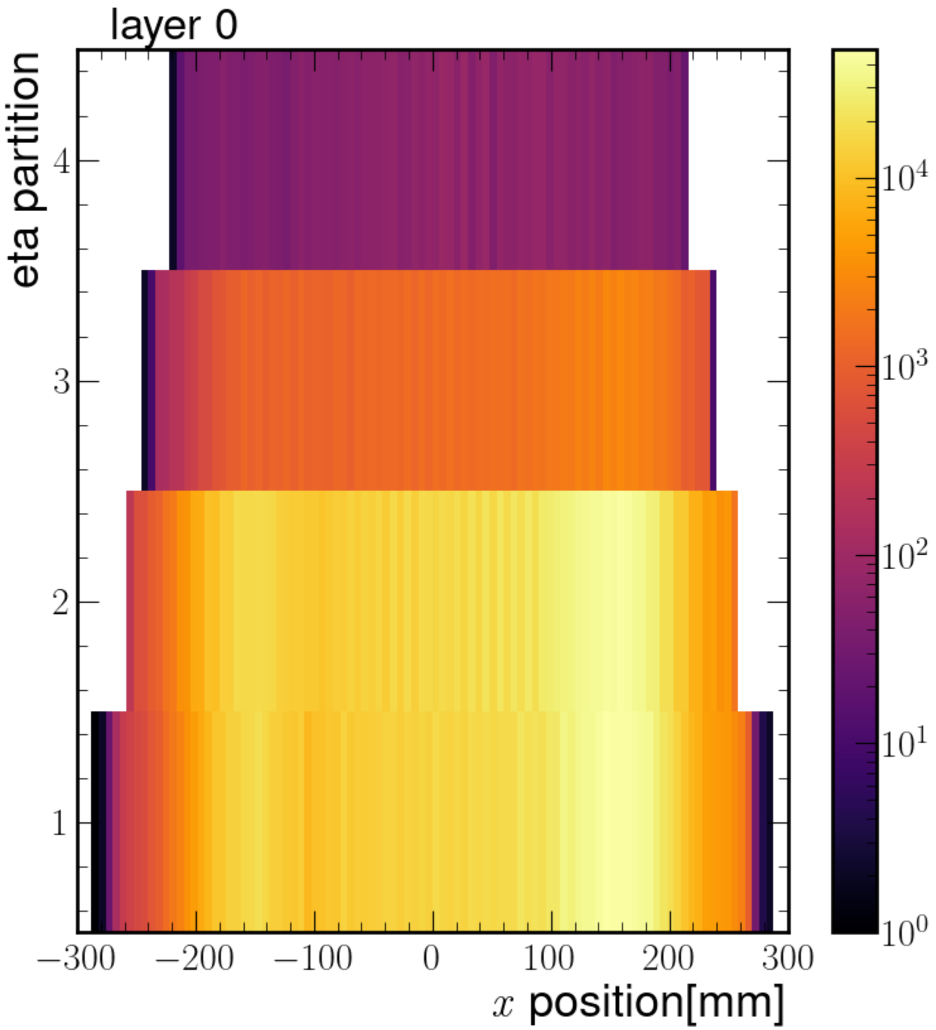
First measurement ever of the **time resolution** with the **6-layer** ME0 stack:

- Single chambers: time resolution $\sim \mathbf{10-12\ ns}$, as required
- Six-layer segments: time resolution of $\mathbf{5.25 \pm 0.18\ ns}$
  → BX identification of 97%

Next step → Demonstrate the time resolution at a trigger level

Thanks for your attention!

Backup



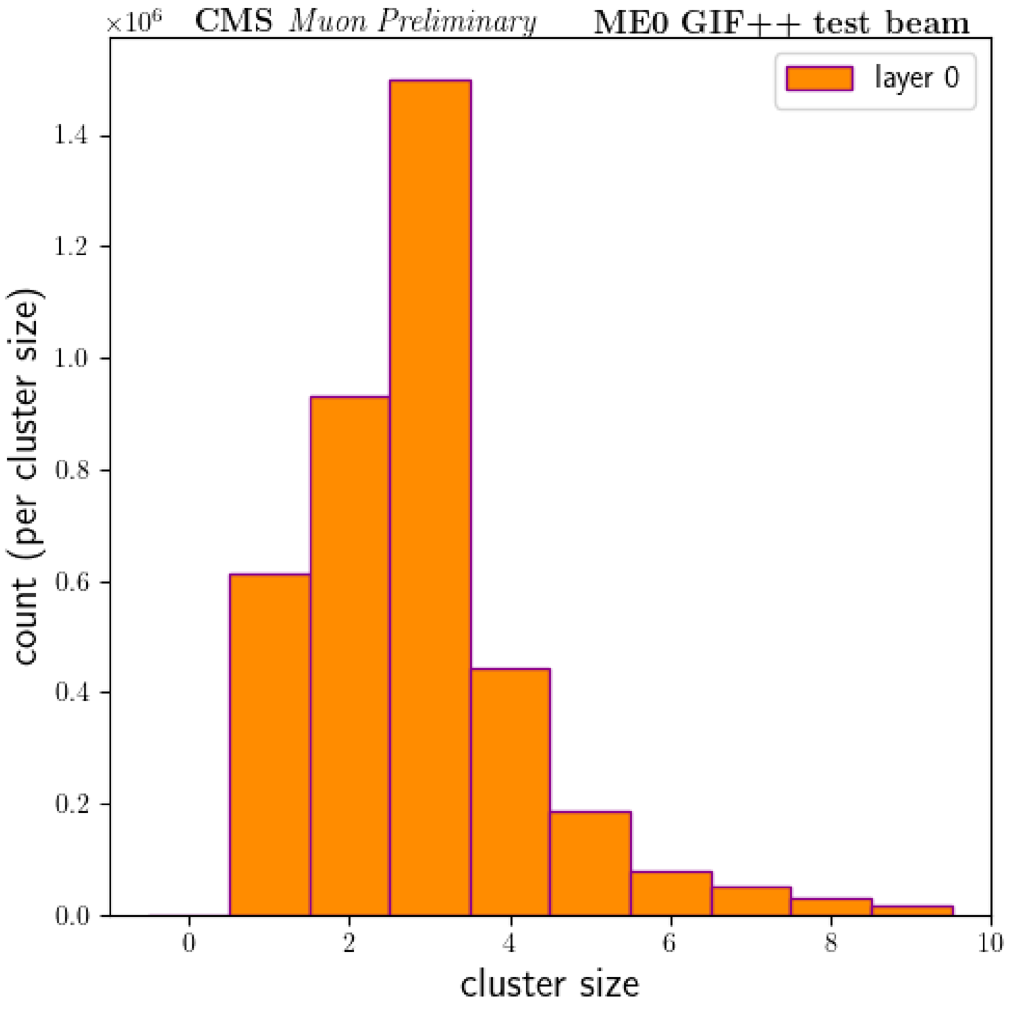
Muon beam profile

BEAM ON – SOURCE OFF

The muon beam hits predominantly eta 1 and 2, and, over x, has a double peak structure.

The cluster distribution shows that muon hits are clusterized mostly over 3 strips.

Muon tracks have very low slope over the x-direction. The parallelogram-shape is due to the geometrical coverage of the stack



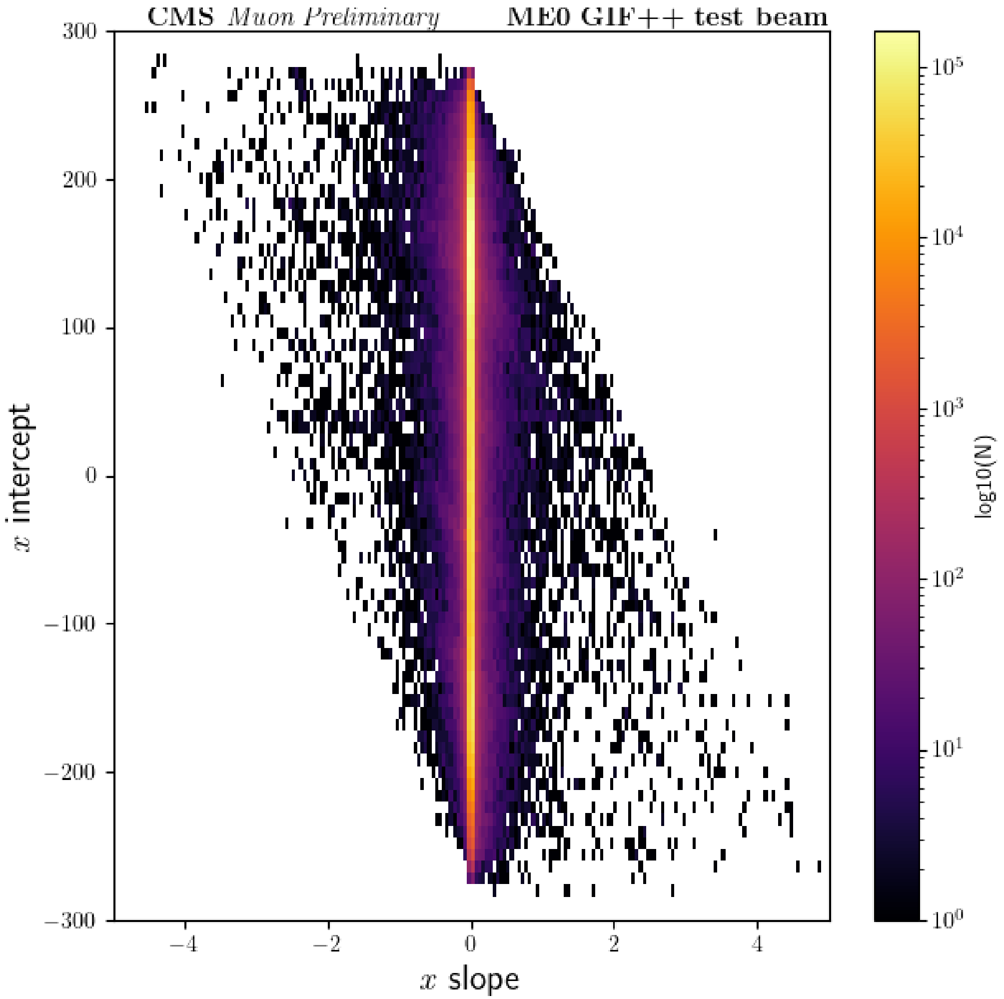
Muon beam profile (2)

BEAM ON – SOURCE OFF

The muon beam hits predominantly eta 1 and 2, and, over x, has a double peak structure.

The cluster distribution shows that muon hits are clusterized mostly over 3 strips.

Muon tracks have very low slope over the x-direction. The parallelogram-shape is due to the geometrical coverage of the stack



Muon beam profile (3)

BEAM ON – SOURCE OFF

The muon beam hits predominantly eta 1 and 2, and, over x, has a double peak structure.

The cluster distribution shows that muon hits are clusterized mostly over 3 strips.

Muon tracks have very low slope over the x-direction. The parallelogram-shape is due to the geometrical coverage of the stack

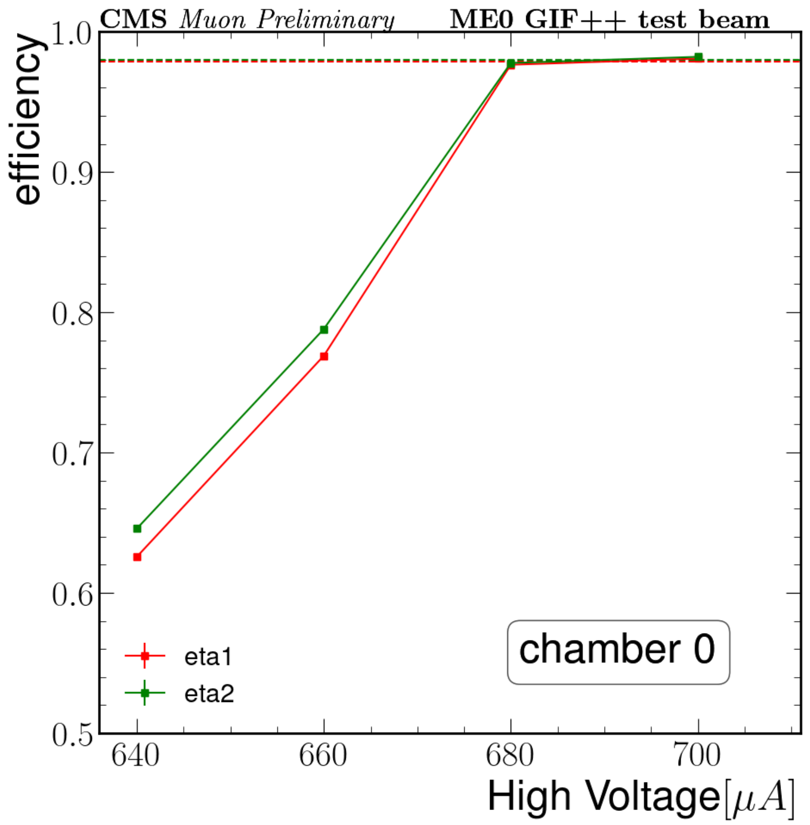
HV scan

Evaluating the efficiency (within a 5σ acceptance region) at different HV points, it appears that the plateau is reached already at $680\ \mu A$ with an efficiency of $\sim 98\%$.

NOTE:

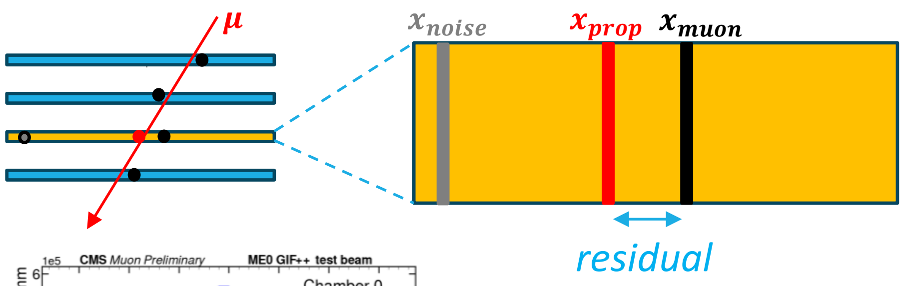
During the current test beam, the compensation algorithm has been developed considering HV filters of $50\ k\Omega$, while after the testbeam we realized that their resistance is equal to $320\ k\Omega$.

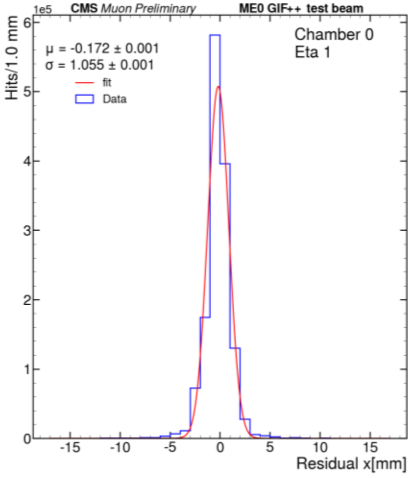
Therefore, the chambers were under-compensated and at ABS = 4.6 the voltage drop on GEM3Bot was approximately $2-5\ V$ → at HV $\sim 700\ \mu A$ the effective voltage in terms of equivalent divider current is $\sim 680\ \mu A$ (still at the plateau!).
We can measure the rate capability due to the electronics only for $ABS \geq 4.6$, for lower ABS the effect of the detector rate capability are no more negligible.

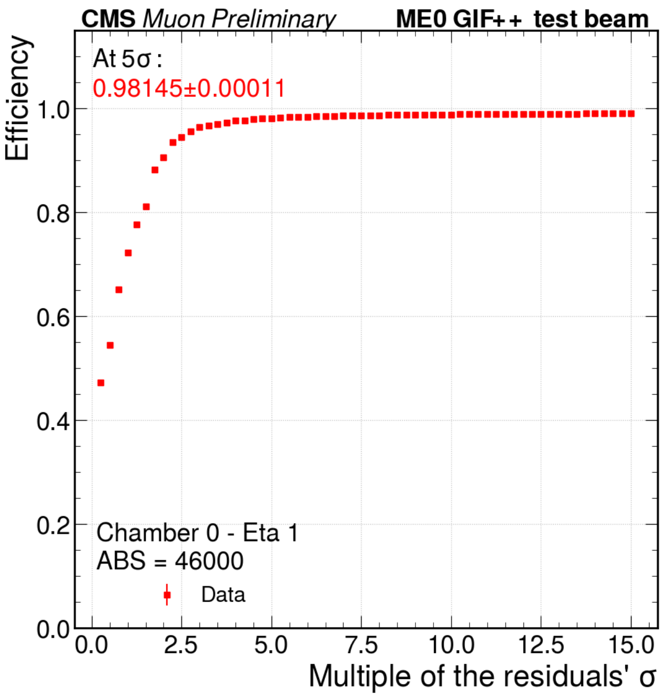


Efficiency measurements

Without background:

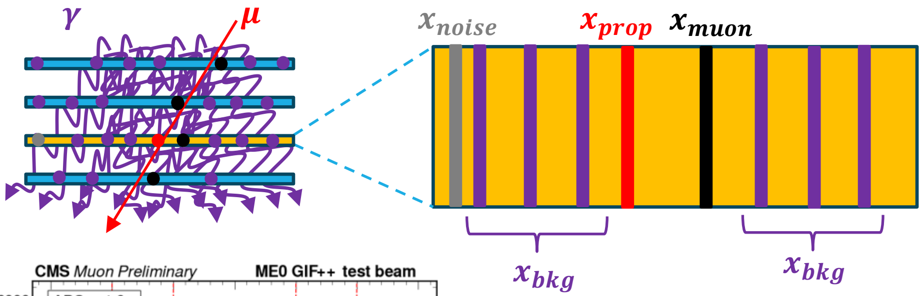


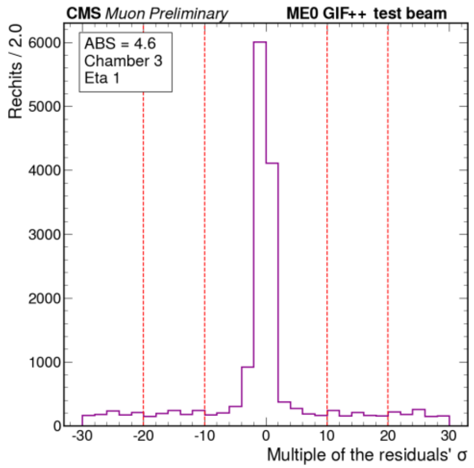


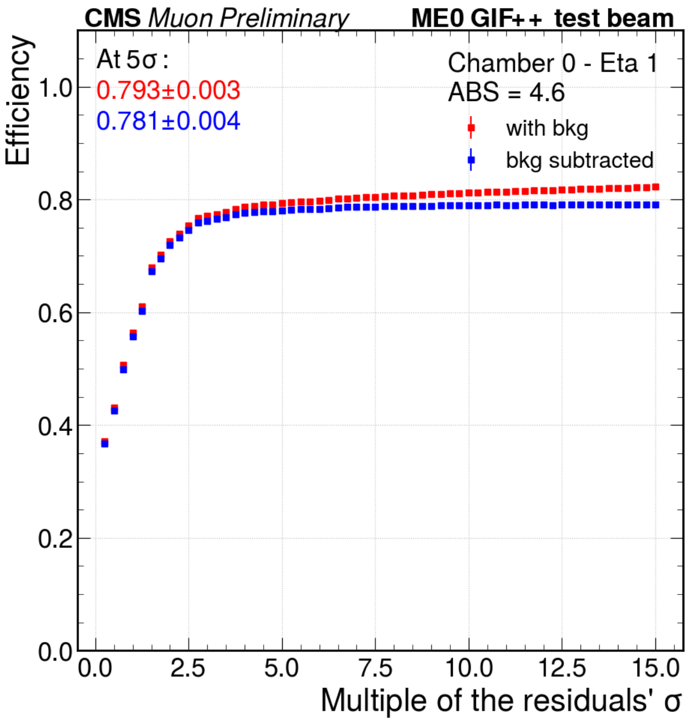


$$\epsilon = \frac{\text{matching propagated hits}}{\text{propagated hits}}$$

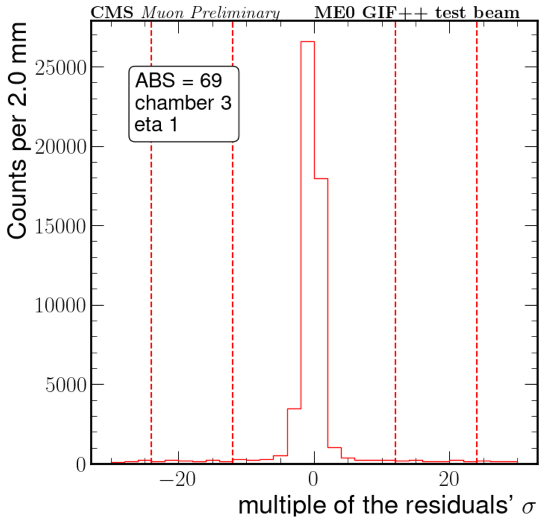
With background:

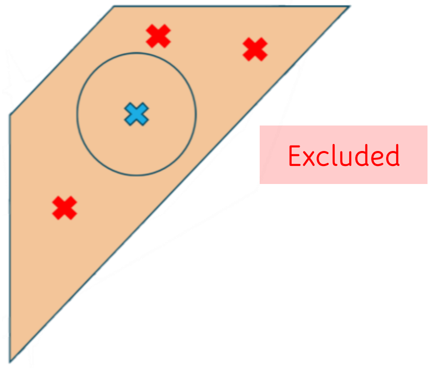


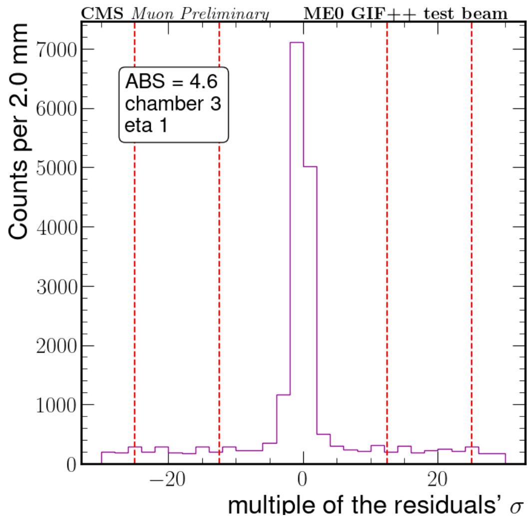


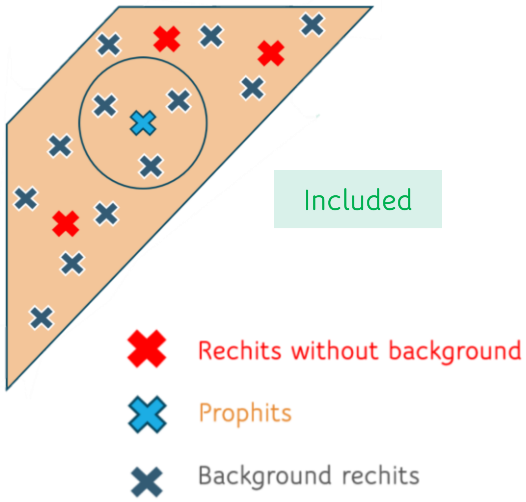


20% decrease in efficiency with background









Efficiency measurement **with background**

The computation of the efficiency in the presence of background is slightly different from the procedure described previously.

As visible from the residuals' distributions, there is an approximately uniform distribution of residuals out of the acceptance region, generated by the γ photons' spurious hits.

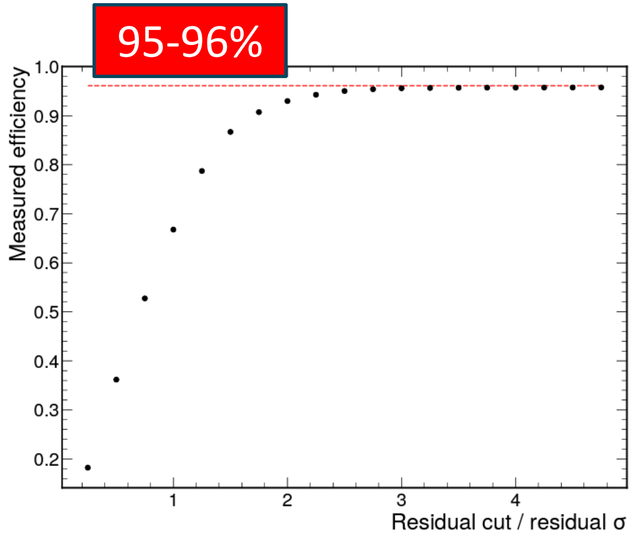
The effective muon reconstruction efficiency:

$$\epsilon = \frac{\epsilon_m - b}{1 - b}$$

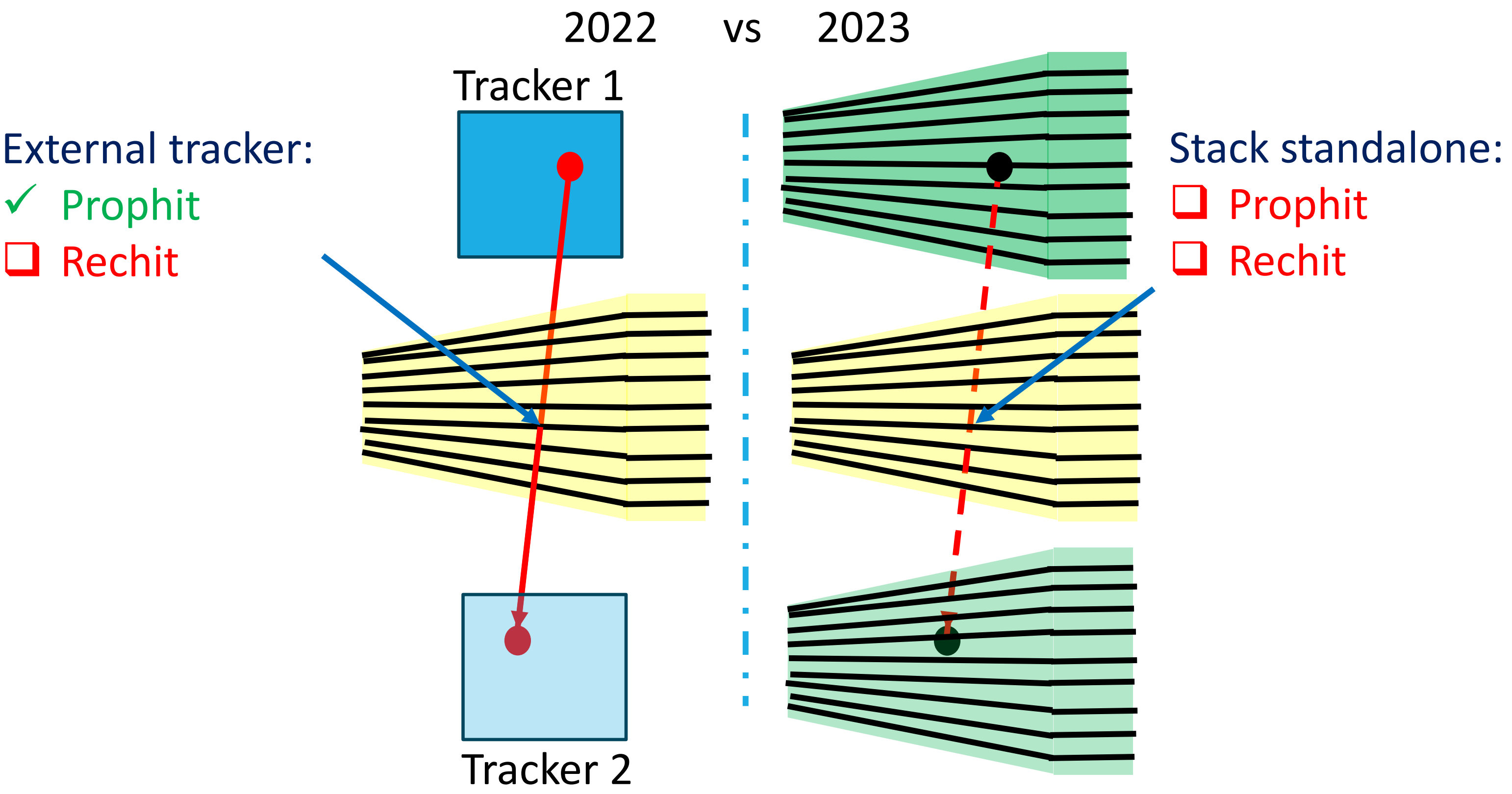
$$\epsilon_m = measured\ efficiency\ (muon + bkg)$$
$$b = probability\ of\ a\ bkg\ hit\ to\ be\ within\ the\ matching\ cut$$

With external trackers

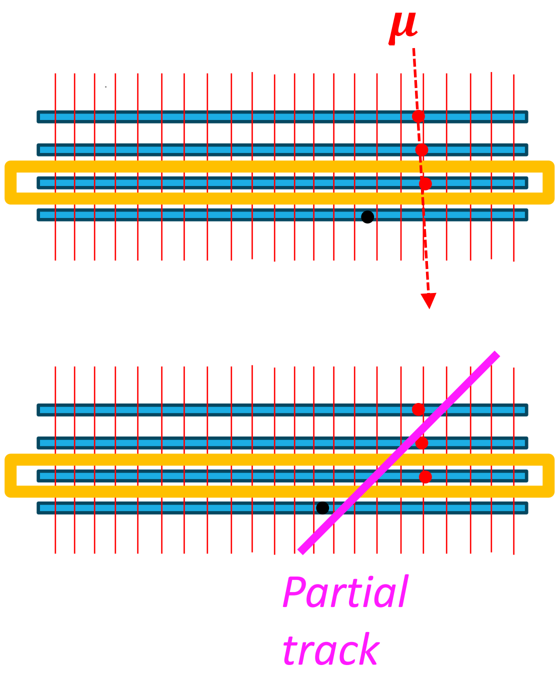
The efficiency saturates at values higher than those observed in measurement in previous test beams, where the upper limit set by the HV segmentation was $95 - 96\%$.



1 layer ME0 Test beam at GIF++ in 2022

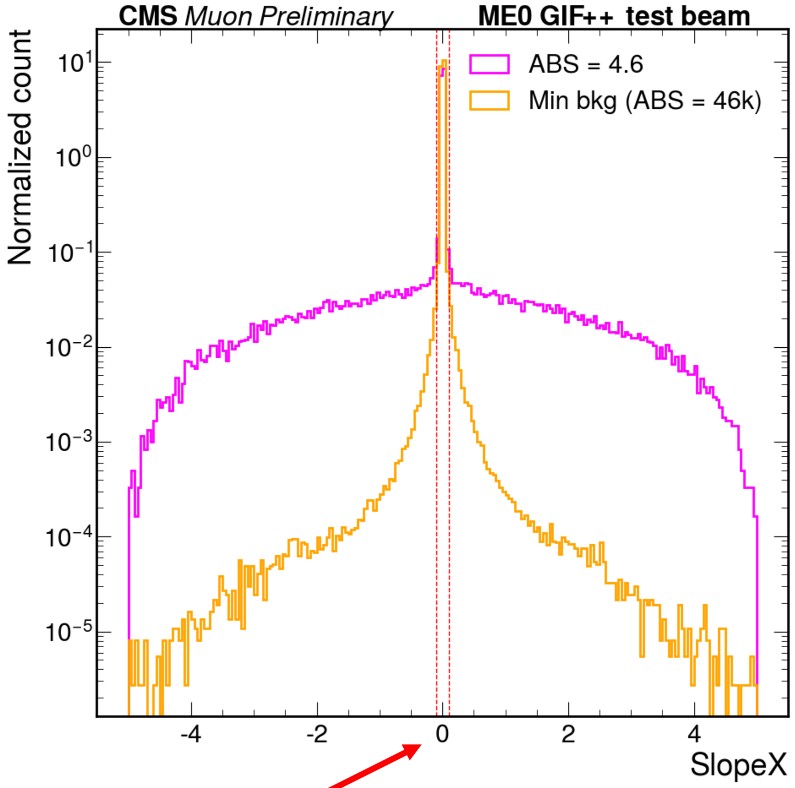


Quality selection over the tracks



muons + background hits complicate the combinatorial process
→ Higher slope **faulty tracks**

One chamber can be tagged as inefficient for an event even if it's not:
EFFICIENCY DROP IS ENHANCED!

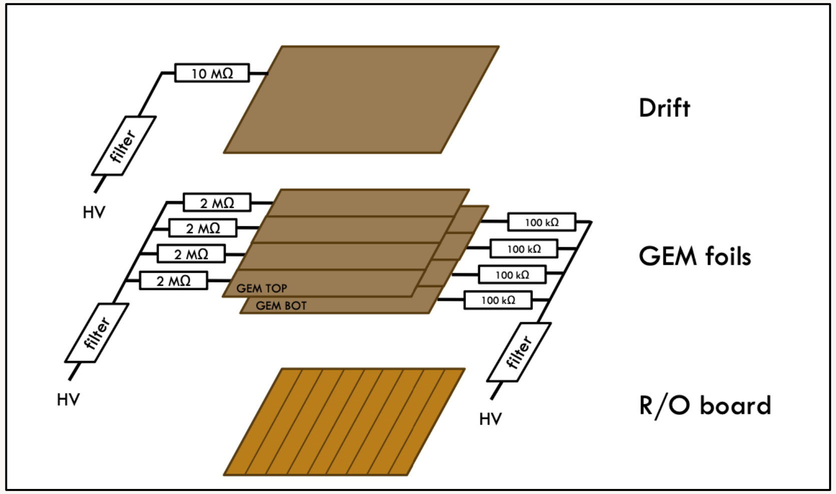


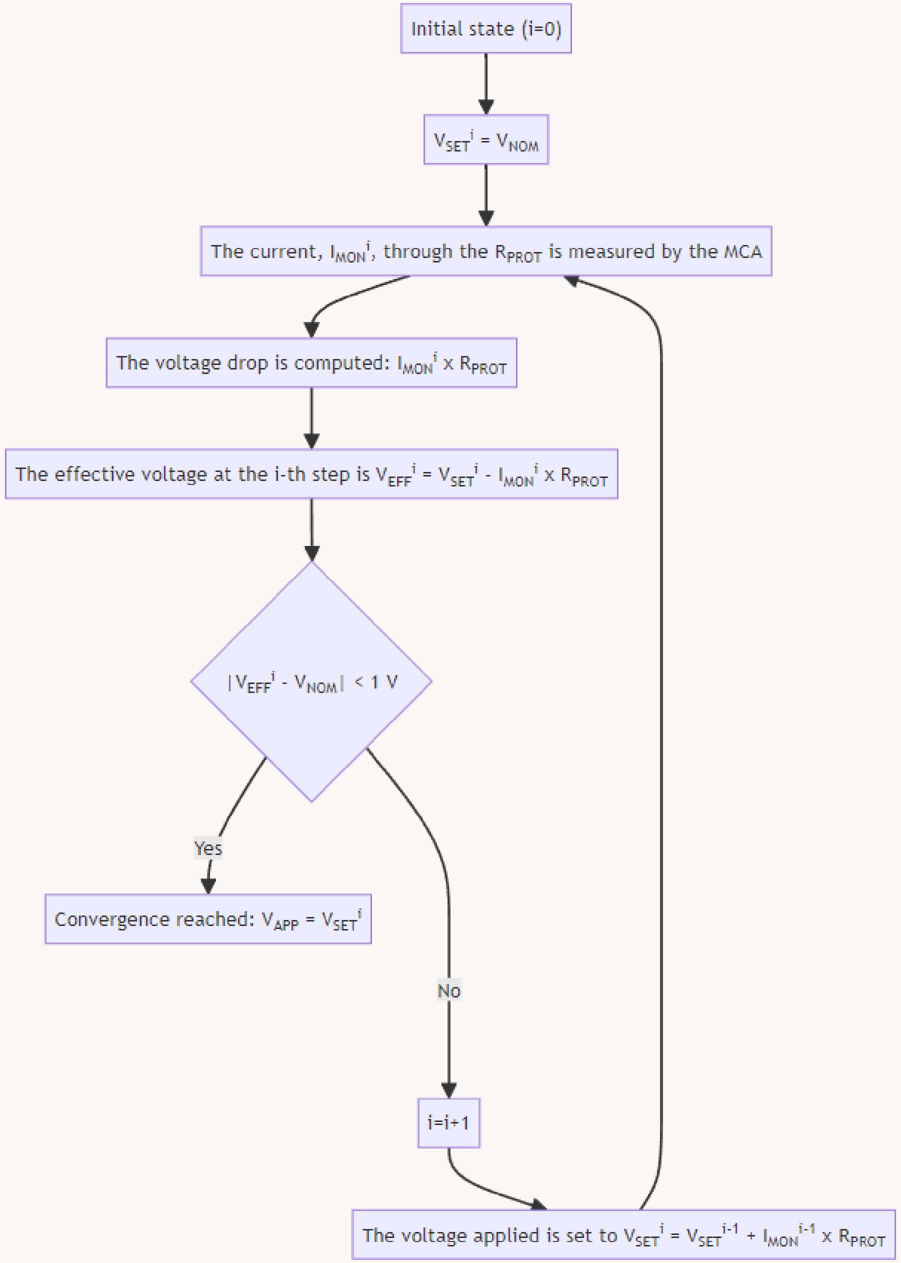
To mitigate the efficiency drop quality selections on the tracks were applied:

- $\chi^2 < 10$
- $|\text{SlopeY}| < 0.01$
- $|\text{SlopeX}| < 0.1$

HV compensation

The electrons moving between the electrodes due to gamma rays emitted by the Cs source generate a non-negligible current flowing through the foils and a subsequent voltage drop causing a drop of gain. To recover the nominal gain HV compensation is applied.





MC simulation for the rate capability

Here the results of a MC-toy simulating the detector electronics behaviour when detecting muons in a high background rate. Assuming a dead time of the VFAT3 chips of $400\ ns$, the dead time of the detector is $\sim 125\ ns$, in agreement with the results obtained from the GIF++ test beam data.