MB/-2/1/11
HE-RBX 17
HE-RBX 16
HE-RBX 15
ME&RE-1/2/32
ME&RE-1/2/30

Performance Measurements of the ME0 Station

for the CMS Muon system at the HL-LHC

Piet Verwilligen

on behalf of the CMS Muon Group

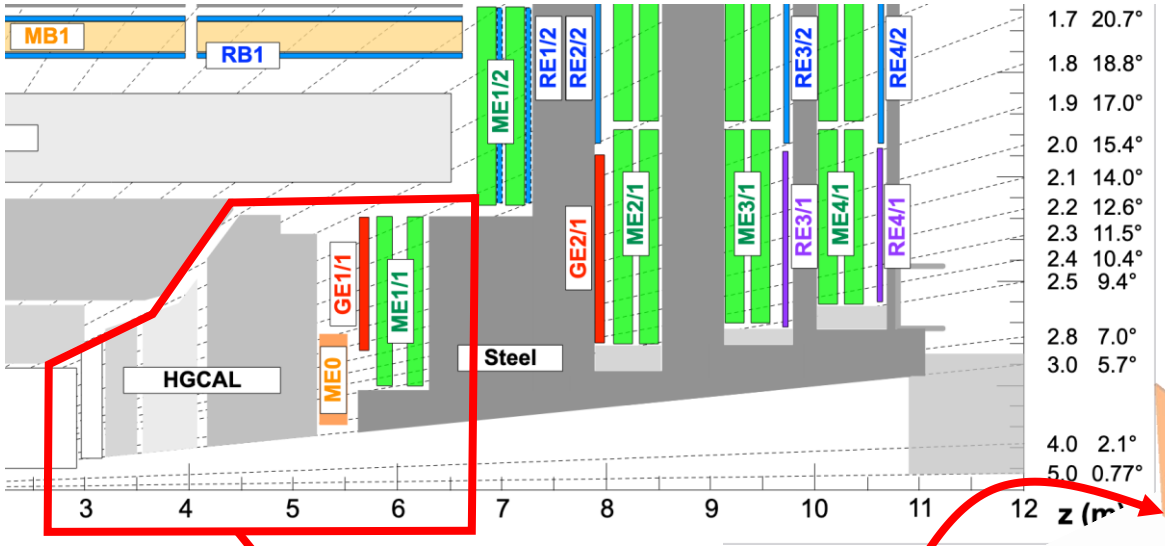
BTTF13 2025

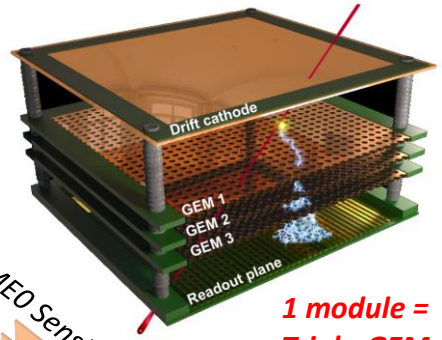
May 20th 2025

IFIC UV-CSIC - Valencia - ESP

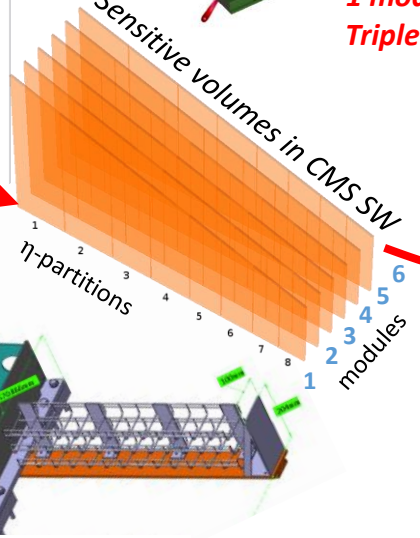
The ME0 detector

Designing Triple-GEM detectors for the highest rates

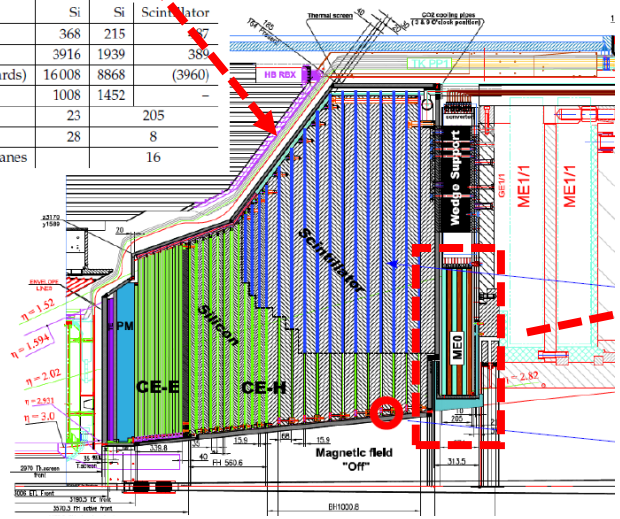




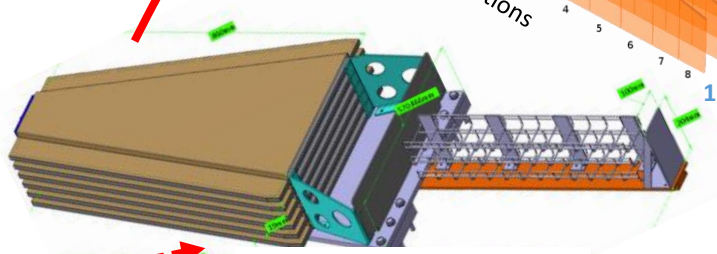
1 module = Triple-GEM



	CE-E Si	CE-H Si	CE-H Scintillator
Area (m^2)	368	215	87
Channels (k)	3916	1939	380
Si modules (Tileboards)	16008	8868	(3960)
Partial modules	1008	1452	–
Weight (t)	23	205	
Si-only planes	28	8	
Mixed (Si+Scint) planes		16	



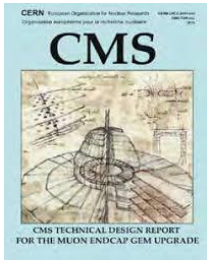
New High-Granular Calorimeter (HGCAL) CMS

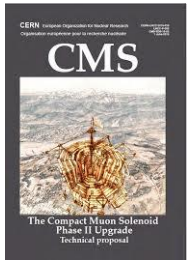


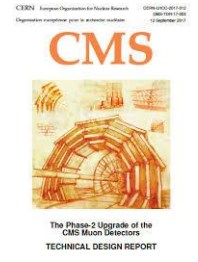
ME0 Stack

- Requirements:
  - 97% module efficiency
  - $< 500\mu$rad resolution
  - 8-10 ns time resolution
  - $\leq 15\%$ gain uniformity
  - *Work in high-rate environment: 150kHz/cm²**
  - *Survive harsh radiation environment: 7.9C/cm²**
  - *Discharge rate that does not impede performance or operation*
  - ** updated w.r.t. CMS Upgrade Technical Proposal & Muon Upgrade TDR*

- 6-Layer stack of Triple-GEM detectors
  - Install behind HGCAL (complex environment)
  - 18 stacks (20°) for each endcap
  - Coverage: $2.0 < \eta < 2.8$







History of CMS GEM Test beams

Test beams omnipresent during design and R&D phase

CERN-LHCC-2015-012

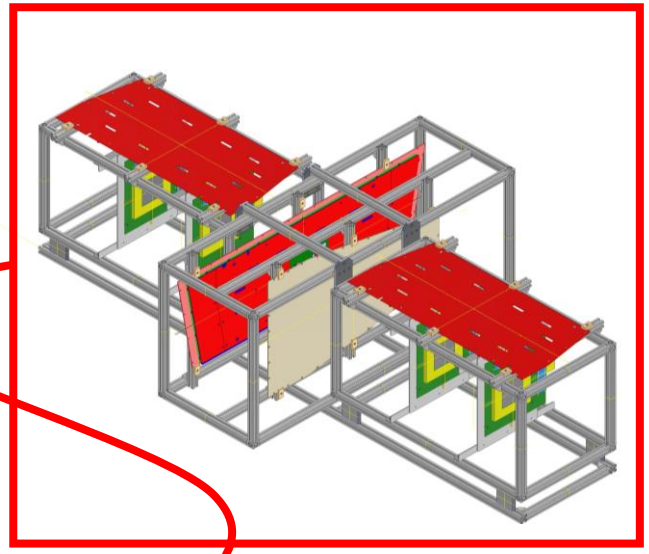
Large-size Triple-GEM R&D — **2010**

GEM TDR — **2015**

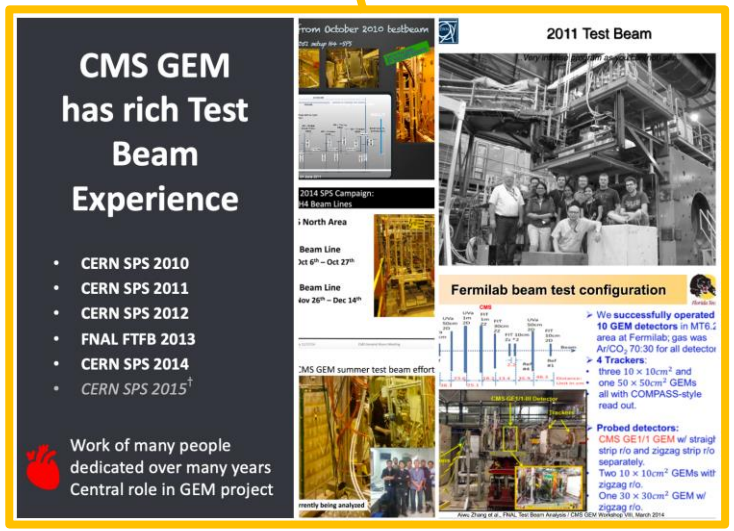
Discharge Test @ CHARM — **2017**

Phase 1 GEM production — **2020**

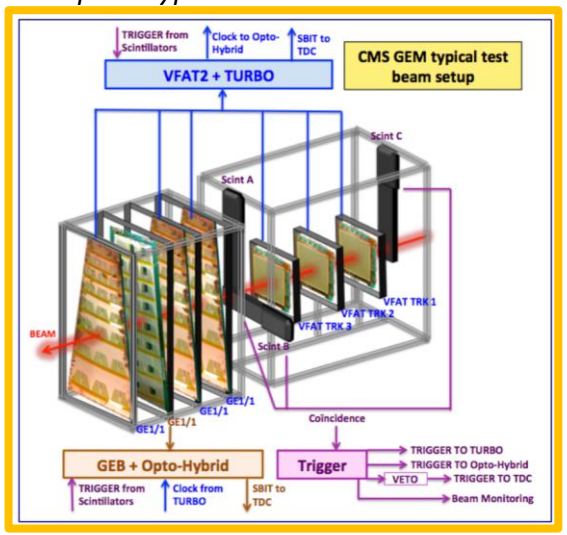
2025

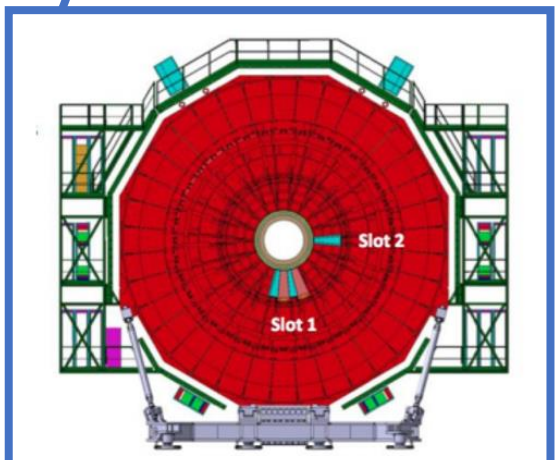


2021 – 2024:
Validation of Phase-2 GEM detectors equipped with final electronics and read by CMS GEM DAQ

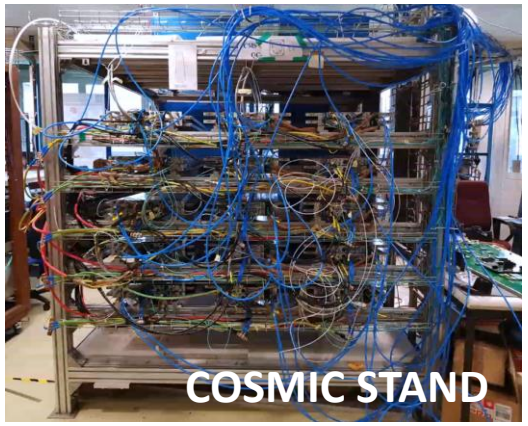


Typical Test Beam setup:
Det prototypes & borrowed electronics





CMS Slice Test 2015-2018
Installation & Operation of 10 pre-series GE1/1 Triple-GEM dets



Construction & Test of 150 GE1/1 dets
Cosmic Stand to test up to 30 chambers
final HV, LV, Electronics, > 100k ch

CMS Test beam campaigns

Test beams are cornerstone of detector validation

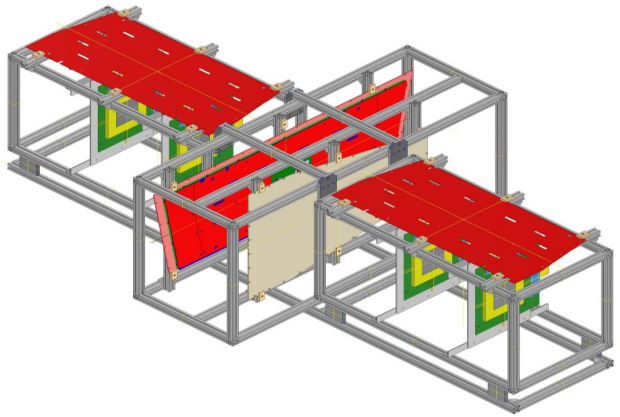
Magnet Test @ GOLIATH (H4)

2020 | 2021 | 2022 | 2023 | 2024 | 2025

- **Design Finalization Phase-2 detectors**
- **Detector Construction**
- **Electronics Production**

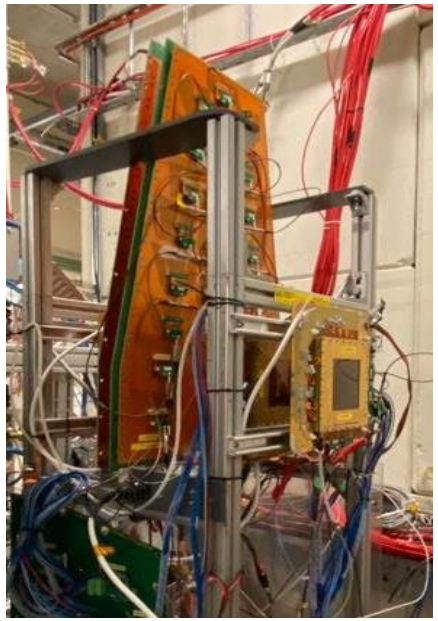
Coining the idea to restart Beam Tests

- *convincing the Collab*
- *DAQ development*
- *Geom & Reco devel*
- *GEM Telescope tests*



1st GEM Phase-2 Test beam

- **October '21 & May '22**
- **CERN SPS H4 *(RD51 slot)***
- **1 Production GE2/1 module**
- **1 Prototype ME0 module**
- **GEM DAQ: high rates**



1st Test beam under irradiation @ GIF++ July 2022

1st Test beam of ME0 Stack

- **Read 33% of final detector**
- **May 2023**

CMS Test beam campaigns

Testbeams are cornerstone of detector validation

Magnet Test @ MNP22 (ENH1)

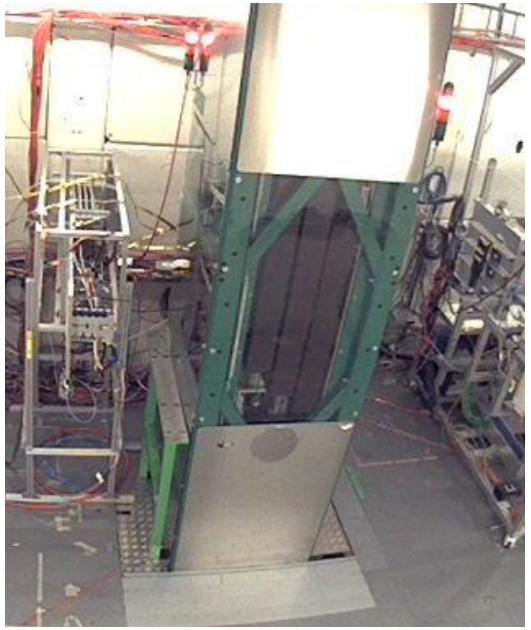
2020 2021 2022 2023 2024 2025

May 2023

1st Test beam of ME0 Stack

- Read 33% of final detector

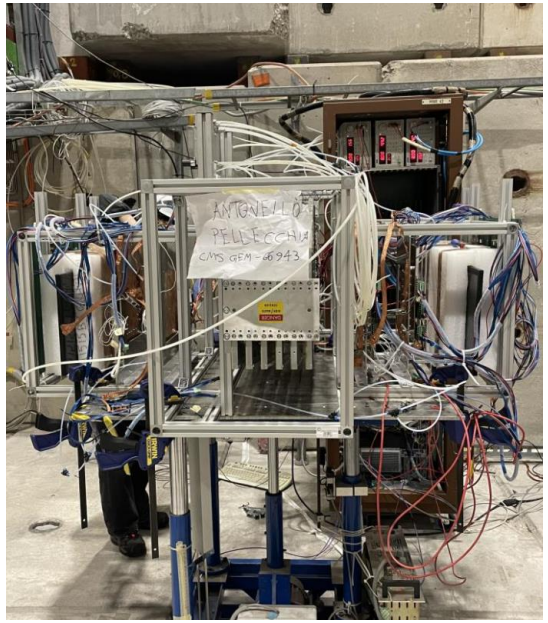
July 2023



1st time ME0 Stack @ GIF++

- Irradiated up to 150 kHz/cm^2

April 2024



1st Full ME0 Stack in Beam

- Timing measurements

July 2024

1st Full ME0 Stack irradiated

- Timing under irradiation

MEO Performance measurements:

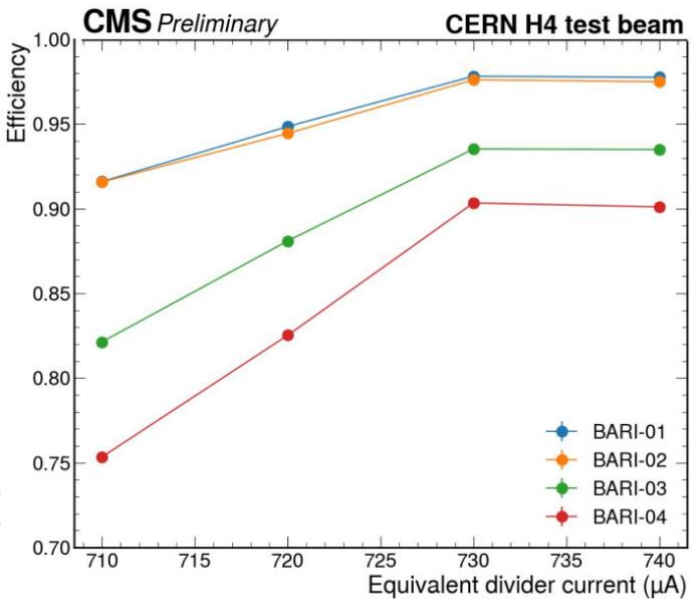
I. GEM Telescope Performance

II. Efficiency & Rate-capability

III. Time Resolution

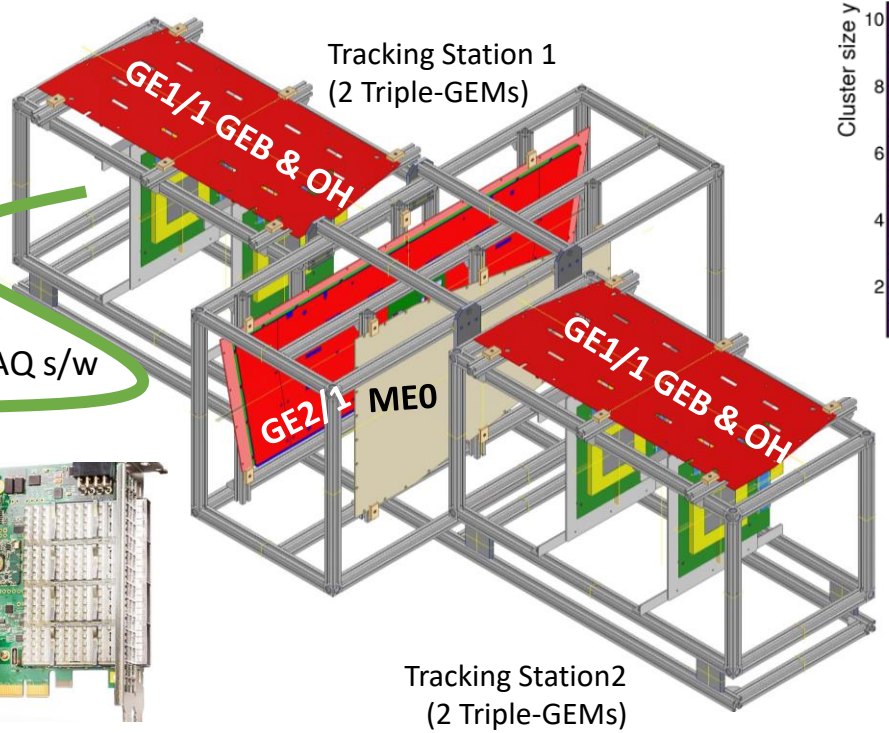
Triple-GEM Telescope Performance

- **Requirements:** *High rate & High-resolution Telescope read with same DAQ*
  - Test 9 x 9cm^2 Tracking GEMs 250um pitch with VFAT3 asic (digital R/O)
  - Test final CMS GEM Phase 2 electronics: fibers read out by FPGA board
- **Setup RD51 Test Beam:** *October 2021 & May 2022 at SPS H4*
  - Tracking detectors read through 1.5m long high-speed Samtec cables
  - Relative low noise (0.5 – 1.25fC ENC) in BARI-01 & BARI-02 lead to $\varepsilon > 95\%$



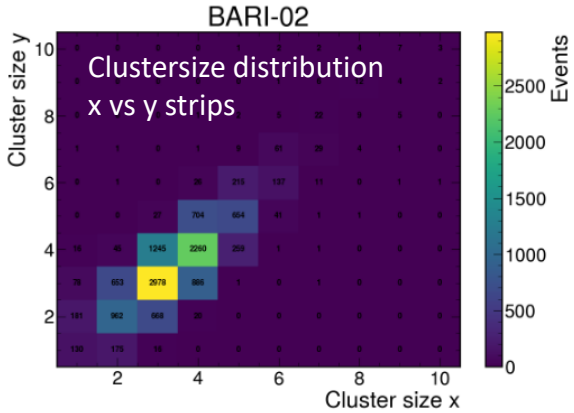
Scintillator Trigger,
4 GEM Tracking Det.,
GE2/1 M5 module,
ME0 module with
new HV segmentation,
CVP13 readout + P5 DAQ s/w

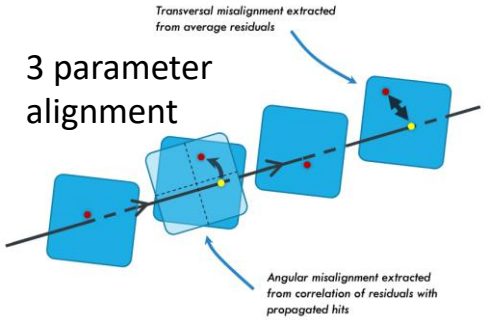
CVP13 based DAQ



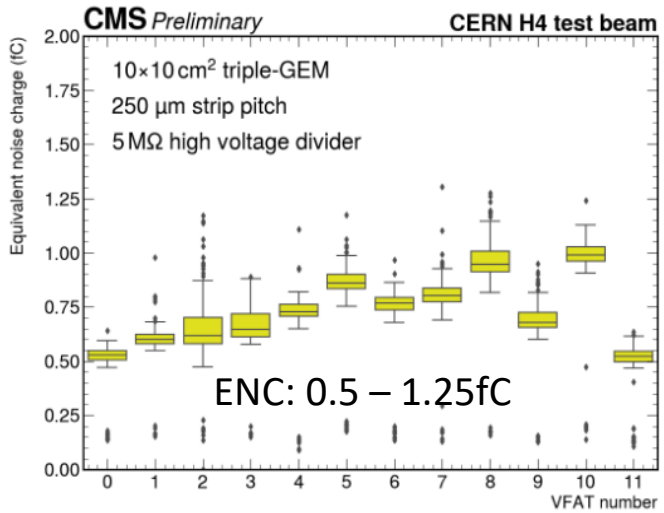
Tracking Station 1
(2 Triple-GEMs)

Tracking Station2
(2 Triple-GEMs)



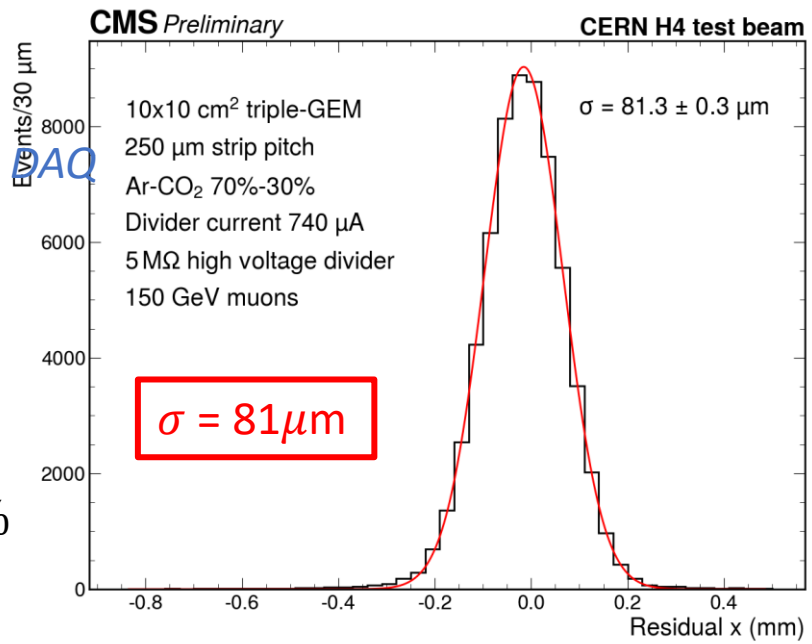


3 parameter
alignment



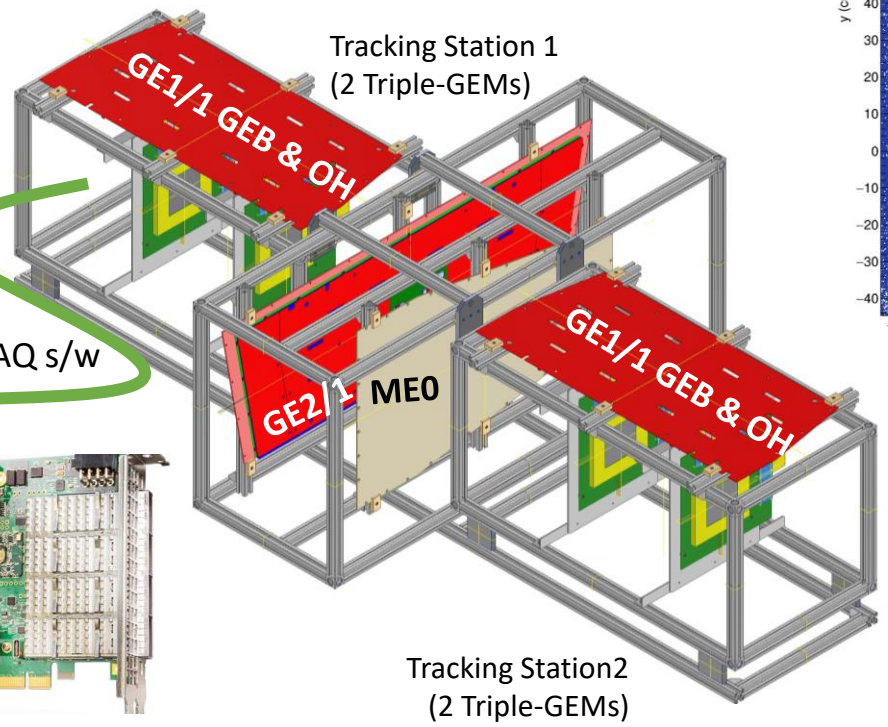
Triple-GEM Telescope Performance

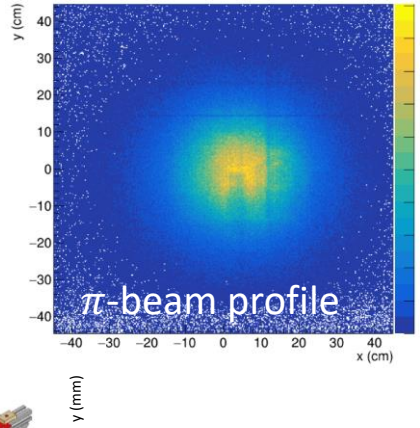
- **Requirements:** *High rate & High-resolution Telescope read with same DAQ*
  - Test 9 x 9cm^2 Tracking GEMs 250um pitch with VFAT3 asic (digital R/O)
  - Test final CMS GEM Phase 2 electronics: fibers read out by FPGA board
- **Setup RD51 Test Beam:** *October 2021 & May 2022 at SPS H4*
  - Tracking detectors read through 1.5m long high-speed Samtec cables
  - Relative low noise (0.5 – 1.25fC ENC) in BARI-01 & BARI-02 lead to $\varepsilon > 95\%$

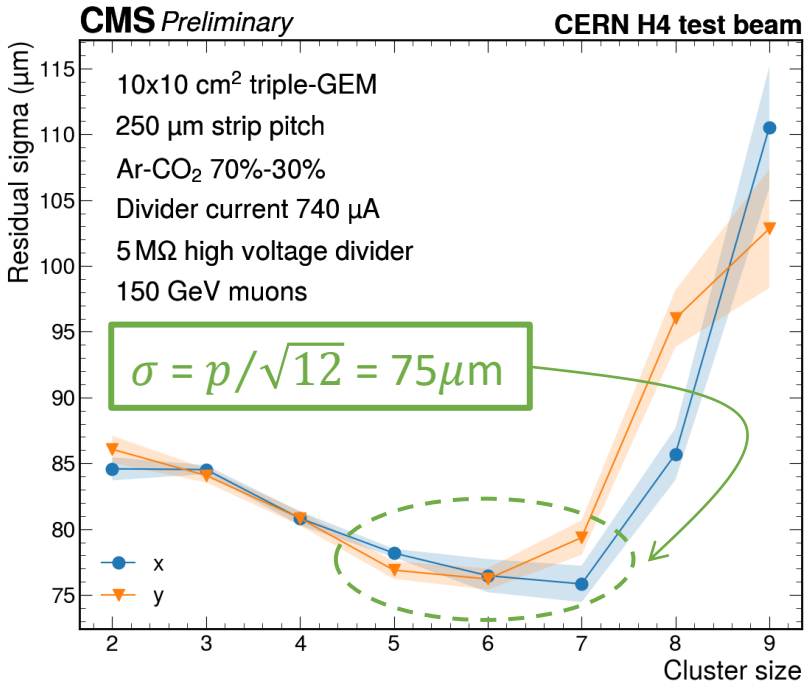


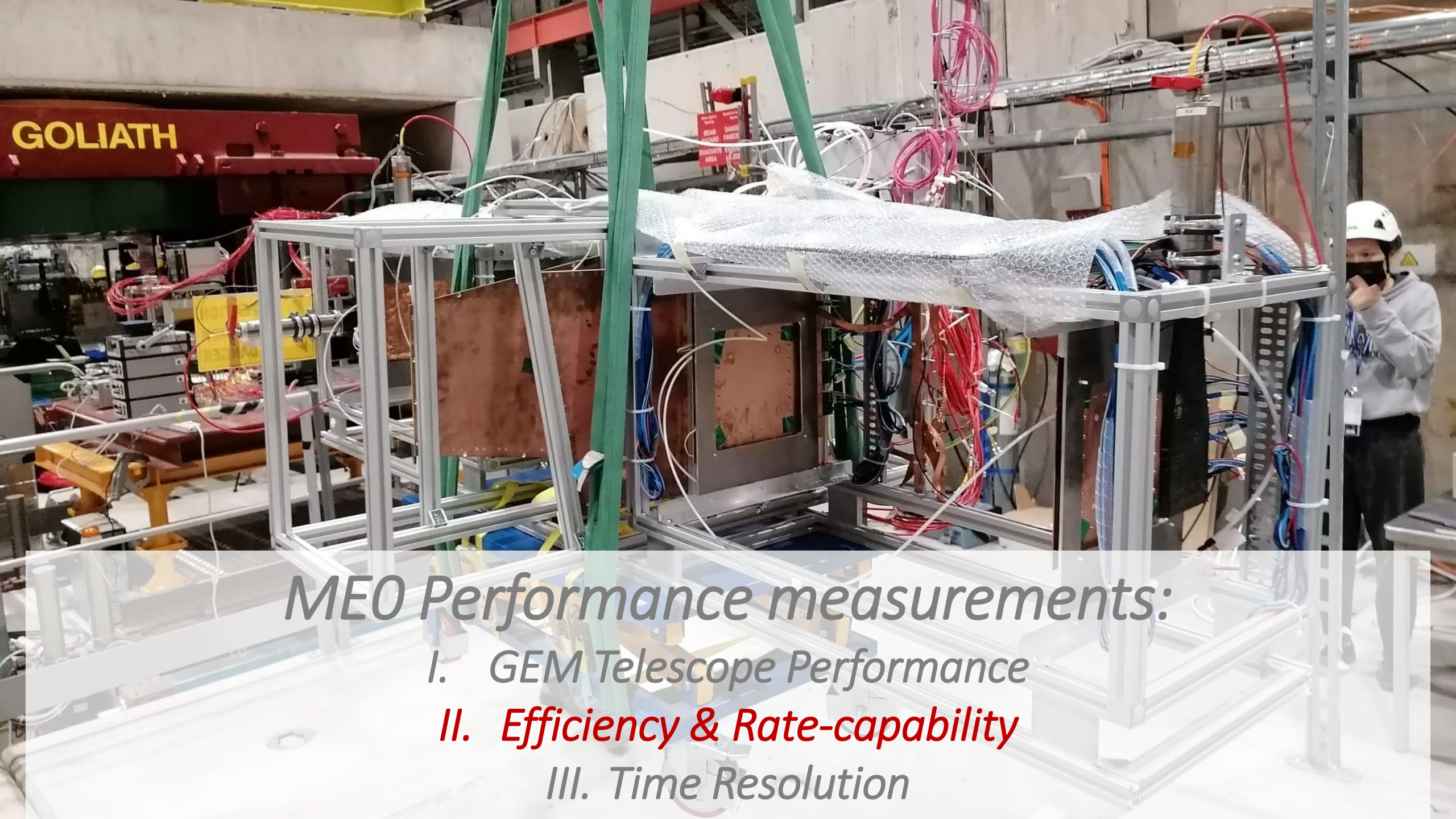
Scintillator Trigger,
4 GEM Tracking Det.,
GE2/1 M5 module,
ME0 module with
new HV segmentation,
CVP13 readout + P5 DAQ s/w

CVP13 based DAQ









MEO Performance measurements:

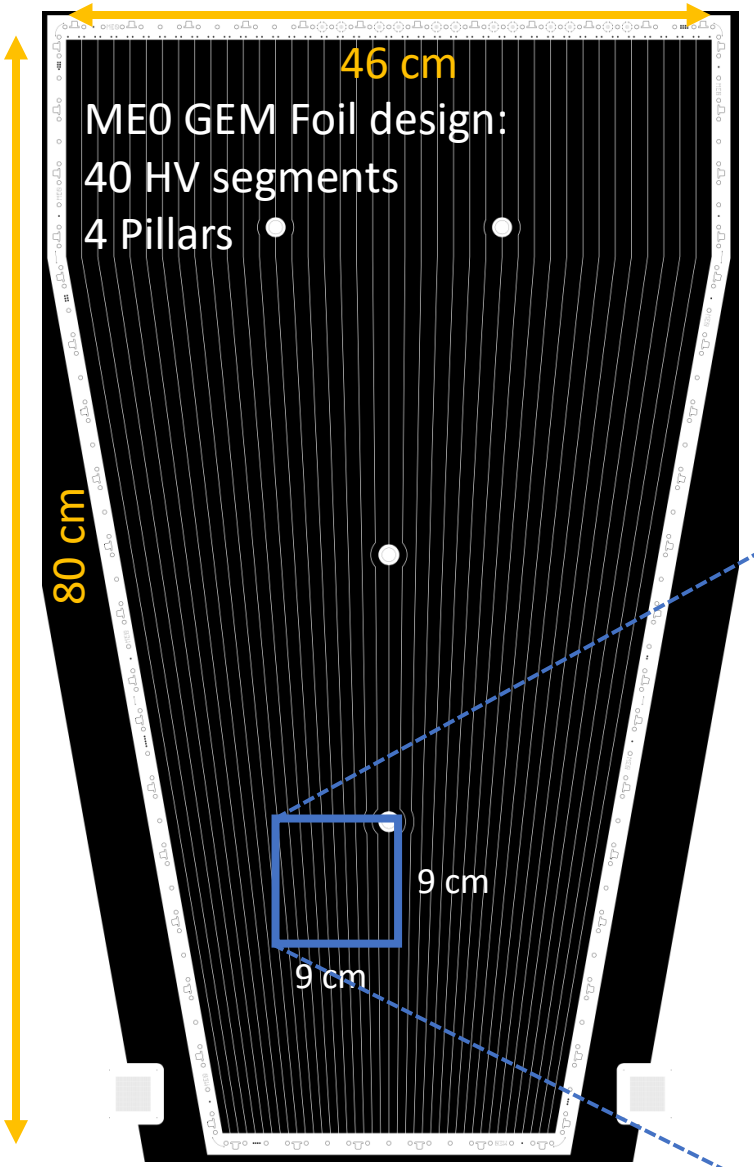
I. GEM Telescope Performance

II. Efficiency & Rate-capability

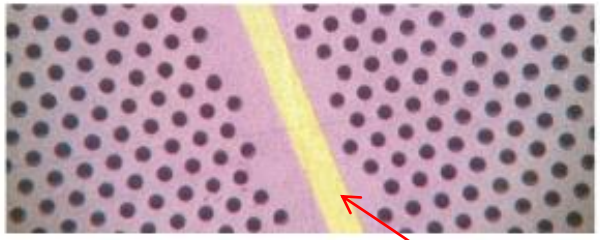
III. Time Resolution

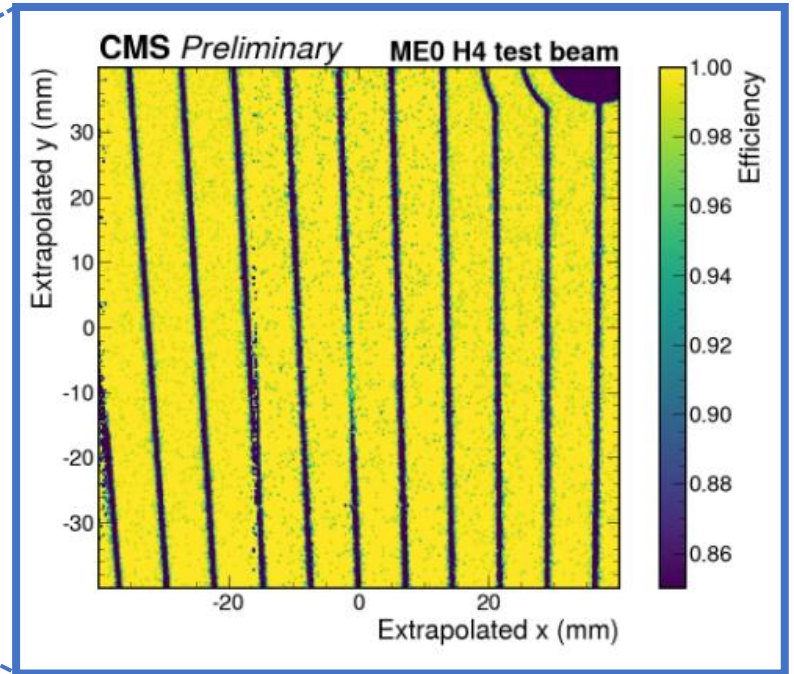
ME0 Module Efficiency measurements with beams

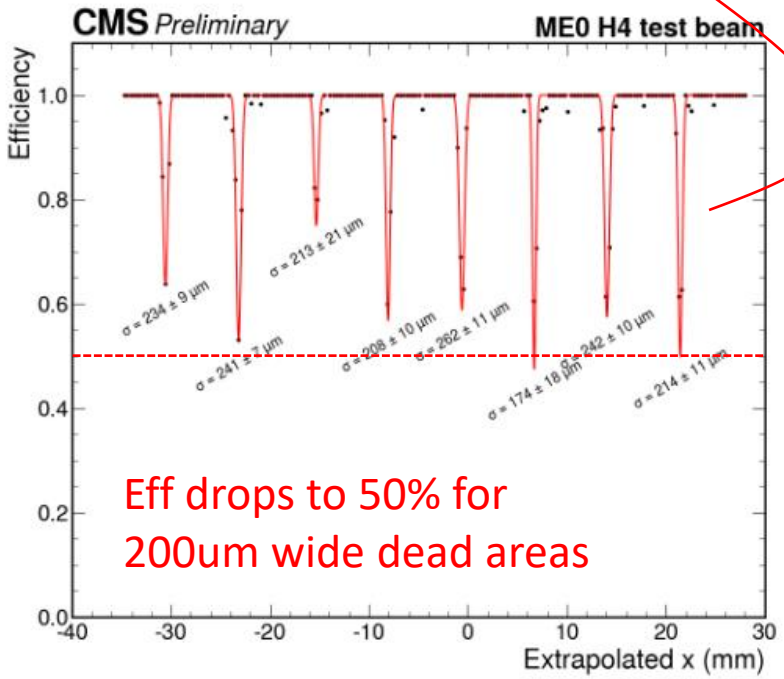
high-resolution telescope images of the ME0 GEM foil



- 4-detector GEM Telescope with σ = 81 μm
- Allows to have a detailed look into design features
- 200 μm dead areas between HV segments are clearly visible
  - Actual distance 2 holes $\geq$ 200 μm





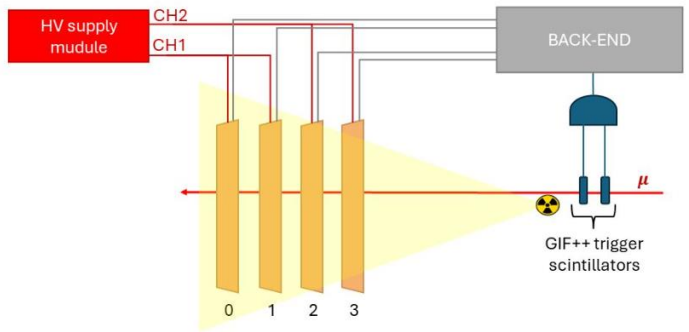


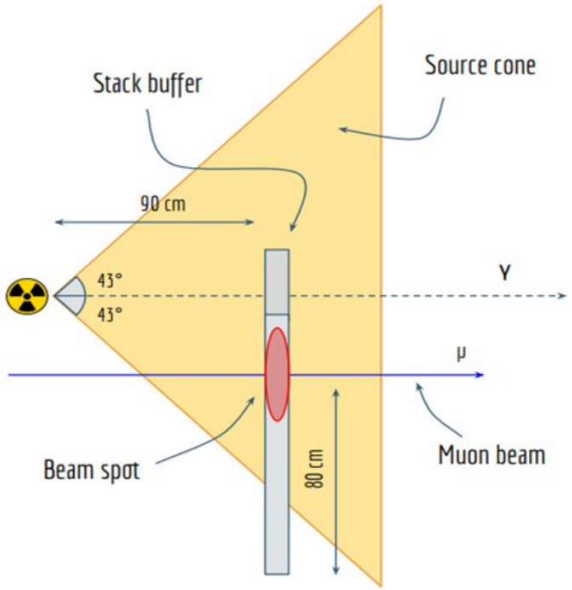
A. Pellecchia - CERN-Thesis-2023-062

ME0 Module Efficiency under irradiation

at the CERN Gamma Irradiation Facility - GIF++

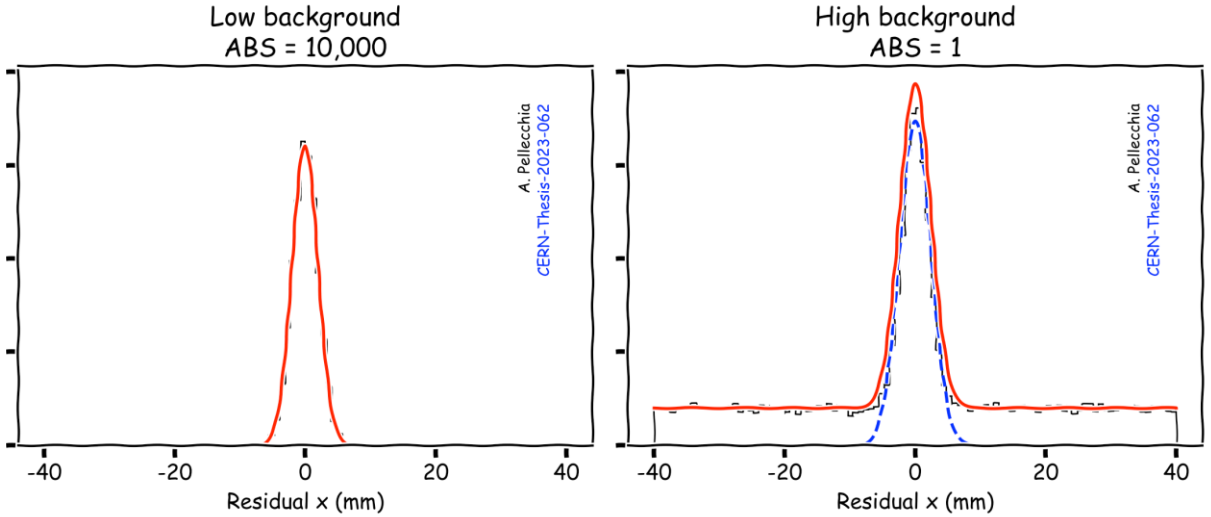
July 2022





1st TB under irradiation @ GIF++
4 ME0 modules – 50% instrumented

- GIF++ provides ~12* TBq ^{137}Cs source + SPS H4 beam
  - Gamma energy: E_γ = 662 keV – Compton scattering
  - Average energy deposit of Compton electron ~5 keV
  - Set of source filters – attenuation factor (AF) 1 – 46,000
- Setup: 2 ME0 protos + 2 Triple-GEM trackers (400 μm)
  - ME0 prototypes only instrumented with electronics for 50%
  - Hit residuals ME0 prototype w.r.t. measured track

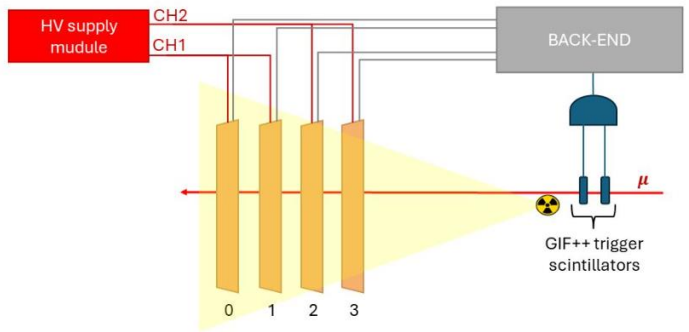


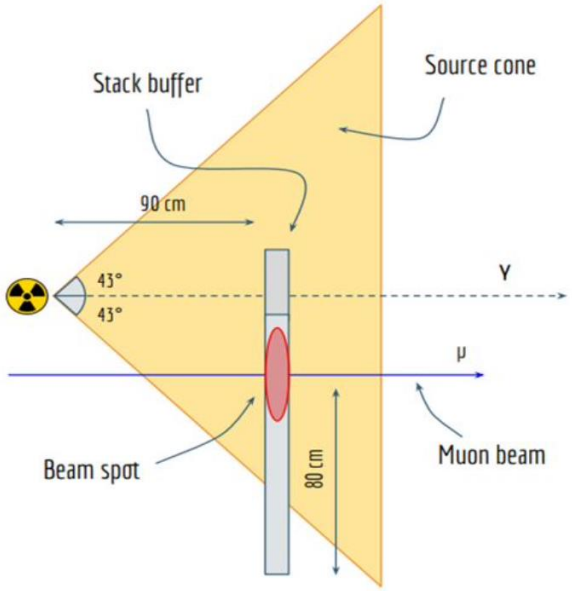
Sketch based on Figures in Master Thesis A. Pellecchia CERN-Thesis-2023-062

ME0 Module Efficiency under irradiation

at the CERN Gamma Irradiation Facility - GIF++

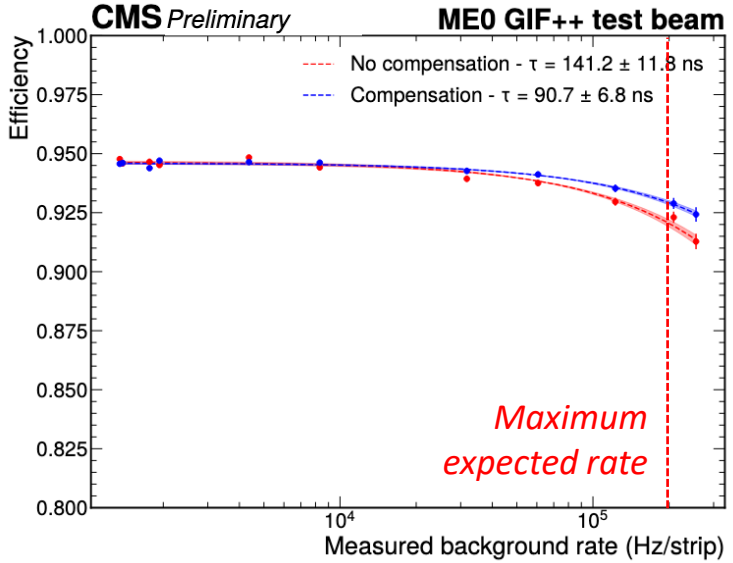
July 2022

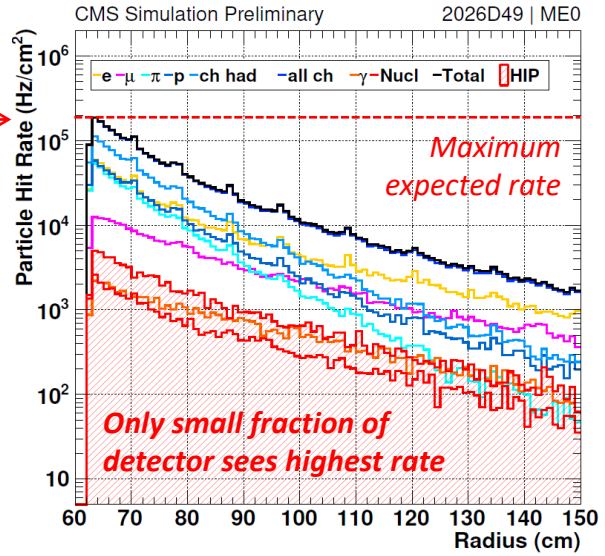




1st TB under irradiation @ GIF++
2 ME0 modules – 50% instrumented

- GIF++ provides ~12* TBq ^{137}Cs source + SPS H4 beam
  - Gamma energy: E_γ = 662 keV – Compton scattering
  - Average energy deposit of Compton electron ~5 keV
  - Set of source filters – attenuation factor (AF) 1 – 46,000
- Setup: 2 ME0 protos + 2 Triple-GEM trackers (400 μm)
  - ME0 prototypes only instrumented with electronics for 50%
  - Max expected Rate (Fluka/GEANT): 200kHz/cm^2 at lowest Radius



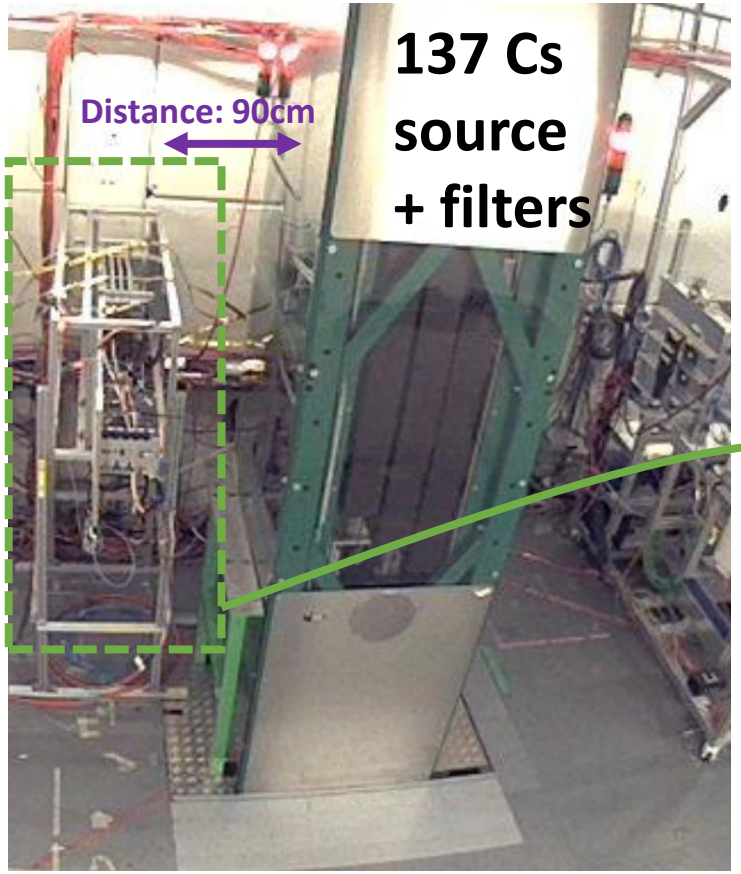


A. Pellecchia - CERN-Thesis-2023-062

ME0 Stack Efficiency under irradiation

at the CERN Gamma Irradiation Facility - GIF++

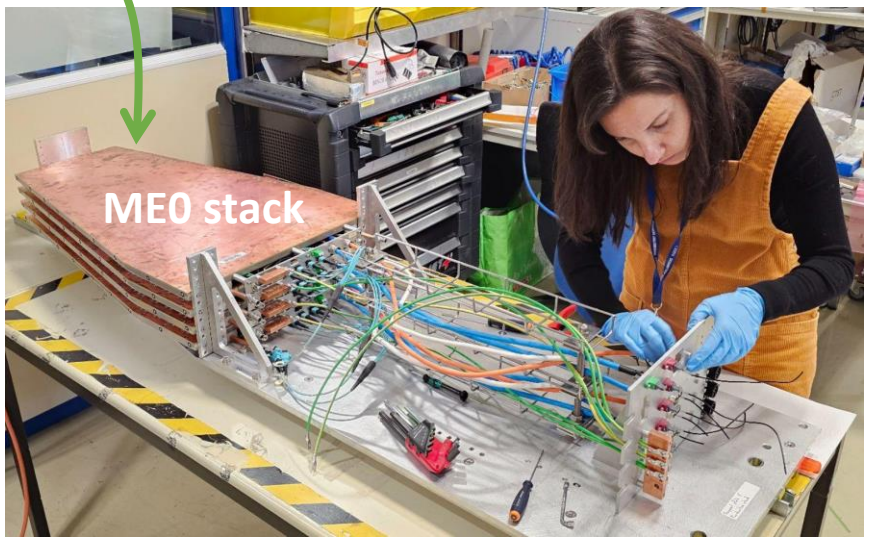
July 2023

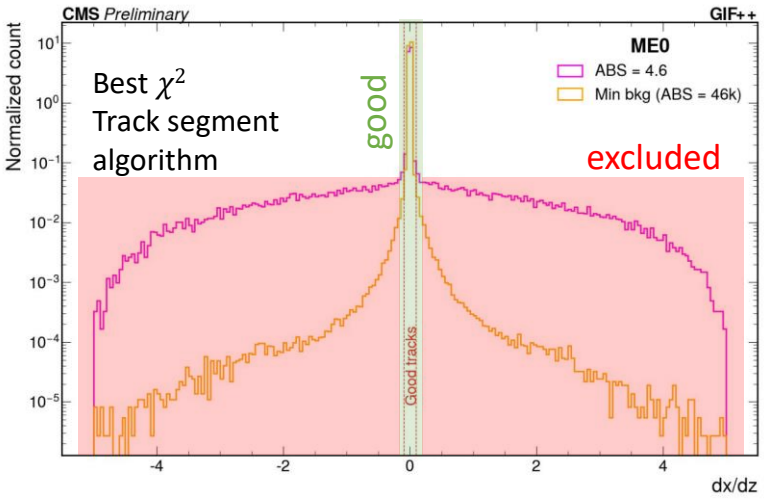


1st ME0 Stack @ GIF++

- **Irradiated up to 150 kHz/cm²**

- Setup: ME0 Stack in front of GIF++ source (90cm)
  - July 2023: 4-layer stack – 50% instrumented
  - July 2024: 6-layer stack – 100% instrumented
- No beam telescope
  - Limited by backend & Issues with noise on the tracking dets
  - Tracking by stack itself: segment fit using N-1 layers
  - Selection of good tracks with -0.1 < dx/dz < +0.1

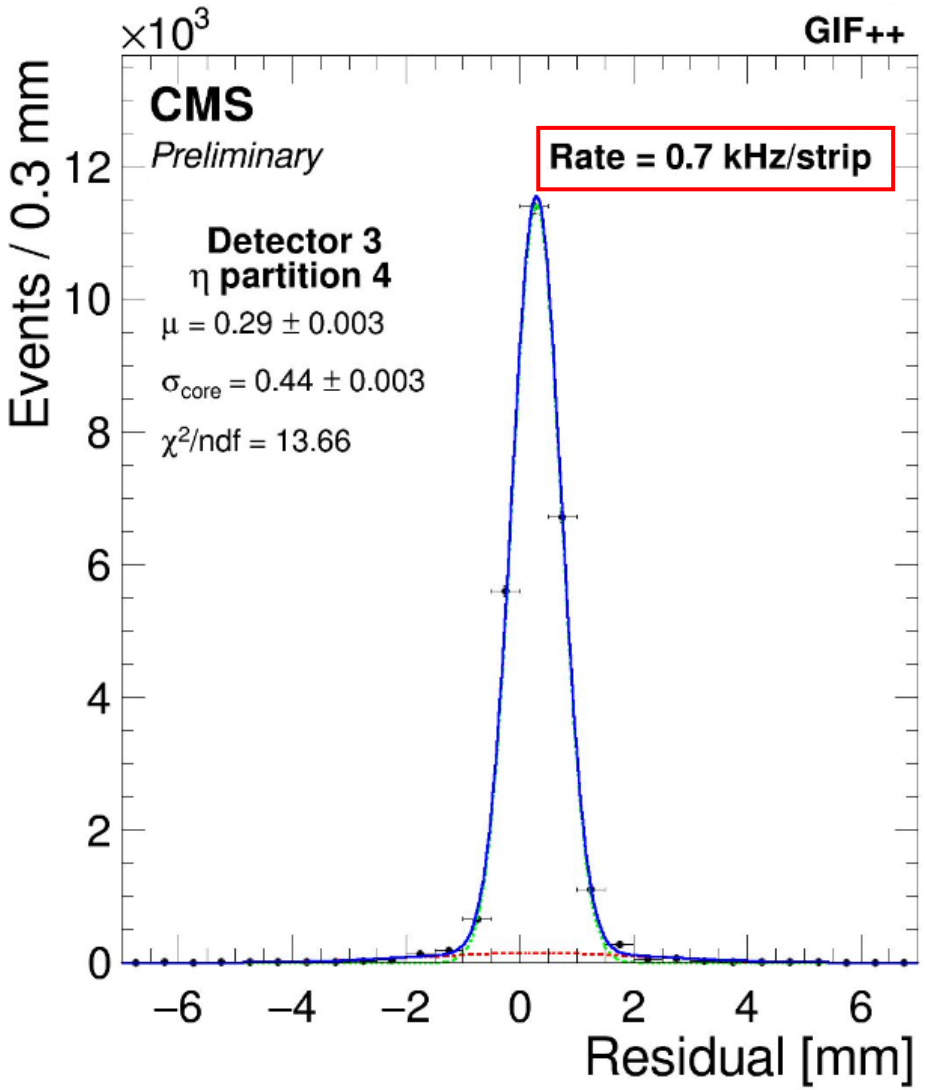


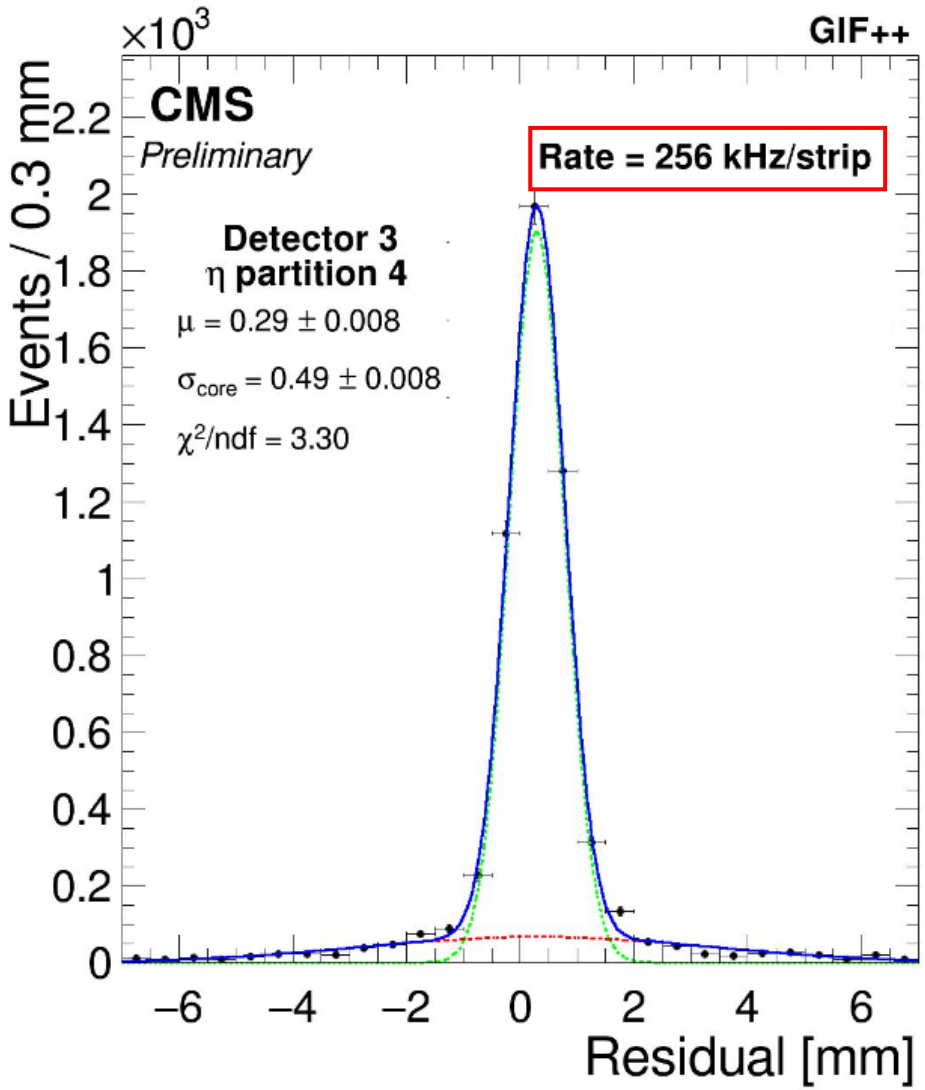


CMS-DP-2024-119

MEO Stack Efficiency under irradiation

at the CERN Gamma Irradiation Facility - GIF++





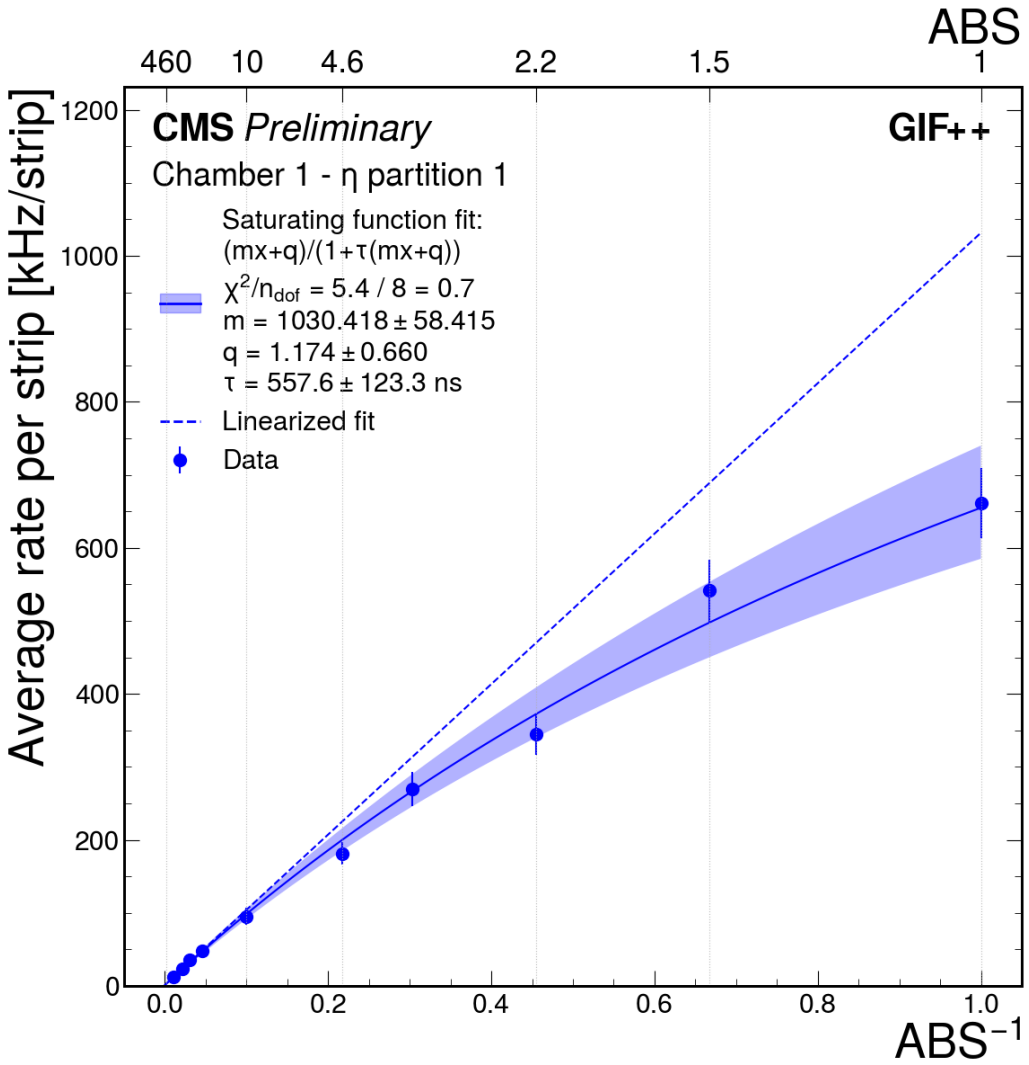
Track hit residual distribution*

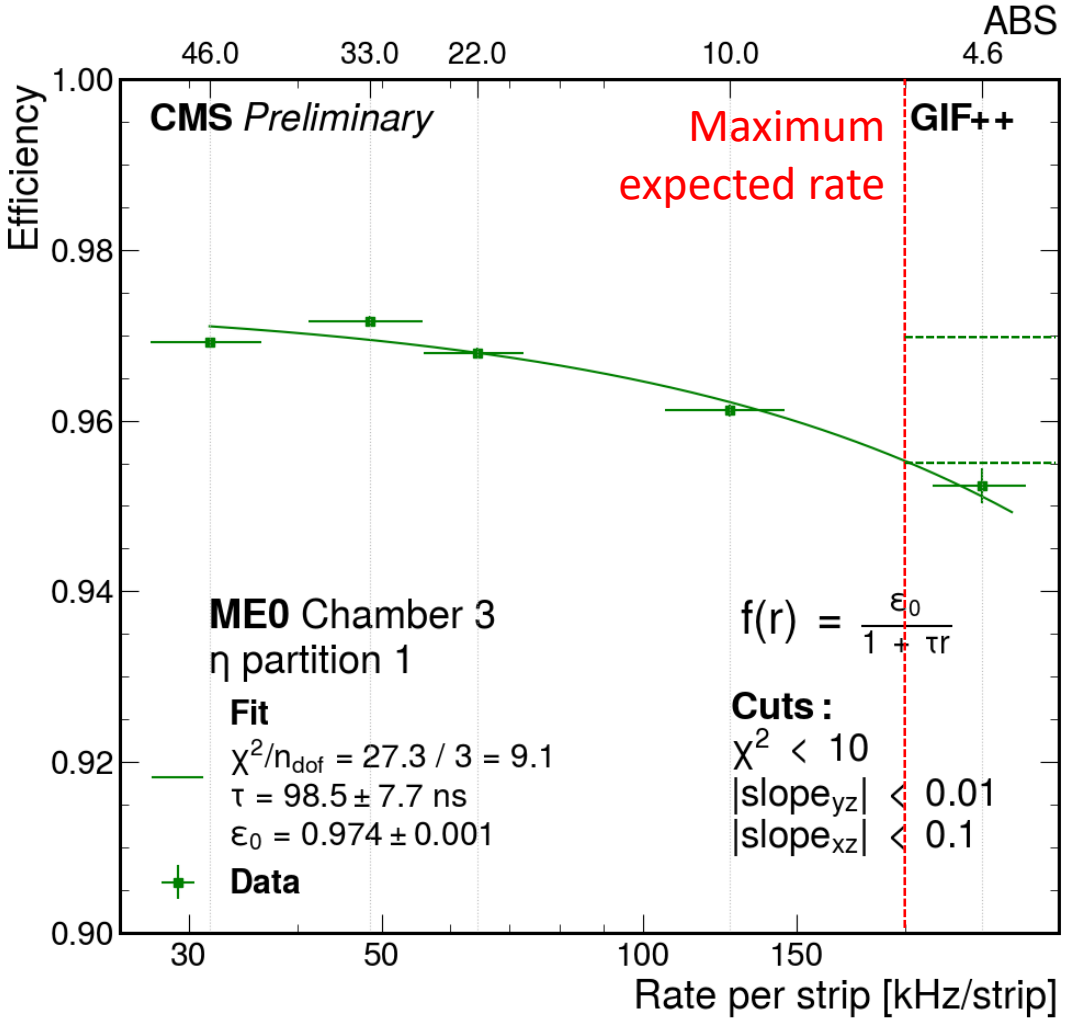
** Considering only closest rechit to the track*

CMS-DP-2025-XXX

ME0 Stack Efficiency under irradiation

at the CERN Gamma Irradiation Facility - GIF++





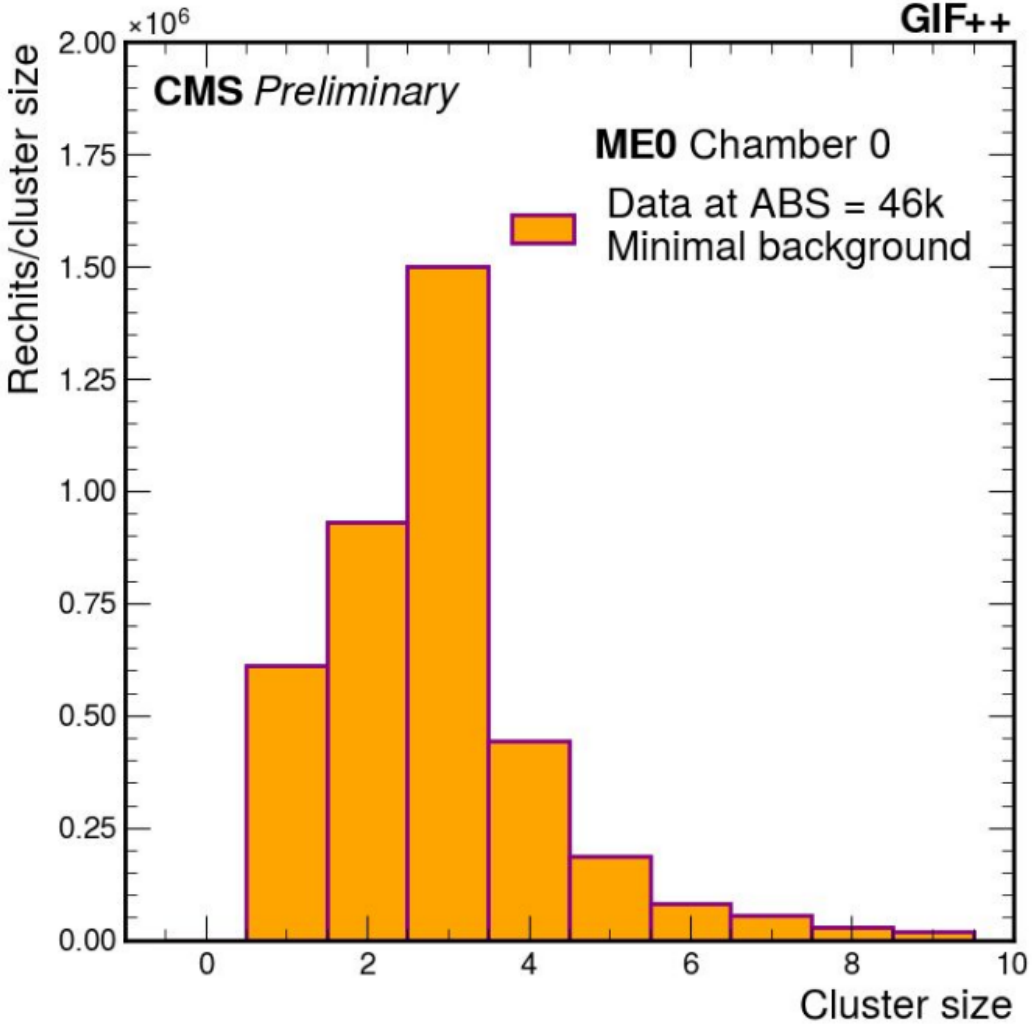
Source rate scan

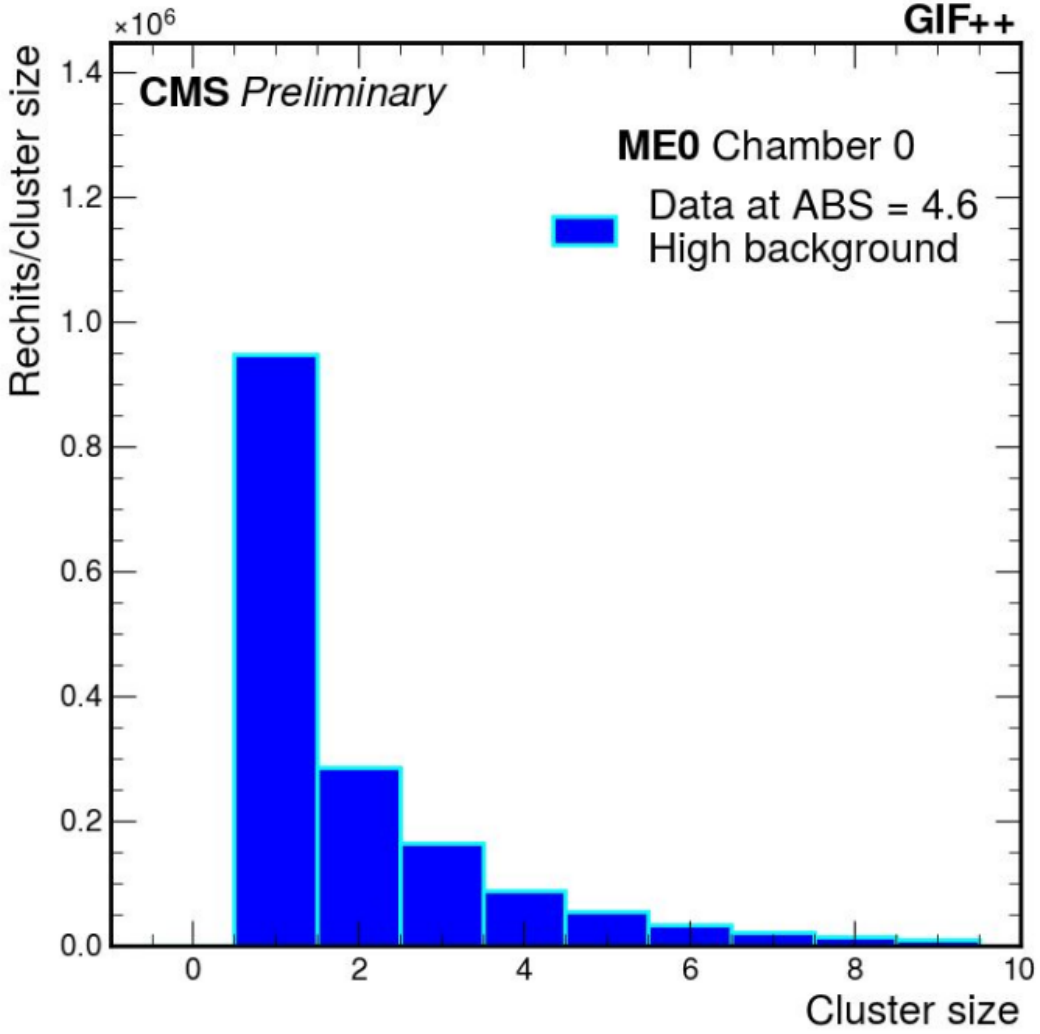
Efficiency as function of Rate

CMS-DP-2024-119

ME0 Stack Efficiency under irradiation

at the CERN Gamma Irradiation Facility - GIF++



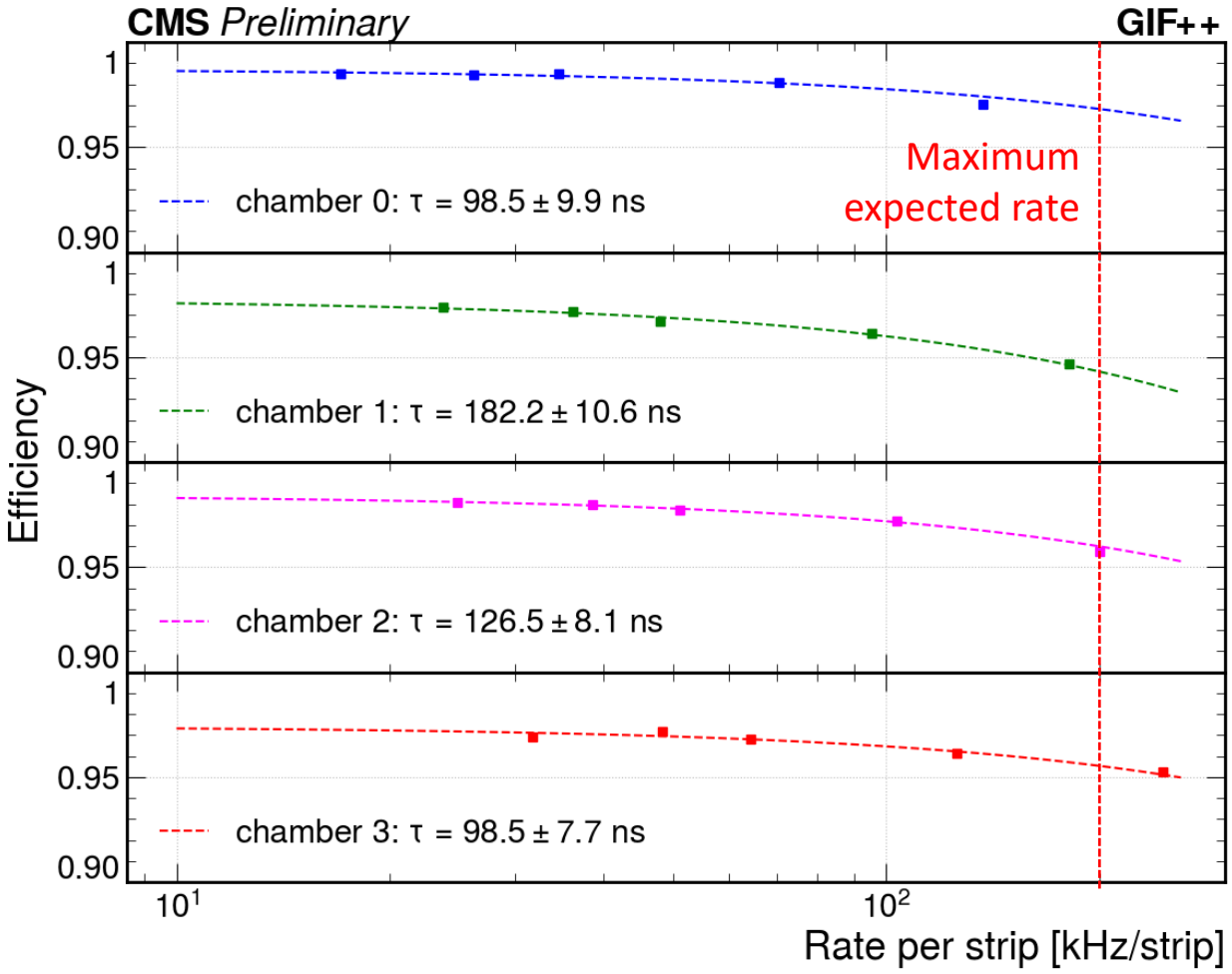


Clustersize Muon hits

Clustersize Background hits

MEO Stack Efficiency under irradiation

at the CERN Gamma Irradiation Facility - GIF++



Efficiency as function of Rate

For the 4 modules inside the stack

Dead time ranges from 100-180ns.

- in agreement with the hypothesis that the dominant contribution of the dead time of the chamber is that of the VFAT3s (400ns – 1us)
- Cluster size lowers effective deadtime / hit to 100-180ns
- Dead time VFAT3 asic depends on E_{dep} and detector gain

CMS-DP-2024-119

© Pixabay Content License

MEO Performance measurements:

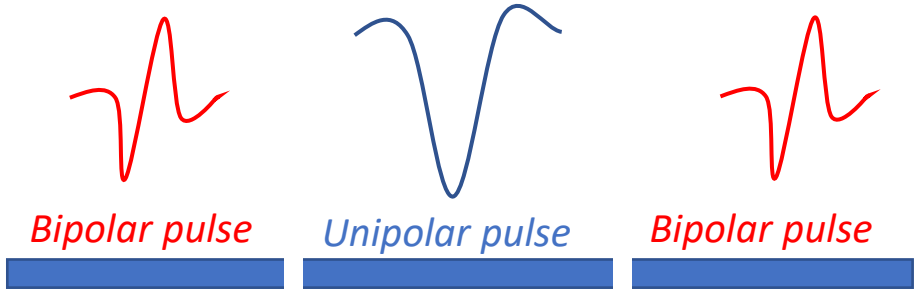
I. GEM Telescope Performance

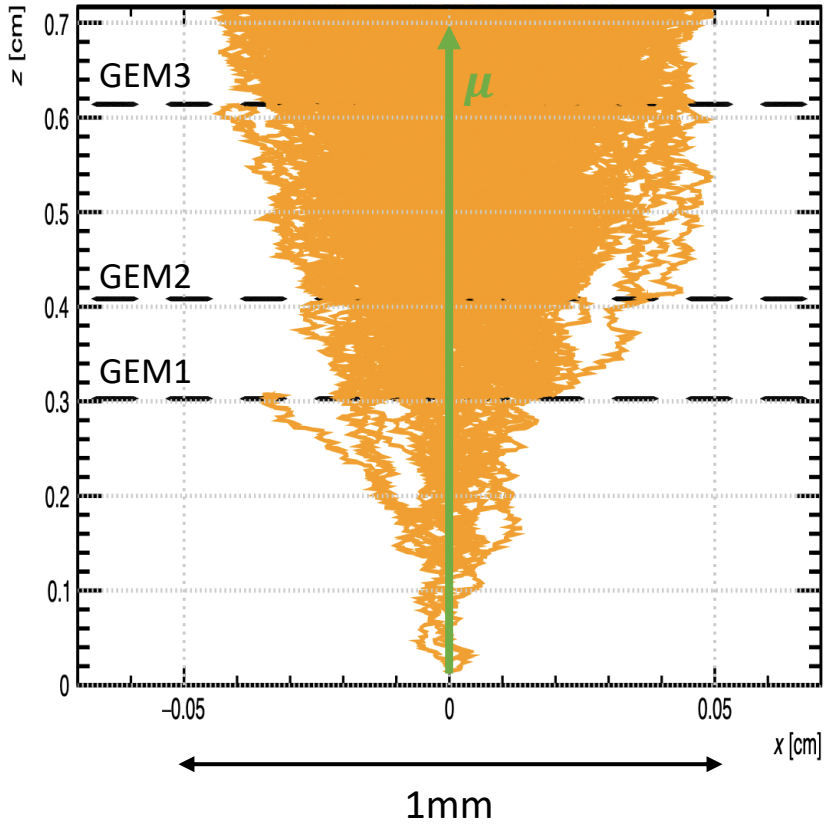
II. Efficiency & Rate-capability

III. Time Resolution

Time resolution of the ME0 detector

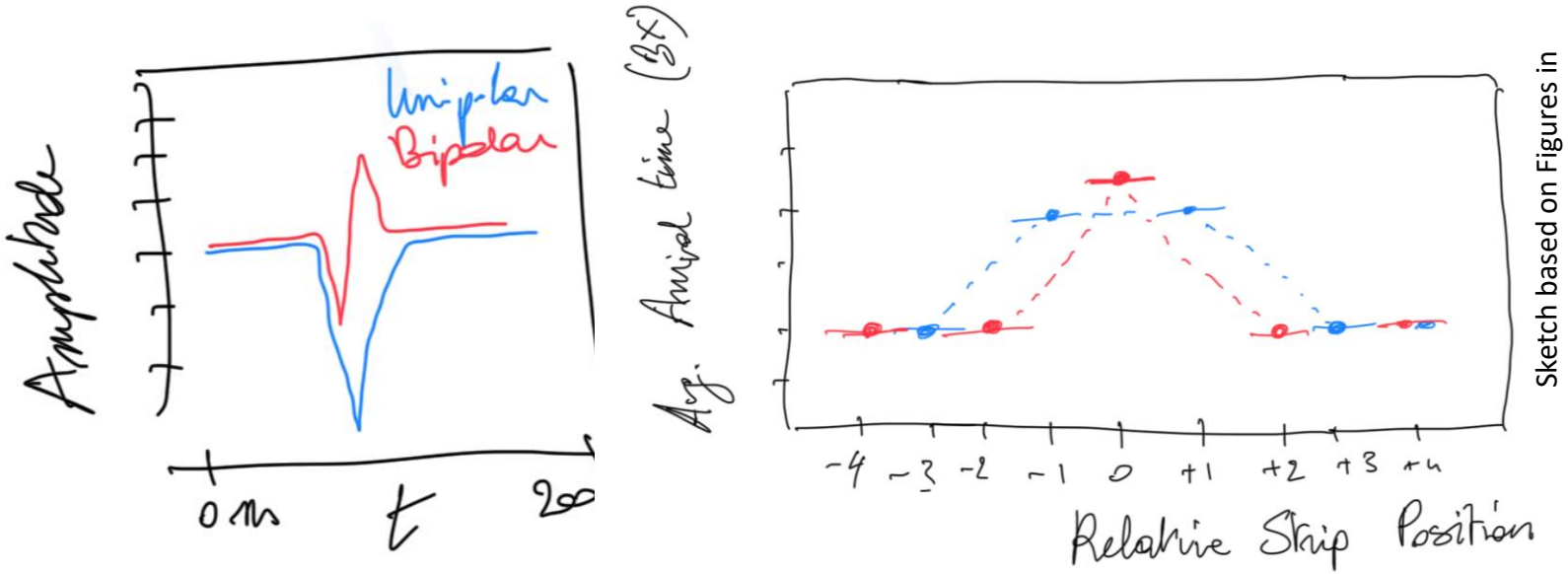
Timing measurements with cosmic muons and muons from beams





- ME0 trapezoidal strip pitch varies 0.6 – 1.2mm
- Spatial extend electron avalanche ~1mm
- Typical clustersize 1.6 – 3.0
- Previously: $t_{rechit} = \langle t_{strip} \rangle \Longrightarrow \sigma_t$ = 18-20 ns
  - *Mix of unipolar & bipolar signals lead to deterioration σ_t*
- Now: $t_{rechit} = \max\{t_{strip}\} \Longrightarrow \sigma$ = 10-12 ns

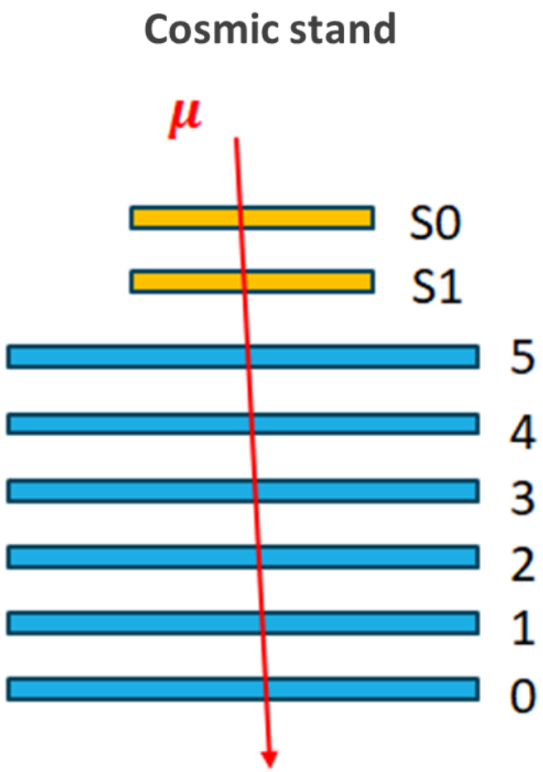
Avg arrival time w.r.t position

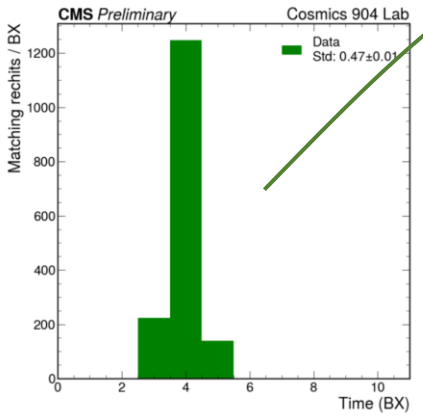


Sketch based on Figures in Master Thesis F. Nenna CERN-Thesis-2024-114

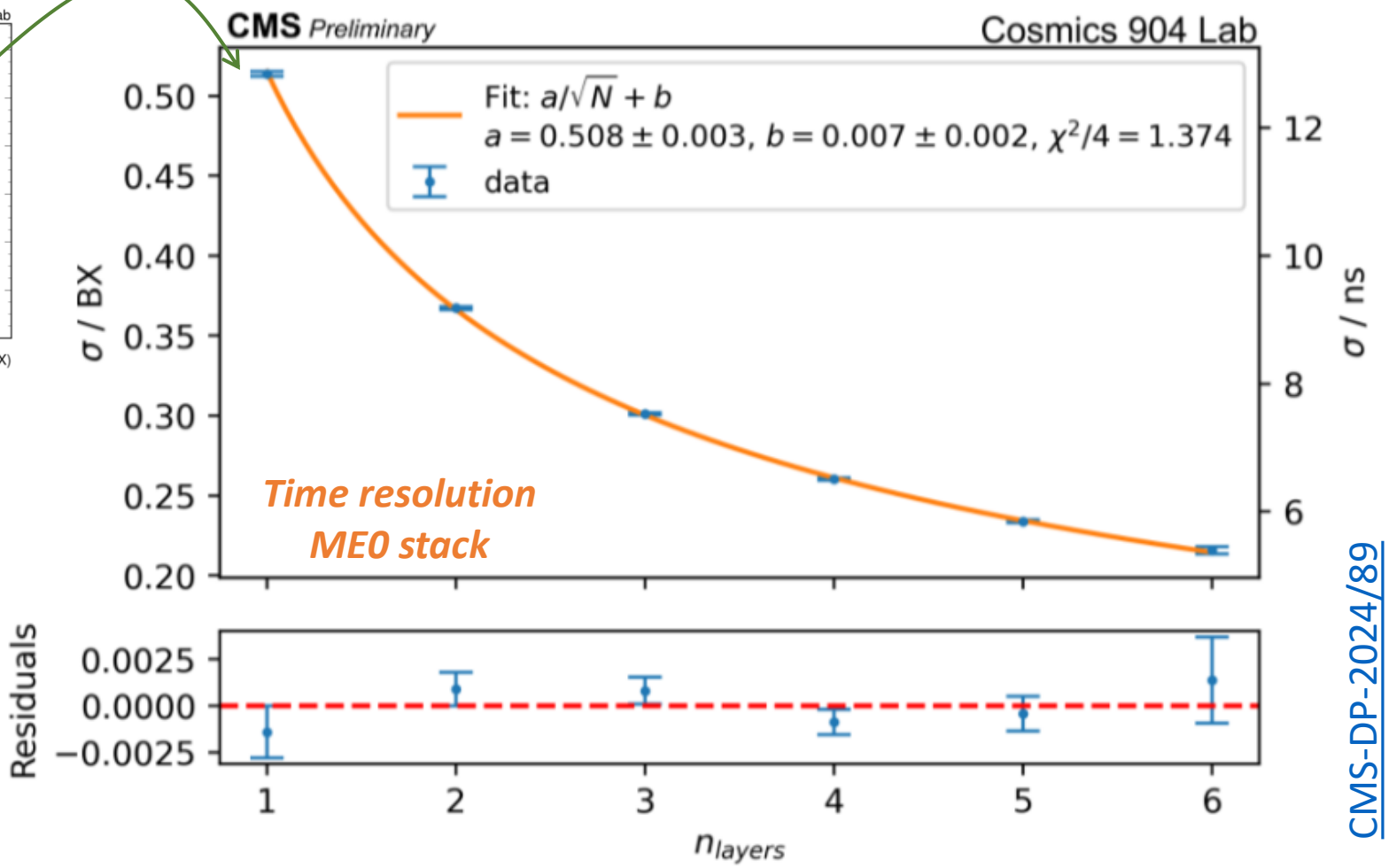
Time resolution of the ME0 detector

Timing measurements with cosmic muons





Time resolution single layer



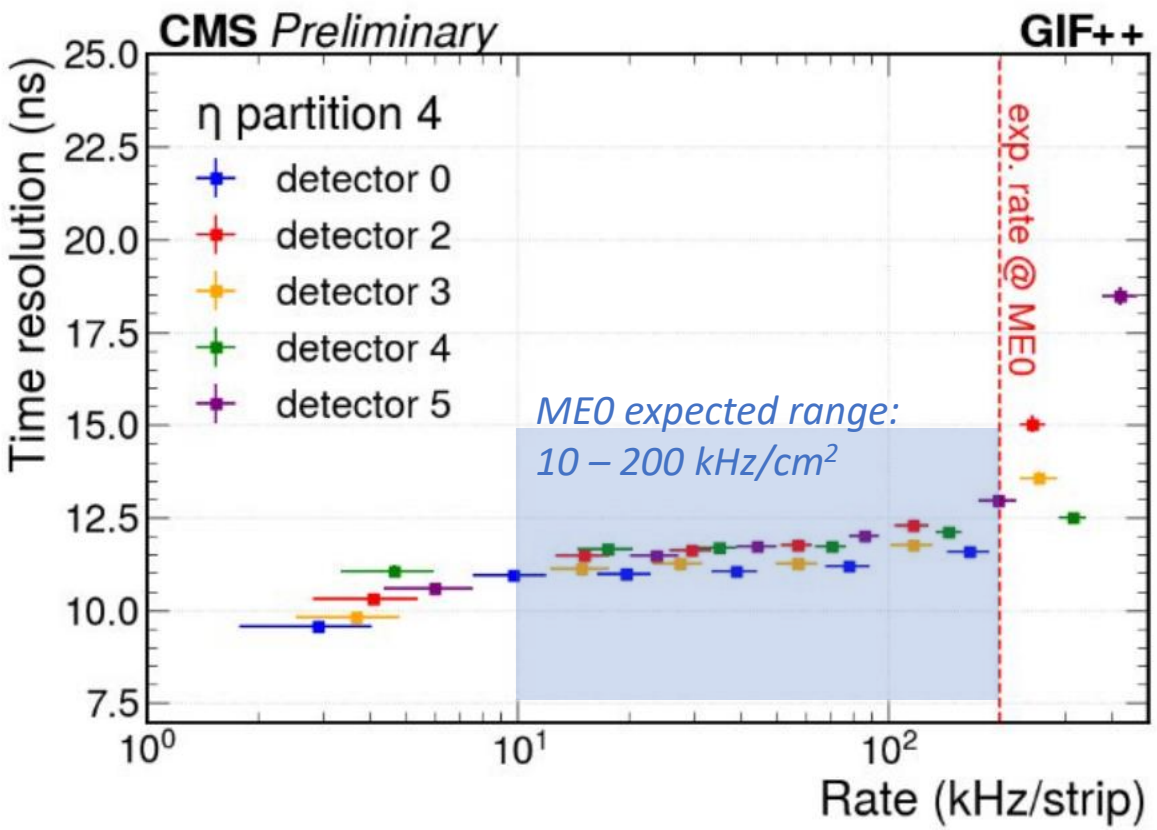
Time resolution ME0 stack

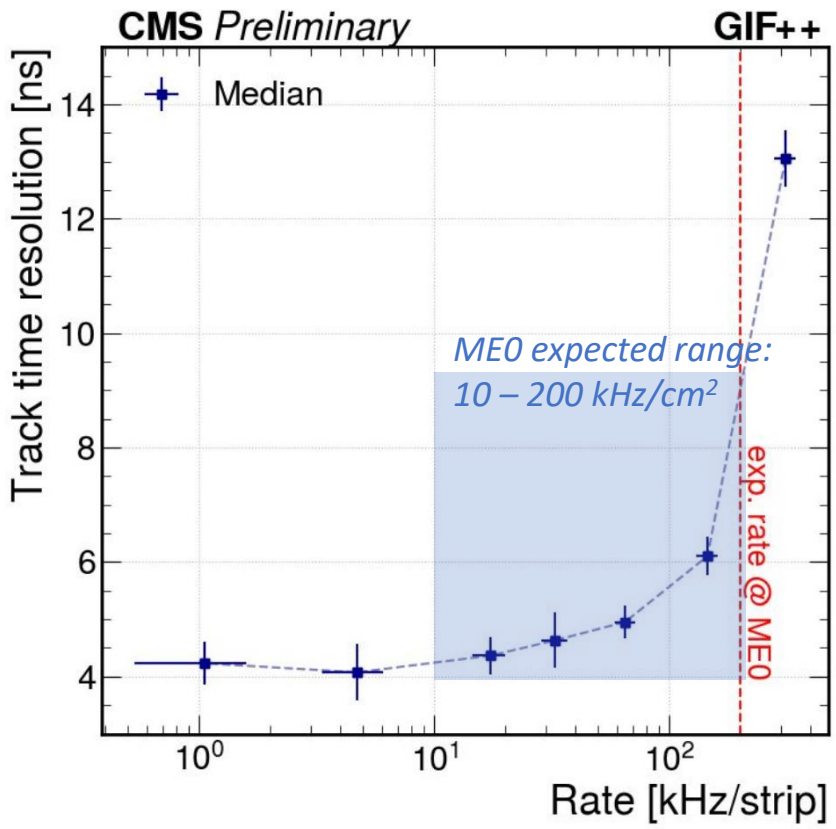
CMS-DP-2024/89

Time resolution of scintillator coincidence (2 ns) not subtracted

Time resolution of the ME0 detector

Timing measurements with beam and under irradiation at GIF++





- **Time resolution of 5 modules at GIF++**
  - *Slightly different rates measured in different layers of the stack due to opening angle & shielding*
  - *Dashed line indicates expected max rate (at high η)*

- **Time resolution of muon track**
  - *Arrival time is computed as median of arrival times of reconstructed hits – avg gives similar results*

CMS-DP-2025/XXX

Conclusions

the work is not finished yet

Testbeams were widely used in the design and R&D phase

- *Several successful test beams of large-size Triple-GEM prototypes 2010-2014*
- *Demonstrated feasibility of the project – TDR & Approval Phase-1 GEM (GE1/1)*
- *However never demonstrated Performance Final Detector + Final Electronics*

We restarted testbeams in 2021

- *To demonstrate the performance of Phase-2 Detectors + Phase-2 Electronics*
- *4 years of intensive testing of ME0 detectors at SPS H4 & GIF++*
- *Demonstrated Eff, Rate-cap, Spatial res, Time res, Clustersize up to 200 kHz/cm^2*
- *Tools & SW developed during Test beams now deployed in P5 and Lab QC tests*

Acknowledgements

to all who are invisibly contributing to these results …

- *"The measurements leading to these results have been performed at the EHN1 / North Area Testbeam (H4) at CERN, Switzerland."*
- "Some of these measurements have also been performed at the GIF++ irradiation facility at CERN, Switzerland."
- *"We would like to thank the RD51 / DRD1 collaboration for their precious help and for hosting us during their Testbeam slots in H4."*

MEO Performance measurements:

I. Telescope Performance

II. Efficiency & Rate-capability

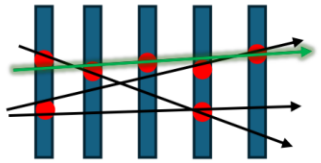
III. Timing

IV. Back-up

Base-road Track Segment Reconstruction

evolution of the track segment reconstruction in Test Beam Analysis

~~Current~~ **algorithm:** Best χ^2



Evaluate χ^2 of **each** N_{layers}-point combination:

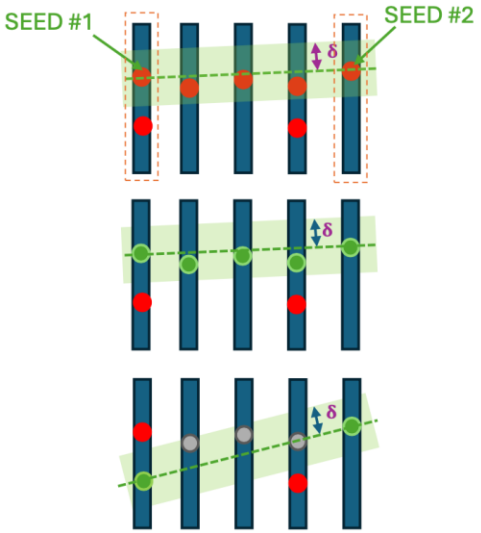
- Nr. of lines ~ $\prod_{i=0}^{N_{layers}-1} n_i$, where n_i is the number of hits in the i-th layer

☺ For small background rate

☹ Very slow when reconstructing tracks at large background rate

→ current limitation: below ~200 kHz/strip → Computational limitation!

Alternative method: Base road[1] ← *official one used in CMSSW*



The steps are the following:

1. Consider the hits in the two extreme layers (first and last);
2. Take one pair of hits, one from the first and one from the last layer, and build the imaginary line connecting the two hits
   1. Consider a «base road» region centered on the imaginary line and with a thickness **δ**
   2. For each of the inner layers, within the base road take the rechit closest to the seeding line
   3. Fit with a linear function → track
   4. If the χ^2 is larger than a threshold (χ^2_{thr}) remove the farthest hit from the track
   5. Save (track, χ^2) and flag the rechits used in order not to reuse them in the reconstruction of the next tracks
3. Repeat the procedure for all the possible pairs ($n_{rechit,layer1} \times n_{rechit,layerN}$)
4. (+) *Take the track with the lowest χ^2 among all the reconstructed one*

Best χ^2 algorithm used 2021-2023
Base-road algorithm used 2024

Base-road:

- Default in CMS SW, used for CSC
- Better background discrimination
- Computationally faster
- Succeed in reconstructing tracks even at highest background rate

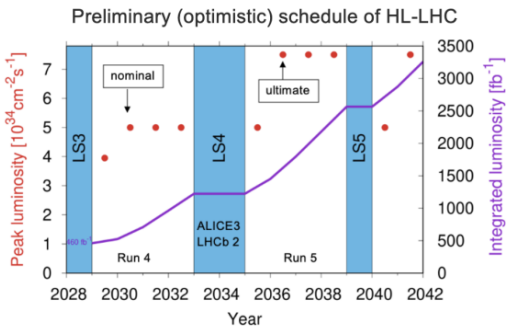
https://www.epj-conferences.org/articles/epjconf/pdf/2016/03/epjconf_mmcp2016_02023.pdf

Upgrade of the CMS Muon System

prepare CMS for unprecedented high luminosity at a hadron collider

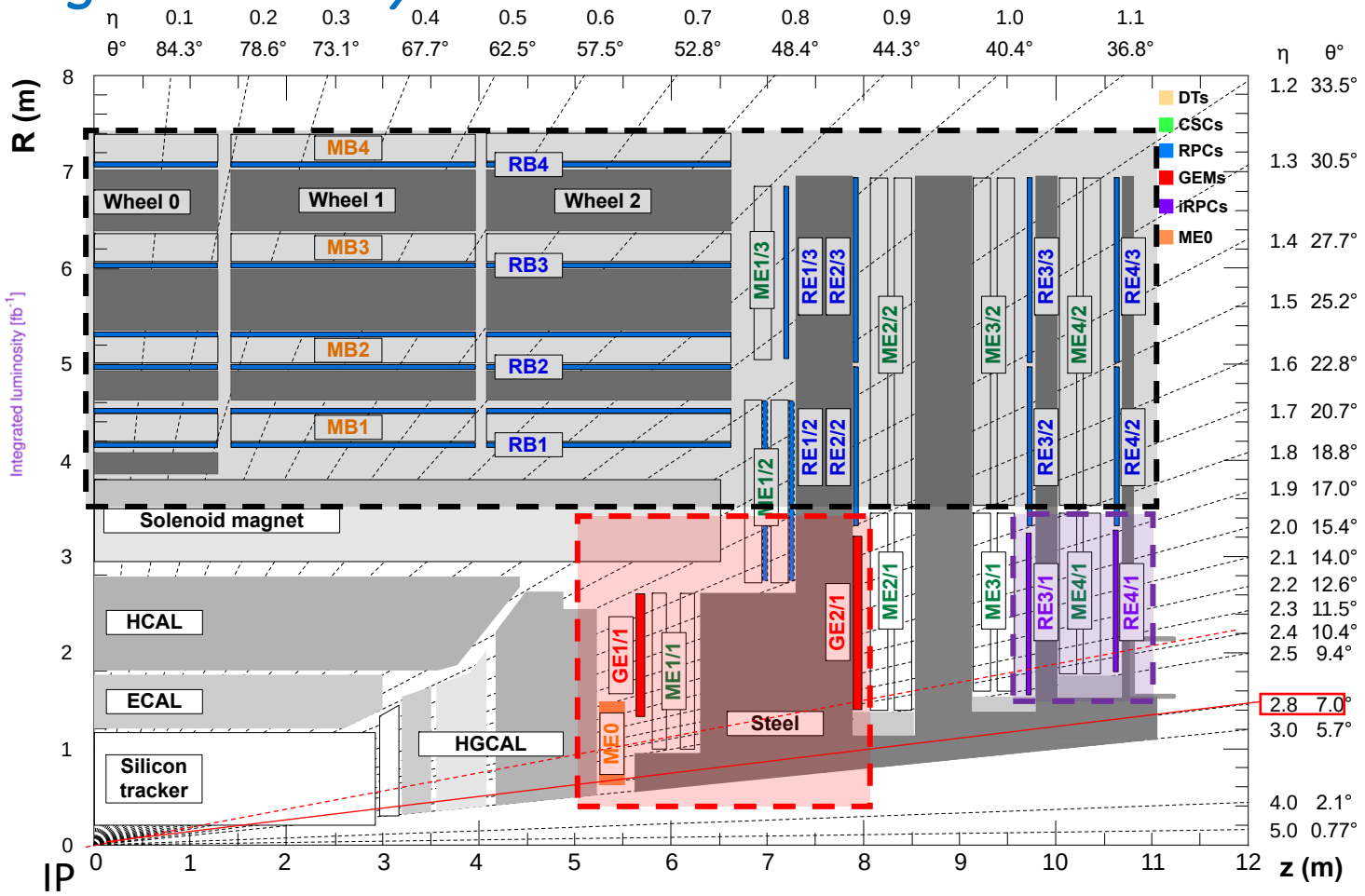
In the High-Luminosity Phase of the LHC (HL-LHC) (2029 - 2042) LHC will provide collisions at 5 – 7.5 times the original design luminosity (1E34cm^{-2}s^{-1})

- Integrate 3 ab^{-1}
- HH, %-level measurement of Higgs-boson couplings



To cope with the high rate Muon System upgrade:

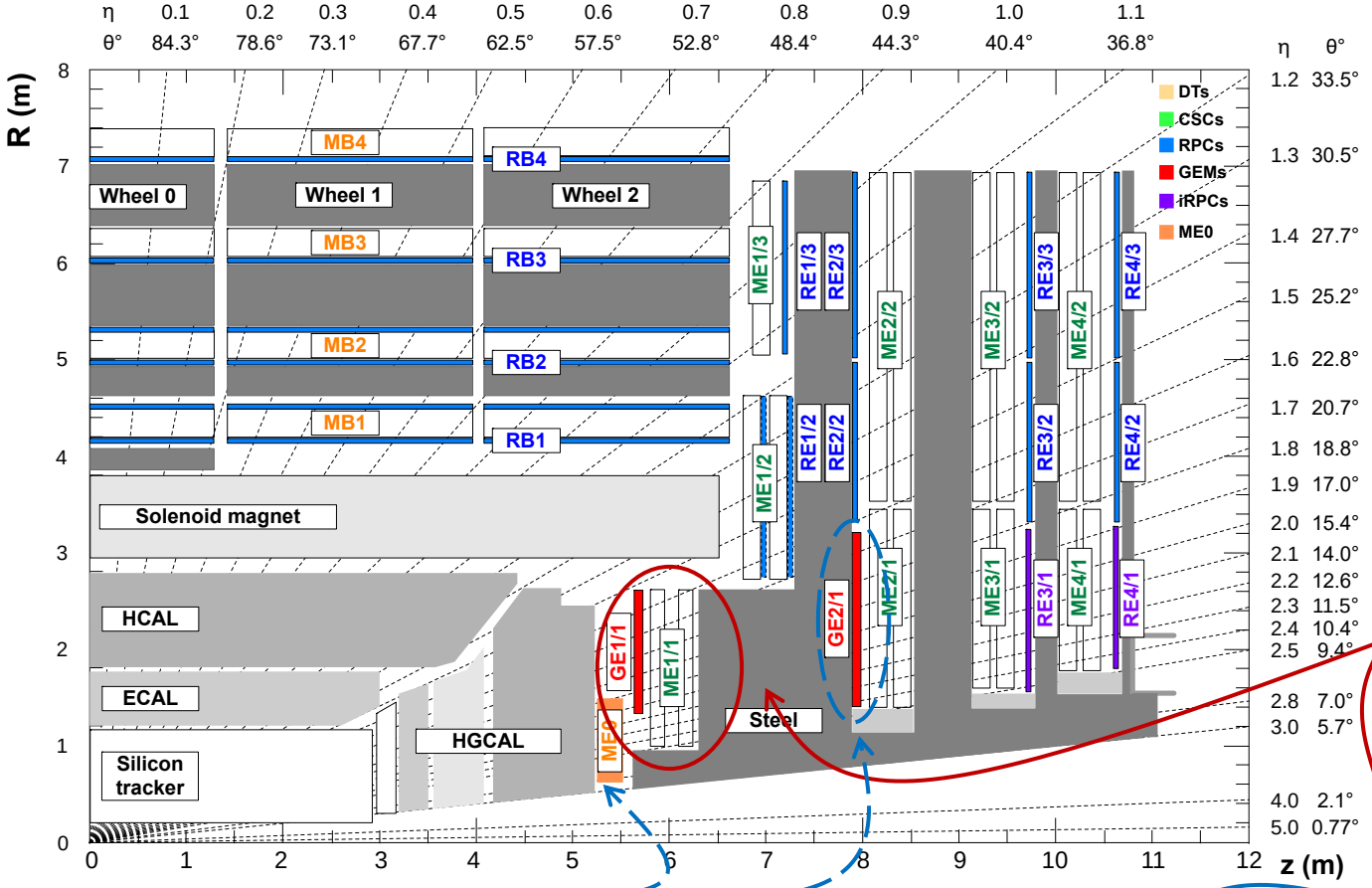
- **Improved electronics for existing CSC, DT & RPC:**
  - Readout w/ high BW, exploit σ_t
  - Longer trigger Latency 12us
  - Higher L1A rate: 100 → 750kHz
- **Gaseous Electron Multiplier (GEM) detectors** for precise (150um) muon reconstruction and triggering in B-field and high background (few kHz/cm^2 – 100 kHz/cm^2 rate)
  - GEx/1 : $1.6 \leq \eta \leq 2.4$ and ME0: $2.0 \leq \eta \leq 2.8$
  - 432 chambers, ~150 m^2 - 1.2M channels



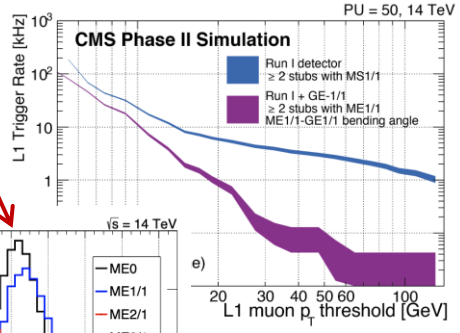
- **Improved Resistive Plate Chambers (iRPC)** for fast triggering (1.5-2ns) and redundant tracking (<1cm) in medium background (< ~1kHz/cm^2)
  - RE3/1 and RE4/1: $1.8 \leq \eta \leq 2.4$ - 72 chambers, ~100 m^2 - 7k channels
- **Gas recuperation plant + search for GWP friendly gas mixtures (for operation > 2033)**

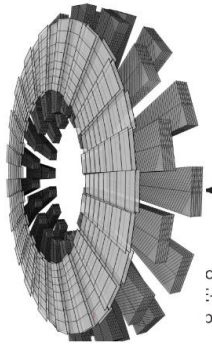
Upgrade of the CMS Muon System

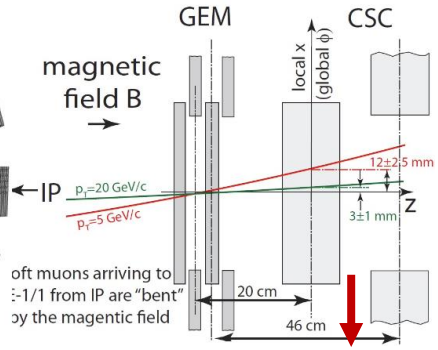
prepare CMS for unprecedented high luminosity at a hadron collider



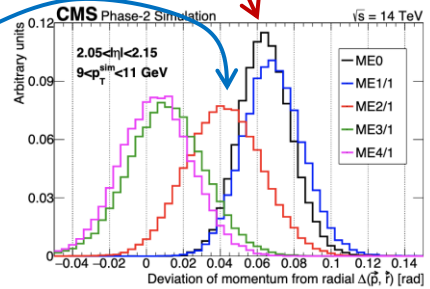
- Improved electronics for existing detectors:
  Drift Tubes, *Cathode Strip Chambers* & *Resistive Plate Chambers*
  - Deal with: Increased L1A (750kHz), latency (12.5us),…
- Instrument Forward spectrometer
  - Highest background – fewest measurements
  - Reduce steeply increasing trigger rate at L1
  - Add Features:
    - *Trigger on Long-lived particles with improved RPCs*
    - *Trigger on Displaced Muons with GEM-CSC tracklets*
- **Phase-1 upgrade :: GE1/1**







- **Phase-2 upgrade :: GE2/1 & ME0**
  - GE2/1: Exploit good bending angle @ 2nd station
    Complement CSC & improve Trigger Primitive
  - ME0 extends coverage muon system up to $\eta \leq 2.8$



Increased Bending-angle leverage (20-45cm) improves p_T measurement at L1 Trigger and leads to Trigger rate reduction in high background

Timeline of the GEM upgrades in CMS

the past, the present and the future

2019	2020	2021	2022	2023
LS 2	LS 2	LS 2 / YETS	YETS: beam commissioning; intensity ramp-up; collisions 1200 bunches - luminosity production	YETS: beam comm; ramp; collisions 1200 bunches - luminosity production; ions; YETS

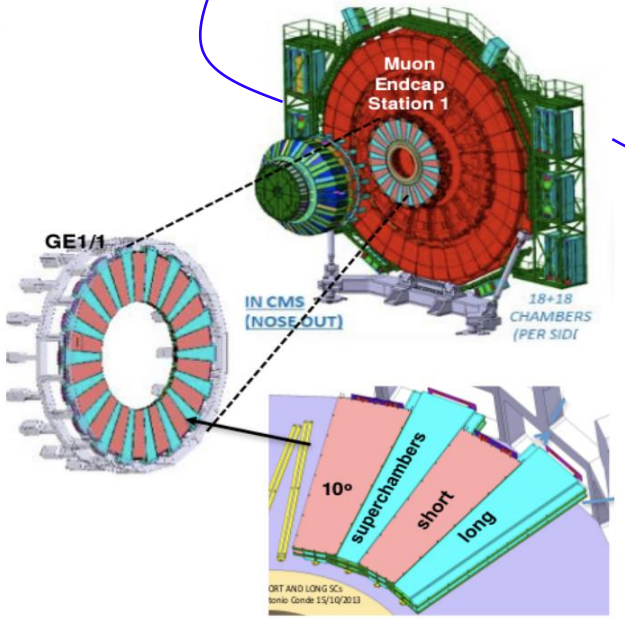
Installation GE-1/1

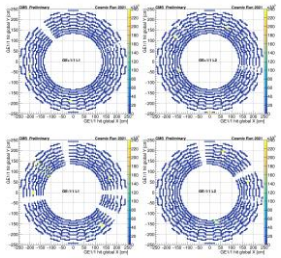
Installation GE+1/1

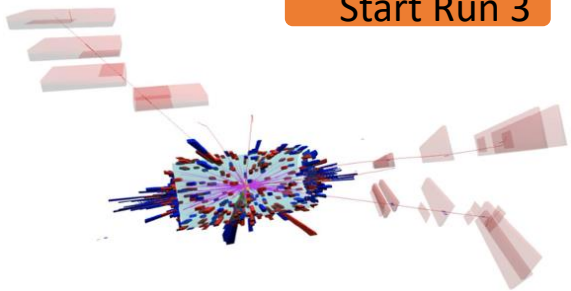
Cosmic Runs

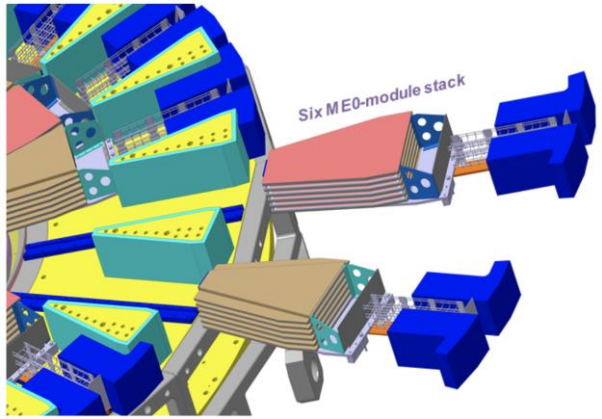
Start Run 3

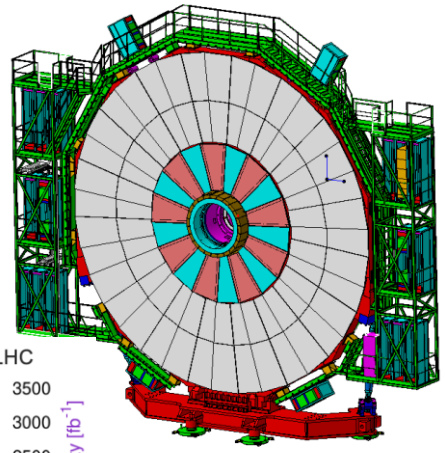
Installation GE-2/1

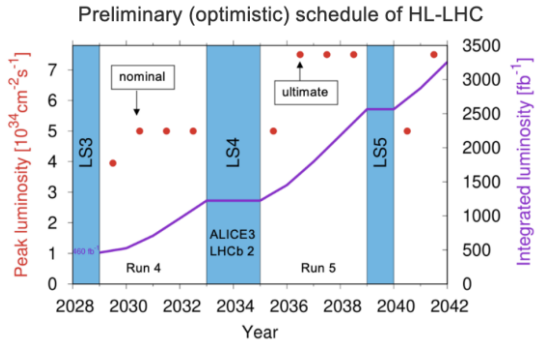












Post LS3
HL - LHC

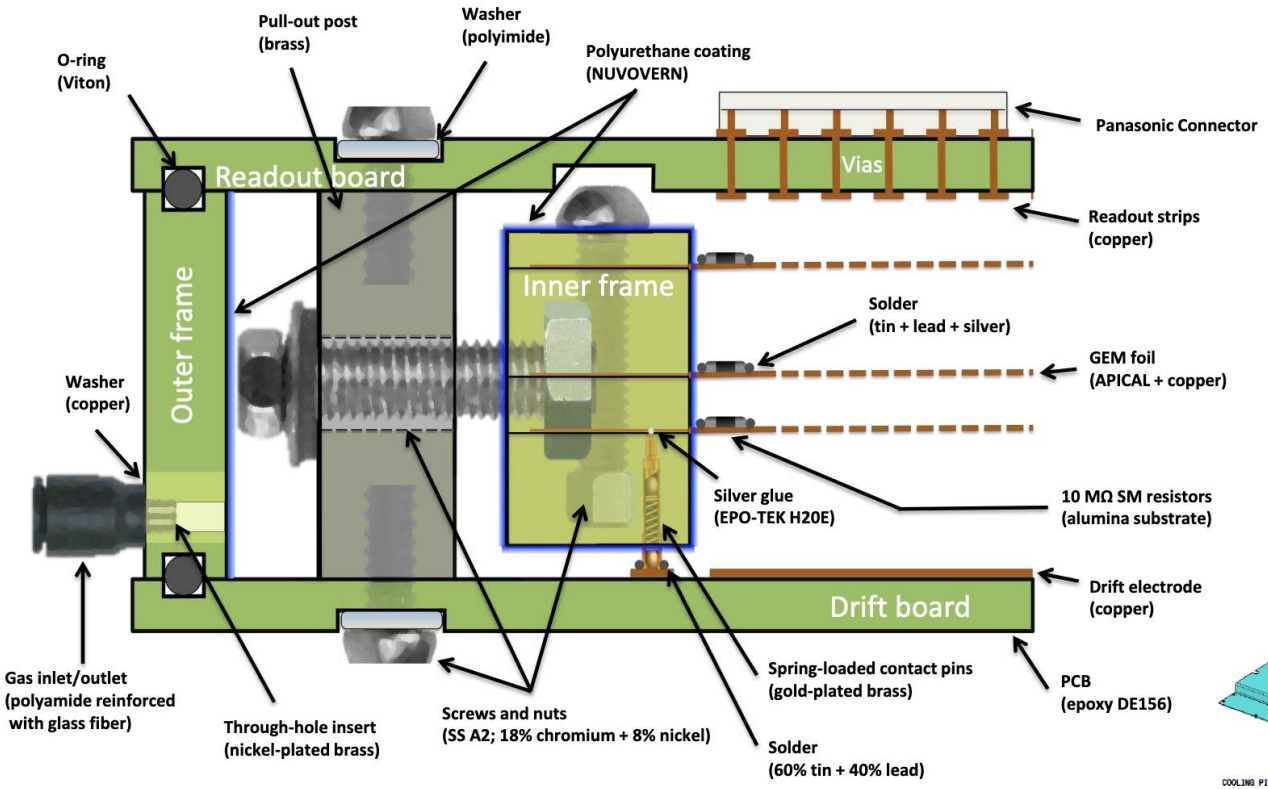
2024	2025	2026	2027	2028
YETS	YETS	LS 3	LS 3	LS 3

Installation GE+2/1

Instal ME0 in HGCAL

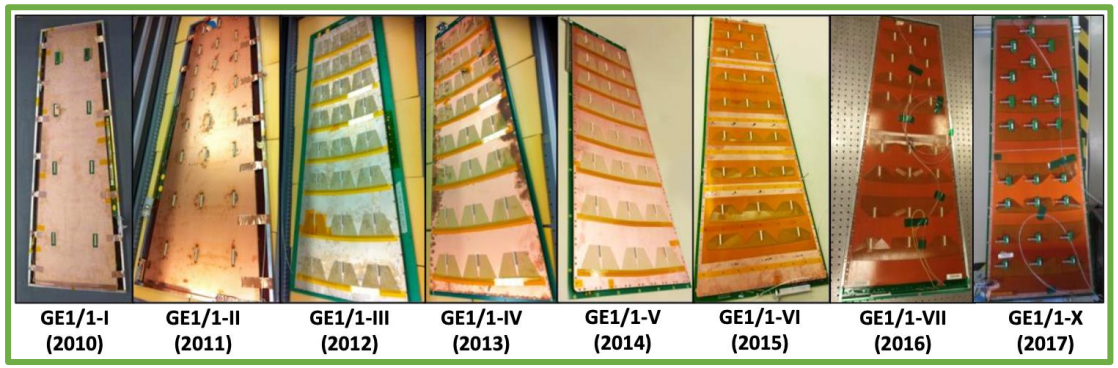
Commissioning & Cosmics

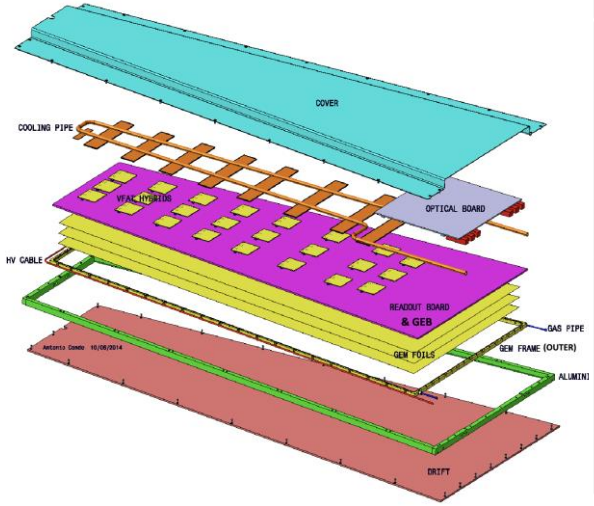
CMS GEM (GE1/1) Detector



- Construction Technique: Stretching, *(NS2 = no spacer, no tretching)*
- Gap config: 3/1/2/1 mm - Ar:CO2 70/30 – Gain = 20,000
- Spatial Resolution < 300 urad
- Rata Capability up to 10 kHz/cm^2
- Two types of Chambers:
  - Long ~4000 cm^2 (l x b_1/b_2: 121cm x 23/45cm)
  - Short ~3000 cm^2 (l x b_1/b_2: 106cm x 23/42cm)
- All Chambers have 24 η x φ sectors – 3072 R/O channels
  - Each sector 128 strips – read by VFAT3
  - Chamber has 8 η partitions
- Strip pitch 600um – 1200 um (460 urad)

Prototypes: 10 generations



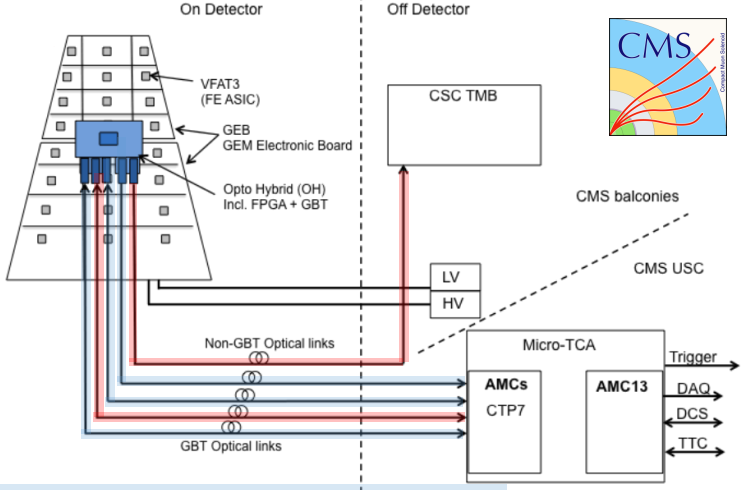


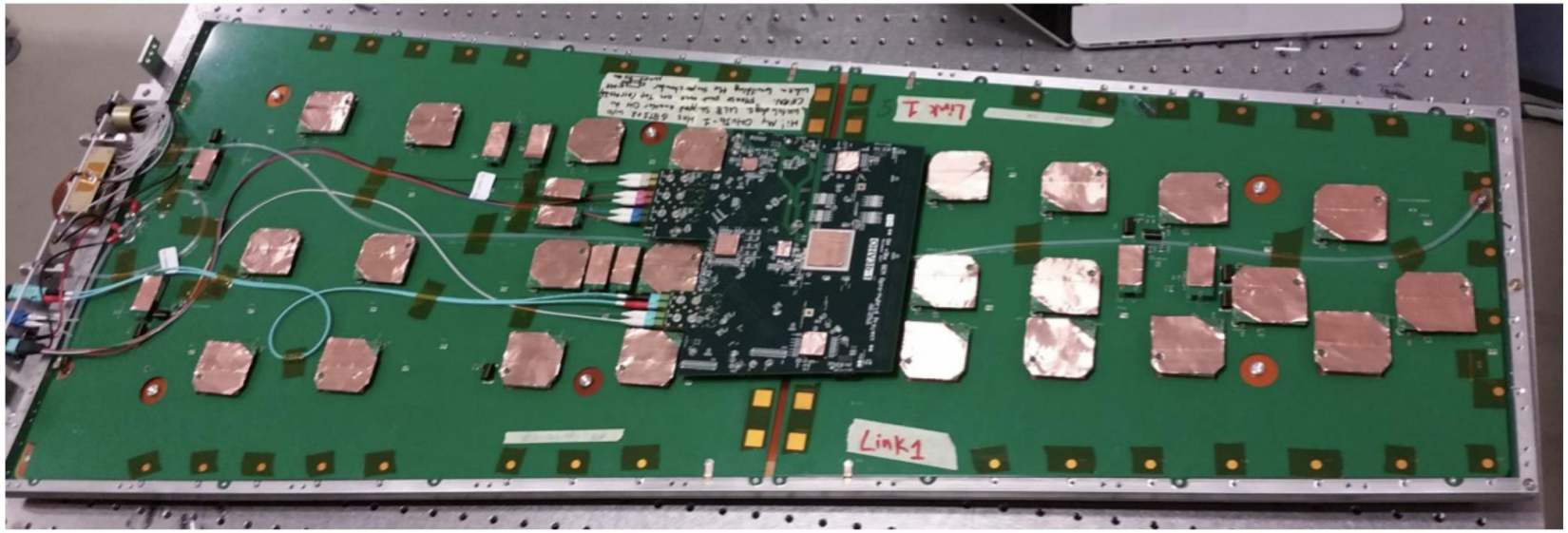
Specification / Parameter	GE1/1
Detector technology	Gaseous detector; micro-pattern gas detector (MPGD)
Charge amplification element	GEM foil (triple, cascaded, tensioned at ≈ 5 N/cm)
Number of chambers in overall system	144 (72 in each endcap)
Chamber shape (active readout area)	Trapezoidal; opening angle 10.15°
Active area overlap in adjacent chambers	2.6 mrad (corresponds to 5.7 readout strip pitches)
Short chamber dimensions (active vol.)	L: 106.1 cm (center line), W: (23.1 - 42.0) cm, D: 0.7 cm
Long chamber dimensions (active vol.)	L: 120.9 cm (center line), W: (23.1 - 44.6) cm, D: 0.7 cm
Total chamber thickness	D: 3.5 cm
Active readout area	0.345 m^2 (short ch.); 0.409 m^2 (long ch.)
Active chamber volume	2.6 liters (short ch.); 3 liters (long ch.)
Radial distance from beam line	130.2 cm (at inner edge of active readout area)
Geometric acceptance in η	1.61 - 2.18 (short ch.); 1.55 - 2.18 (long ch.)
Signal readout structure	Truly radial readout strips
Readout strip dimensions	230 μrad angular strip width; 463 μrad angular pitch
Number of η-segments in readout	8
Number of readout strips per η-segment	384
Number of readout strips per chamber	3,072
Counting gas mixtures	Ar/CO_2 70:30 or $Ar/CO_2/CF_4$ 45:15:40
Nominal operational gas flow	1 chamber volume per hour
Number of gas inlets	1
Number of gas outlets	1
Nominal HV applied to drift electrode	3200 V (Ar/CO_2); 4000 V ($Ar/CO_2/CF_4$)
Nominal operational gas gain	1-2 × 10^4
Demonstrated rate capability	100 MHz/cm^2

CMS GEM (GE1/1) Electronics

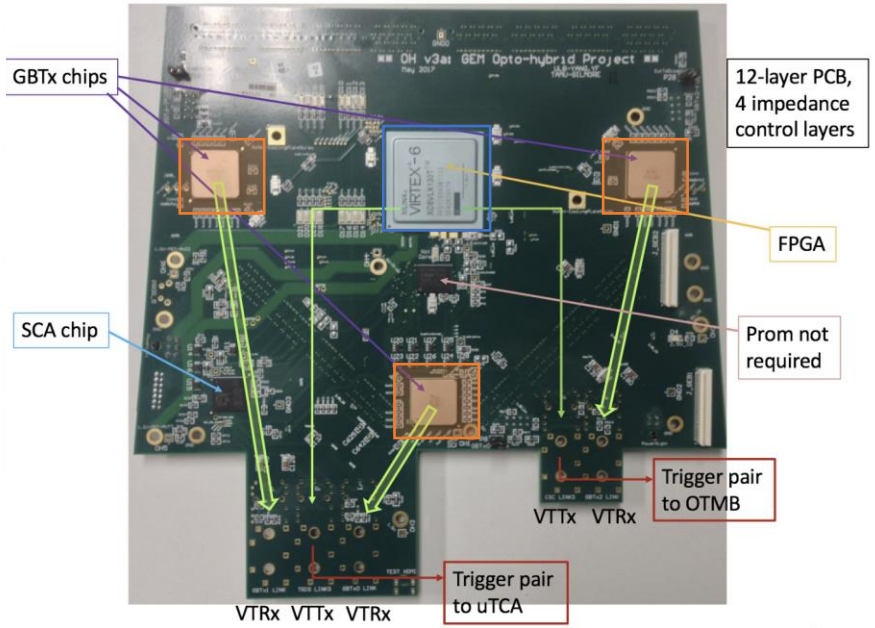
- **VFAT3 Front-End ASIC**
  - 128 ch – 320 MHz – ≥12.5us buffers
  - Trigger data = OR 2 strips
- **GEB = GEM Electronics Board** (8 layer, 1mm)
  - 2 PCBs to avoid long track lenghts
  - 1 power, 1 shield , 1 GND, 2 signal
- **FEAST DC-DC convertors** (#9, 1.2V, 2.5V, 3.2V)

- **Opto-Hybrid (OH) mezzanine card**
  - Xilinx Virtex-6 FPGA (promless)
    - *Only to send trigger data*
  - 3 Gigabit GBTx chips
    - *3 x Tracking & slow control (VTRx = bi-directional OL)*
    - *2 x Triggering (VTTx = mono-directional OL)*





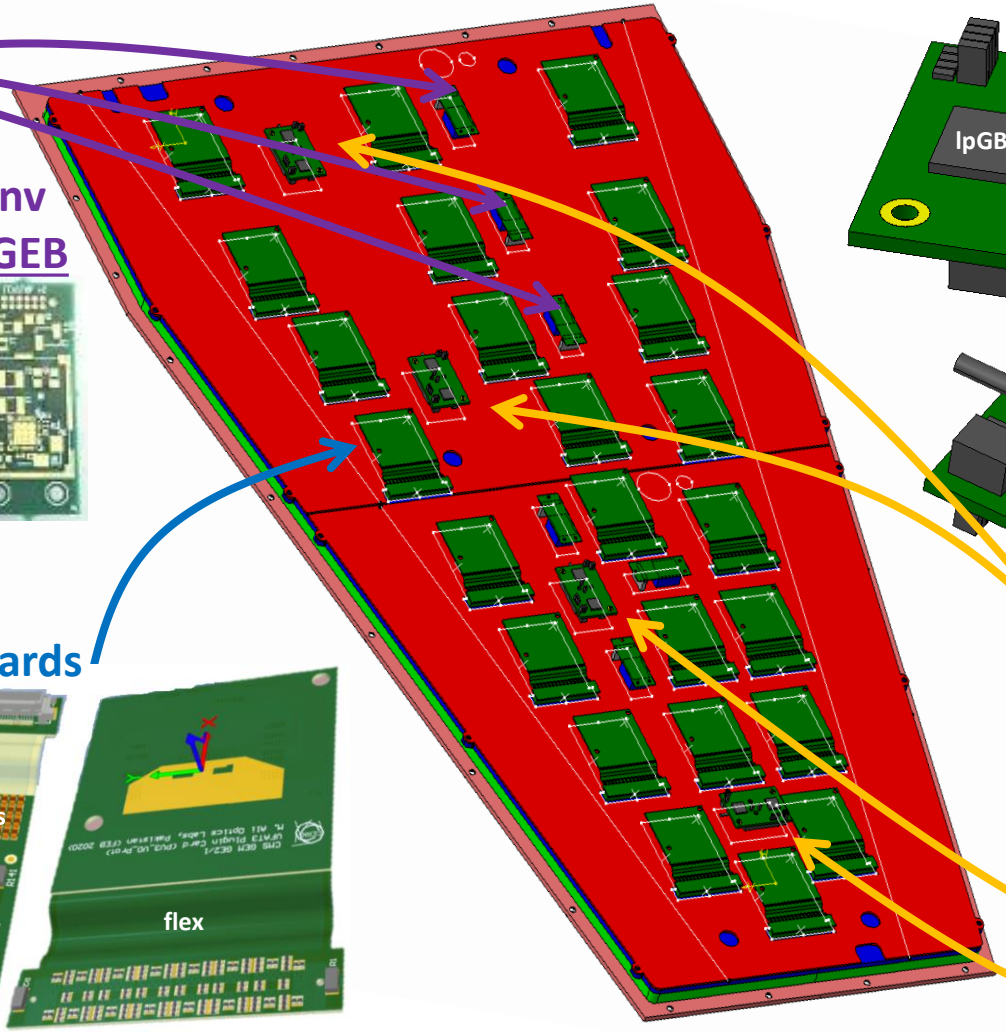
GE1/1 detector with 2 GEBs, 1 OH, 24 VFATs, 5 Ols, 10 FEASTs

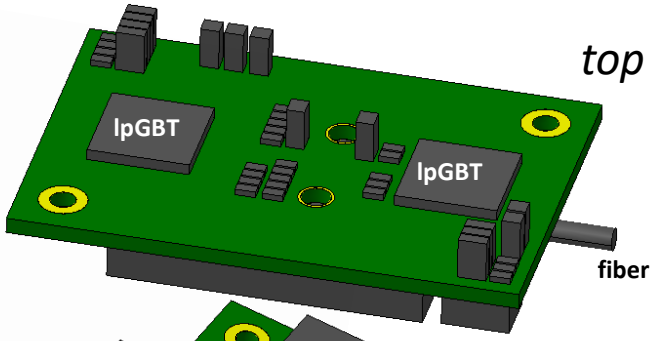


GE1/1 Opto-Hybrid board

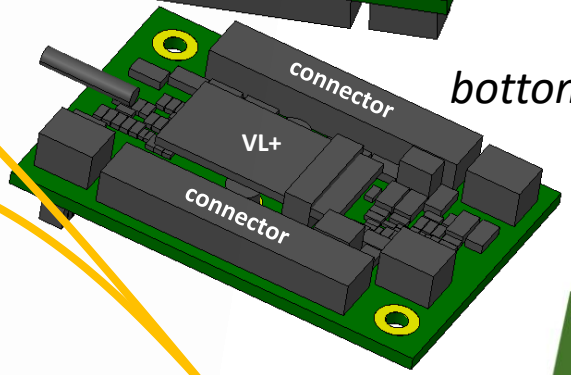
CMS GEM (ME0) Electronics

3 bPOL
DC-DC conv
for each GEB

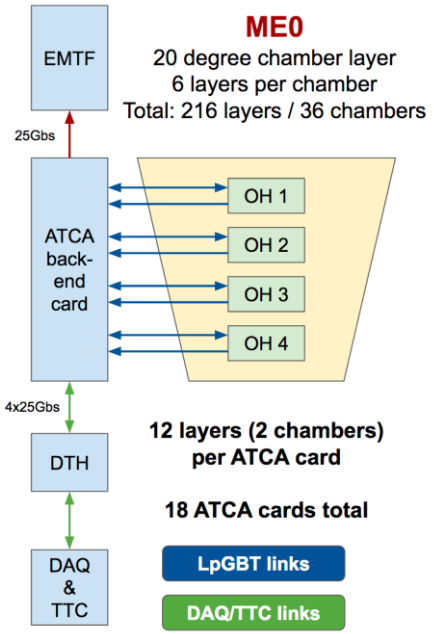




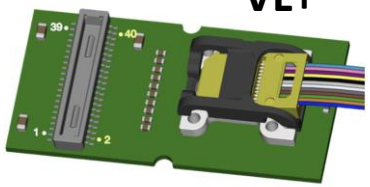
top



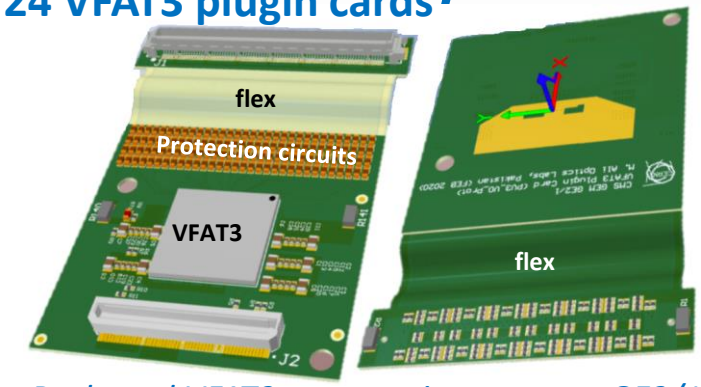
bottom



VL+



24 VFAT3 plugin cards



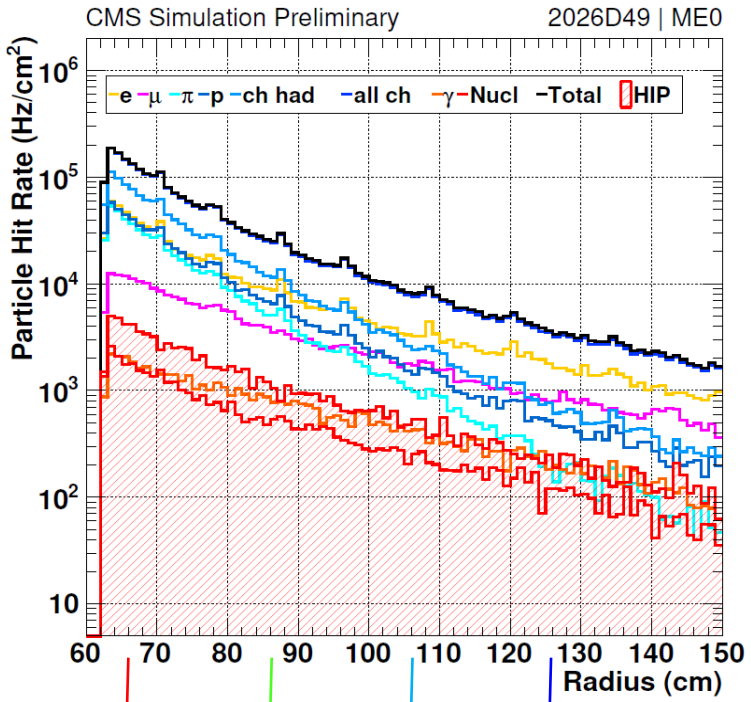
Packaged VFAT3 + protection same as GE2/1
GE1/1 used naked chip wirebounded on hybrid

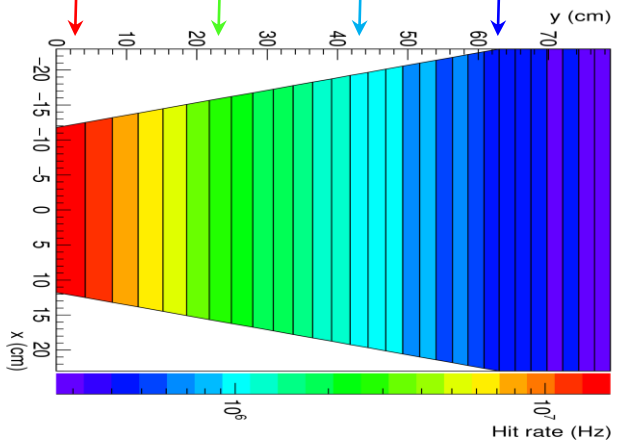
4 FPGA-less OH

2 OH for each GEB.
Each OH has 2 lpGBT chips
and reads 6 VFAT3
Each OH has a single VL+ optical link
No data-processing on detector
FPGA is on X_2O back-end board

The ME0 detector

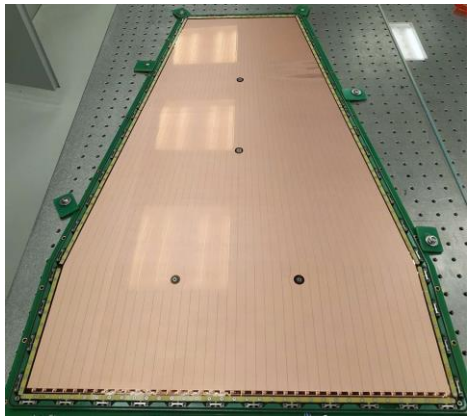
Optimalization of ME0 GEM Foil HV sectors

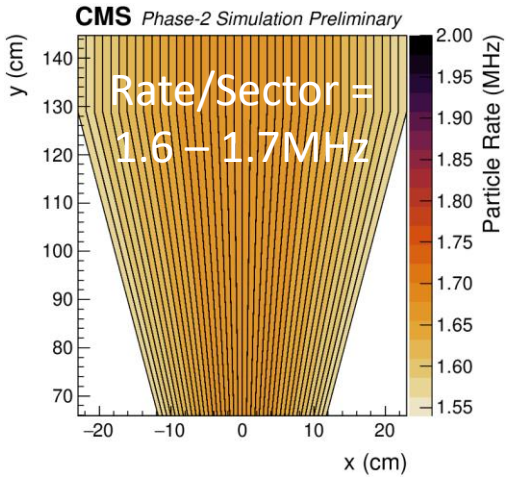




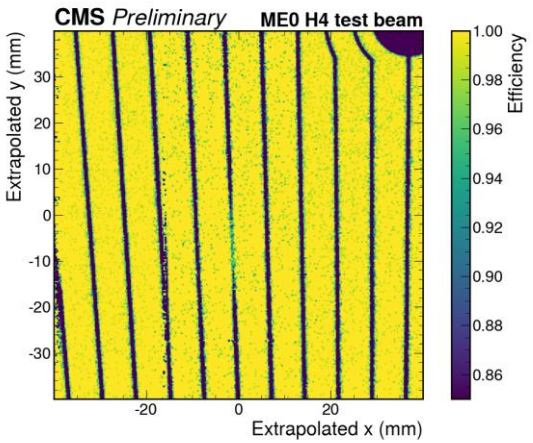
Highly non-uniform Rate/Sector

- **Expected Particle Rate on ME0 is Exponential**
  - Highest rate: 150kHz/cm^2 – Lowest rate: 2kHz/cm^2
  - Optimization of horizontal sectors would depend on functional form of background chosen – which is only known from simulation - Uncrt?
- **New HV segmentation paradigm: Radial sectors**
  - Rate on each HV sector is equalized => also current through protection resistors will be equalized
  - Allows for uniform Gain compensation by ΔV on GEM foils
- **Prototype with radial HV segments validated with beam**
  - Excellent efficiency – *However Large # segments => Large Dead Area*





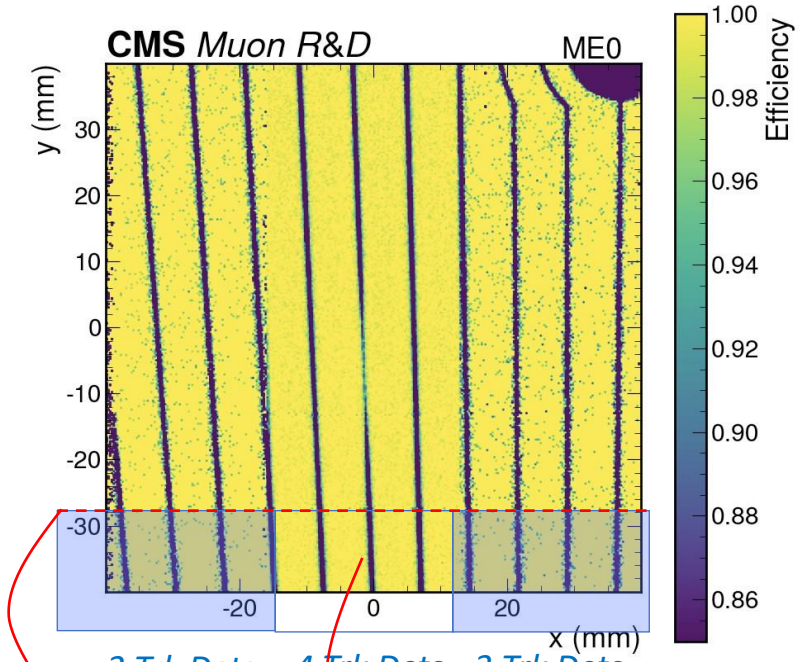
Equalized particle rate per HV sector

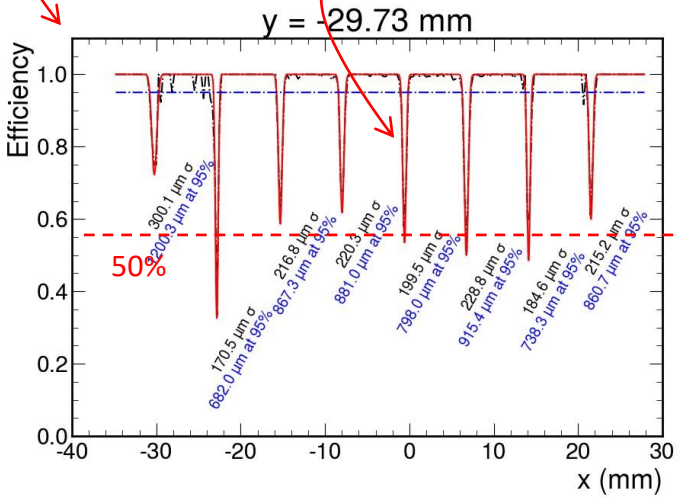


Radially segmented ME0 in TB

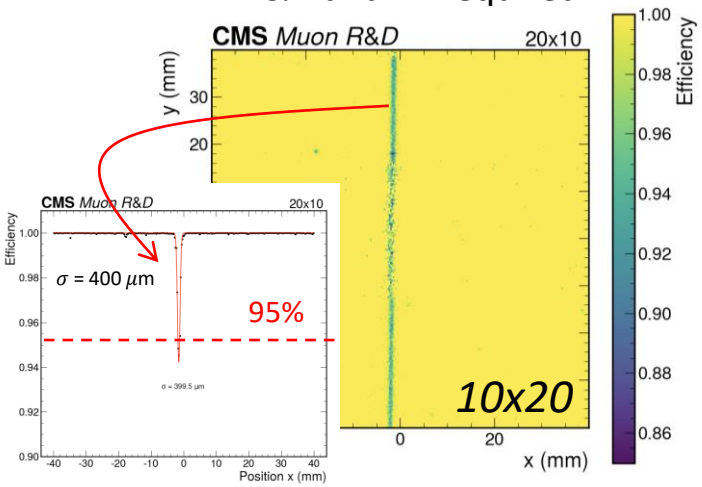
The ME0 detector

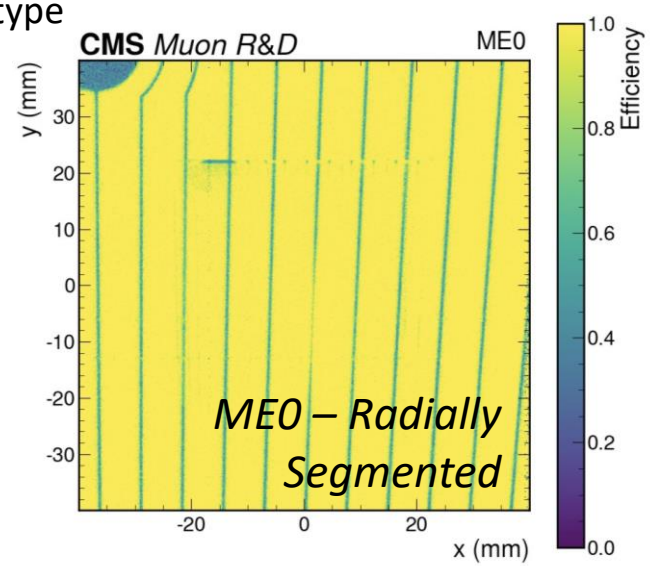
Adoption of "Random hole" sectors technique during GEM Foil Etching

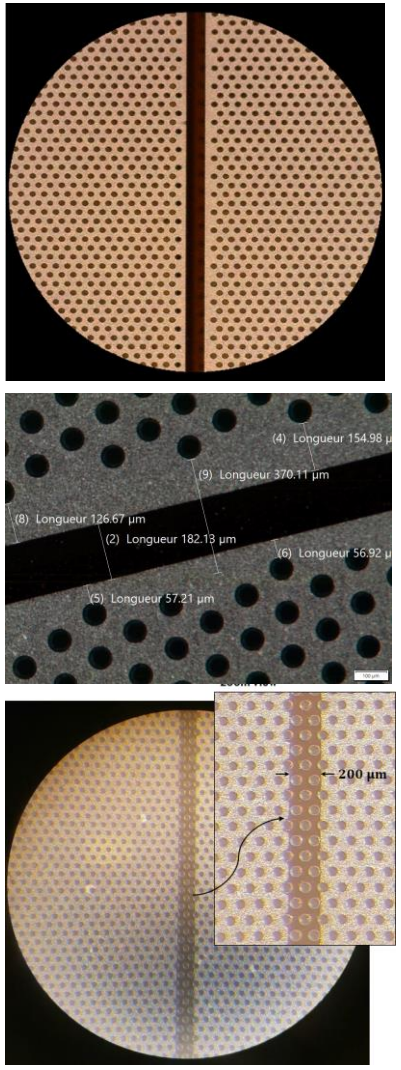




- Traditional segmentation (horizontal)
  - leads to dead area of A= 200um x ℓ
- Radial segmentation leads to a variable distance hole-to-hole
  - Dead area extends to A = 500um x ℓ
  - Test beam observes Efficiency drops < 50% at segmentation line
- New technique Rui / CERN MPT workshop: "Random hole"
  - GEM foil perforated everywhere
  - Subsequent removal of 200um Cu strip
  - creates holes w/random Cu border around
- Tested in testbeam – *Efficiency drops in 'dead area' to 95%*
  - October '21 with 10x20 prototype chamber (4 segments)
  - May '22 with full ME0 prototype
  - R&D and TT required

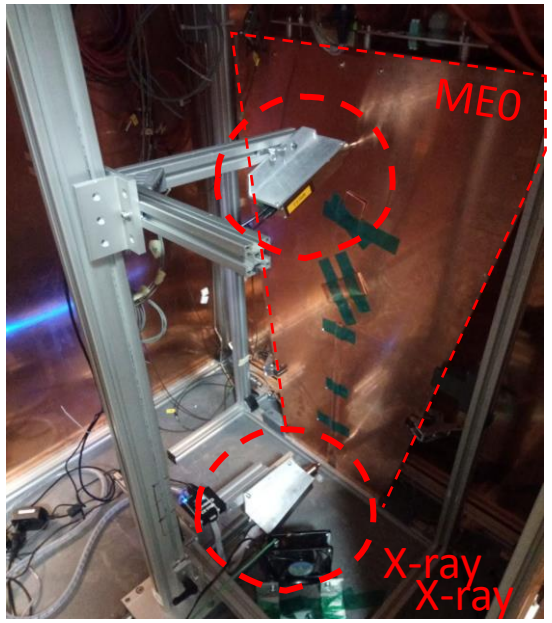






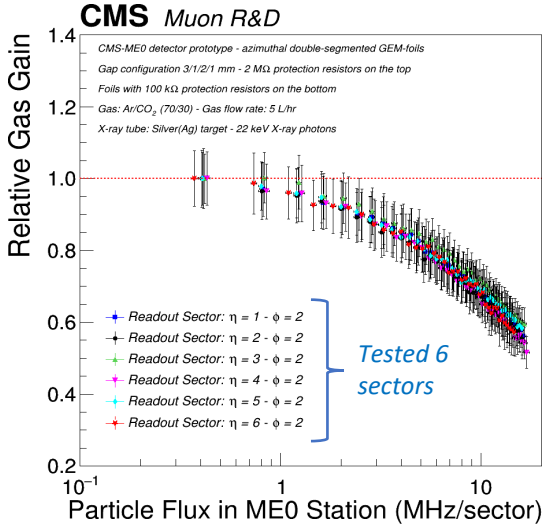
The ME0 detector

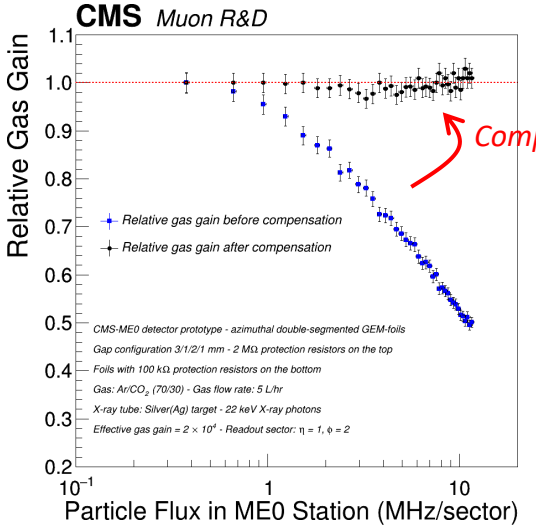
Rate capability tests with X-rays



Verify Validity of new ME0 design and Gain compensation with asymmetric X-ray irrad

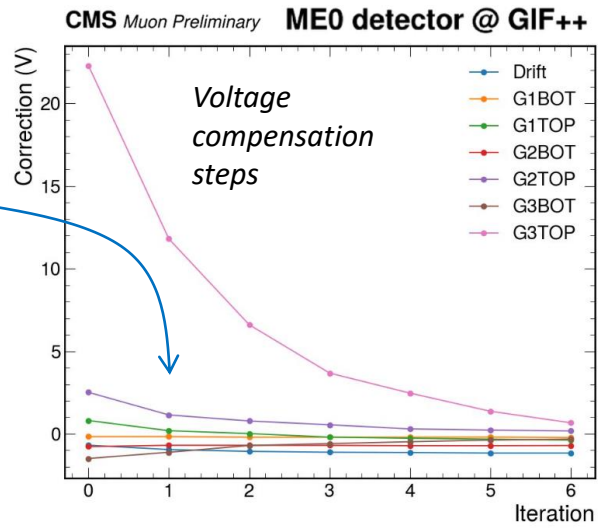
- Global X-ray irradiation entire detector + Intense X-ray irradiation of highest η partition of ME0
- ME0 detector without HV-Filter
  - Correct behaviour of filter on rate-capability can only be established with uniform irradiation of chamber
- Measure gain on <u>all</u> η partitions
- All partitions lose gain in same way
  - consequence of radial segmentation – currents are running now along entire detector
- Compensation demonstrated up to 10MHz/sector: *(cfr: CMS: expect 1.7 MHz/sector – 200 e-)*
  - increase V on each electrode according to current flowing through it until desired ΔV reached





Compensated!

$$V_{eff} = V_{set} - \underbrace{R_{electrode} \times \varphi \times G \times n_0}_{\text{1 – 10V in the ME0 BKG range}}$$

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

- Gain restored in all η parts!
- At 140PU we expect 1.6 MHz/sector
- Demonstrated up to 10 MHz/sector!
- Check effect of HV filter with uniform irradiation @ GIF++ *(see next slide)*