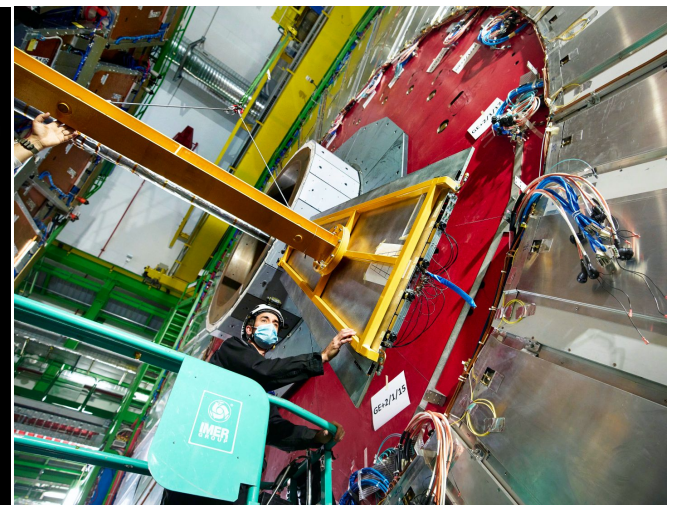
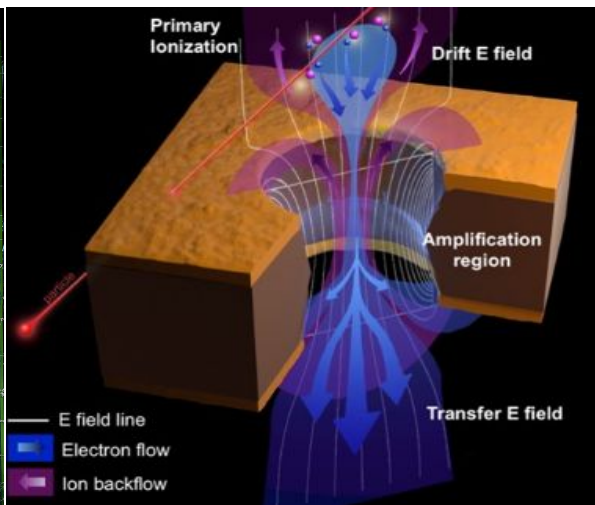
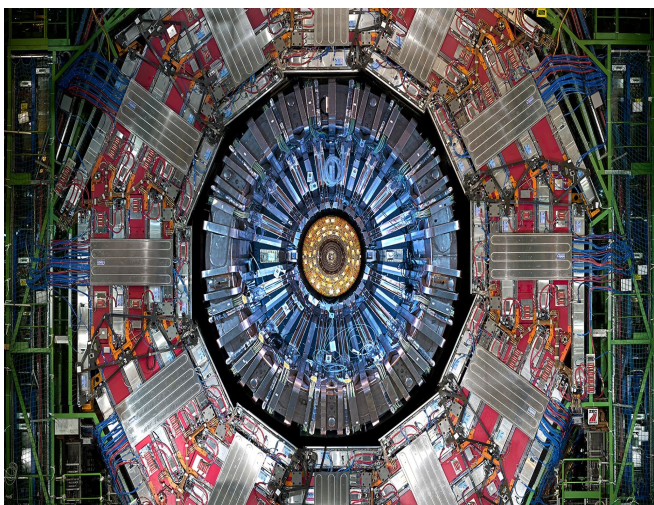


Mahesh Kumar Saini, Chandra Prakash, Prof. Ashok Kumar, Prof. Md. Naimuddin
University of Delhi, Delhi
On behalf of the CMS Muon Group

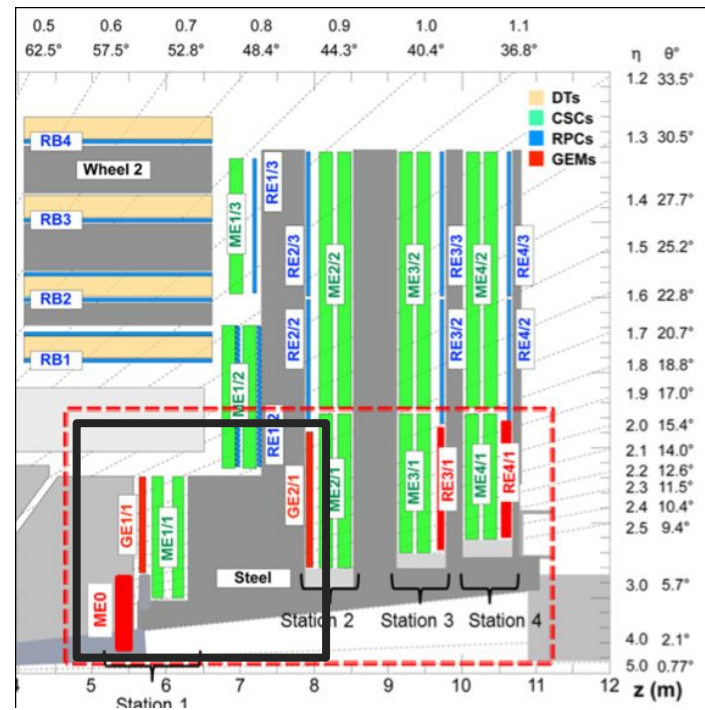
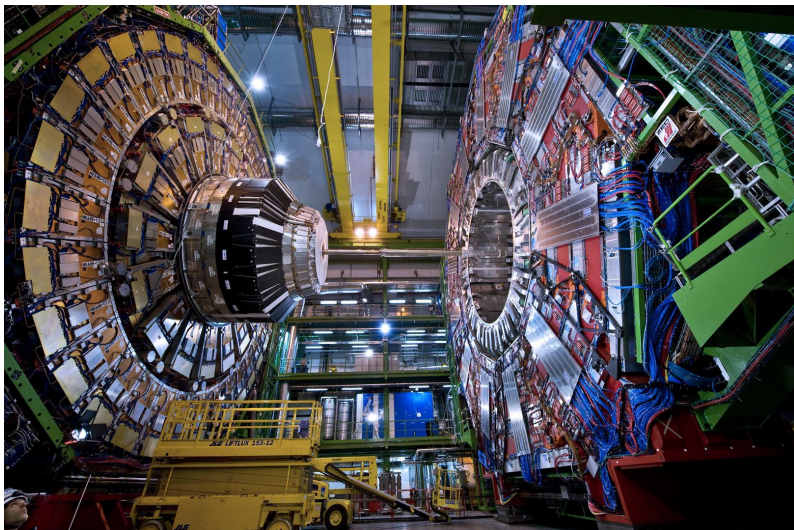


**International Conference on Technology & Instrumentation in
Particle Physics 2026**

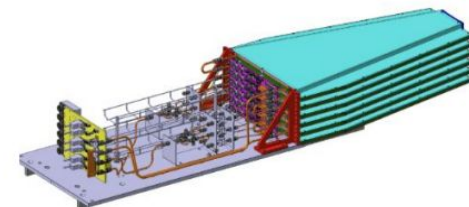
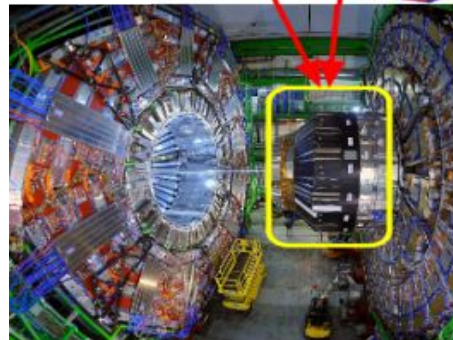
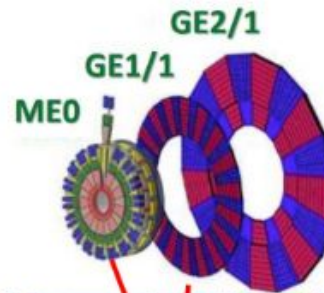
TIFR, Mumbai (India), February 2-6, 2026

- ❖ **CMS GEM Upgrade**
- ❖ **Introduction of the GEM detector**
- ❖ **Production and QCs**
- ❖ **Operation of GEM**
- ❖ **Current Status**
- ❖ **Summary**

- The High-Luminosity LHC upgrade is expected to raise the luminosity up to $5-7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.
- In order to cope up with this, CMS experiment is enhancing its muon spectrometer with three new stations of triple-GEM detectors: GE1/1, GE2/1 and ME0 (in black box).
- GE1/1 & GE2/1: Enhance muon triggering and tracking redundancy in the forward region. ME0: Extends muon system coverage to higher pseudorapidity ($|\eta| \lesssim 2.8$) regions.



- **GE1/1** was installed during the second Long Shutdown (LS2) of the LHC (2019–2020), commissioned with cosmic rays and proton–proton collisions, and is currently taking data in Run 3.
- **ME0** is scheduled for installation during LS3 of the LHC (2026 to 2029).
- The **GE1/1** station consists of 144 super chambers.
- Each super chamber made of two layers of triple GEM detector for Pseudorapidity coverage $1.55 \leq |\eta| \leq 2.18$.
- The GE1/1 SC is mounted in the CMS nose in front of the CSC ME1/1 chambers.



- A **ME0** stack consist of 6 layers of the GEM modules for Pseudorapidity coverage $2.0 \leq |\eta| \leq 2.8$.
- 18 stack for each end-cap. 216 modules needed.
- For full system 72 **GE2/1** chambers for Pseudorapidity coverage $1.6 \leq |\eta| \leq 2.45$.
- 36 chambers per endcap organized in two layers of 18 super chambers (Total modules 288).
- The GE2/1 chamber consists of four modules (either M1, M2, M3, M4 or M5, M6, M7, M8).

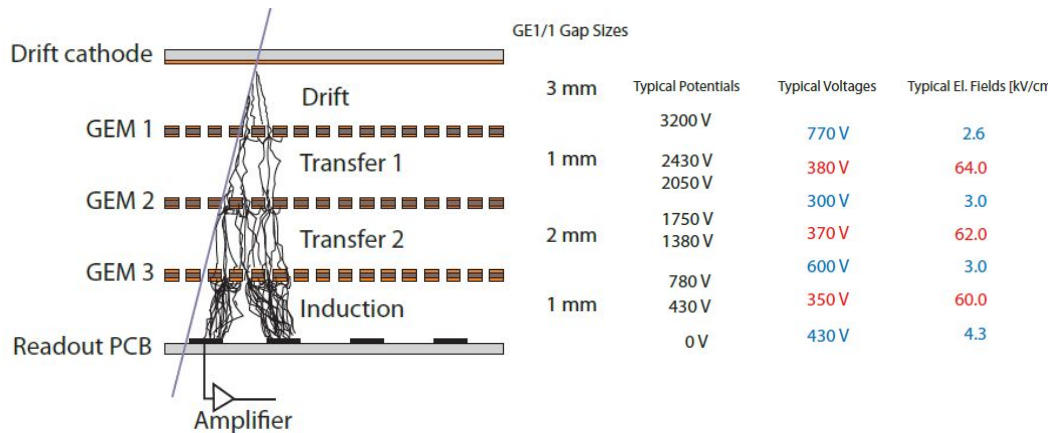
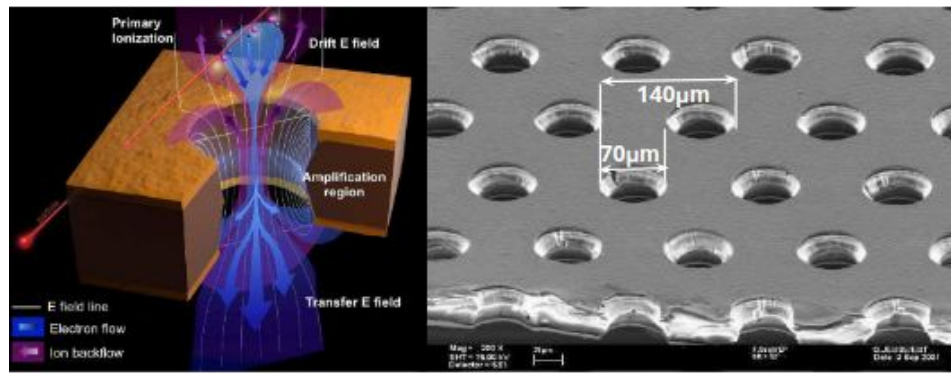
Construction:

- Copper-clad Kapton foils with micro-holes with outer diameter 70um and inner 50 um with 140um pitch.
- Bi-conical hole structure for charge amplification.

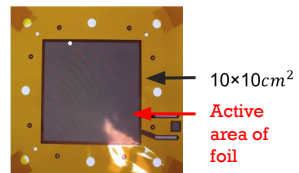
Gas Mixture: 70% Argon + 30% CO₂ for optimal operation.

Performance Highlights:

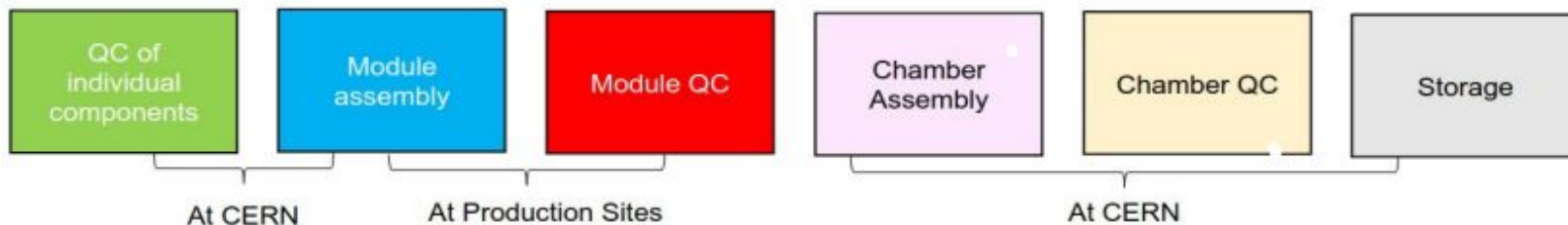
- **High Rate Capability:** ~MHz/cm² (handles intense particle flux).
- **Gain:** ~2 × 10⁴ (strong signal output).
- **Spatial Resolution:** ~100 μm (precise tracking).
- **Time Resolution:** ~8-12 ns (fast response).



Fabio Sauli introduced a milestone in detector world

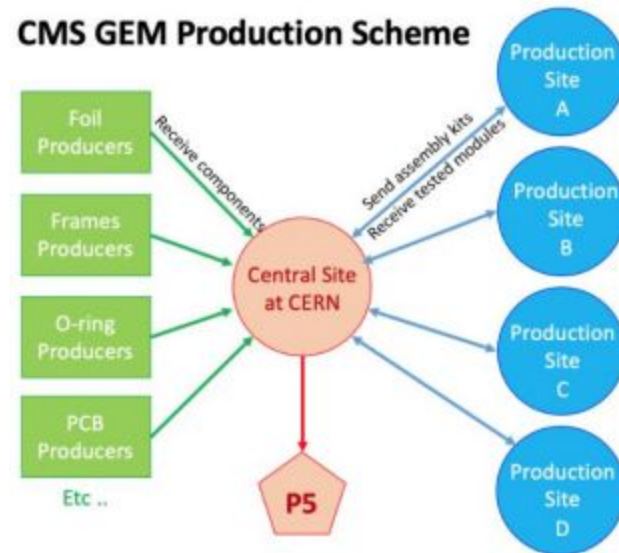


Production flow of GE1/1, GE2/1 and ME0



- Distribution of the production among several sites.
- Components manufactured, after QC shipped to CERN
- CERN: Material inspection + Preparation of assembly kits + Shipments
- Production Sites: Assembly + QCs + Database updates
- 4 production sites in EU (**Gent, Bari, Frascati, and Aachen**), 2 production sites in India (**Delhi and Punjab**), 1 production site in **China** (PKU)
- Repair and storage site at **CERN**

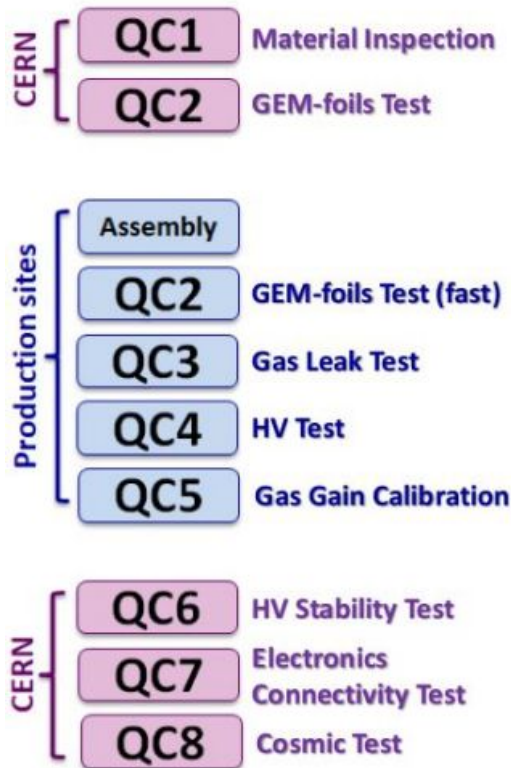
CMS GEM Production Scheme



❖ Quality Control (QC) Flow for GE1/1, GE2/1 and ME0

All modules undergo all steps to ensure their quality:

- Checks on individual components (extra checks for foils)
- Gas tightness tests
- HV tests
- Gain tests
- Electronics test
- Final validation with cosmic ray



Assembly requirements:

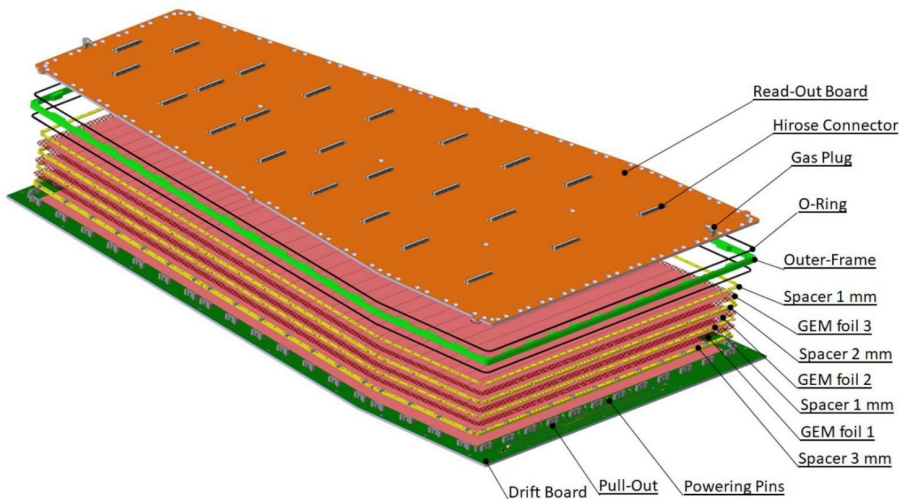
- Require clean room of class 1000 or better , RH not more than 35%.
- 3 segmented GEM foils to minimize discharge probability.
- Drift, readout board, spacers (3-1-2-1 mm), external frame (for gas volume), and O-ring for gas tightness.

Clean room at 904 CERN



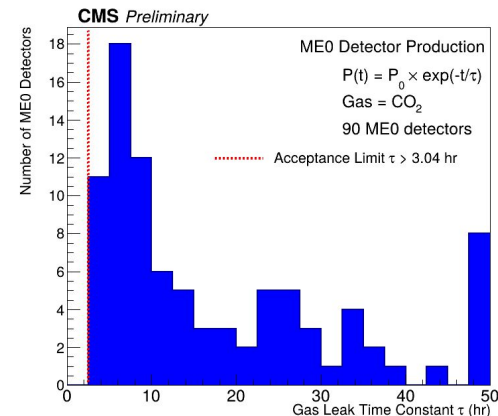
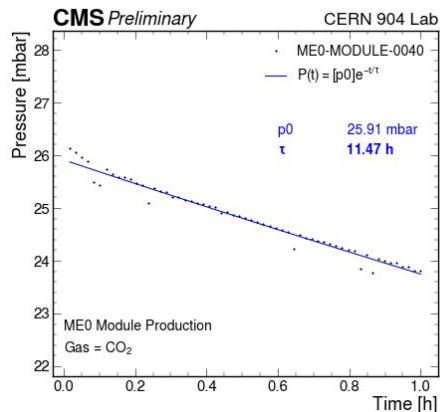
Procedure and preparations:

- Readout and drift.
- Foil inspection and preparation (leakage nA or $R > 10 \text{ G}\Omega$, low sparks).
- Stack preparation.
- Foil stretching.
- Closing of the chamber.
- HV testing of the foils and gaps.



QC3 – Gas Leak Test

- QC3: quantify gas leak rate of a detector by monitoring the internal over-pressure as a function of time.
- **Acceptance limit set to tau > 3.04 hours.**

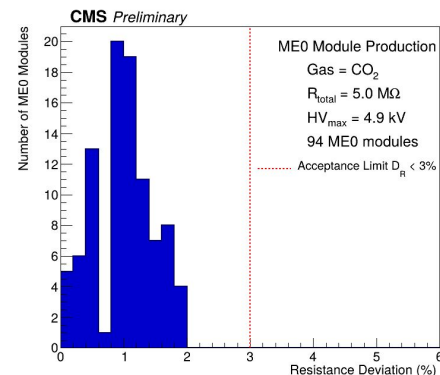
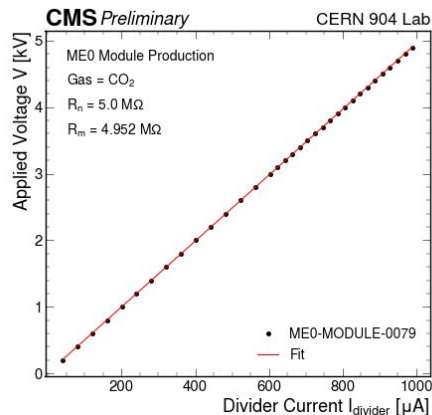


QC4 – Linearity test with an HV divider

- QC4: check the on-detector HV circuit and stability.
- Deviation of resistance of powering circuit:

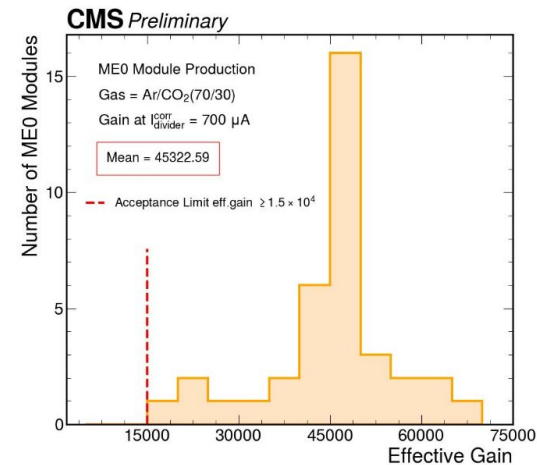
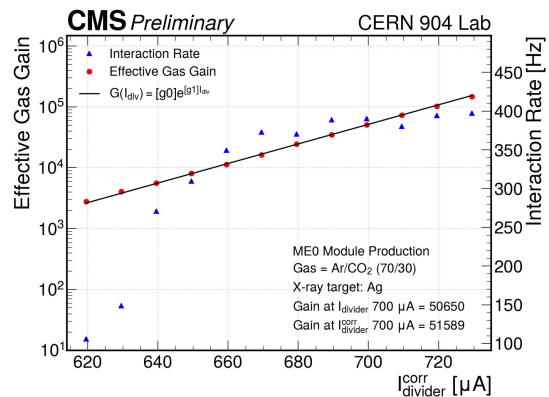
$$D_R = (R_{\text{measured}} - R_{\text{nominal}}) / R_{\text{nominal}}$$

- **Acceptance limit set to < 3% deviation in resistance.**



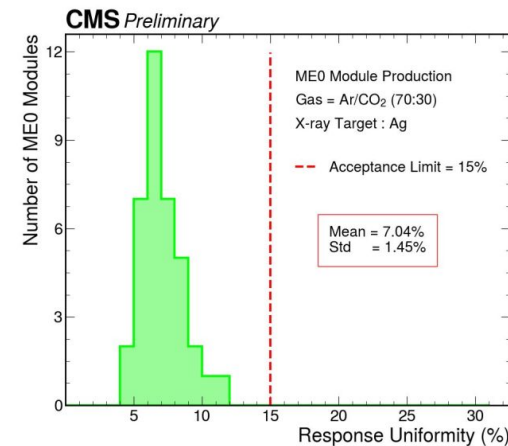
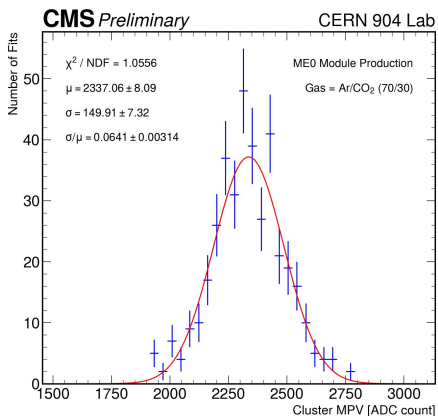
QC5 (Part-1) – Effective Gas Gain

- QC5.1: measure multiplication factor of electrons that reach to anode.
- Effective gas gain: $G = I/(R \cdot e \cdot Np)$



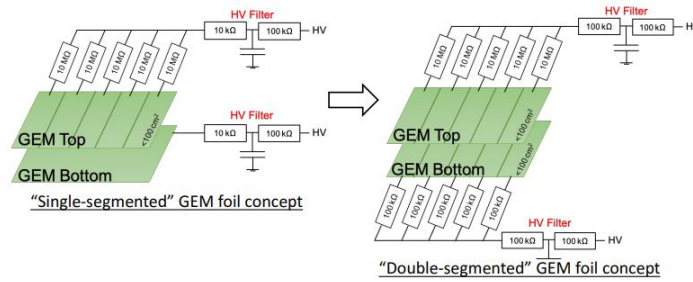
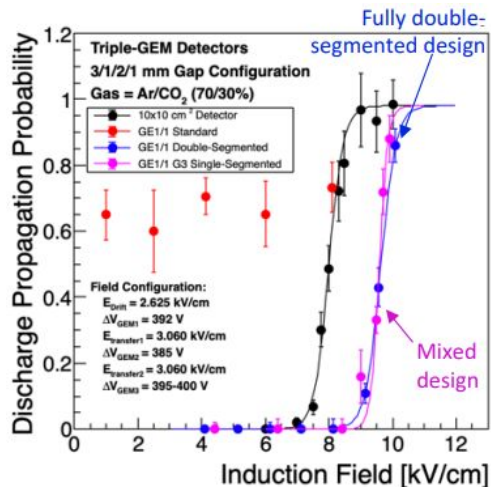
QC5 (Part-2) – Response Uniformity

- Signal amplitude across entire detector.



Observed channel losses in GE1/1 slice test.
Traced back to **discharges** propagating to the readout

Solution: Double segmented GEM foils, but keep GEM3 foil (closest to readout strips) single segmented to avoid cross-talk.

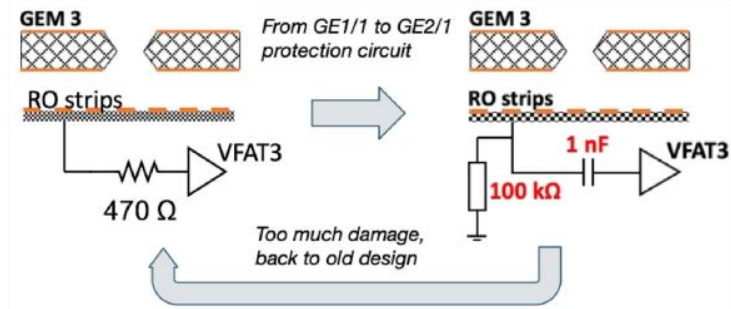


In addition: Many different protection circuits were studied for GE2/1.

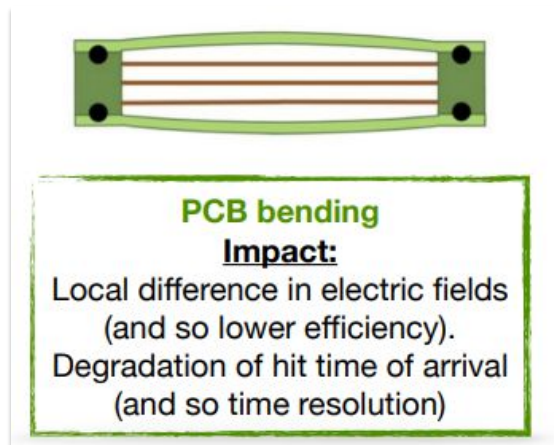
Solution tested successfully in the lab, but again channel loss during test beam. Back to old design, which worked under background radiation. Noticed electronics resets in coincidence with discharges.

Resets traced back to be due to leakage current to VFAT GND.

Solution: improved grounding on readout board with copper bars.

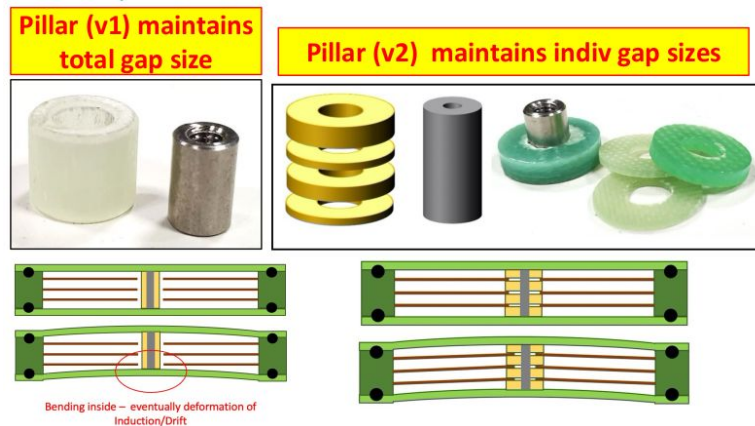


GE1/1 Basin Effect: Up to 40% variation in gain measured in gain uniformity tests during mass production.



Solution:

Add pillars (for the GE2/1 and ME0)



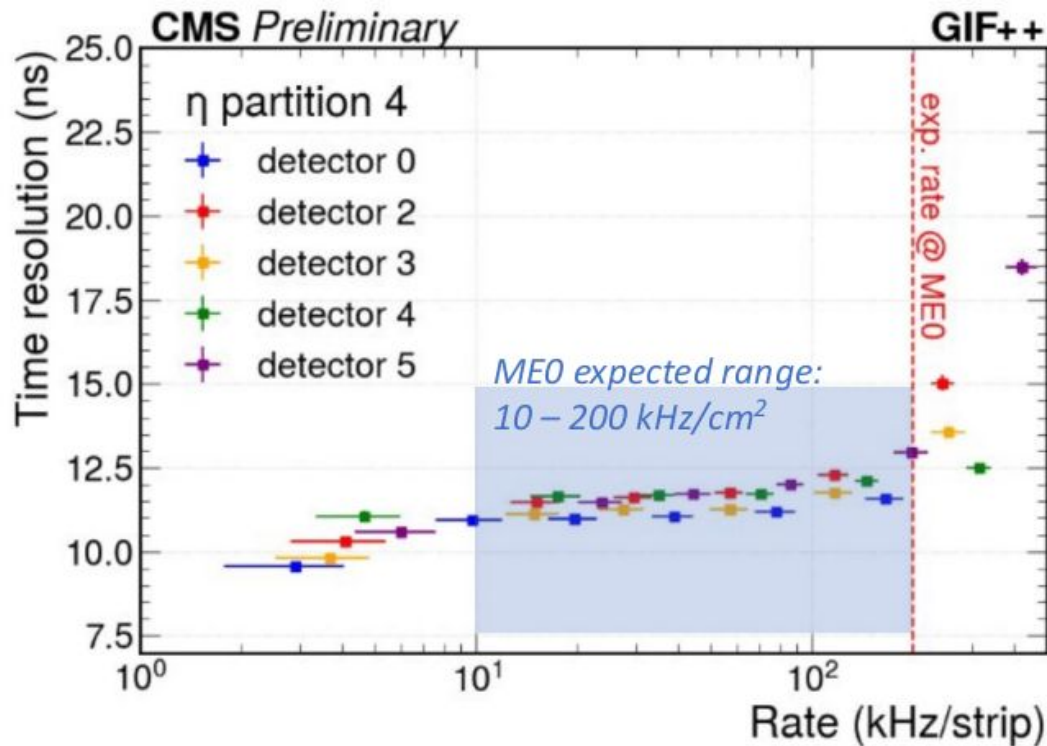
No passivation applied on drift and readout PCB to protect against oxidation Shorts forming on GEM foils, found copper dust on readout PCBs

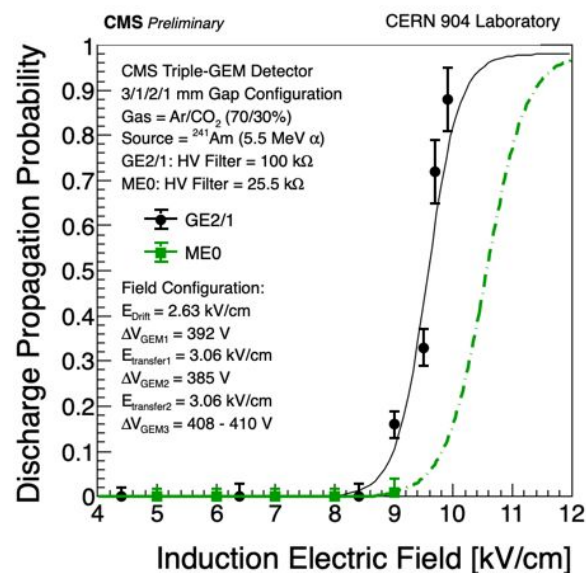
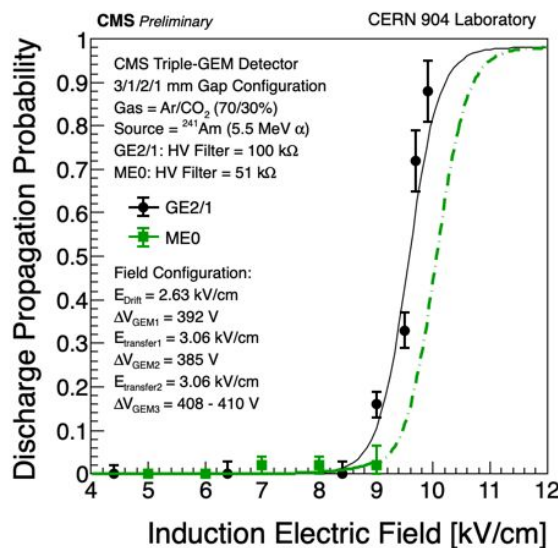
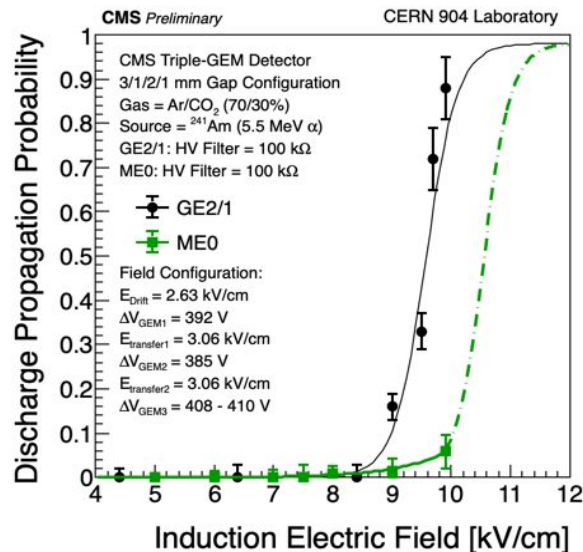
Solution for ME0:

- Passivation applied on already produced ME0 PCB.
- Reviewed PCB production procedure.
- Added microscope inspection of all boards.

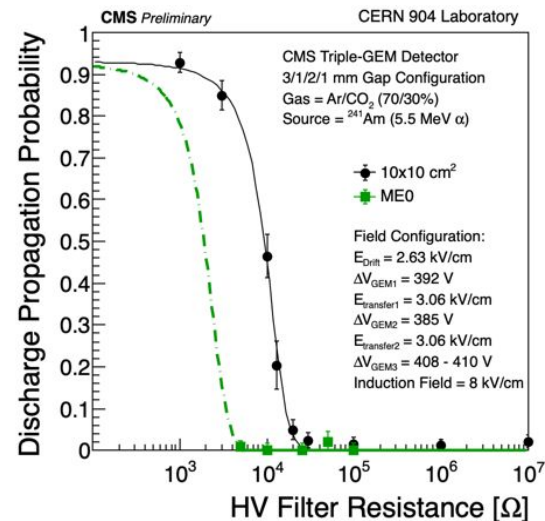
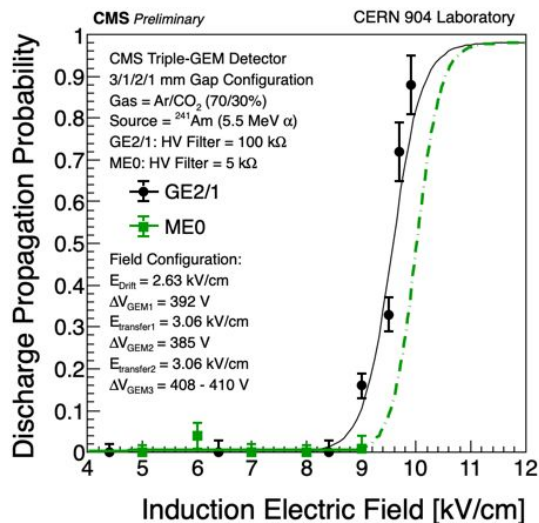
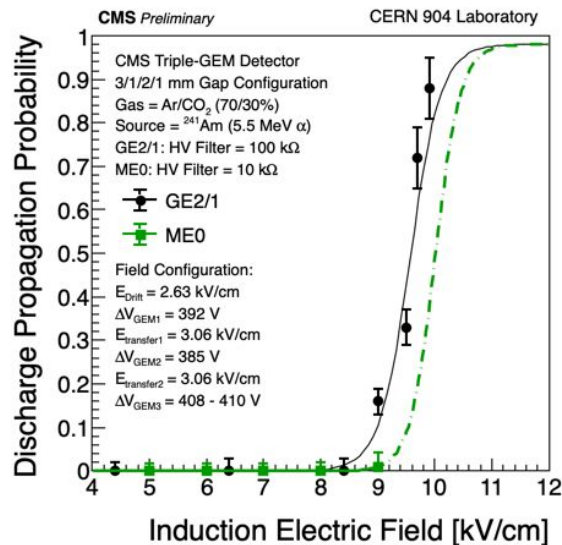
ME0 Time Resolution Studies

- Measurements were performed at GIF++ using an 80 GeV muon beam combined with low-energy gamma background from a Cs-137 source.
- Time resolution measured for 5 modules at GIF++. Rate differences across layers come from geometry and shielding. Dashed line shows the expected max rate at high- η .

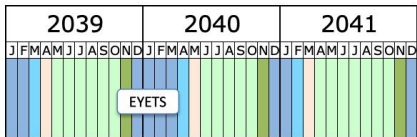




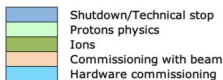
- Discharge propagation probability versus the induction electric field for the GE2/1 configuration (black) with HV filter resistance of 100 kΩ and ME0 configuration (green) for different HV filter resistances (100, 51, 25.5, 10, 5 kΩ).



- Discharge propagation probability versus the HV filter resistance for applied induction electric fields of 8 kV/cm on ME0 (green) and 10cmx10cm (black) triple GEM muon detector.
- Based on measurements using ME0 without electronics, azimuthal segmentation and lowering the filter resistance from 100 kΩ to 5 kΩ do not significantly impact the discharge propagation.



Last update: November 24



Longer term LHC schedule: Update September 2024:

Short YETS 25/26

Extend Run 3 to end June 2026

Start LHC LS3 July 2026

Start final Hardware Commissioning January 2030

First beam June 2030

LS3 - beam to beam: 3 years 11 months, 47 months

- LS3 will start on the 1st of July, 2026

System	Extraction	Installation
GE+1/1	11 September, 2026	11 September, 2028
GE-1/1	25 August, 2026	10 August, 2028
ME0+	-	29 November, 2027
ME0-	-	8 September, 2027

- CMS GEM group has a long experience in building triple-GEM detectors for high-rate application.
- GE1/1 Muon Detection Efficiency is stable and high (~95%).
- Due to GE1/1 limitations, a refurbishment plan is foreseen during the LS3 (~1.5 years), including mainly the cleaning & passivation of PCBs, using the same GEM foil stack, small components & electronics refurbishment.
- 138 active GE1/1 chambers with 6 extracted in YETS 24/25.
- Many lessons learned during design and production of existing GE1/1.
- ME0 module production is progressing smoothly and remains on schedule.

Global message:

- GEM community squeezing out all the attainable performance from the detectors
- Robustified the system
- Mitigated issues that where possible.

Major achievements:

- Time resolution MPV \approx 12 ns

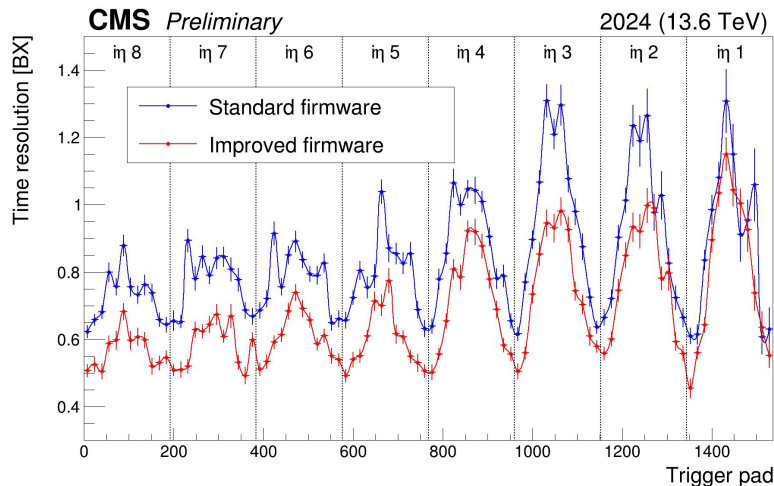
Future further improvements: HV shorts (partial) compensation, etc.



Backup

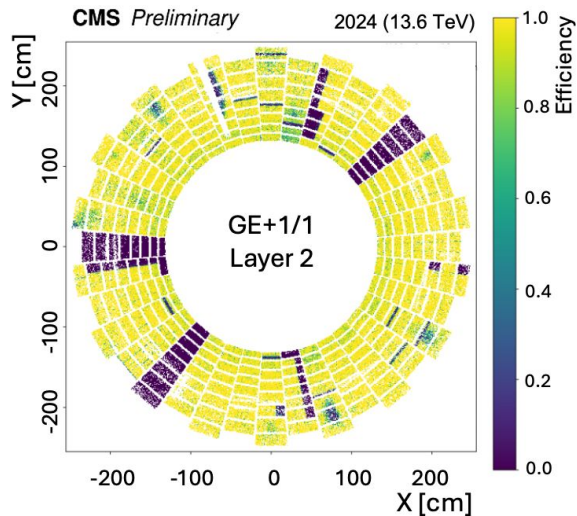
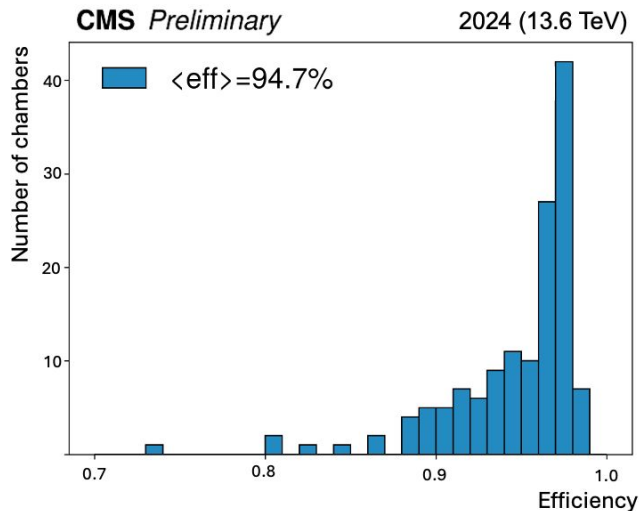


- Distribution of the time resolution as a function of the trigger pad (pair of two readout strips) for a long GE1/1 chamber, with different firmware versions.
- Each entry represents the width of the time distribution of a group of 16 trigger pads (one quarter of a GE1/1 readout sector).
- The new on-chamber electronics (OptoHybrid) FPGA firmware has a feature that is called “x-talk suppression”. It consists in cancelling the hits coming from the inter-readout-strip x-talk, which are assigned an earlier Bunch Crossing (BX) with respect to the muon hit.
- The plot shows results from collision runs with both the new and standard firmware versions.
- For all runs, the selected GEM hits are the ones matching to a muon track with $p_T > 10$ GeV.
- The time resolution is clearly improved for the new firmware.
- In the low ieta area of the detector, the time resolution worsens significantly, due to the bending of the printed circuit boards in the GE1/1 chambers.

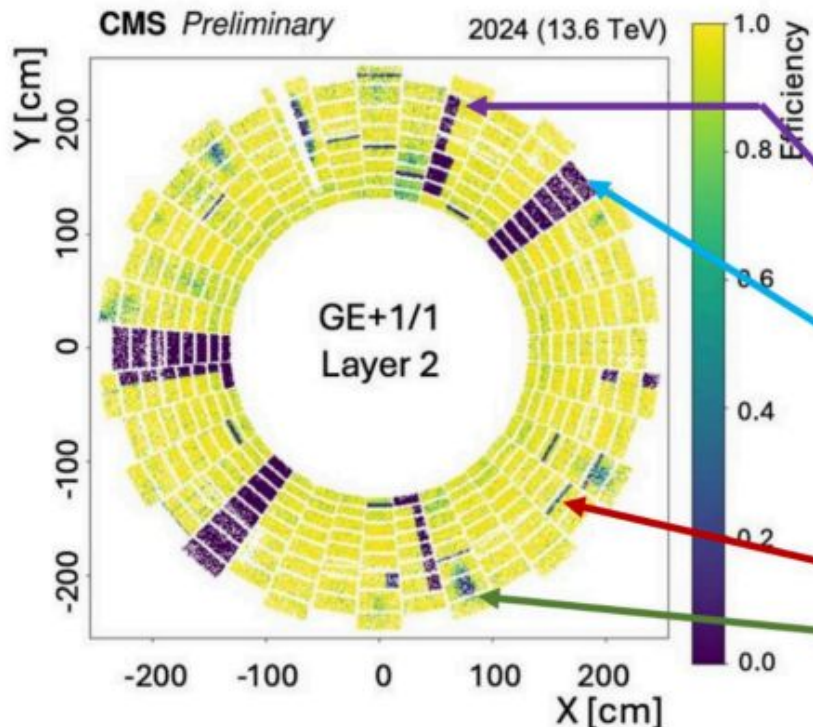


Efficiency of GE1/1

- Active Channels, Noisy and damaged channels are carefully monitored on daily basis. Muons detection efficiency is being monitored on run by run basis for the correctly communicating chambers.
- The efficiency is calculated for chambers properly communicating and operating at optimized HV settings Chambers are running well with: $\sim 94\text{-}95\%$ efficiency for standalone muons.



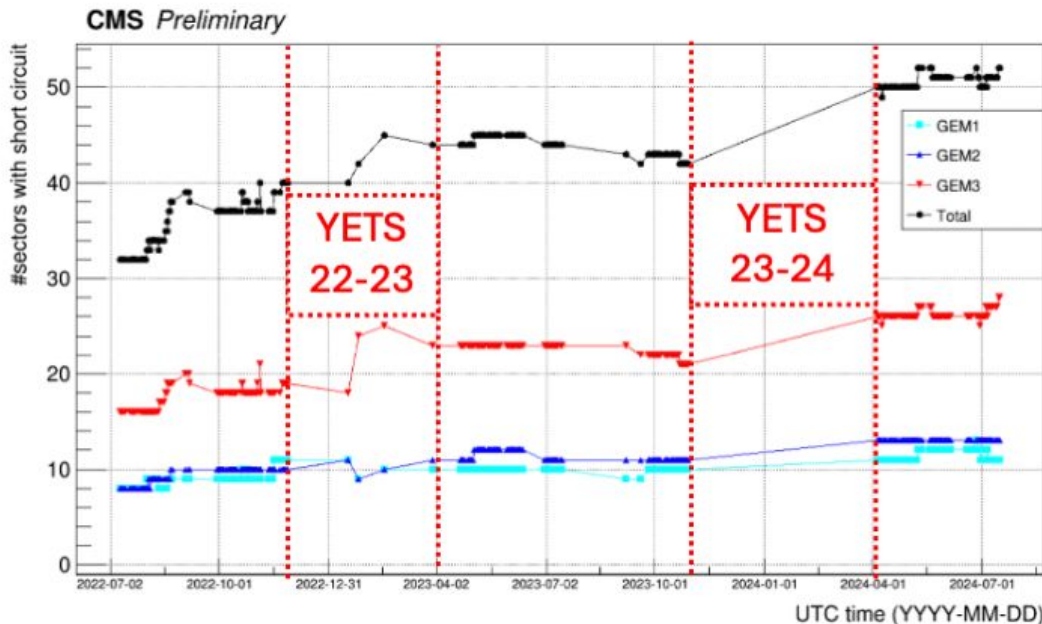
- High resolution efficiency plot of the GE+1/1 layer 2 chambers in 2024.
- The overall efficiency is high, but the chambers with communication issues (fully purple) or HV shorts (purple lines) are visible.
- On some of the long chambers one can also see an efficiency drop along the wide side due to the bending of the printed circuit boards.



High resolution efficiency plot of the GE+1/1 layer 2 chambers in 2024.

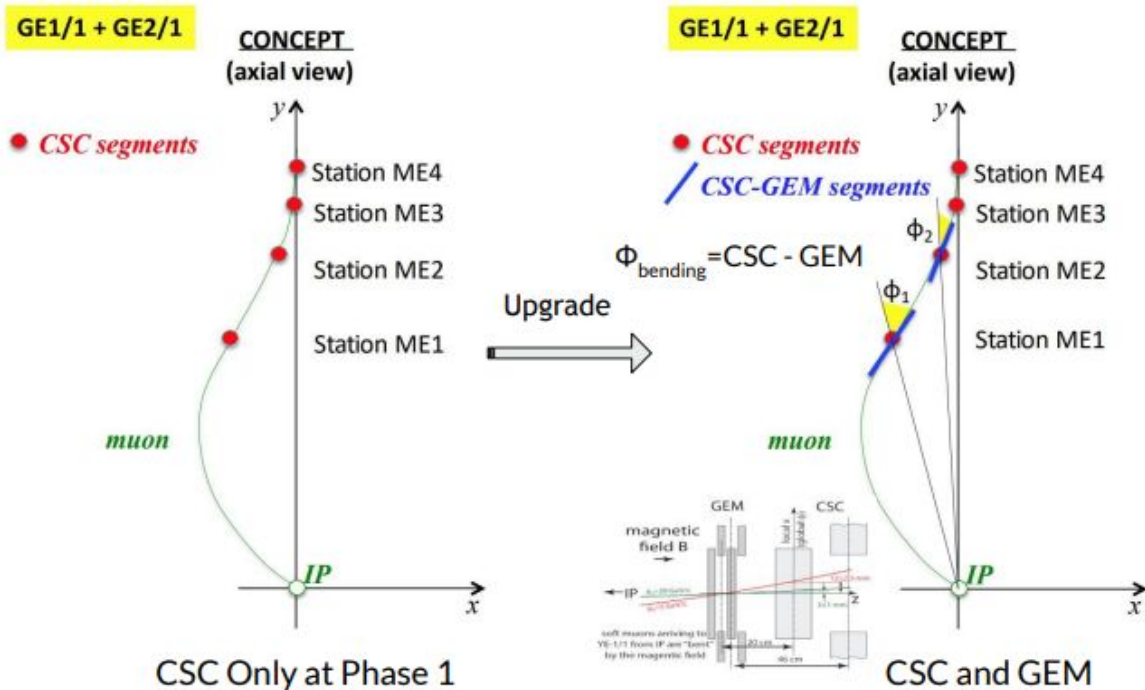
- The overall efficiency is high (Average: 94.7 %)
- **Issues:**
 - chambers with communication issues
 - Due to:
 - Outgassing of the VTRX optical transceiver [3]
 - This makes unstable the Giga Bit Transceiver (GBT) reading the front-end electronics
 - Can result in:
 - All the front-end connected to **one GBT is not read**
 - **Electronics fully off** if GBT publishing the FPGA temperature is affected (safety power off of the LV)
 - Electronics refurbishment during LS3
 - **Short circuits in GEM foils** (purple lines)
 - On some of the long chambers one can also see an efficiency drop at the wide side due to the **bending of the PCBs**.

Short circuit in GE1/1

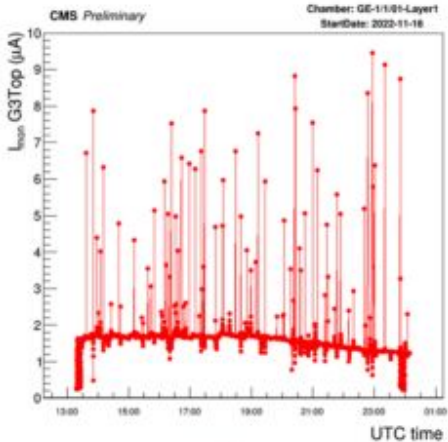


- Evolution in the number of HV sectors affected by a short circuit in GE1/1 detectors during 2022-2024 data-taking period and detector commissioning activities (YETS).
- The 3 GEM foils are segmented in 40 (47) HV sectors for the 72 short (long) modules. Due to the regular maintenance activities avoiding regular runs, no points were added during YETS 23-24. The total number of HV sectors in the GEM foils for the whole GE1/1 station is 18792.

Banding Angle



It can be an accurate measurement of ϕ direction at the ME1 and ME2 stations.
 The installation of the GEMs is aimed at reduce the trigger rate in the region which currently suffering from the highest background rates and a non-uniform magnetic field. This trigger rate reduction could be possible with the improved momentum resolution deriving from precision measurements of the bending angle performed the lever arm between the CSC and GEM. (*CMS-CR-2014-349)

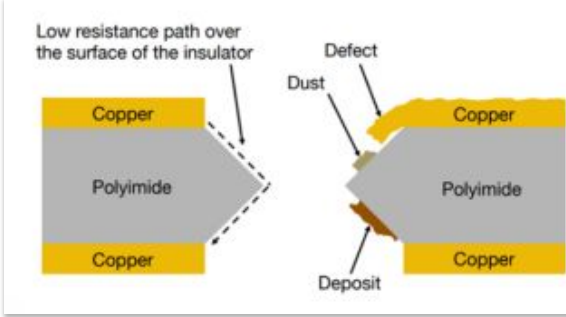


Discharges
Impact:
HV instability, short circuits in GEM foils, reset and dead channels in electronics

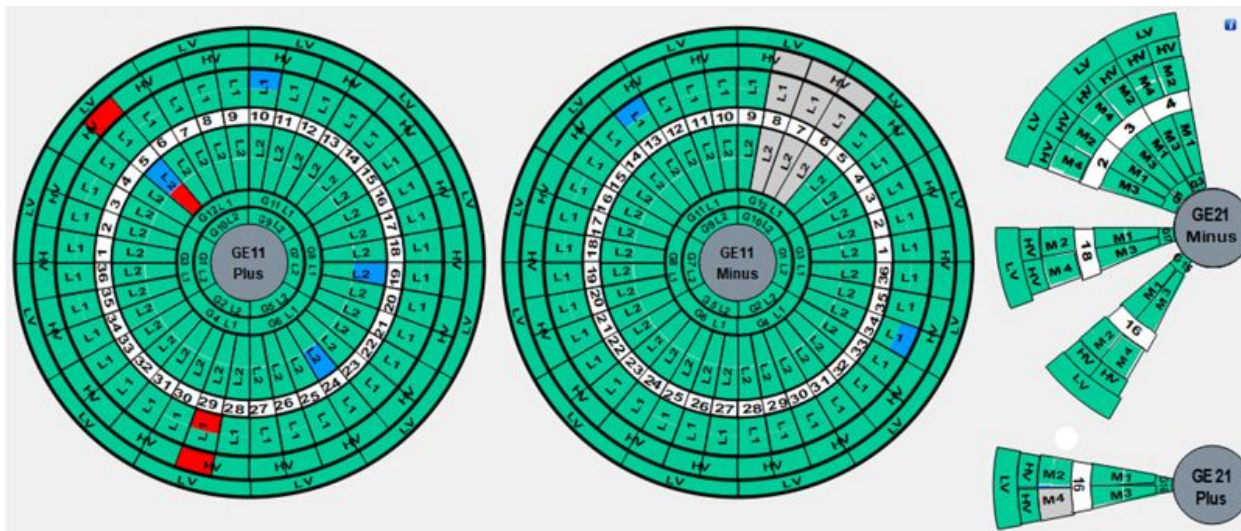


PCB bending
Impact:
Local difference in electric fields (and so lower efficiency).
Degradation of hit time of arrival (and so time resolution)

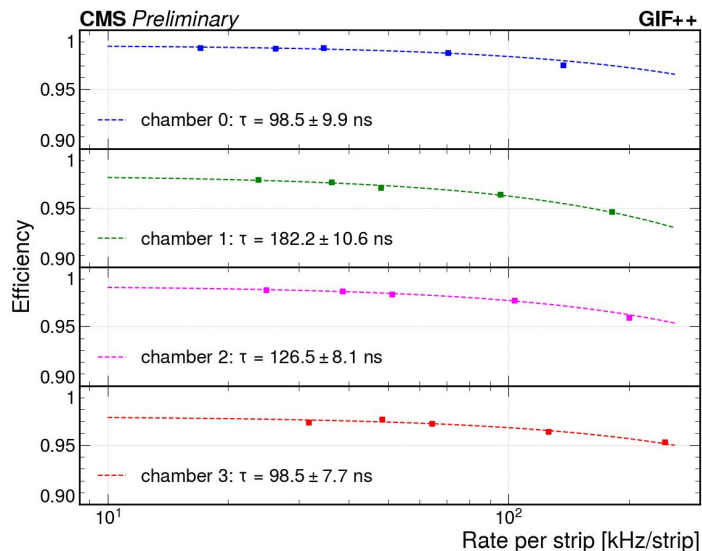
Short circuits in GEM foils
Impact:
Inefficient areas, lower voltage applied to the whole foil



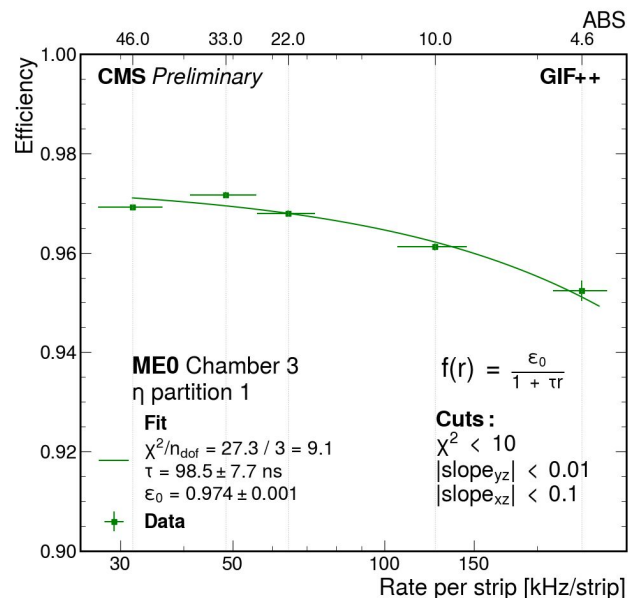
- ❖ GE1/1 detector was installed during LS2:
 - Total of 144 chambers that have been operating since 4 years. Currently, 138 chambers are active; 3 SC were extracted in YETS 24/25.
- ❖ GE2/1 detector:
 - Currently only 6 chambers are installed; 5 in GE-2/1 + 1 prototype in GE+2/1



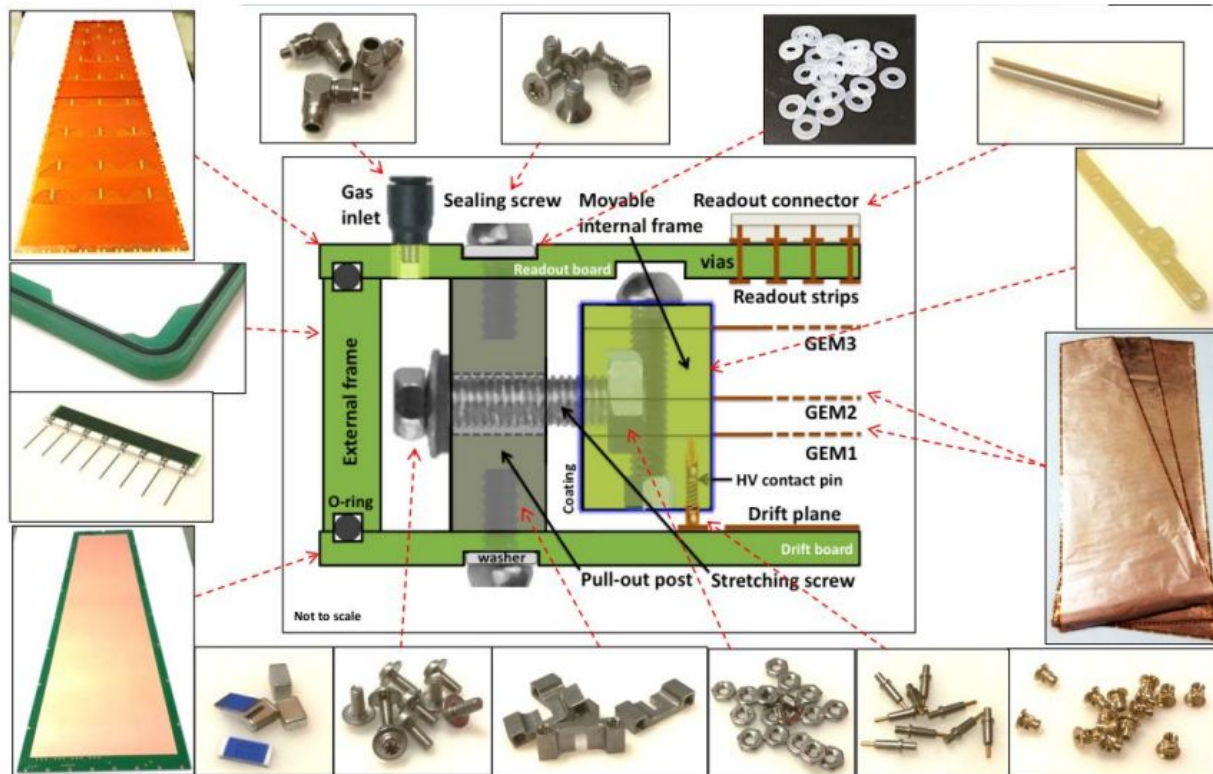
Rate Capability of ME0



Summary rate capability of 4 Modules as a function of the rate per strip. The dead time, inferred through the fit with the rate capability function, ranges from 98.5 ns to 182.2 ns (dominant contribution from VFAT3s).



Efficiency of a Module as a function of the rate per strip.



- ❖ GE2/1 installation planned in the YETS after Run 4 & the reconstruction will be resumed after finishing the ME0.

Specification / Parameter	ME0
Detector technology	Gaseous detector; micro-pattern gas detector (MPGD)
Charge amplification element	GEM foil (triple, cascaded, tensioned at ≈ 6 cN/cm)
Number of modules in overall system	216 (108 in each endcap)
Chamber shape (active readout area)	Trapezoidal; opening angle 20°
Chamber dimensions (active vol.)	L: 78.8 cm (center line), W: (23.6–51.4) cm, H: 1.8 cm
Total module thickness	H: 3.34 cm
Active readout area	0.296 m^2
Active module volume	2.1 liters
Radial distance from beam line	63 cm (at inner edge of active readout area)
Geometric acceptance in $ \eta $	2.03–2.8
Signal readout structure	Truly radial readout strips
Readout strip dimensions	0.94 mrad angular pitch
Number of η -segments in readout	8
Number of readout strips per η -segment	384
Number of readout strips per module	3072
Counting gas mixtures	Ar/CO ₂ 70:30
Nominal operational gas flow	1 module volume per hour
Number of gas inlets	1
Number of gas outlets	1
Nominal HV applied to drift electrode	3200 V (Ar/CO ₂)
Nominal operational gas gain	$1-2 \times 10^4$
Demonstrated rate capability	100 MHz/cm ²

Layer	Material	Thickness [mm]
Protective cover	Al	1.0
Cooling pipe	Cu (filled with H ₂ O)	8 external \varnothing , 6 inner \varnothing
Cooling pads	Cu	1.0
GEB board	Cu/FR4	0.140/0.856
Readout board	Cu/FR4/Cu	0.035/3.2/0.035
Induction gap	Ar/CO ₂	1.0
GEM 3	Cu/polyimide/Cu	0.005/0.050/0.005
Transfer gap 2	Ar/CO ₂	2.0
GEM 2	Cu/polyimide/Cu	0.005/0.050/0.005
Transfer gap 1	Ar/CO ₂	1.0
GEM 1	Cu/polyimide/Cu	0.005/0.050/0.005
Drift gap	Ar/CO ₂	3.0
Drift board	Cu/FR4/Cu	0.035/3.2/0.035

Muon subsystem	RE3/1 + RE4/1	GE1/1	GE2/1	ME0
Detector technology	iRPC	GEM	GEM	GEM
$ \eta $ range	1.8–2.4	1.6–2.15	1.6–2.4	2.0–2.8
Number of chambers	36 + 36	144	72	216
Number of channels	13 824	442 368	442 368	663 552
Number of layers/station	1	2	2	6
Surface area of all layers	93 m^2	54 m^2	105 m^2	64 m^2
spatial resolution	$\sim 0.3 \text{ cm}$	$200-340 \mu\text{m}$	$200-410 \mu\text{m}$	$160-390 \mu\text{m}$
time resolution	1.5 ns	8 ns	8 ns	8 ns