Beam test of the GEM detectors for the Phase-II upgrade of CMS

Antonello Pellecchia[1,2], Piet Verwilligen[2], Anna Stamerra[1,2], Michele Bianco[3]

on behalf of the CMS Muon Collaboration

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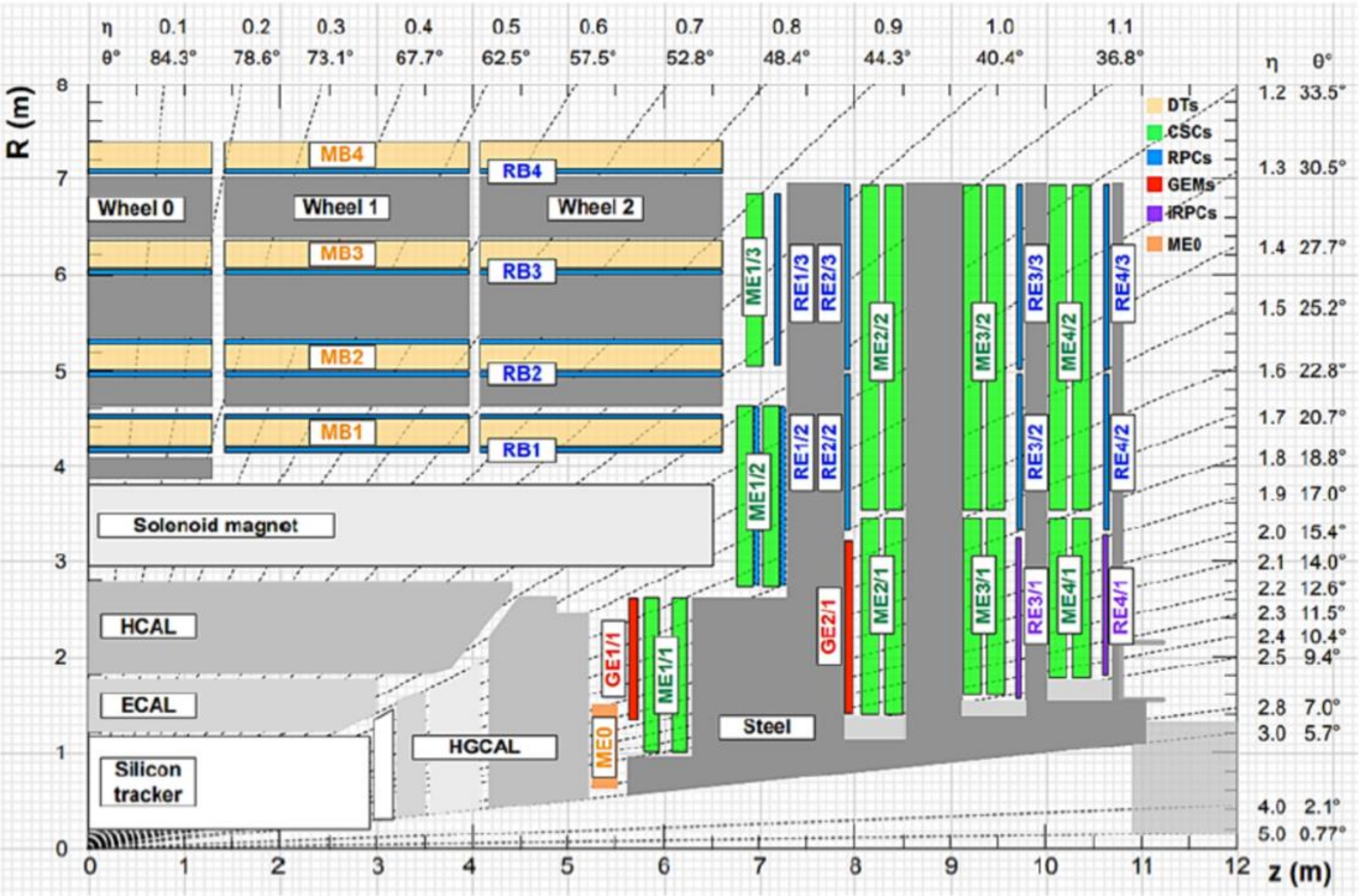
[1]Università degli Studi di Bari [2]INFN, Sezione di Bari [3]CERN, Switzerland

The HL-LHC Phase: Upgrade of the CMS Muon System

Section of the CMS Muon Spectrometer



For the HL phase at the LHC, the CMS Muon System will be upgraded by adding **new stations of GEM detectors**

- **GE2/1** in the region 1.6<|η|<2.4 to enhance redundancy
- **ME0** in the region 2.4<|η|<2.8 to extend the acceptance

GEM 2021 Test Beam

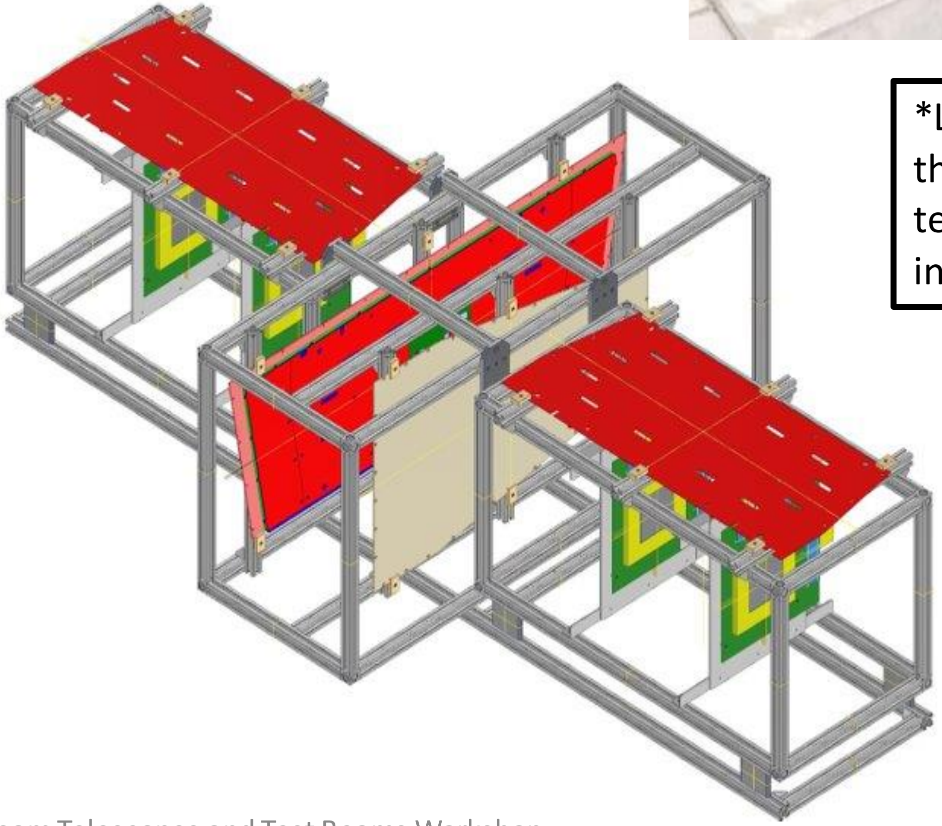
Main goals

- *First operation and performance measurement with beam of final-design **CMS Phase-2 GEM detectors** with their **full front-end electronics and DAQ***
- *First beam operation of **ME0 prototype** with new GEM foil design.*
- *Measure the **space resolution** of tracker (LEMMA Test Beam*)*

*LEMMA Test Beam will use the 10x10 cm^2 GEM for beam telescope and GE2/1 modules in the muon arms.

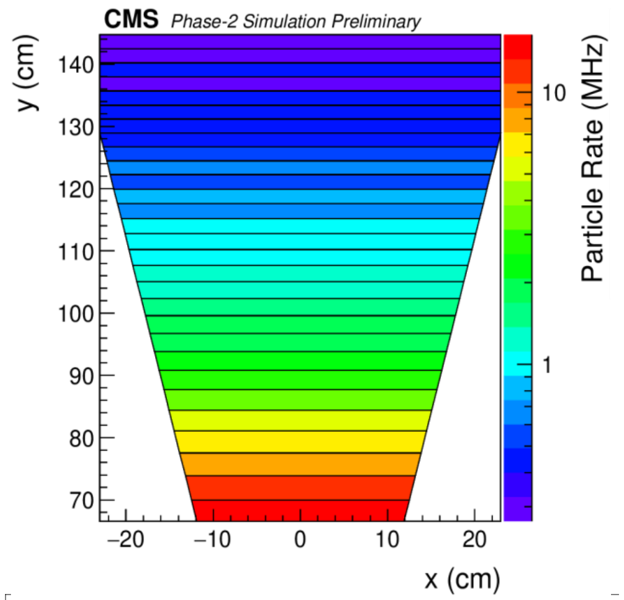
Detectors under test

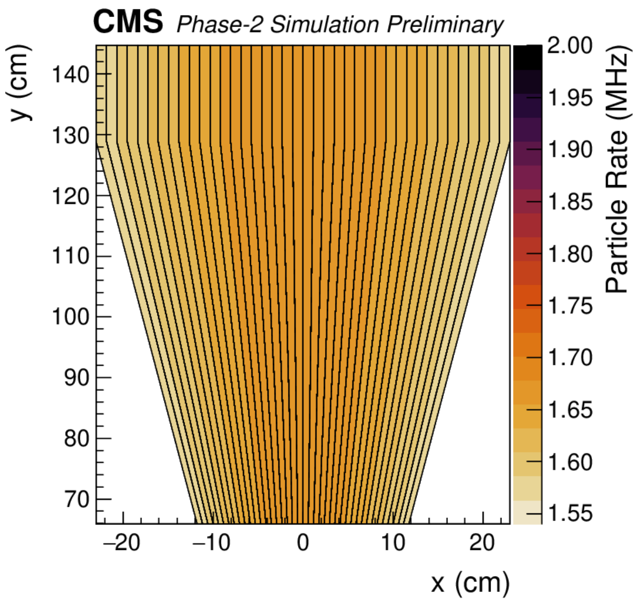
- 4 **high-resolution** 10x10 cm^2 triple-GEM chambers for beam telescope
- CMS Phase II GEM detectors (**GE2/1** and **ME0**)
- 20x10 cm^2 **random hole segmented** prototype



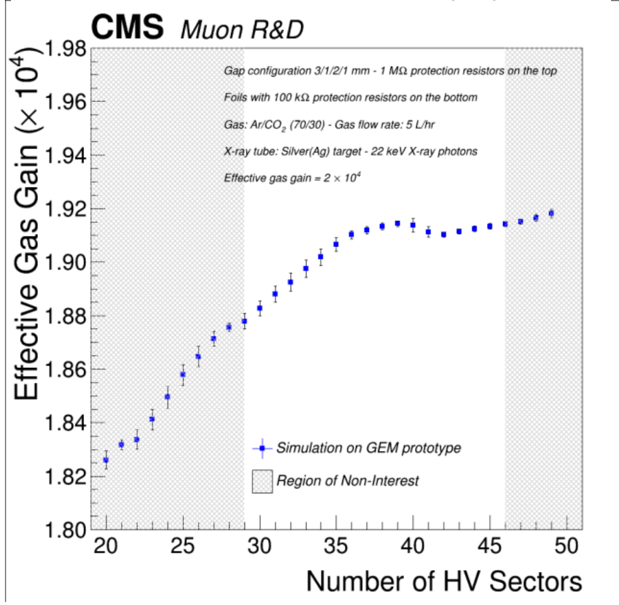
R&D for ME0 design

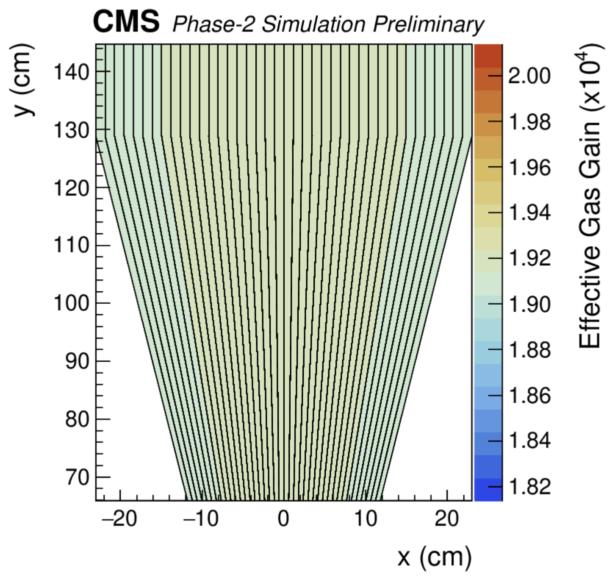
MEO station: first CMS muon endcap station from beam line
Hostile background environment (up to 150 kHz/cm²) → new GEM foil segmentation studied to minimize the average gain drop





Simulated background particle rates in ME0 detectors with original (left) and azimuthal (right) segmentation



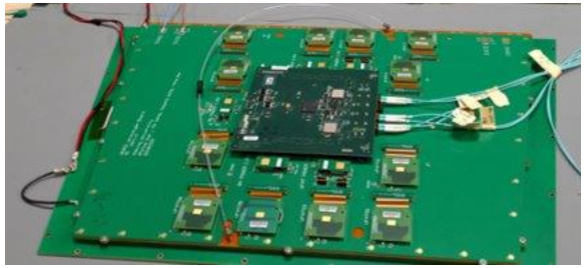


Simulated gain in ME0 detectors with azimuthal segmentation

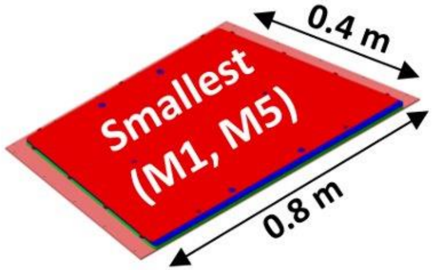
More on arXiv:2201.09021v1

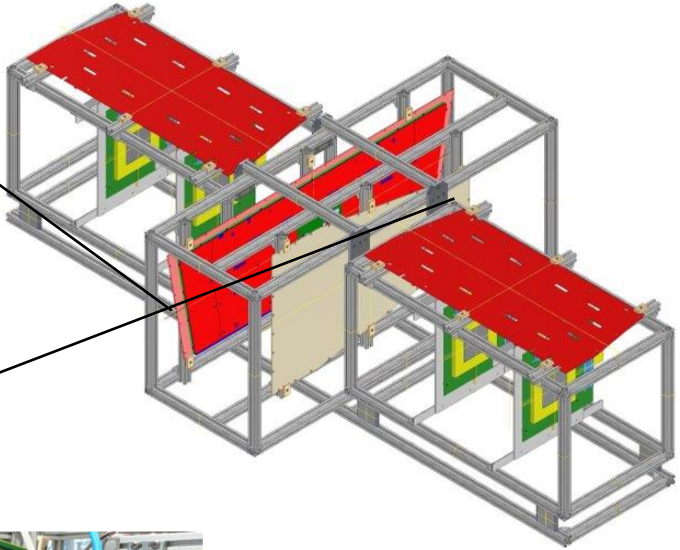
Experimental setup: CMS Phase II GEMs

GE2/1 Production detector
(M1 module)

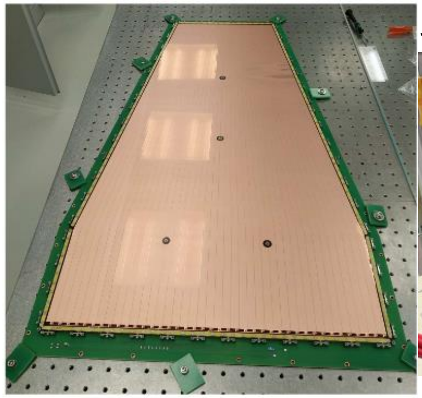


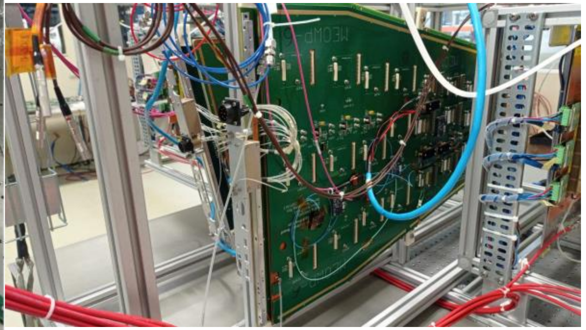
348 radial strips,
pitch 1.3 – 1.7 mm
(expected space resolution
380 – 500 μm)

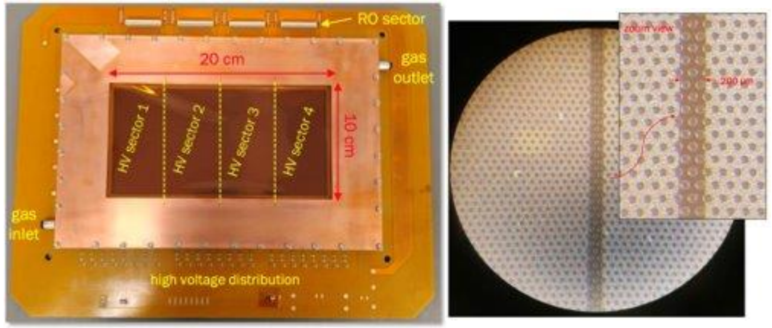




ME0 second generation with
azimuthal segmentation







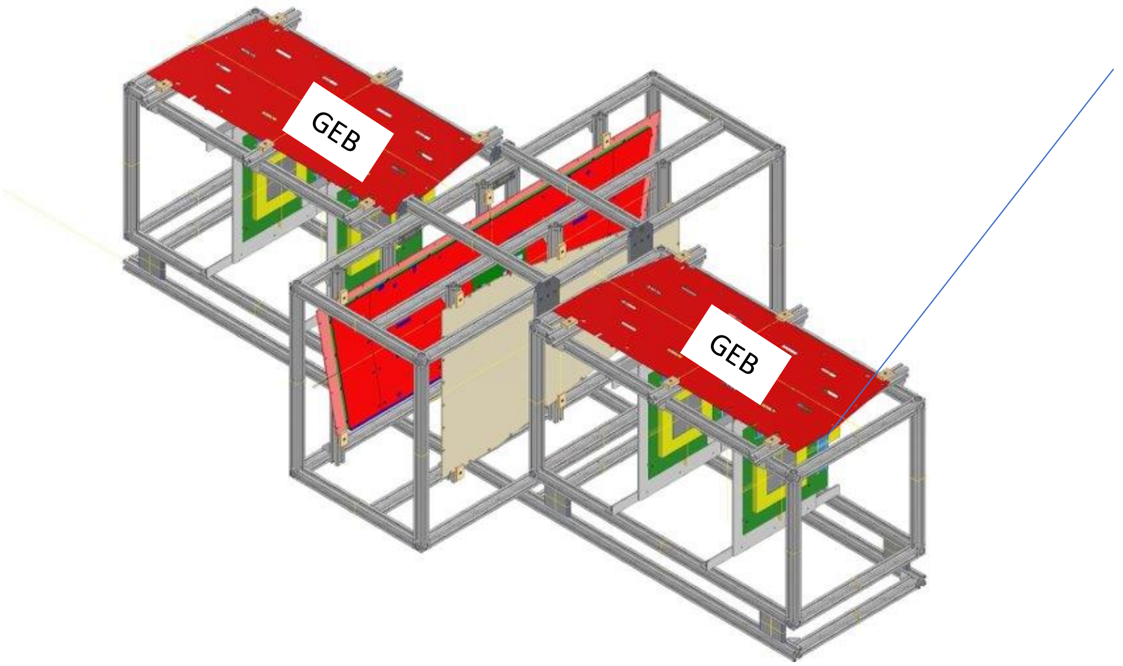
Additionally: R&D 20×10 prototype
with random hole segmentation that offers a simpler masking and the possibility to **recover inefficiency** areas due to sectorization in GEM foils (possible R&D for ME0)

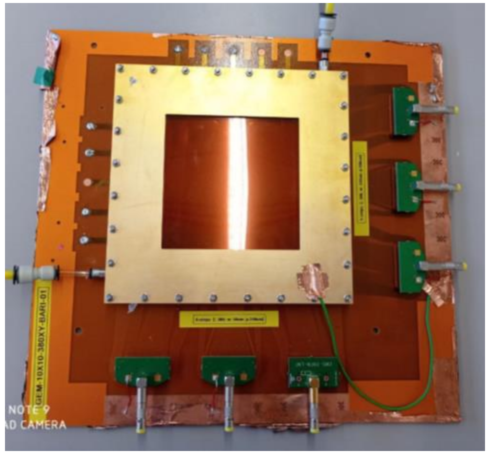
More on [this presentation]

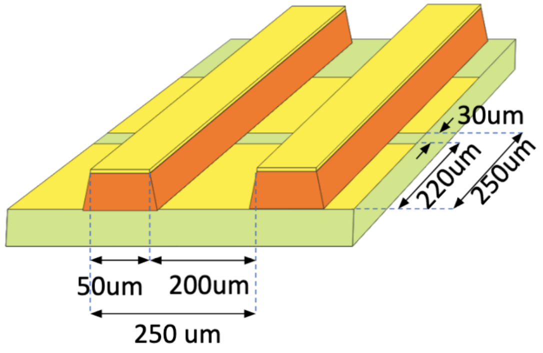
Later added in the setup

Experimental setup: Beam telescope

- **Four** 8.9x8.9 cm^2 **high-resolution** triple-GEMs
  358 strips, 250 μm pitch
  (expected space resolution 75 μm)
- **Trigger: three-scintillator coincidence** (2 front + 1 back)

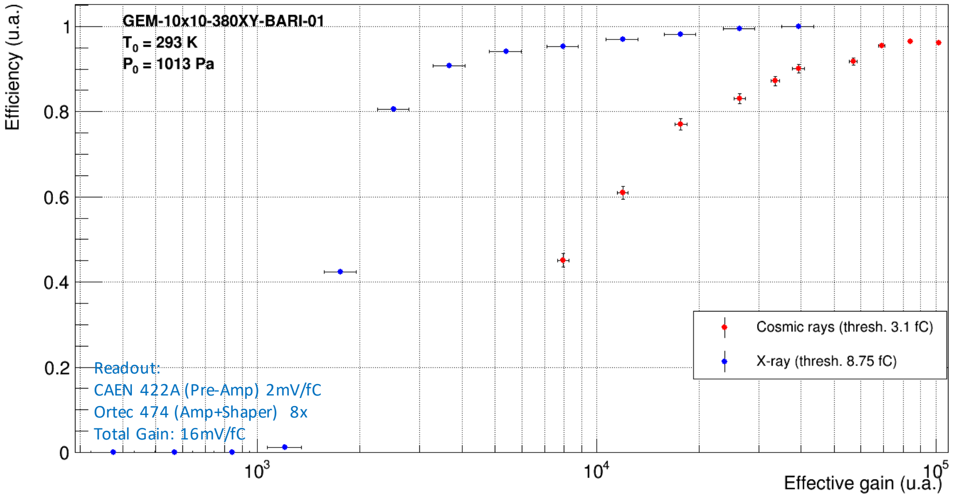






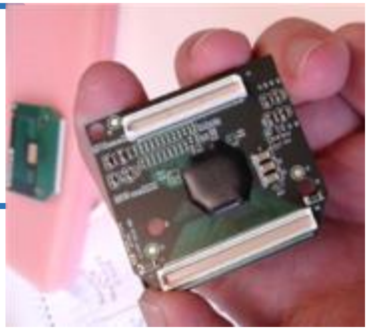
Tracker chamber readout strips

Efficiencies measured with cosmics before test beam



DAQ: Front-end electronics

Front-end ASIC: VFAT3
- *128 channels*
- *High sensitivity (45 mV/fC)*
- *0.5 MHz/strip rate capability*

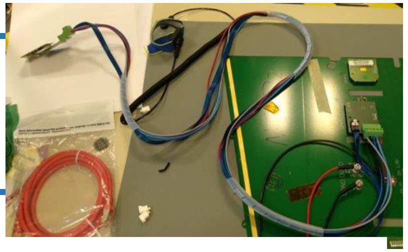


VFAT3

Plugin cards for VFAT connection to GEB

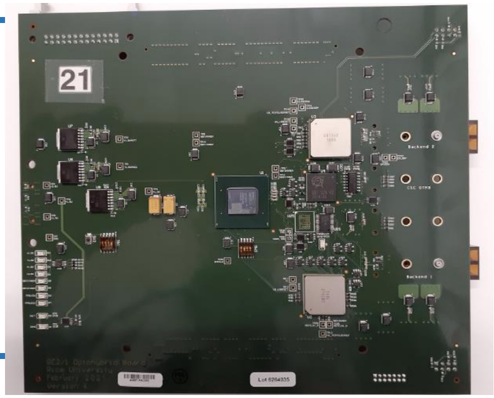
Plugin card

Fire-Fly cables 1.5 m long for VFAT connection to tracking chambers to GEB



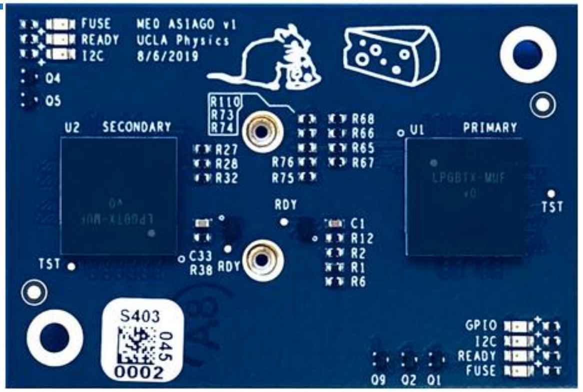
Fire-Fly cable

For GE2/1 and Tracking chambers
On-detector FPGA: OptoHybrid
(Xilinx ARTIX-7) [CMS-TDR-013]
3x (one per GEB)
- *VFAT e-links to GBTx*
- VTRx + fibers to back-end
- VTTx to trigger lines (unused)



Optohybrid picture

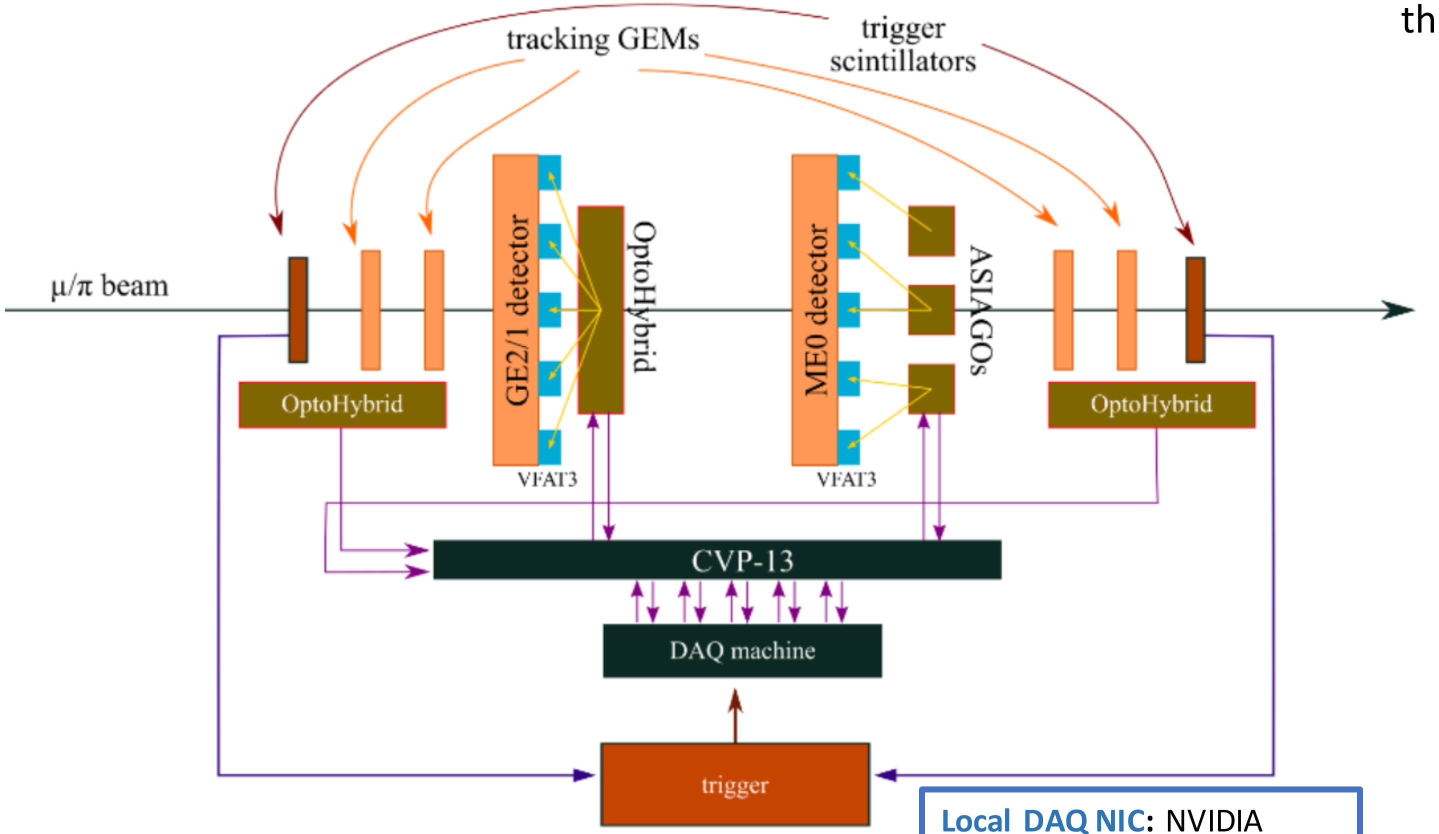
For ME0
On-detector FPGA-less:
OptoHybrid ASIAGO
- Readout interface for 6 VFATs on the ME0 GEB
- 2 lpGBT chips and 1 VTRx+ transceiver on each OH board
- Sends data to backend without compression (no FPGA)



Optohybrid ASIAGO

DAQ: Back End

- All data sent to BE over optical links
- Custom PCIe back-end based on commercial FPGA
- 1 Gb/s Ethernet-based local readout on DAQ machine through additional network card



CVP-13 inside DAQ machine + **network card** (local DAQ) + water **cooling**

Local DAQ NIC: NVIDIA Mellanox MCX4121A-XCAT

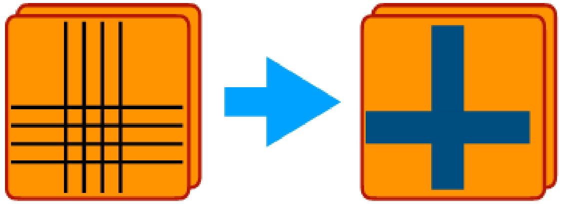
SFP+ limit 10 \Gb/s

Back-end board: *CVP-13 commercial PCIe board with* ***VU13P FPGA***

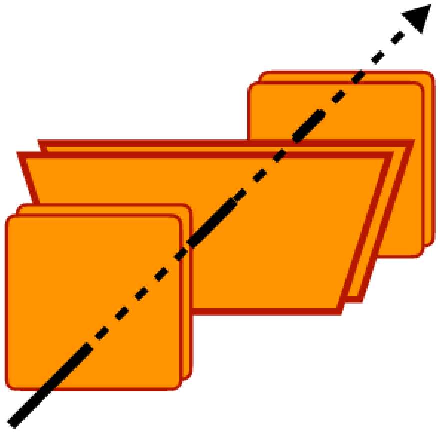
Reconstruction and analysis – Track building

1st step: **Unpack data** converting raw binary data to readable objects (Digi)

2nd step: Clusterize the digi information to construct RecHits (**Local reconstruction**)

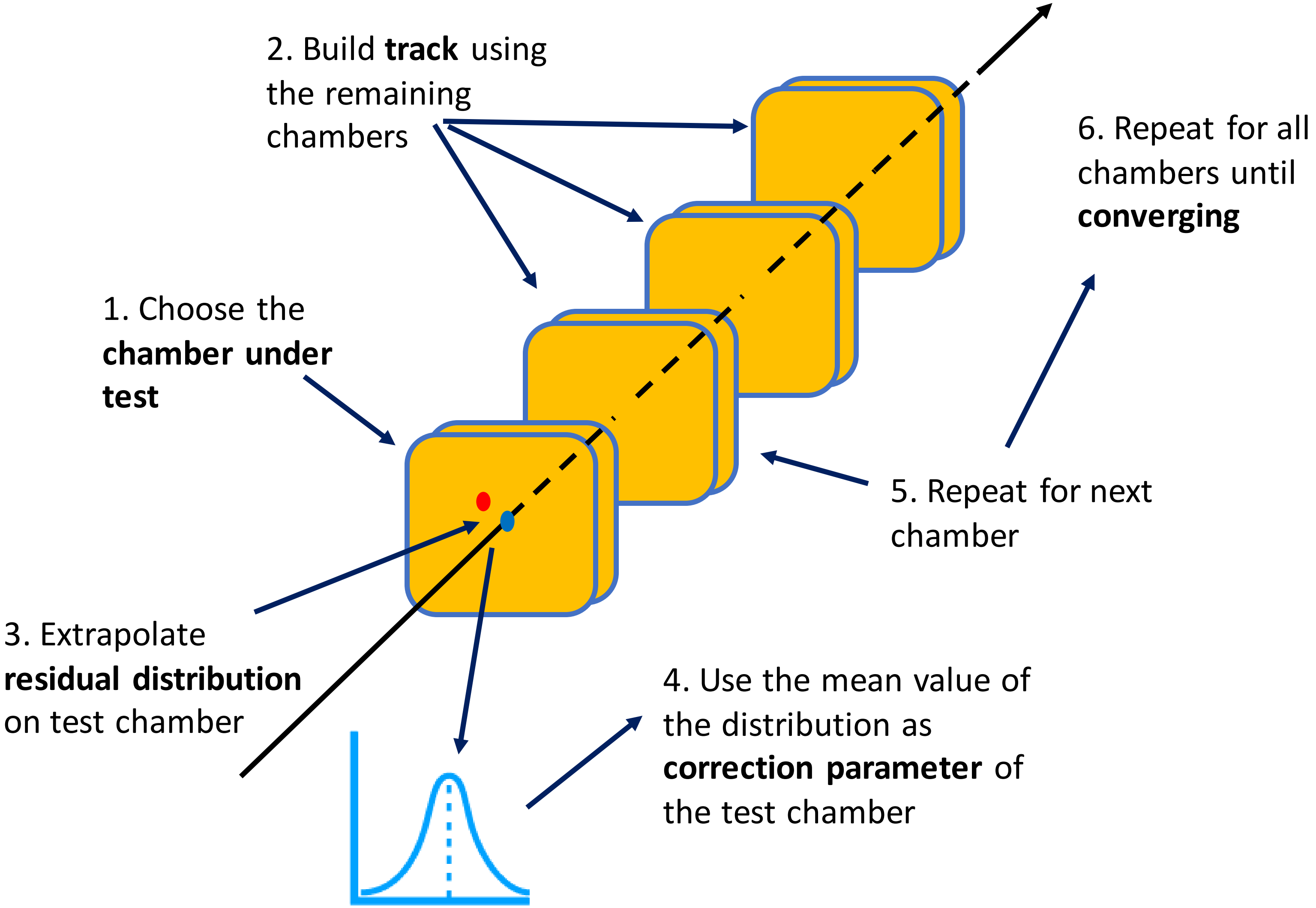


3rd step: **Build tracks** from the RecHits of each tracking chamber



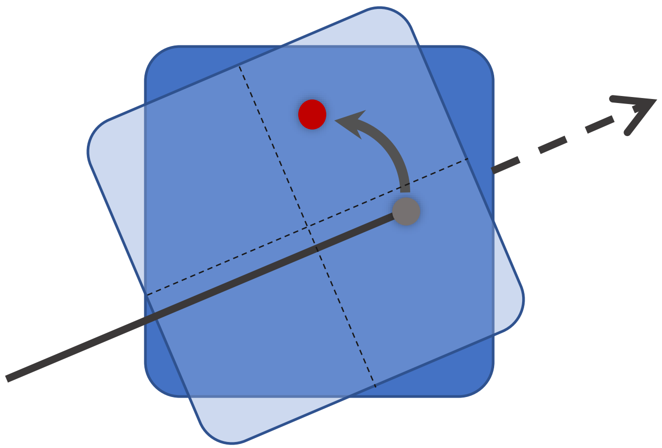
4th step: **Analyze tracks** to extract efficiency, residuals, etc.

Reconstruction and analysis – Transversal alignment



Reconstruction and analysis – Angular alignment

Iterative method similar to transversal alignment



Method: determining chamber misalignment from residuals vs propagated hit position.

Assuming x_{prop} is the correct value and x_{rec} is misaligned by θ,

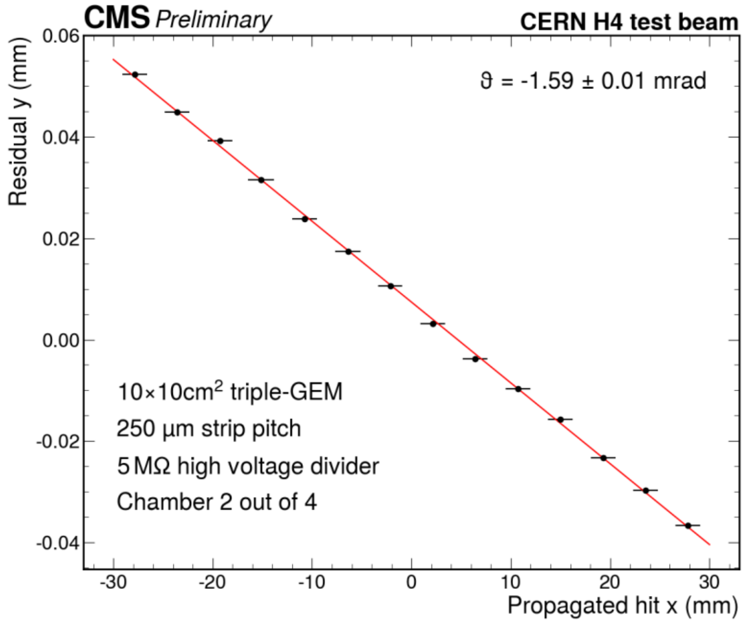
$$\begin{cases} x_{\text{rec}} = x_{\text{prop}} \cos\theta - y_{\text{prop}} \sin\theta \\ y_{\text{rec}} = x_{\text{prop}} \sin\theta + y_{\text{prop}} \cos\theta \end{cases} , \qquad (1)$$

$$\text{so} \quad \begin{cases} \delta x = x_{\text{rec}} - x_{\text{prop}} = x_{\text{prop}}(\cos\theta - 1) - y_{\text{prop}} \sin\theta \\ \delta y = y_{\text{rec}} - y_{\text{prop}} = x_{\text{prop}} \sin\theta + y_{\text{prop}}(\cos\theta - 1) \end{cases} . \qquad (2)$$

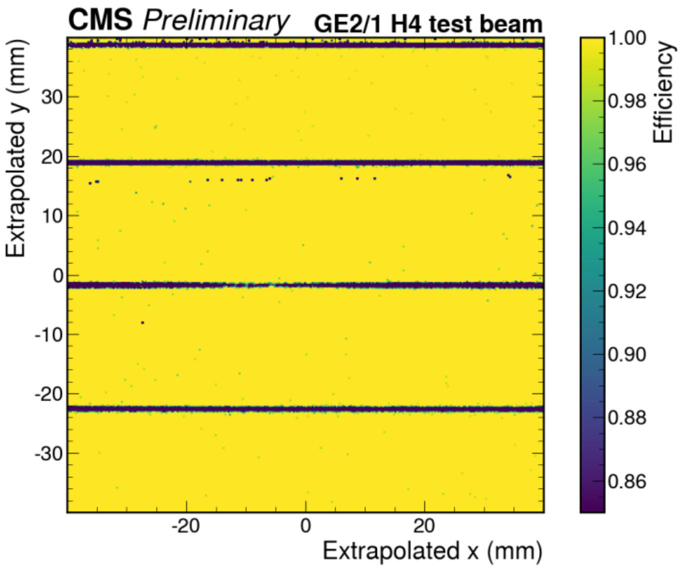
Considering that

$$\cos\theta - 1 \sim O(\theta^2) \quad \text{while} \quad \sin\theta \sim O(\theta),$$

it is most sensitive to extract θ from the correlation of δx vs y_{prop} (or from δy vs x_{prop}).



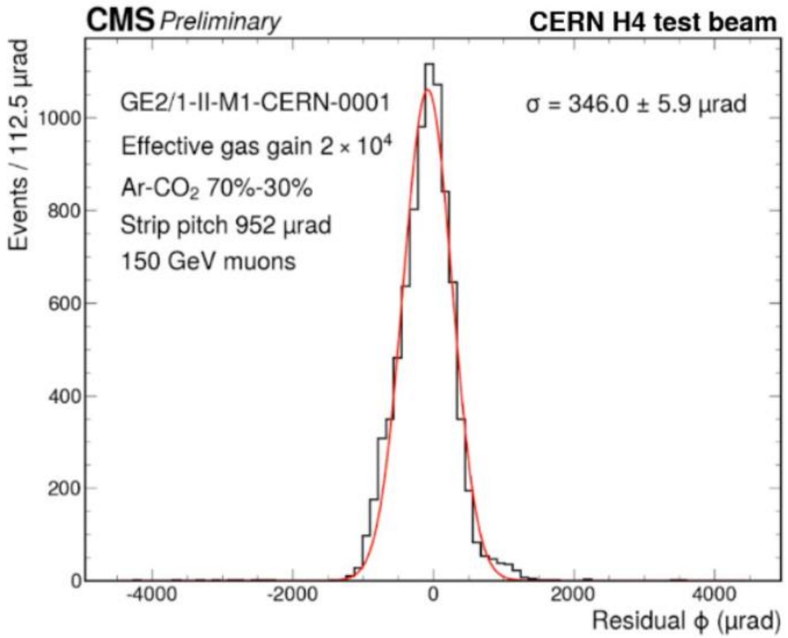
GE2/1 performances



Efficiency map

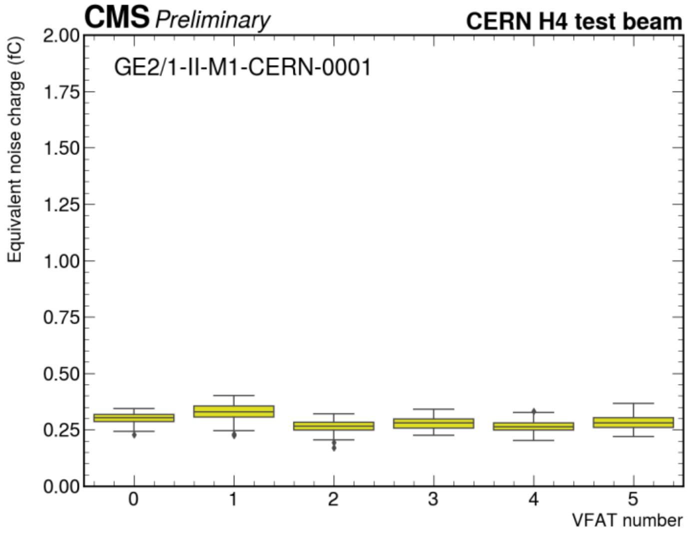
Excellent local efficiency to 150 GeV muons reachable thanks to lower electronic noise at a gain of 2×10^4. Average efficiency limited to 98% by **sectorization dead areas**.

Residual distribution



346 ± 5.9 μrad space resolution in angular coordinate

Noise level per VFAT



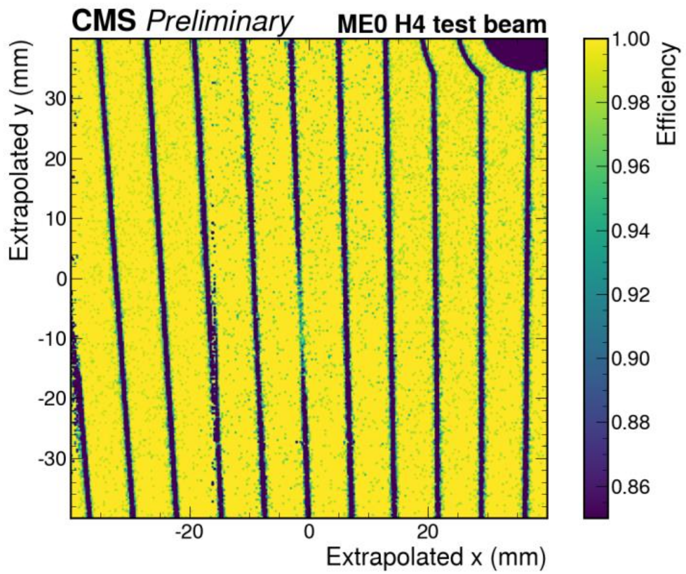
Noise level of front-end electronics attached to GE2/1 detector: the **shielding** provided by the GEB and the several **grounding pins** of the VFAT3 plugin cards allow to keep the **noise below 0.5 fC**

ME0 Efficiency

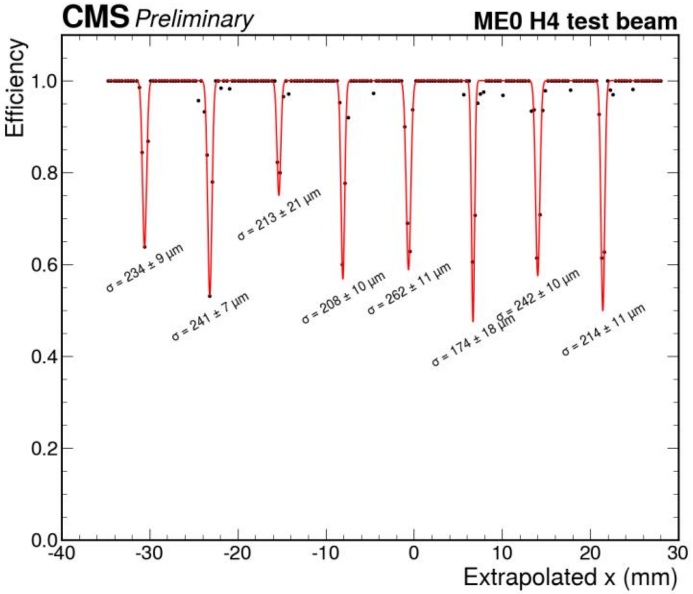
Comparison of efficiency profiles for ME0 second generation detector and 20x10 random-hole segmented prototype:

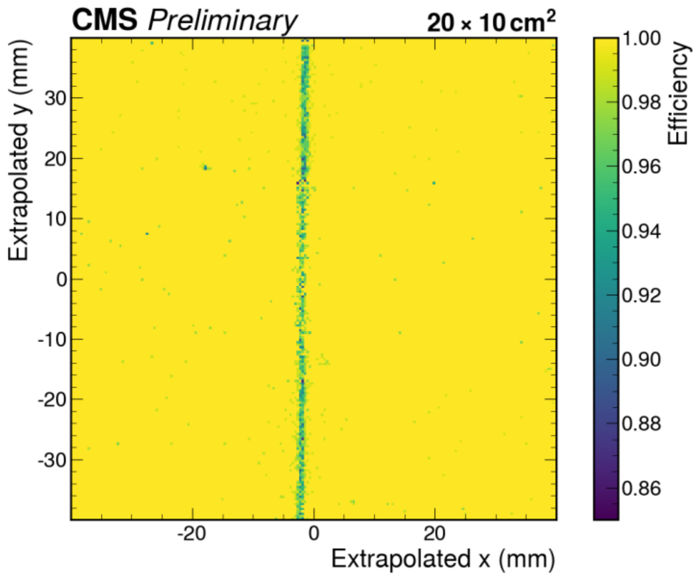
- The profile is obtained by slicing the two-dimensional efficiency map along the y direction. The efficiency profile is fitted with a Gaussian function comb, shown in the red line. The labels indicate the sigma of each efficiency dip extracted from the gaussian fit.
- The inefficiency areas due to the sectorization in ME0 can be recovered by the **random-hole sectorization** that limits the inefficiency dips to 5%

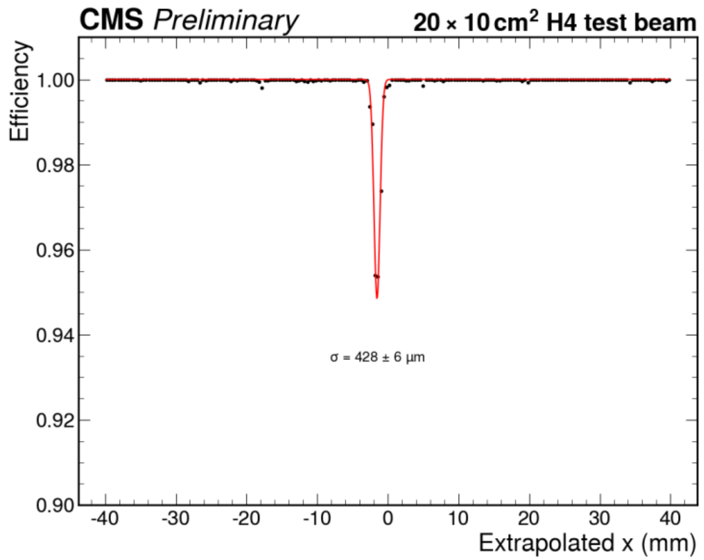
Efficiency map



Efficiency profile



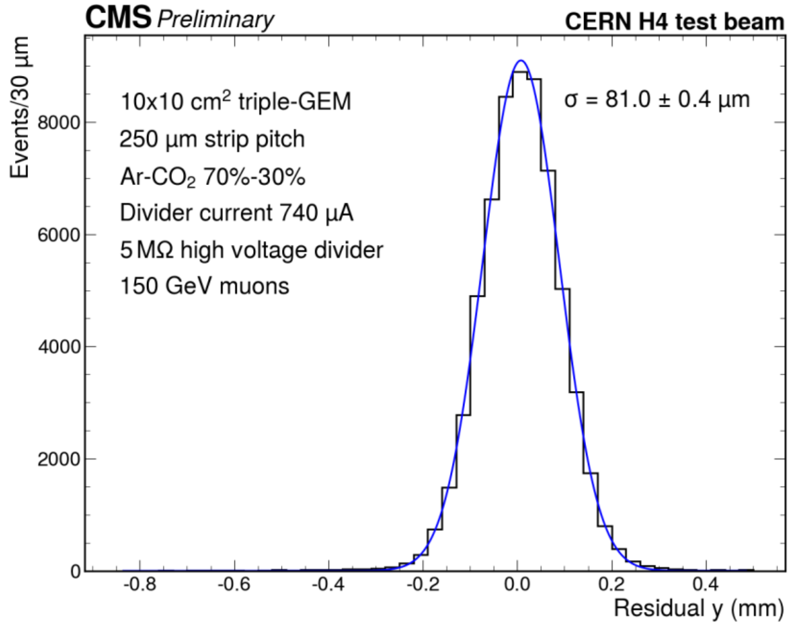




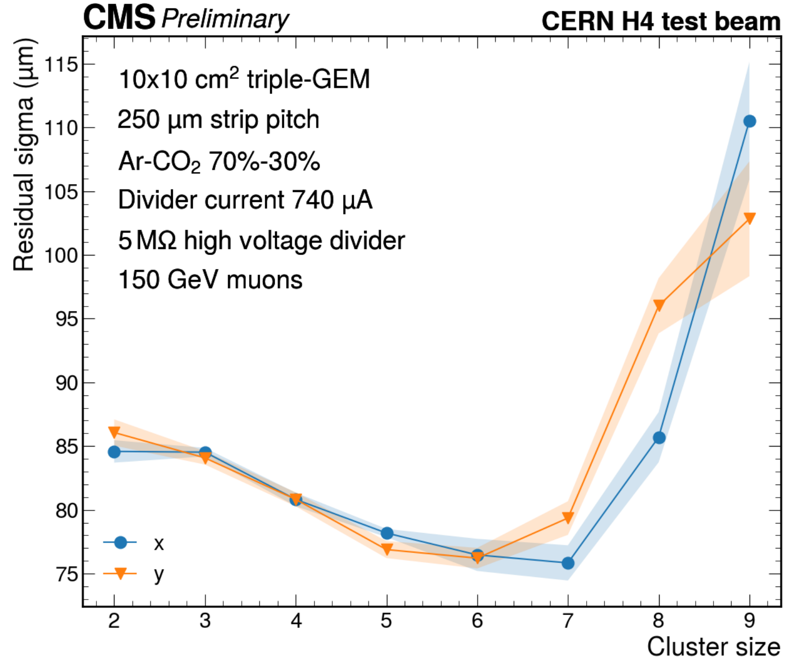
Triple GEM tracker performances – Space resolution

- Average space resolution of **81 μm** extracted from residual distribution
- Space resolution depends on cluster size:
    - At low cluster size: **low-charge clusters** reconstructed with wrong number of strips due to **high threshold**
    - At high cluster size: **asymmetric signal spreading** due to **delta rays** in single cluster

Residual distribution for tracking chamber 2 in y-direction for cluster size < 10



Space resolution of tracking chamber 2 vs cluster size

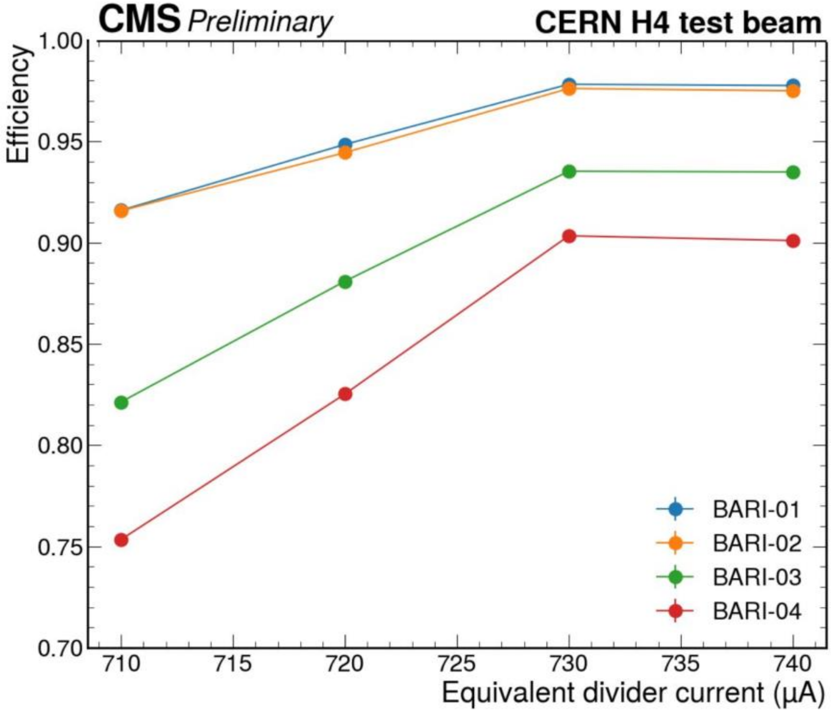


Triple GEM tracker performances – Efficiency

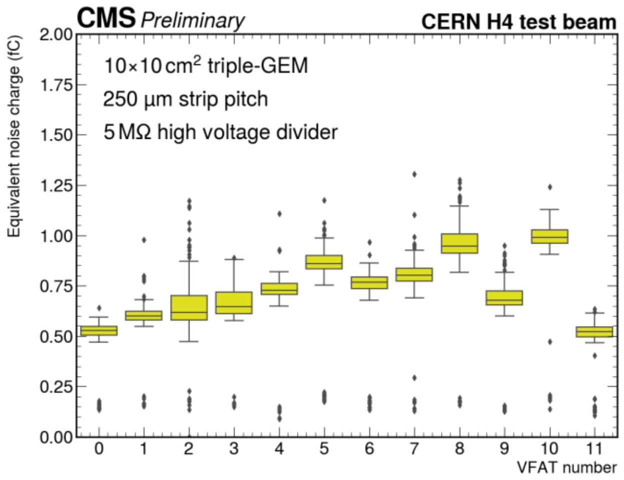
HV efficiency scan obtained by requiring that
- The extrapolated hit of the track on the test chamber falls in the active area of the chamber
- The extrapolated hit matches a 2D reconstructed hit

Efficiency to muons between 90% and 100% for BARI-01 and BARI-02 operated at effective gas gain of 10^5

Lower efficiency for BARI-03 and BARI-04 operated at a lower effective gain



Main limitation due to **low signal to noise ratio**



Conclusions and future plans

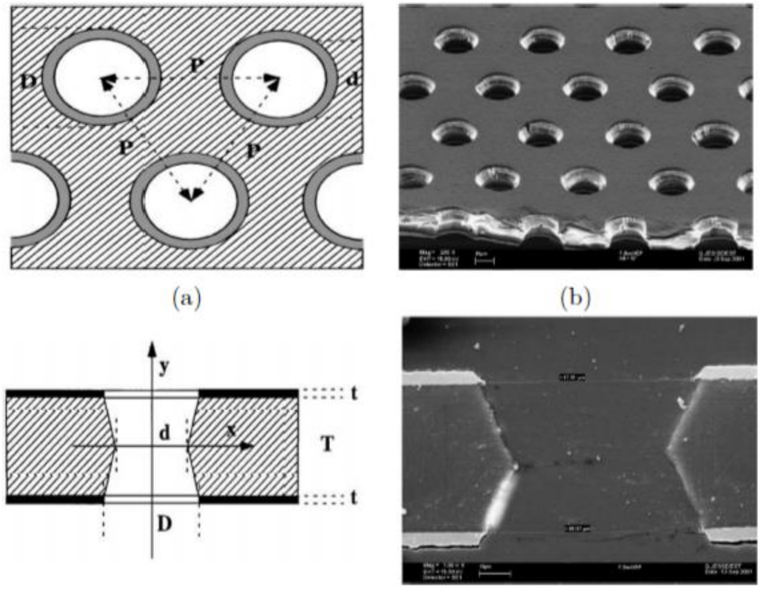
- The performance of final CMS Phase-2 GEM detectors was demonstrated in particle beam with good tracking performance provided by 10x10 cm^2 triple-GEMs.
- An **excellent efficiency** was observed in the CMS Phase-2 detectors.
- A random-hole segmented triple-GEM has shown the possibility to recover the inefficiency induced by the segmentation dead area.

In the 2022 CMS GEM test beam a full **ME0 detector with random hole segmentation** will be tested and a **time resolution measurement** on the CMS GEM detectors with final electronics will be performed.

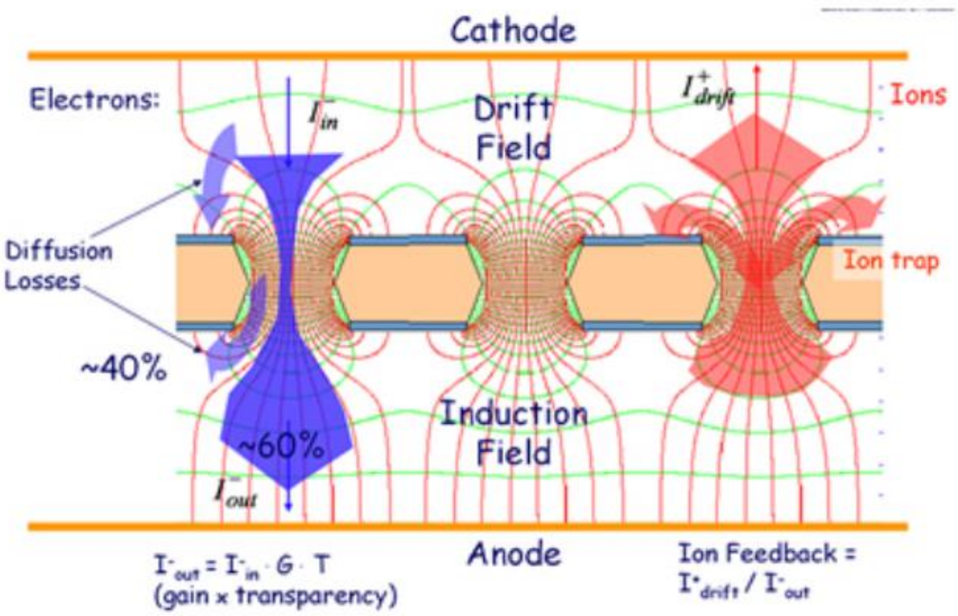
Backup

GEM Detector – Working principle

GEM foil

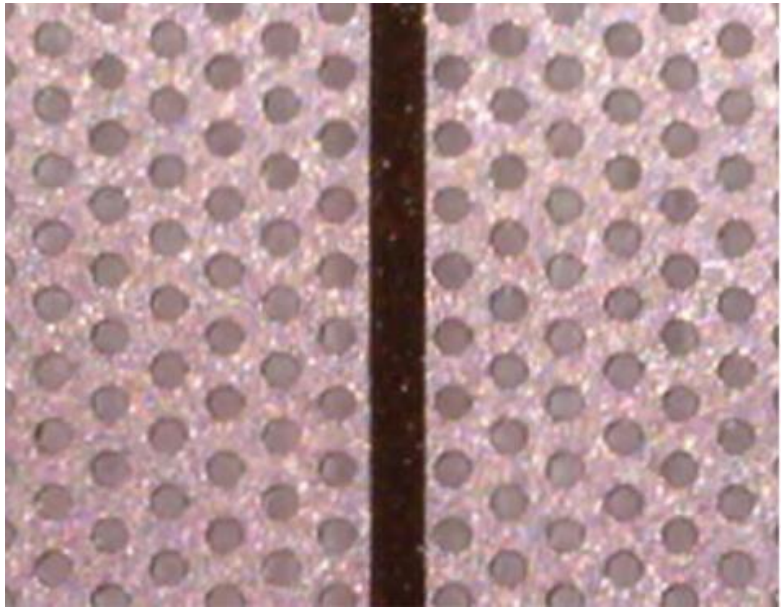


Single-GEM detector

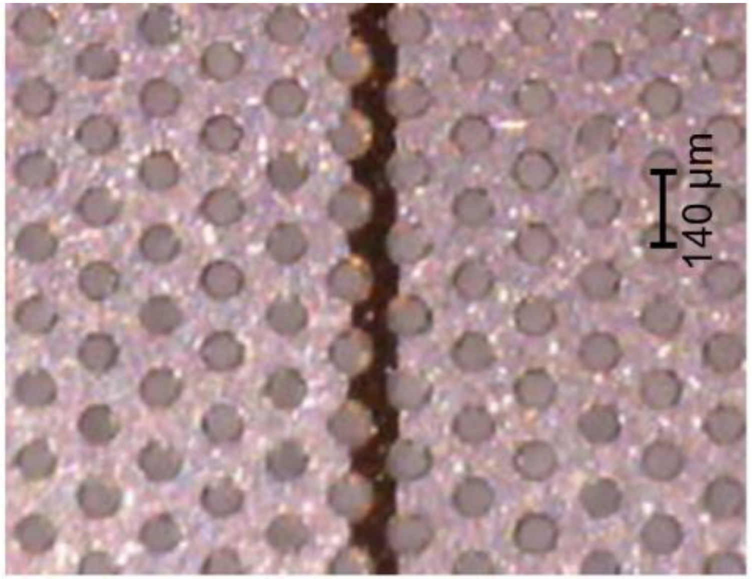


HV GEM foil sectorization

Microscopic view of the separation area of two HV sectors



Microscopic view of random hole sectorization



For more detalis see thispaper

Data taking summary

Official data-taking window (oct 20 – nov 2)

- 1-2 days: detector commissioning, touching up **DAQ** and local readout, first latency scan
- Days 3-5: tracker data taking with **muons**
- 7 days: HV training on GE2/1 detector finished, data taking with all GE2/1 setup
  - long overnight runs + shorter daily runs and debugging
- Pion runs:
  - 2 long runs at max beam intensity (~2MHz/cm^2)
  - L1A rate limited from 800 kHz to 100 kHz by introducing dead time
  - 2 rate scans (10^5- 10^8 pions per spill)

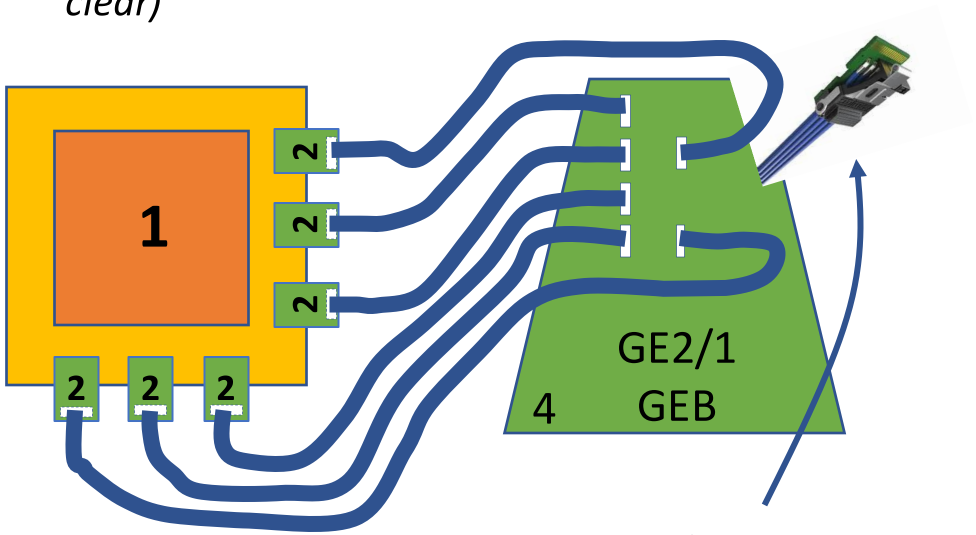
1 week break (nov 3 – nov 10)

Parasitic run (nov 10 – nov 15)

- Main activities: more statistics and rate scans with GE2/1
- Introduced R&D GEM prototypes

Tracker noise level

Trk detectors (10x10) have still same basic design as 10-15years ago …
Improvements made for GE21 and ME0 with shielding in ROB and GEB are very clear)



Frontend ASICs on 10x10 connected to “hanging” GEB by Firefly cables (2 trackers/GEB)