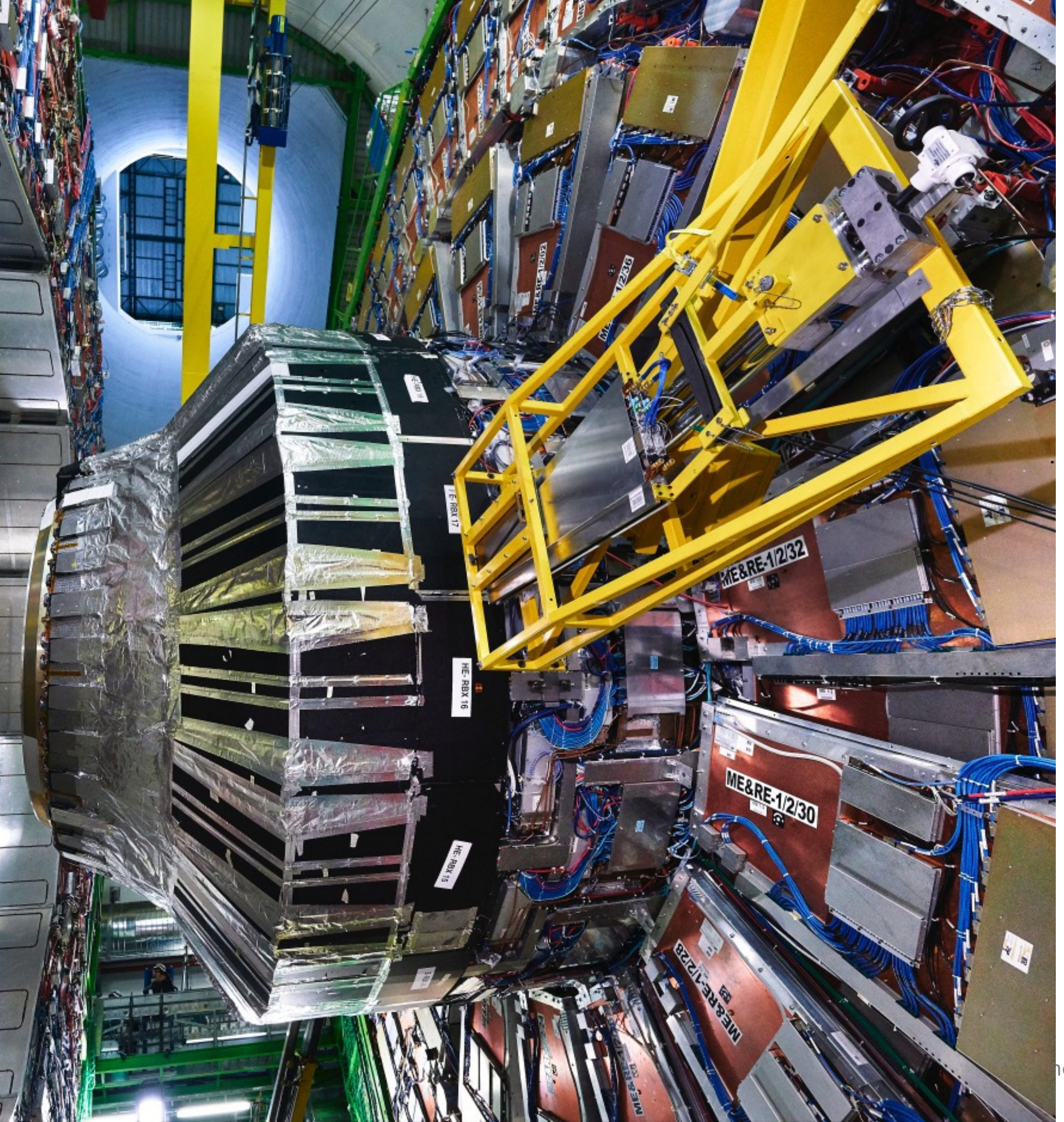
16th Topical Seminar on Innovative Particle and Radiation Detectors

Design validation of the CMS Phase-2 Triple-GEM Detectors

Federica M. Simone[1,2], Antonello Pellecchia[2], Piet Verwilligen[2]
on behalf of the CMS Muon group

[1]Bari Physics Department, [2]INFN Bari

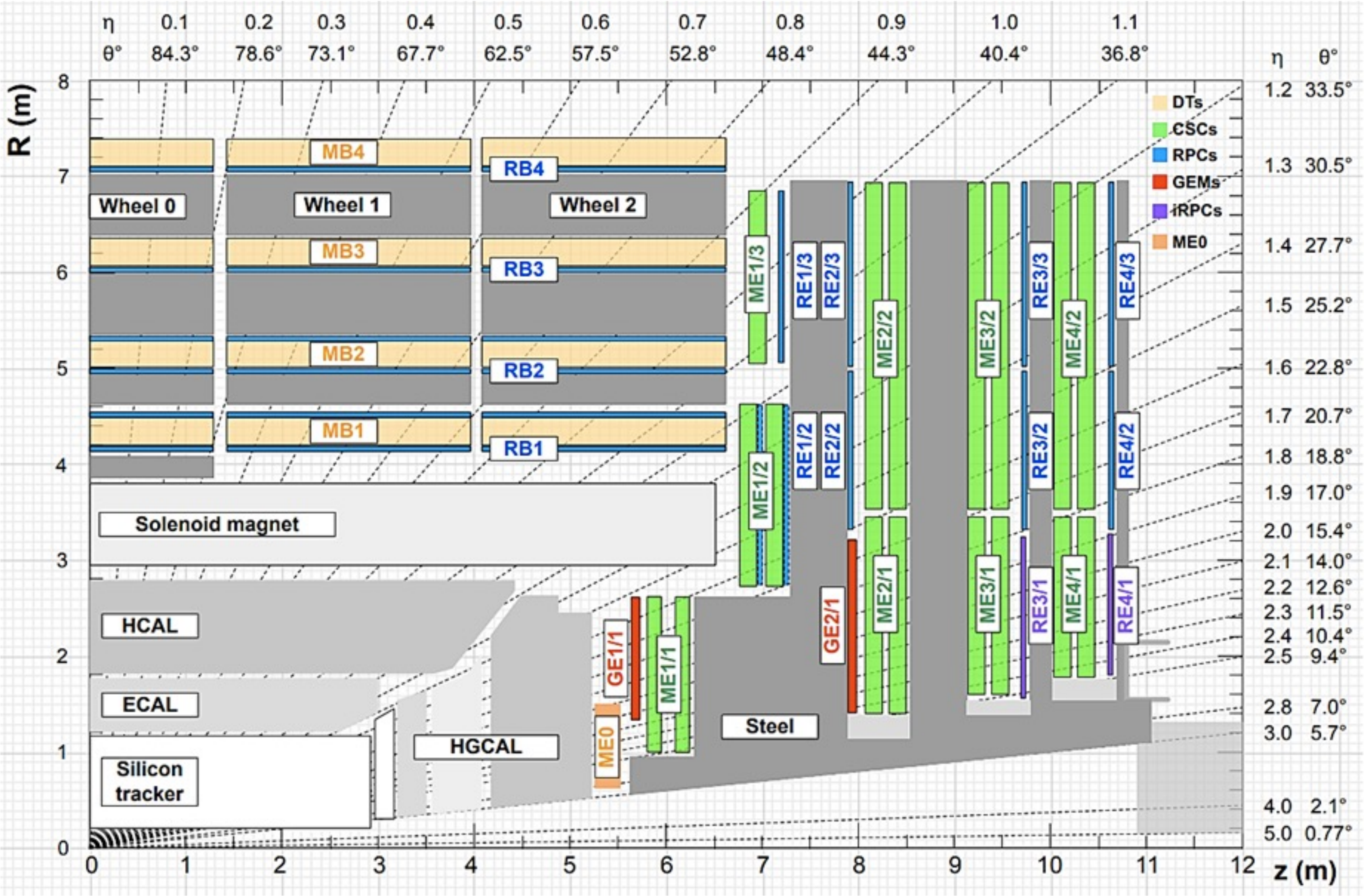
25-29 September 2023, Siena, Italy



Outline

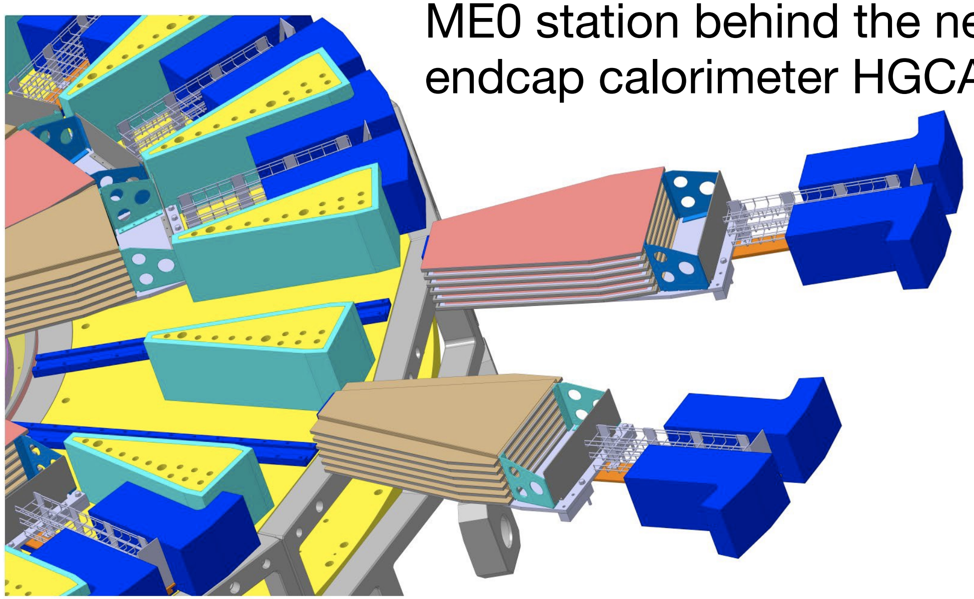
- The GEM Phase-2 upgrade
- ME0 background
- ME0 detector design
- Rate capability studies
  - Validation of the foil design
  - Studies on the full RO chain

The Muon System Phase-2 Upgrade



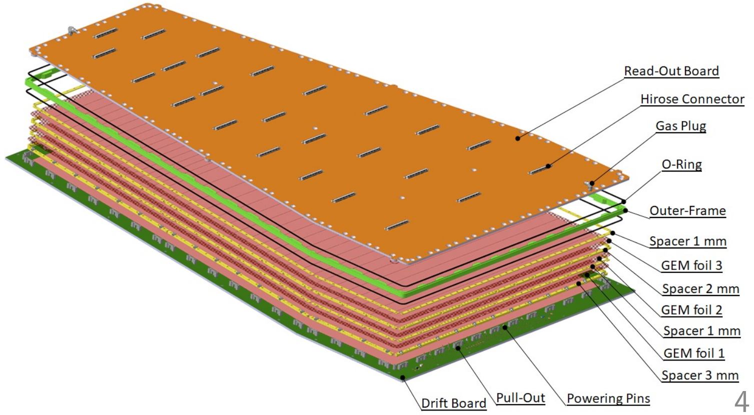
[Talk by A. Pellecchia on the Muon Phase-2 Upgrade]

The ME0 upgrade

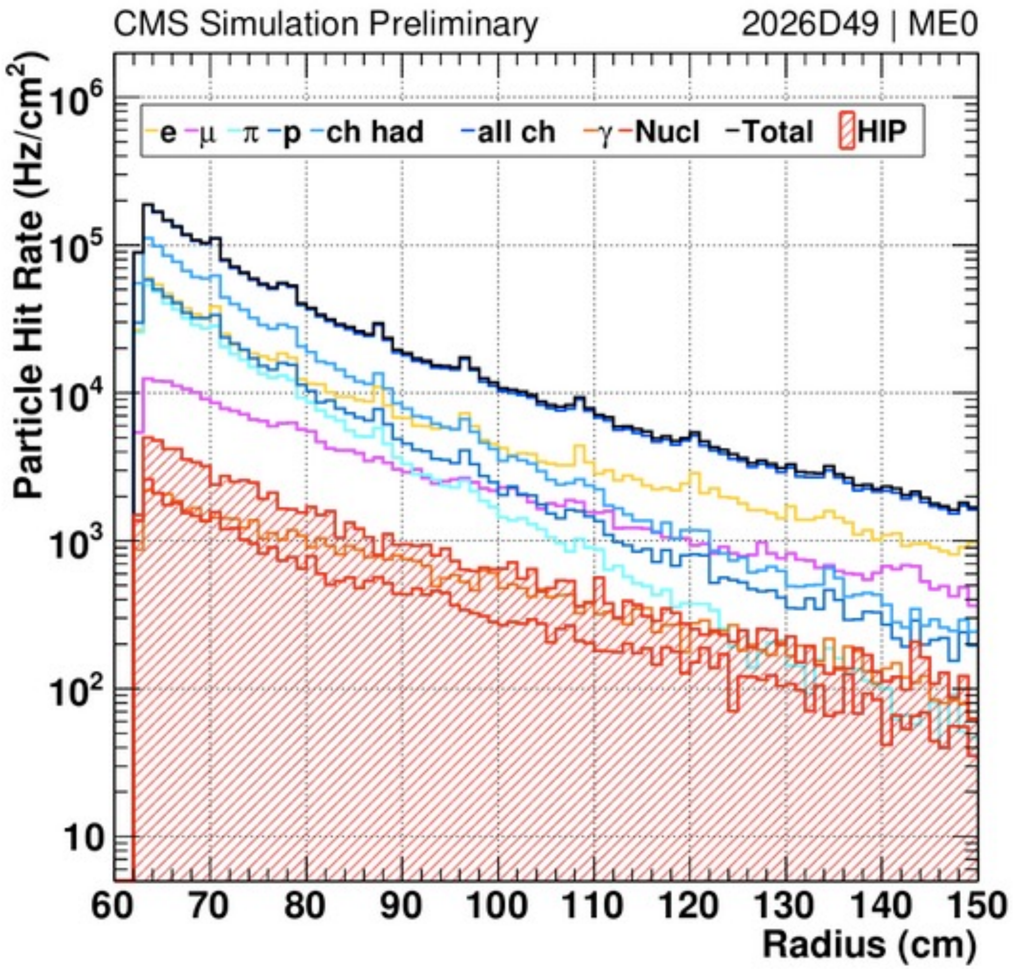


ME0 station behind the new endcap calorimeter HGCAL

- Complementing GEM/CSC for muon p_T measurement in $2 < |\eta| < 2.4$
- Extending CMS Muon System acceptance up to $|\eta| < 2.8$
- 18 ME0 stack per endcap, each made of six layers of triple-GEM detector for efficient tagging of muon tracks
- Each stack covers $\delta\phi = 20°$, $\delta\eta = 0.8$
- **Will face harsh radiation and background conditions**



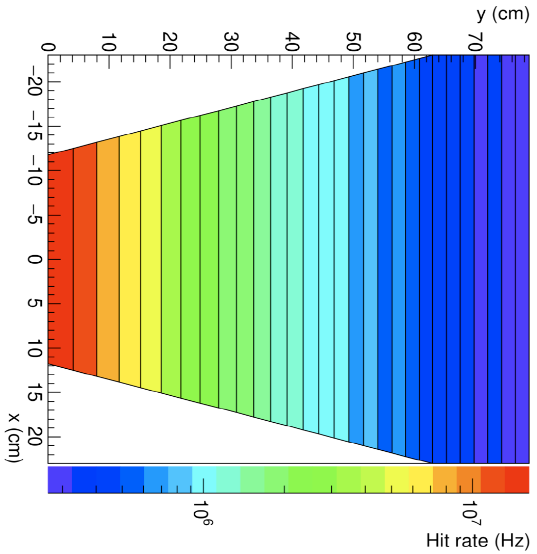
ME0 Background



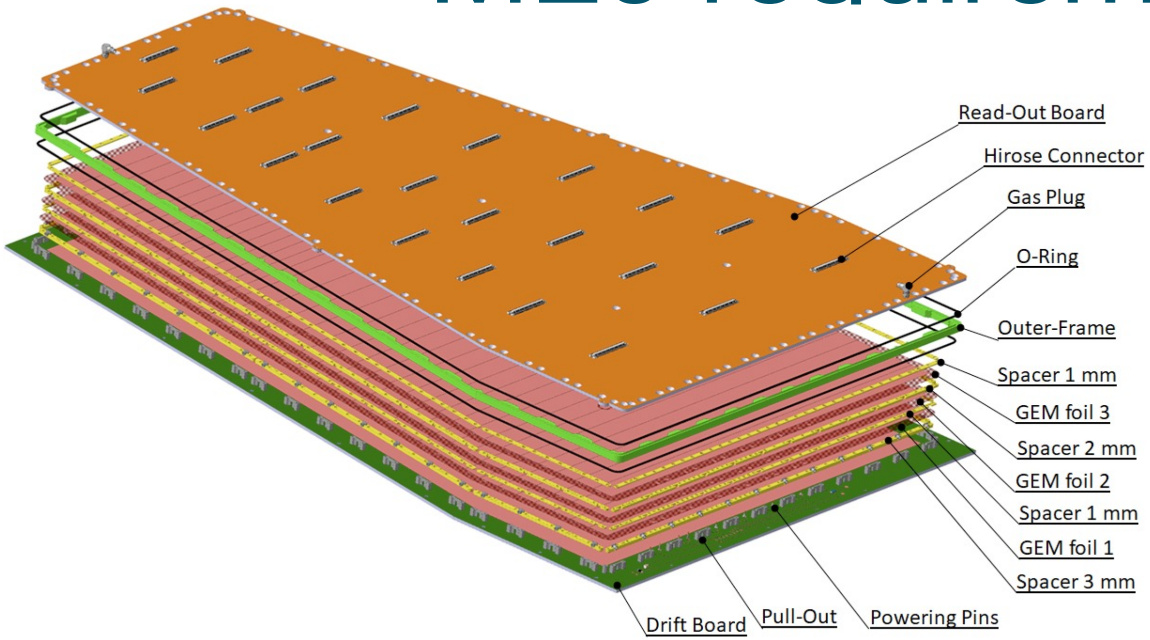
Highly non-uniform rate along the chamber profile

Expected background in ME0 for the HL-LHC scenario (5×10^{34} Hz/cm^2):

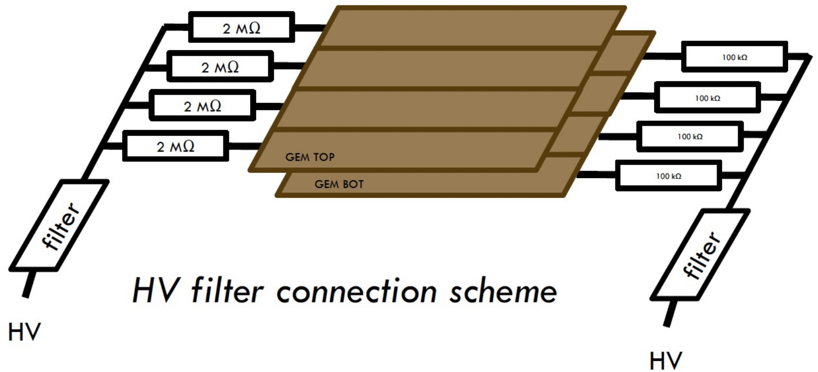
- Rates up to 200 kHz/cm^2 in the highest-η region
  - Highest of any large-area gaseous detector station in a HEP experiment
  - Corresponding to 150 kHz/cm^2 average rate in the highest-η readout sector
- Dominated by charged hadrons
- Highly uneven background as a function of distance from beam line



ME0 requirements and design



- 97% module efficiency
- < 500μrad resolution
- 8-10 ns time resolution
- ≤ 15% gain uniformity
- Work in high-rate environment: 150kHz/cm^2
- Survive harsh radiation environment: 7.9C/cm^2
- Discharge rate that does not impede performance or operation



HV filter connection scheme

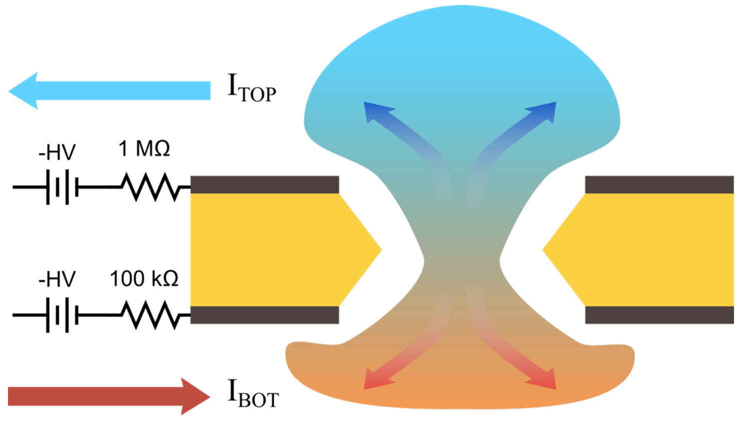
Design mostly inherited from GE1/1 and GE2/1 R&D

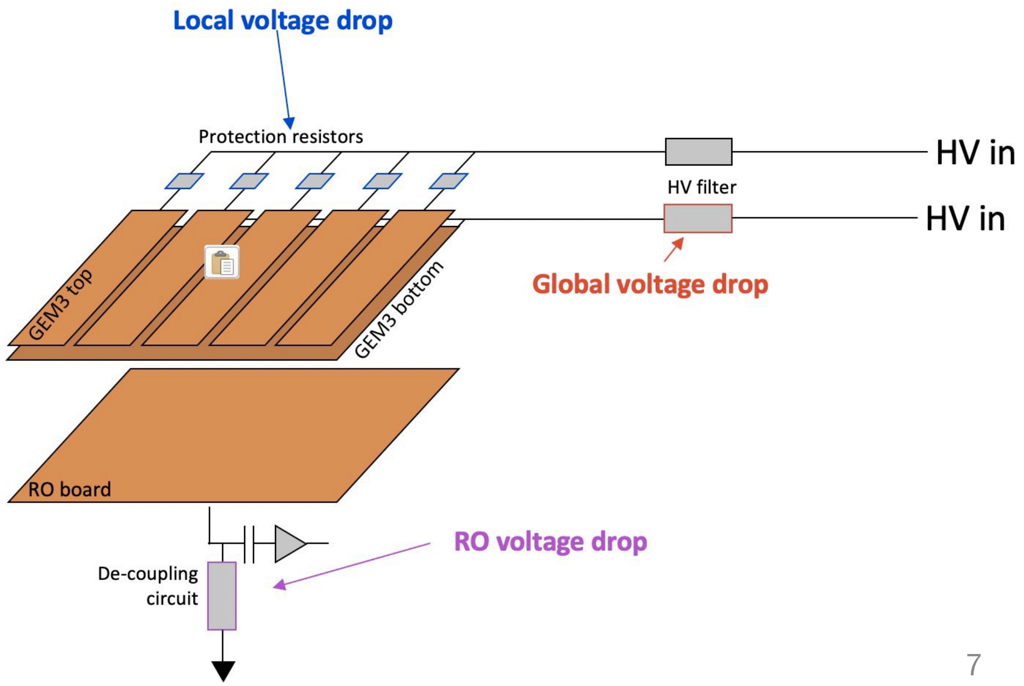
- Double segmented foils to reduce discharge probability
- Baseline design: HV sectors along η direction

Rate capability of GEM detectors

- **GEM rate capability:**
  - ion space-charge effects
    - intrinsic to the GEM technology
    - can be probed by irradiating small areas
    - rate capability of $\mathcal{O}(10^8\ Hz/cm^2)$

    → not a limiting factor
  - voltage drop on the protection and filter resistors
    - depends on the integrate **particle flux per GEM foil sector**
    - rate capability of $\mathcal{O}(10^5\ Hz/cm^2)$
    - can be tuned by changing the HV design parameters
- Rate capability of the **detector+RO chain**:
  - dead time of the electronics, depends on the **signal rate** per strip

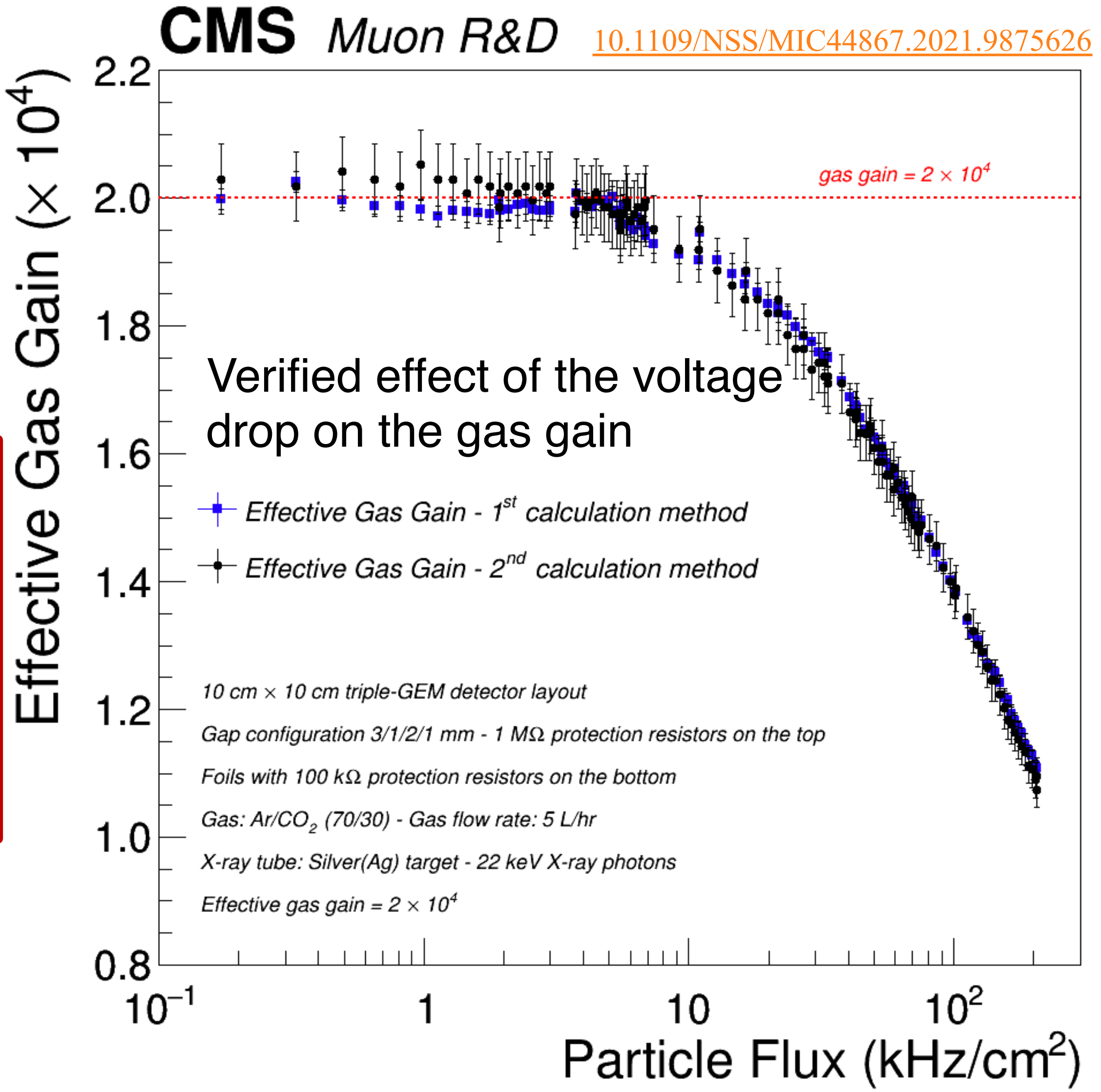




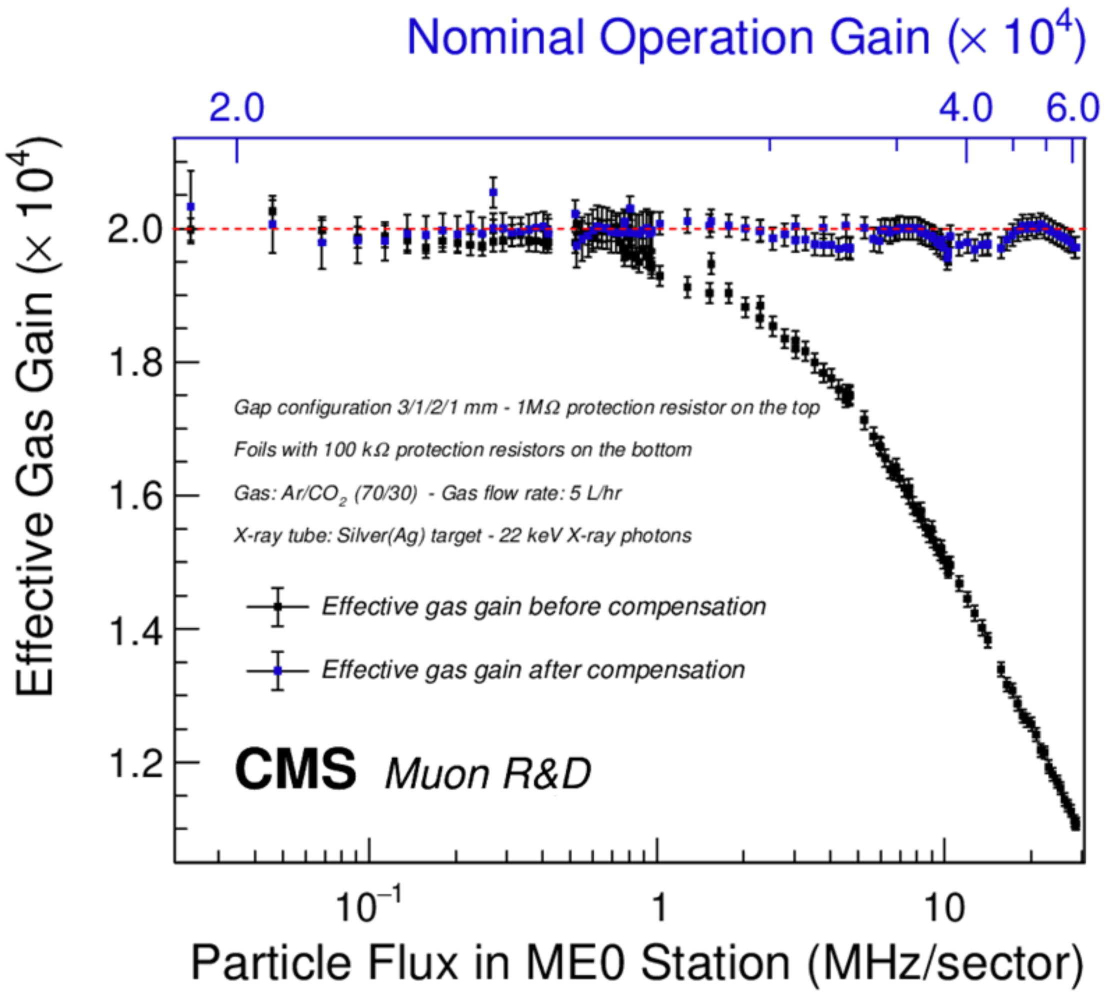
Rate capability of GEM detectors

- **GEM rate capability:**
  - ion space-charge effects
    - intrinsic to the GEM technology
    - can be probed by irradiating small areas
    - rate capability of $\mathcal{O}(10^8\ Hz/cm^2)$

    → not a limiting factor
  - voltage drop on the protection and filter resistors
    - depends on the integrate **particle flux per GEM foil sector**
    - rate capability of $\mathcal{O}(10^4\ Hz/cm^2)$
    - can be tuned by changing the HV design parameters
- Rate capability of the **detector+RO chain**:
  - dead time of the electronics, depends on the **signal rate** per strip



Voltage compensation method



Voltage drop depending on the particle flux, number of primary electron-ion ionisation pairs and protection resistance:

$$V_{eff} = V_{set} - R_{electode} \times \varphi \times G \times n_0$$

Global electrode resistance; Flux on the electrode; Effective gain; Number of primaries

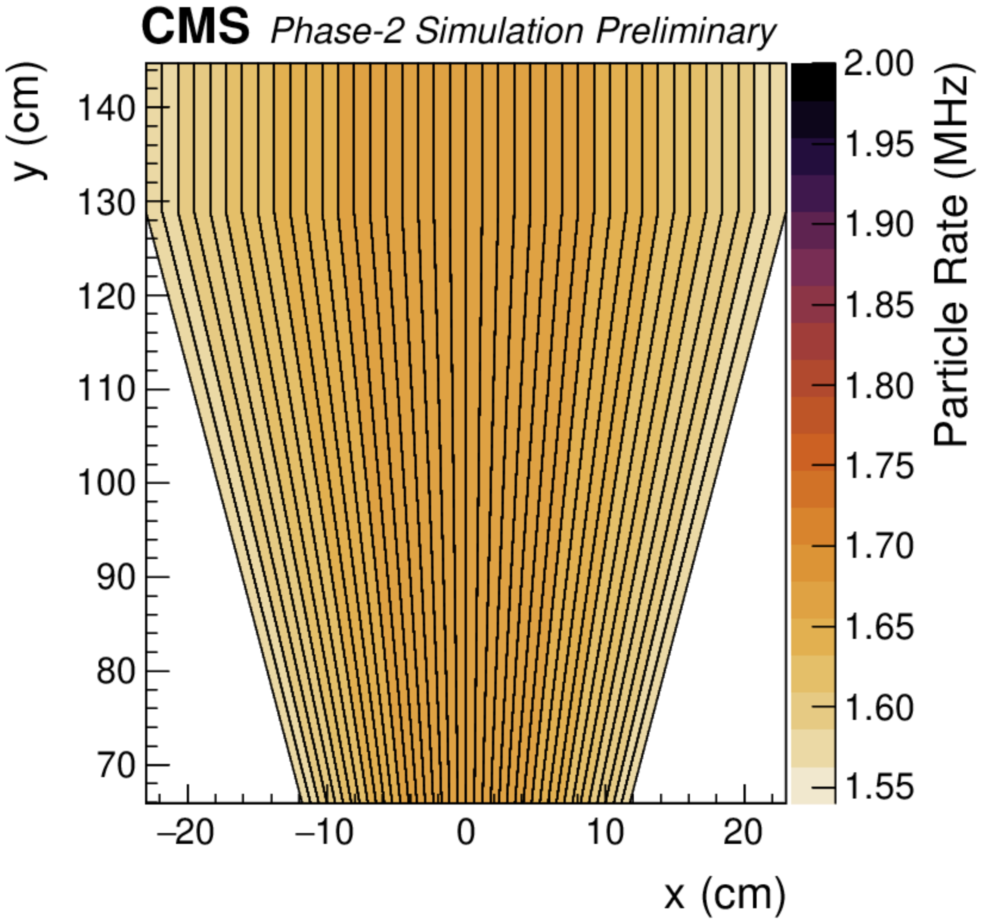
1 – 10V in the ME0 BKG range

Compensation:

- determine iteratively the effective voltage to operate at the nominal gain
- procedure successfully applied to triple-GEM prototypes under x-ray irradiation

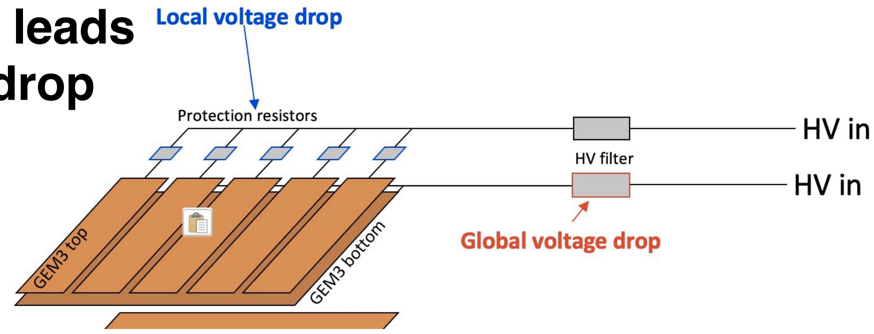
In ME0: large voltage drop in the highest ME0 eta sector (10MHz expected rate)

ME0 GEM foil segmentation



- non-uniform background as a function of η
- need to power all HV sectors with a single HV channel

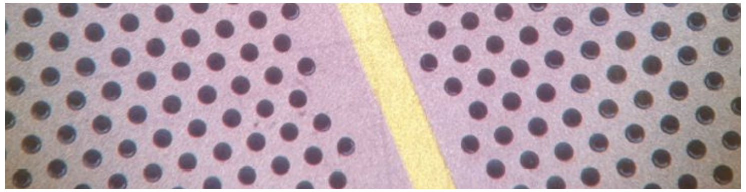
→ **standard segmentation leads to highly even voltage drop**
→ **not possible to apply compensation method**



Solution: radial GEM foil segmentation w.r. to beam line
→ Expected equal background particle rate per sector
→ Uniform gain drop per HV sector (at 140PU we expect 1.6 MHz/sect)

ME0 segmentation design:

- 40 sectors
- sector smaller than 100 cm^2 to reduce discharge energy
- cons: dead area at sector separation



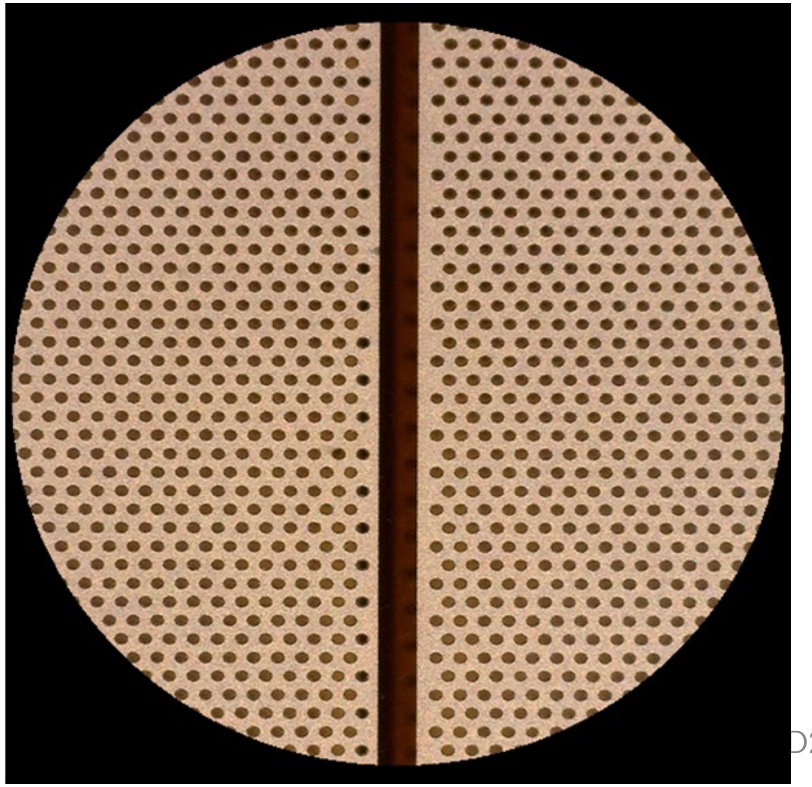
Separation between GEM foil sectors on ME0 detector seen at microscope

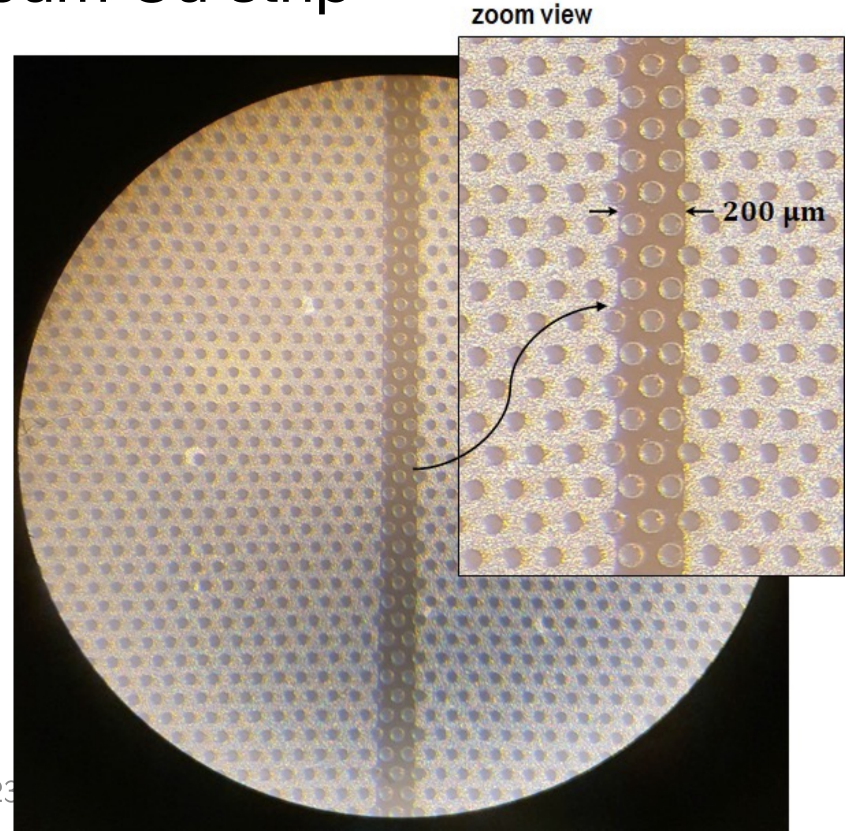
ME0 GEM foil segmentation (2)

Radial segmentation leads to wide dead area (500 µm)

New technique developed @ CERN MPT workshop: “*Random hole*”

- GEM foil perforated everywhere
- Subsequent removal of 200um Cu strip





Validation of the ME0 design

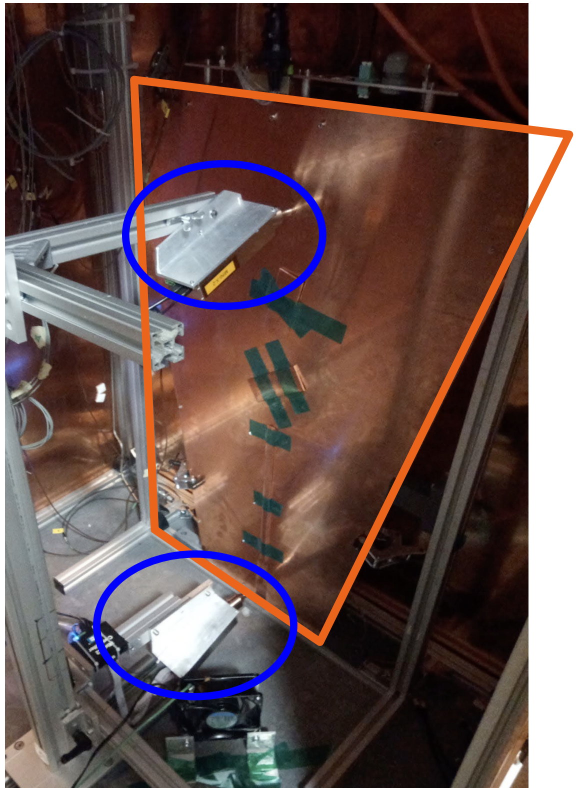
- Validation of the voltage compensation method using radially segmented foils
- Optimization of the HV resistive circuit
- Validation of the radial segmentation design in terms of efficiency
  - comparison between *standard* and *random hole* techniques

X-ray irradiation:
- pro: controlled environment, tunable rate
- cons: only probes local effects (i.e. protection resistors)

Test beam @ GIF++:
- uniform irradiation, we probe global effects (i.e. HV filter)
- efficiency measurement using reference detector

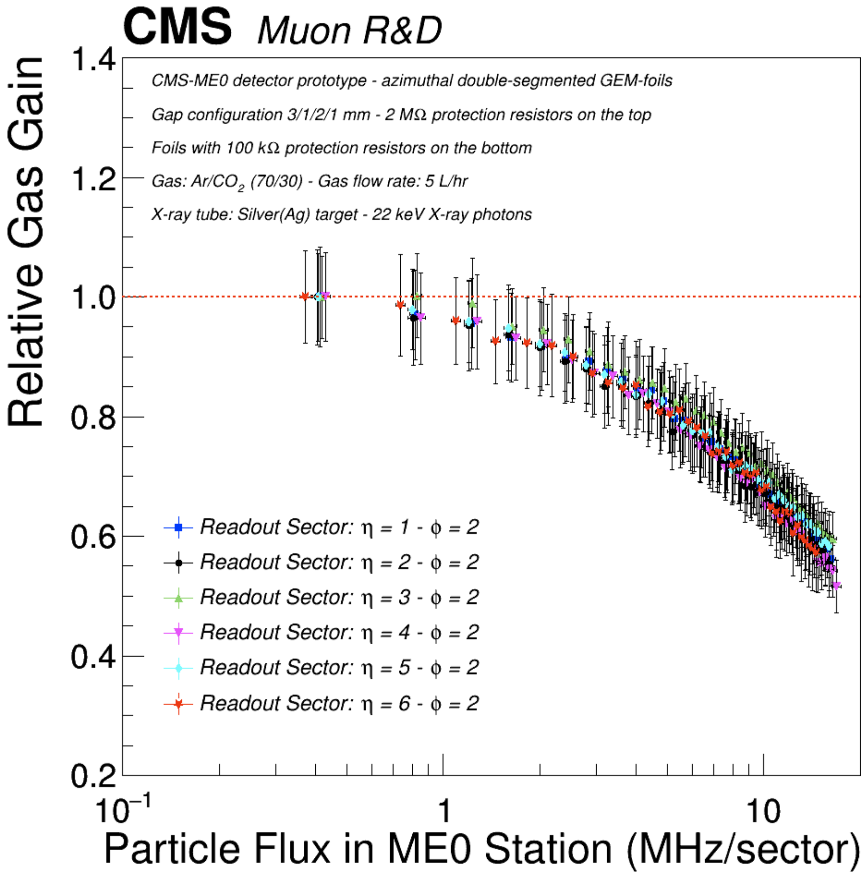
ME0 rate capability studies with x-rays

Setup: ME0 layer irradiated using two x-ray guns
- global x-ray irradiation
- high flux on highest η partition of ME0



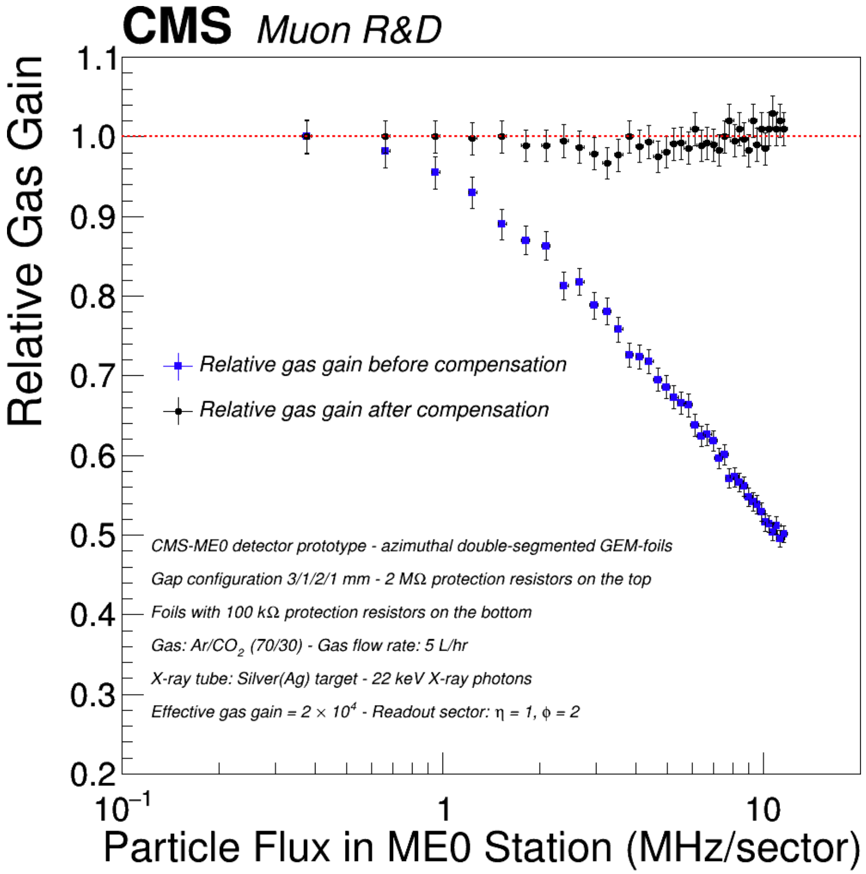
Validation of the radial segmentation design

Gain drop uniform across the sectors



Voltage drop compensation applied to ME0 detector

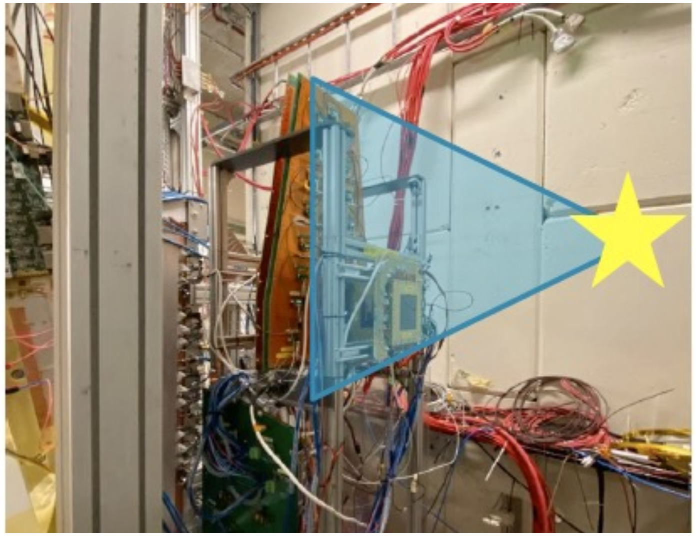
Demonstrated up to 10MHz/sector



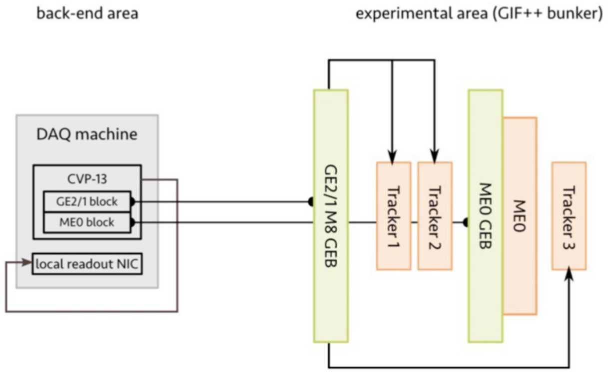
ME0 rate capability studies at the GIF++

Setup: ME0 layer + reference GEM tracker

- Placed inside the source cone for uniform and intense irradiation
- Full RO chain (VFAT3 frontend)

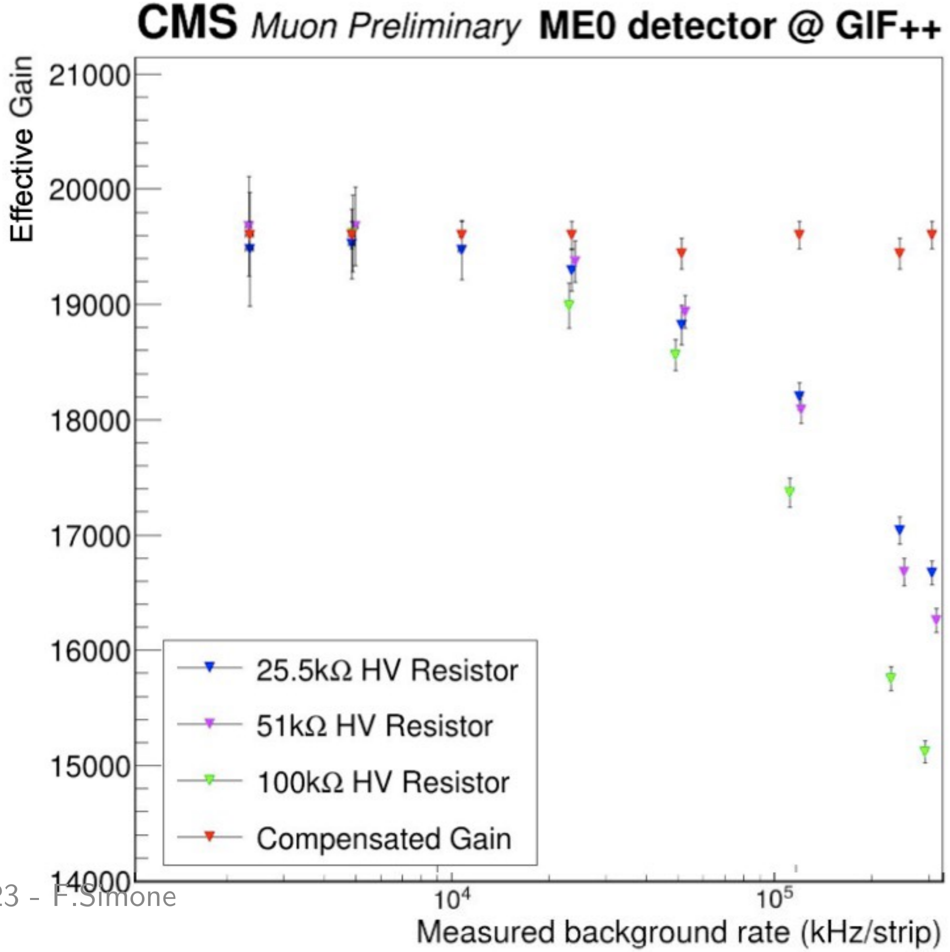


Source:
137 Cs (14TBq)
γ (662 keV)



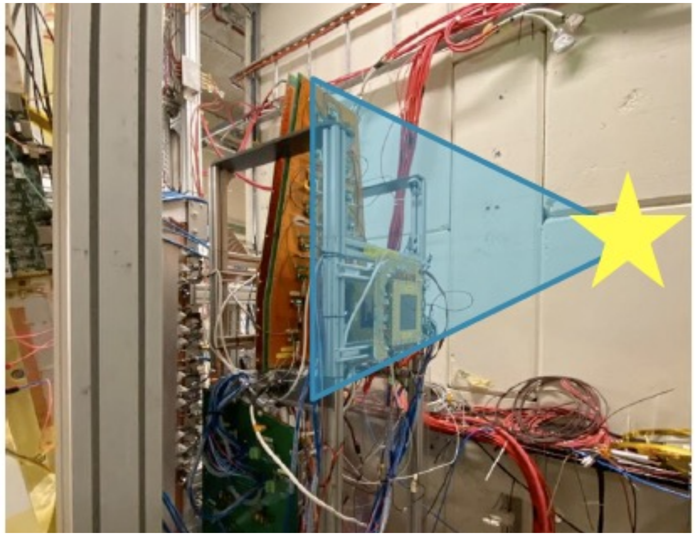
Compensation demonstrated with different HV filters

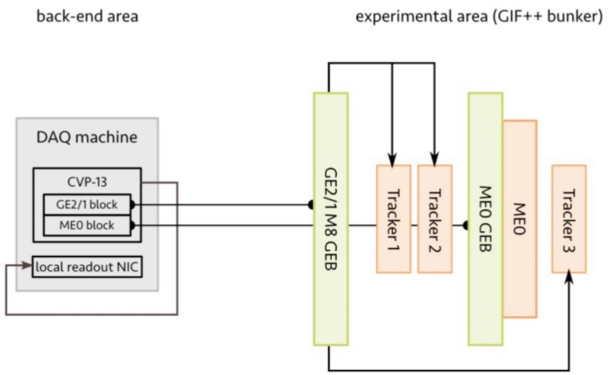
Gain recovery demonstrated up to 2.2 MHz/sector or 280 kHz/strip and with different HV filters up to 100 kΩ



ME0 efficiency at the GIF++

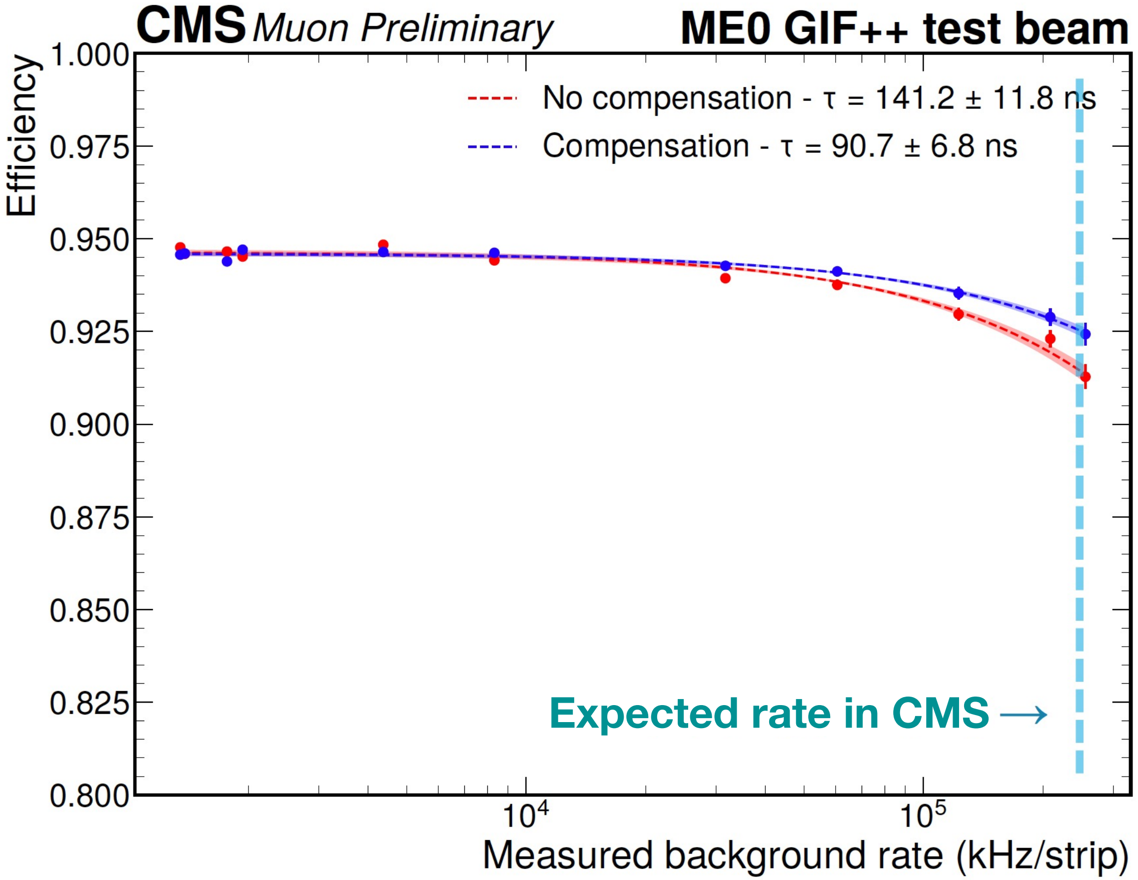
Background:
137 Cs (14TBq) γ (662 keV)
+ SPS beam of 80 GeV muons





Validation of detector + RO electronics

- Efficiency loss not recovered by voltage compensation.
  - Due to frontend chip dead time (400 ns)
  - Limited impact (3%) at CMS expected rate.

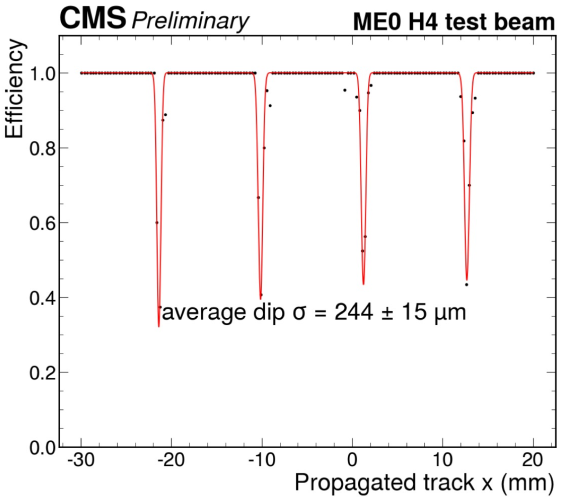


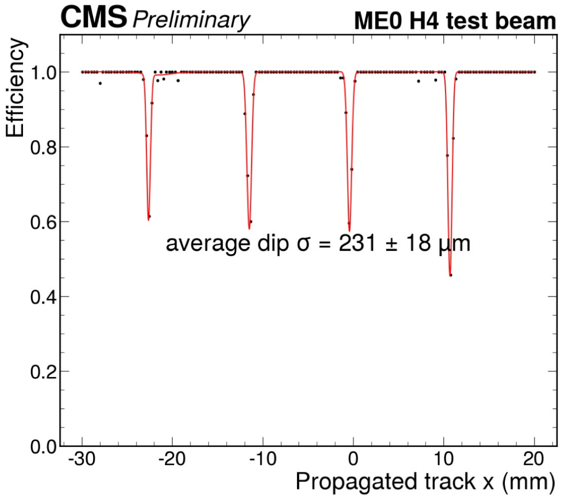
ME0 efficiency studies

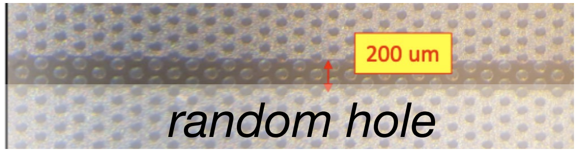
Performance studies under pion and muon irradiation at SPS H4

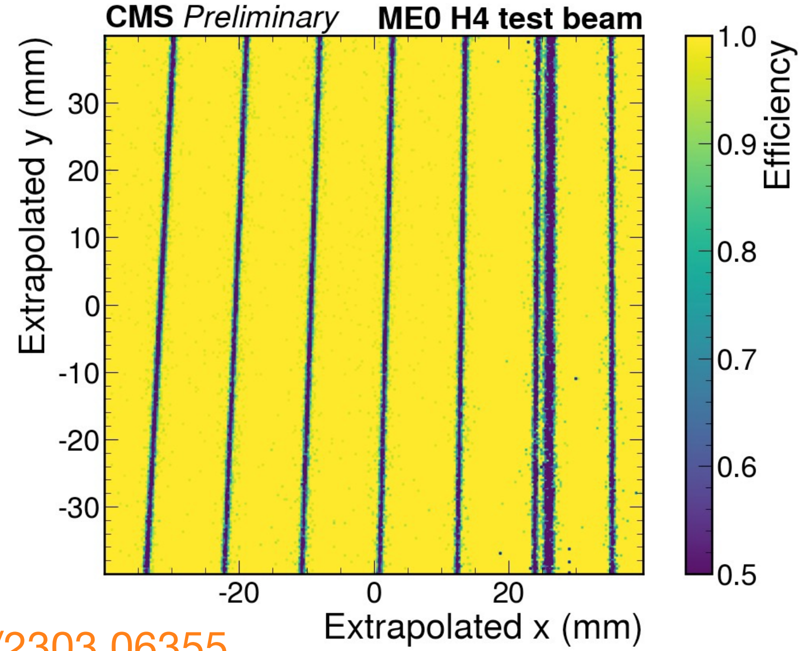
- **Spatial resolution** of 240 µrad
- Local efficiency >99%
- **Loss of efficiency** due to dead area at **HV sectorisation**
- **Recovered** adopting **random hole segmentation**

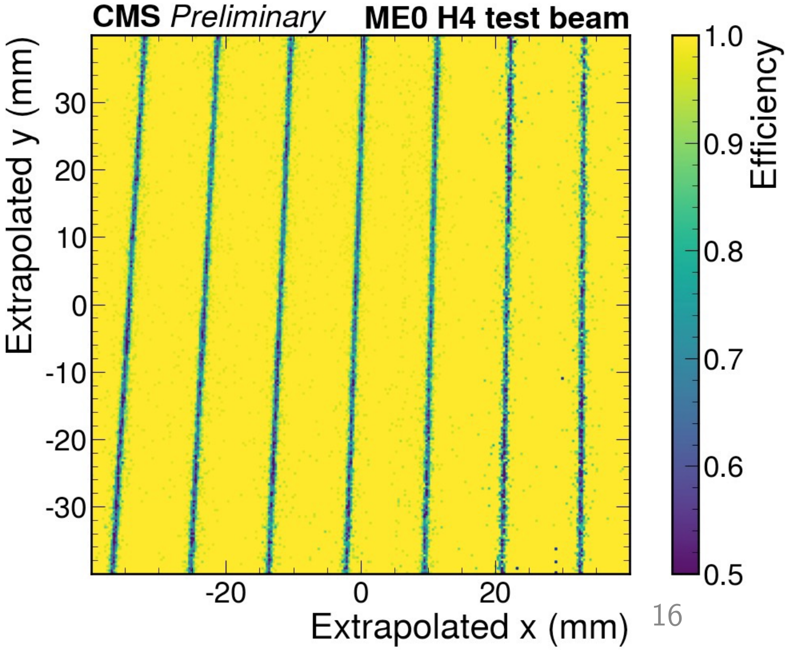
Random hole is still in R&D phase, not in the final design despite the promising results due to time constraints.









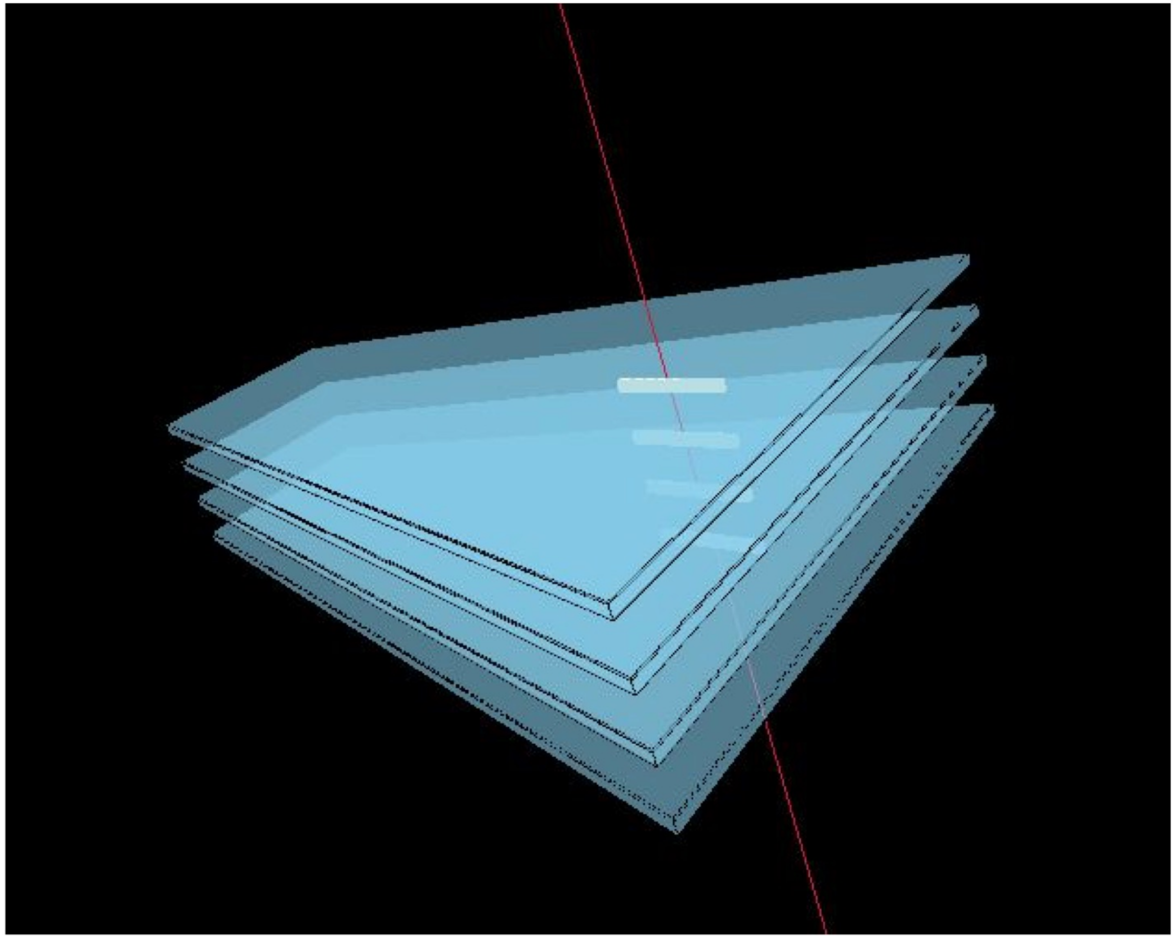


https://arxiv.org/abs/2303.06355

Conclusions and perspectives

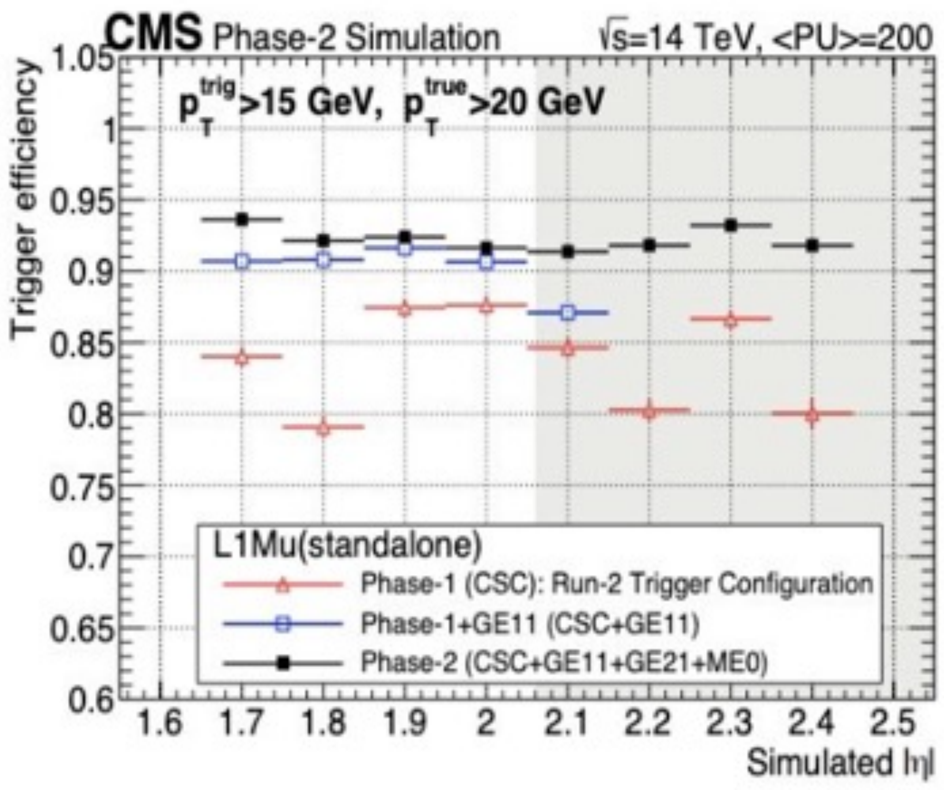
ME0 R&D on the detector design at very advanced stage

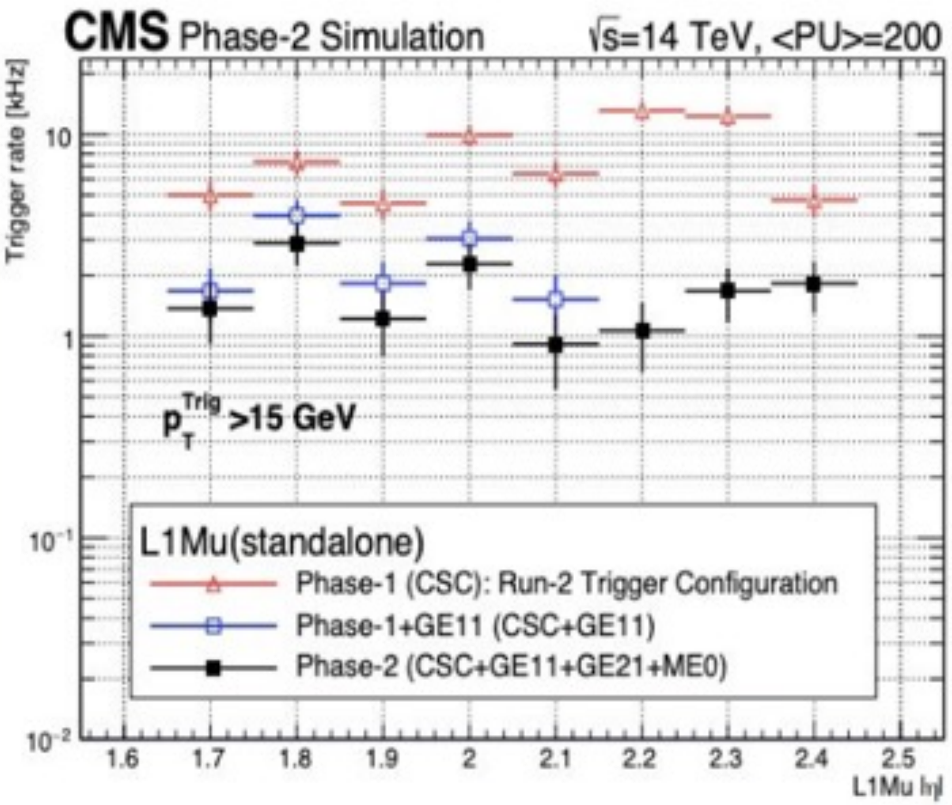
- Accessed rate capability
- Implemented mitigation strategies: radial HV segmentation, voltage drop compensation
- Quantified impact of HV filters
- Design validated and fixed
- Started pre-production
  - ME0 foils mass-production is going to start (Sept 2023)
  - Installation in January 2027



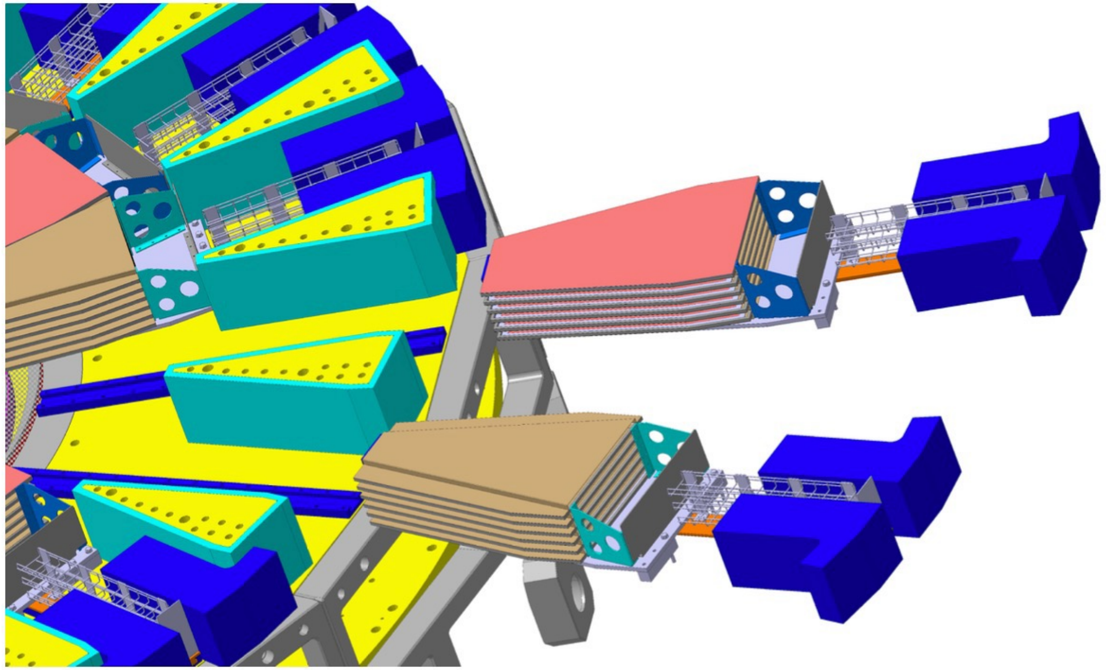
Backup

GEM upgrade: motivations





LHC schedule



ME0 Installation

ME0 ELECTRONICS

VFAT3: 128-channel front-end ASIC for digital readout

- Common plugin-card format for GE2/1 and ME0
- Ongoing final checks on channel input protection circuit (see later)

GEM Electronic Board (GEB): 1mm 8-layer PCB providing electrical links, powering the front-end and shielding the detector

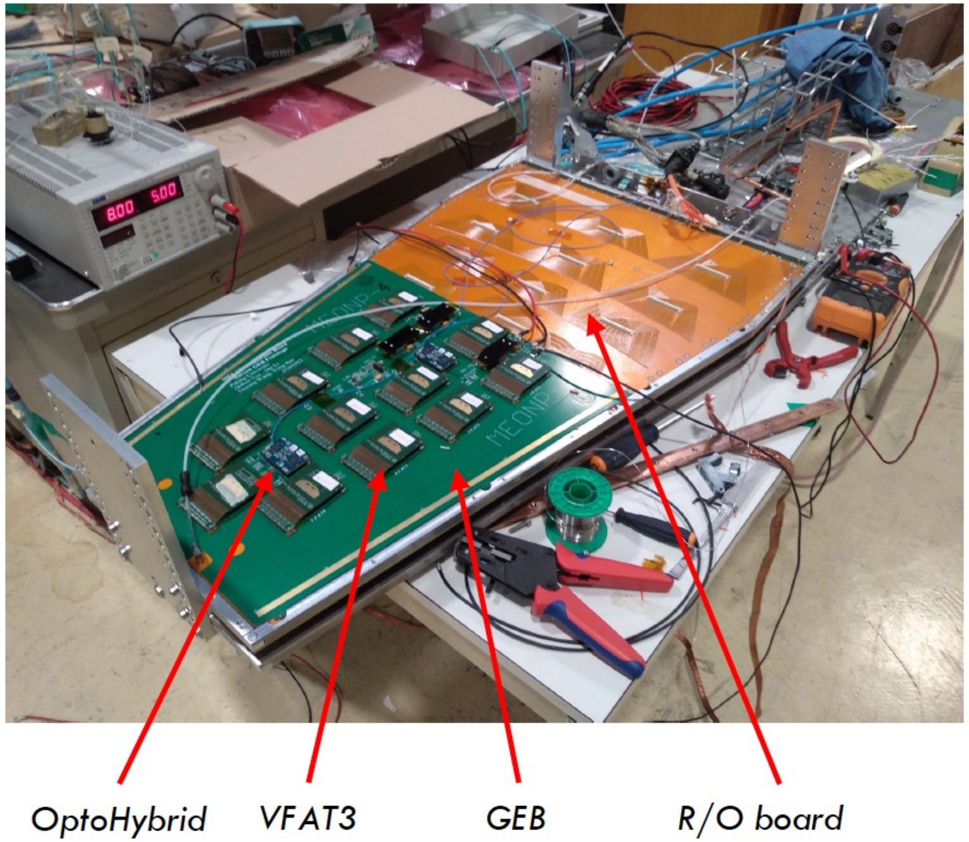
DC-DC converter: FEASTs to be **replaced by bPOLs**

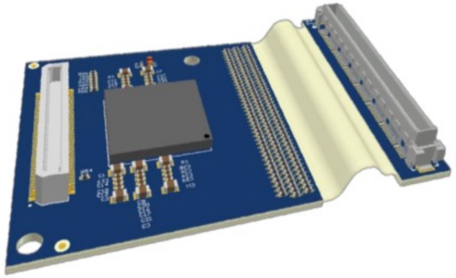
OptoHybrid: Front-end concentrator, reads out 6 VFATs

- 2 lpGBT (main/secondary) for front-end, 1 VTRx+ to back-end
- No FPGA, radiation-hard electronics

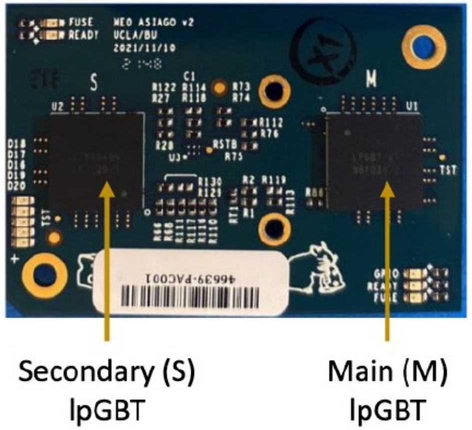
X2O ATCA board: common back-end for CSC, GE2/1 and ME0

All front-end components in pre-production state and operated extensively in lab & test beam





VFAT3 plug-in card



OptoHybrid