The CMS ME0 Upgrade: Enhancing Forward Muon Reconstruction at the HL-LHC

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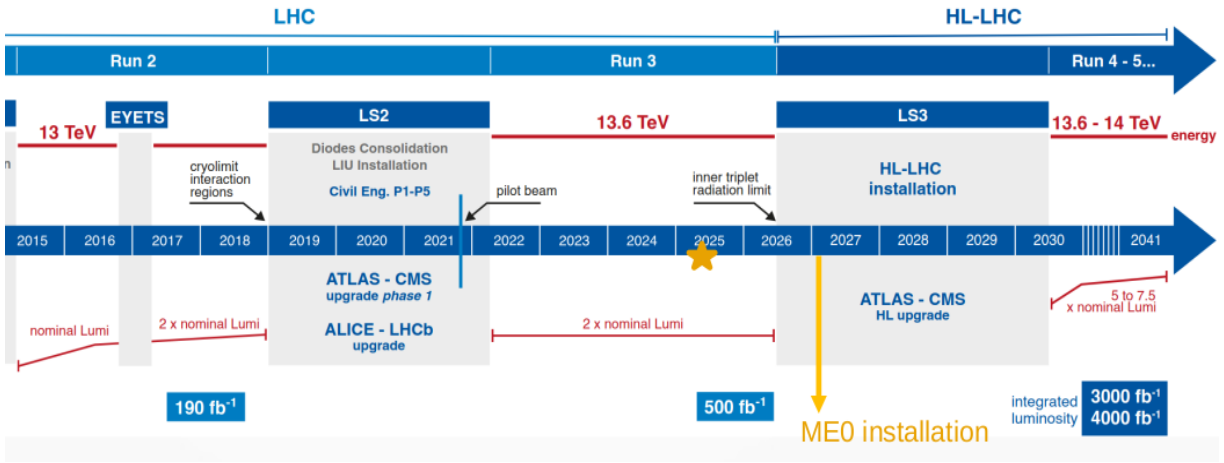
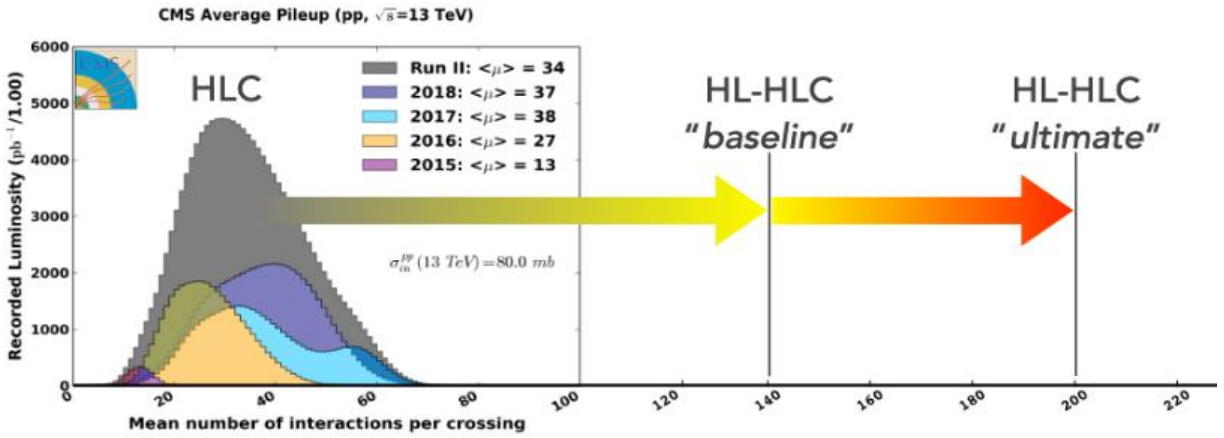
On behalf of the CMS Muon group

LEPTON PHOTON 2025: 27/08/2025, MADISON

Motivation: Why Upgrade the CMS Muon System?





- **HL-LHC challenges:**
  - √s = 14 TeV, 140–200 pile-up events.
  - ×10 design luminosity → 3000–4000 fb⁻¹.
  - Harsh environment: very high background rates (γ, neutrons) and strong radiation → detectors must handle high rates & be radiation tolerant.

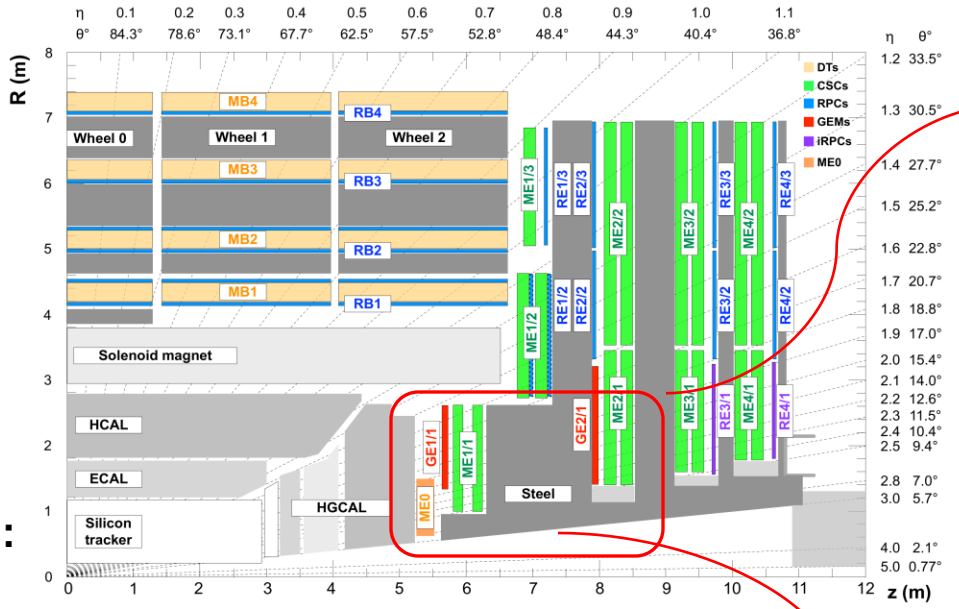
- **Forward region gap:**
  - Current muon coverage limited to |η| < 2.4.
  - Physics opportunities lost beyond this → ME0 extends acceptance to |η| ≈ 2.8.

- **Physics drivers:**
  - Precision Higgs couplings & rare decays (HH, H→μμ, H→Zγ).
  - Lepton Flavor Violation searches (τ → 3μ).
  - Discovery potential for BSM physics (SUSY, heavy resonances).

TDR Link

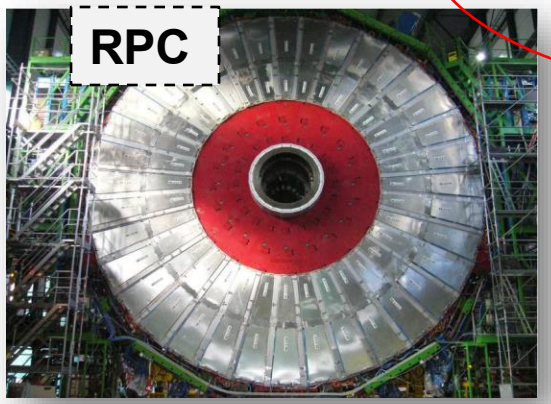
CMS Muon System

- CMS muon system (|η| < 2.4) uses 4 gaseous detector technologies:
  - **Drift Tubes (DT) :** Barrel tracking, ~100 μm resolution.
  - **Cathode Strip Chambers (CSC):** Endcap tracking, 40–160 μm resolution.
  - **Resistive Plate Chambers (RPC):** Barrel + endcap timing, ~1.5 ns resolution.



TDR link

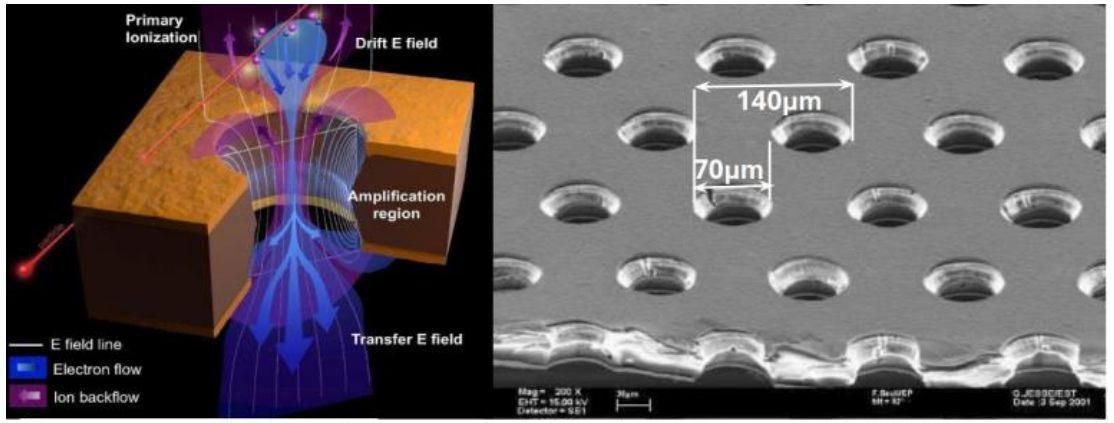
- **Gas Electron Multiplier (GEM) :** In the endcap improves trigger efficiency, muon p_T resolution, and radiation tolerance at high rates.
- η coverage - GE1/1: 1.6–2.2 (installed LS2), GE2/1: 1.6–2.4 (postponed), ME0: 2.0–2.8 (LS3).

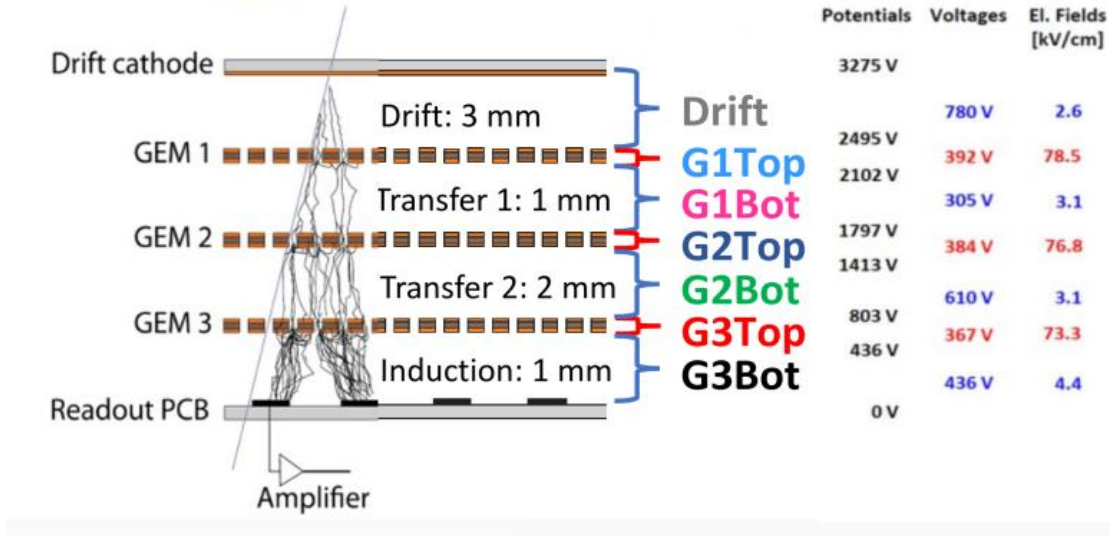


Introduction to GEM working in CMS

- **Principle of Operation:**
  - Copper-clad Kapton foil with bi-conical holes (~70 μm, 140 μm pitch) with gas mixture: Ar/CO_2 (70:30).
  - High voltage → strong fields in holes → electron avalanches.
  - Triple-GEM cascade → high gain, efficient charge transfer, stable operation.

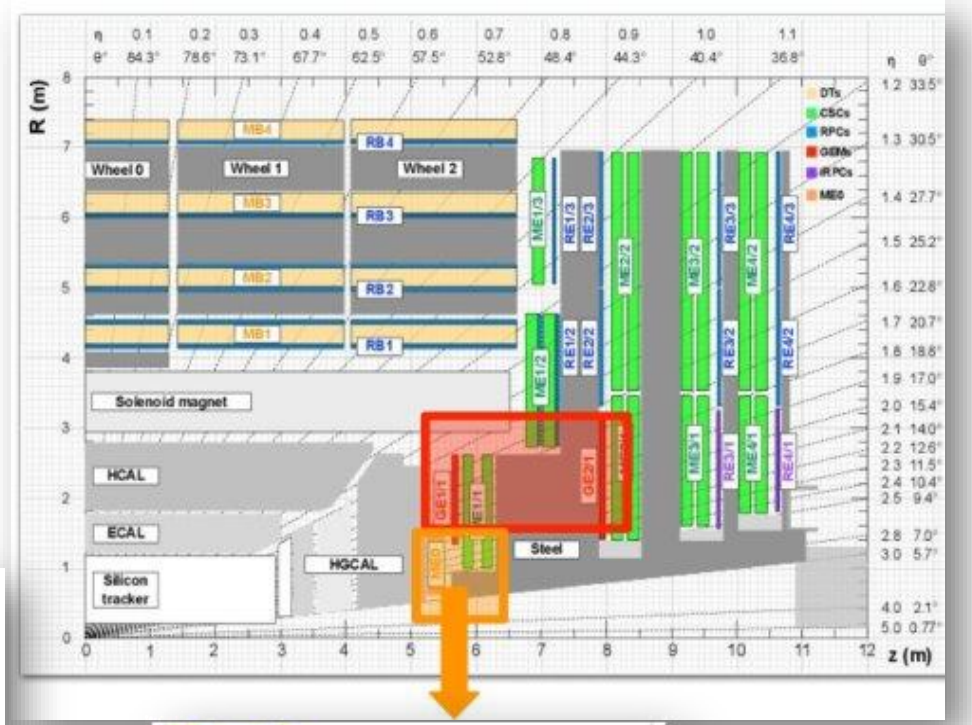
- **Performance & Advantages:**
  - High rate capability: up to MHz/cm².
  - Excellent spatial : ~100 μm and timing: 8–10 ns resolutions.
  - High gain (~2×10^4) with stable operation.
  - Radiation tolerance & long-term stability.

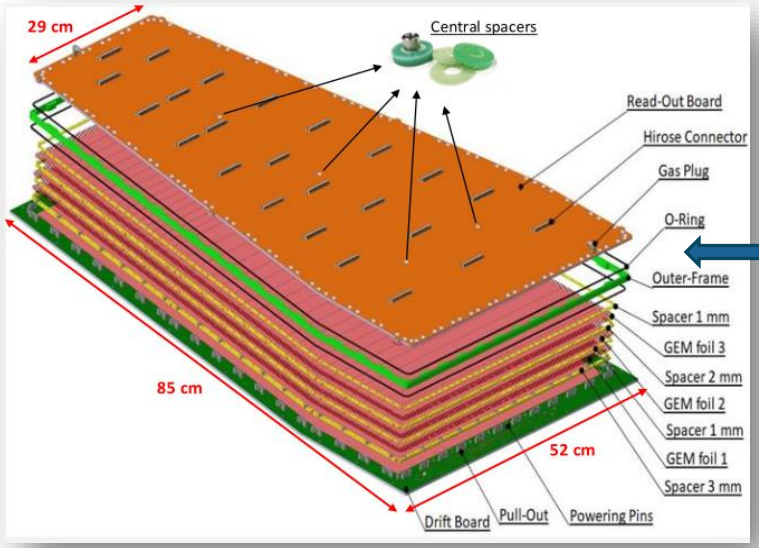




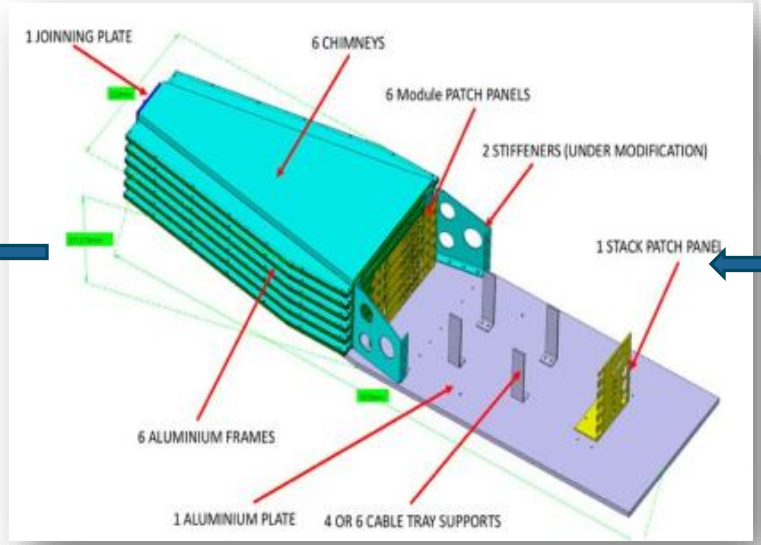
The ME0 Detector upgrade in CMS

- **Location:** ME0 = Muon Endcap '0', Installed in the very forward region, behind the new high-granularity calorimeter (HGCal) .
- **Coverage & Design:** Extends muon acceptance 2.0 < |η| < 2.8; 18 stacks/endcap (36 total), 6 modules/stack → 216 modules (+spares).
- **Performance:** Efficiency >97%, φ resolution ≤ 500 μrad, timing 8–10 ns.
- **Environment:** Operates under high rate (~150 kHz/cm²) and high radiation (7.9 C/cm²).

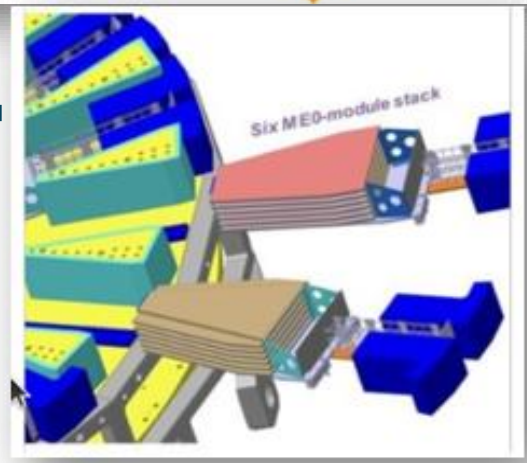




Layout of Single ME0 module

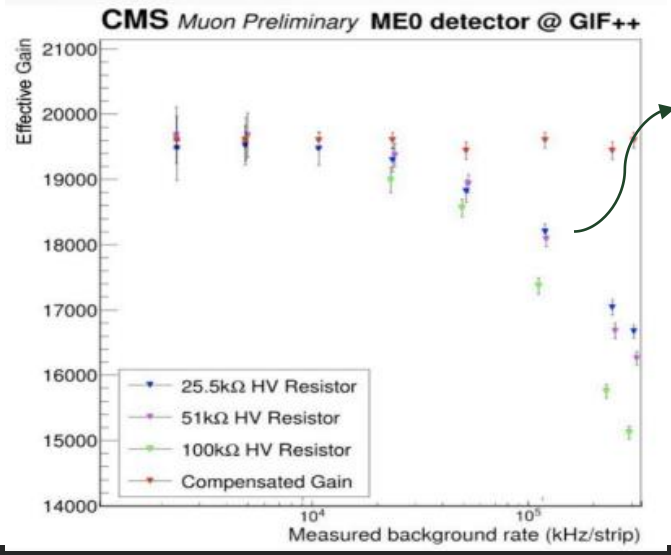


Layout of Single Stack: 6 * ME0 module



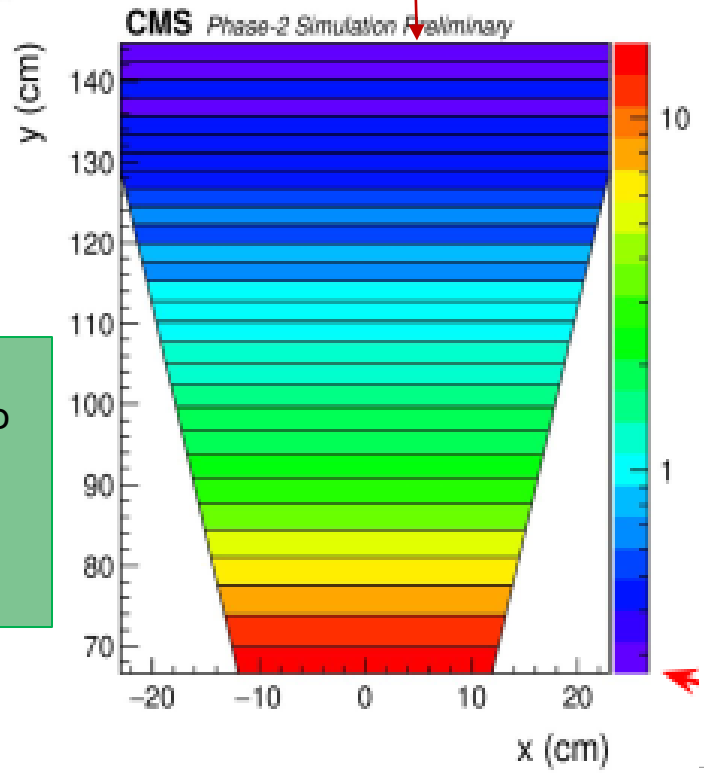
ME0 GEM Foil Segmentation

- Segmentation is needed to equalize the highly non-uniform background rate across η and minimize discharge energy by limiting sector size.
- Non-uniform background as a function of η with Horizontal Segmentation.
- Uniform background particle rate per sector with Radial segmentation of GEM foil.
- Divided into 40 sectors. Each sector is smaller than 100 cm² to minimize discharge energy.

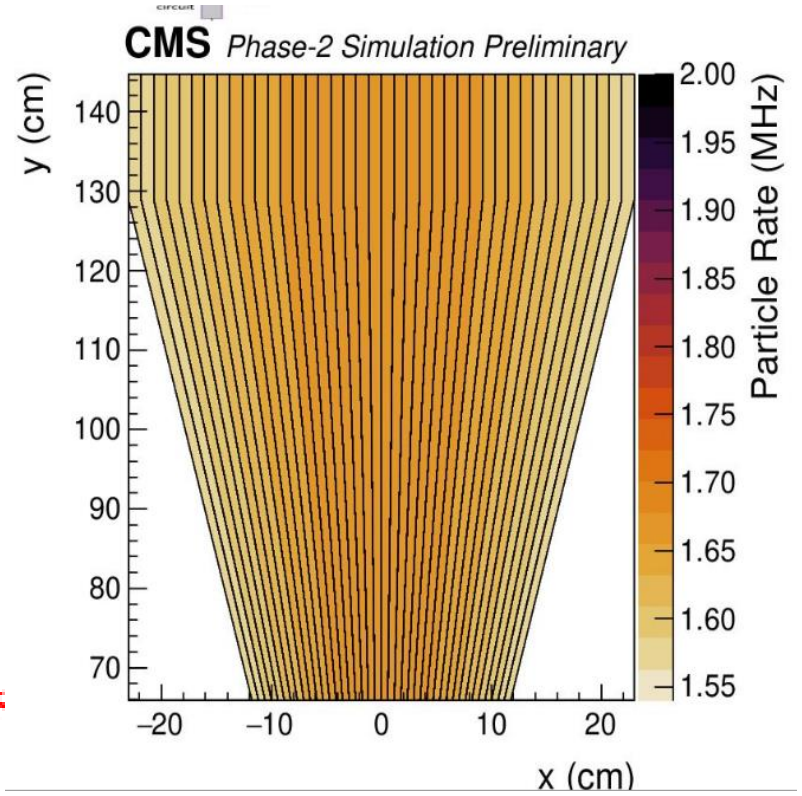


Gain recovery demonstrated up to 2.2 MHz/sector or 280 kHz/strip and with different HV filters up to 100 kΩ

Highly non-uniform rate along the chamber profile.

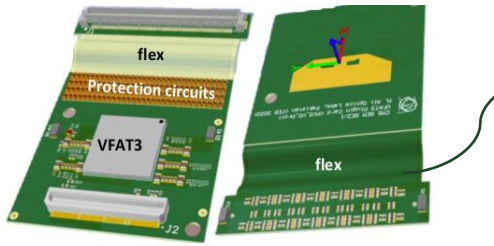


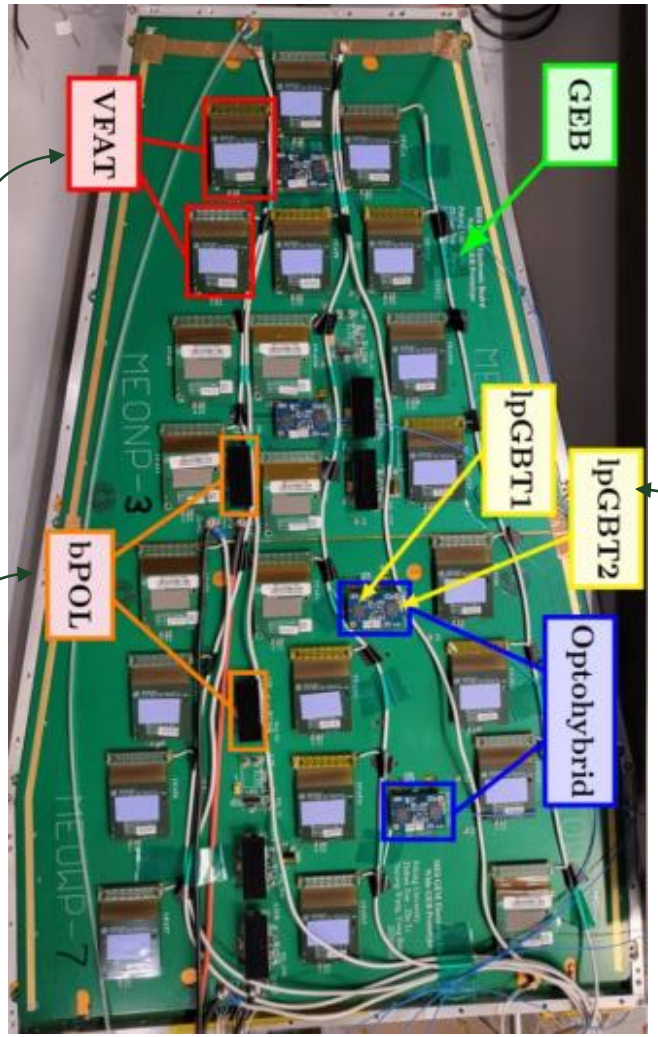
Drawback: dead area at sector separation.

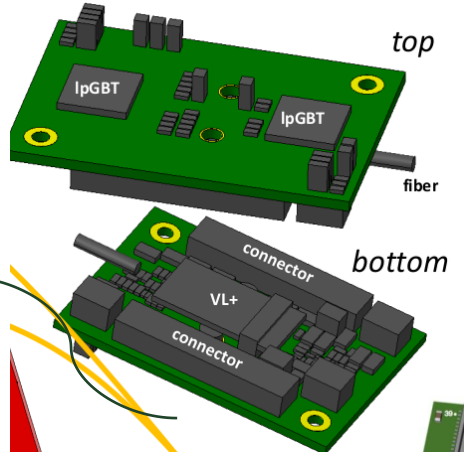


ME0 Electronics

- **VFAT3 (Very Front-end Analog Transceiver 3)** plugin cards: digitizes and reads out ionization signals for 128strips.
- **OH (Optohybrid)** sends data from 6 VFATs to back-end.
  - **lpGBT** (low power Gigabit Transceiver) chips used for data processing on the OHs.
- **GEB (GEM Electronics Board)** routes connections between VFATs and OHs .
- **bPOL:** DC-DC converters supplying voltage to front-end electronics.

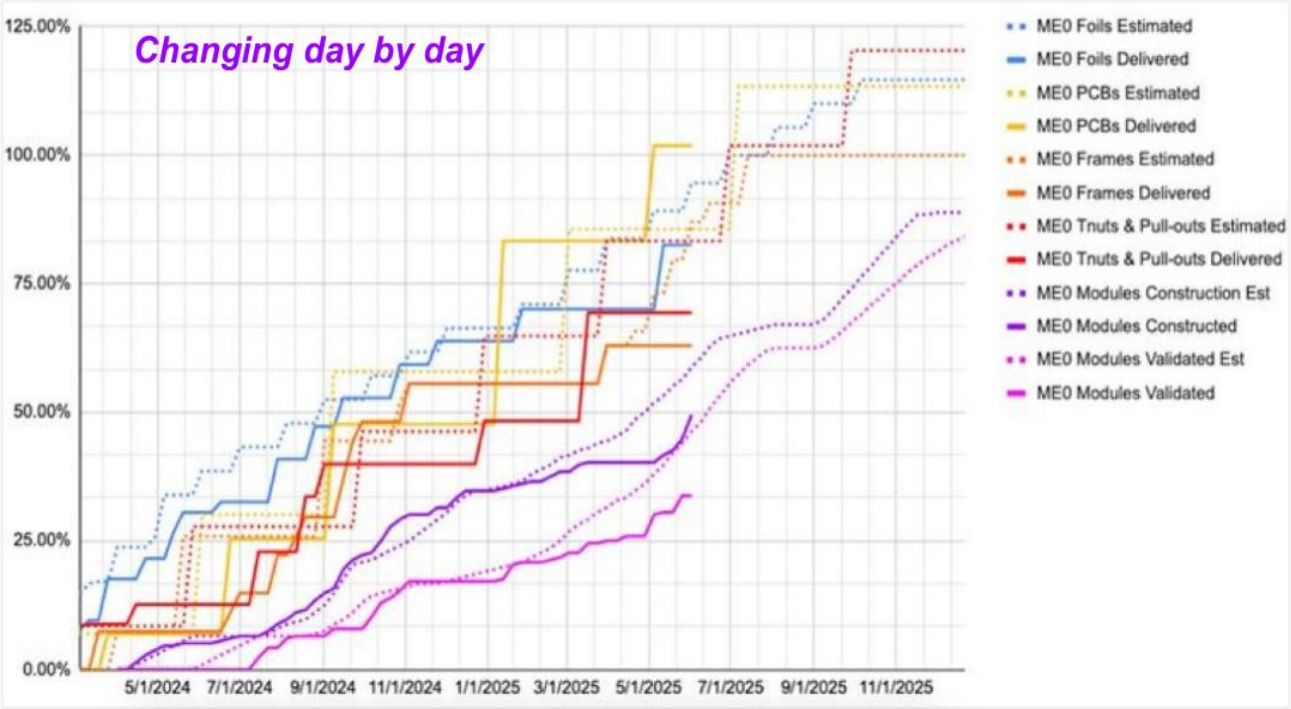


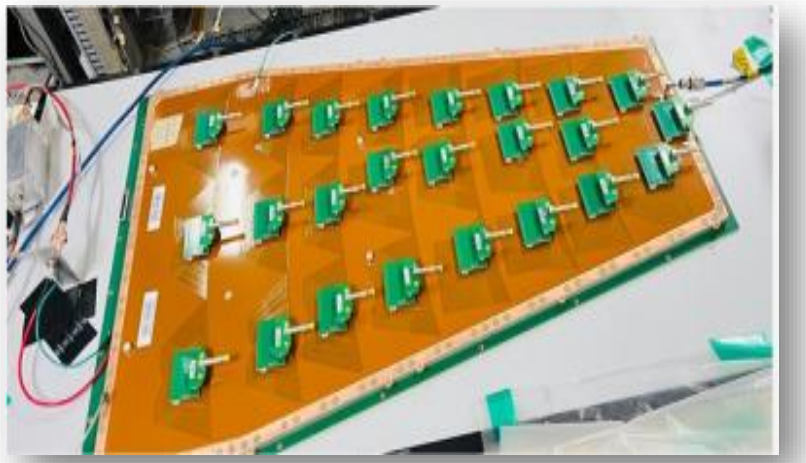


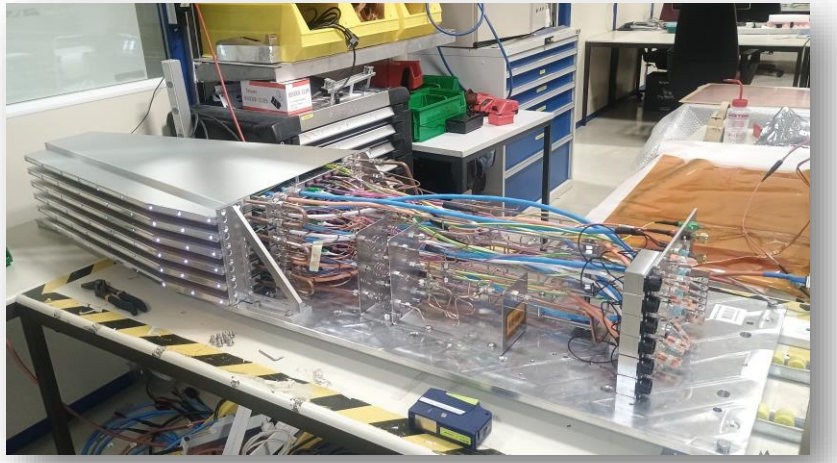


ME0 Production and Validation Status

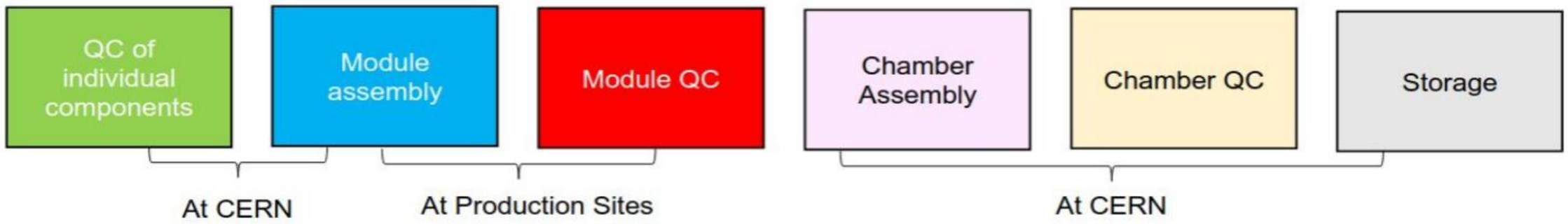
- **Stacks:** Production initiated; first stack validated with cosmic stand.
- **Rate:** Target of ~3 stacks/month; nearly 50% of production completed.
- **Monitoring:** Production and delivery closely tracked; validation steadily improving.



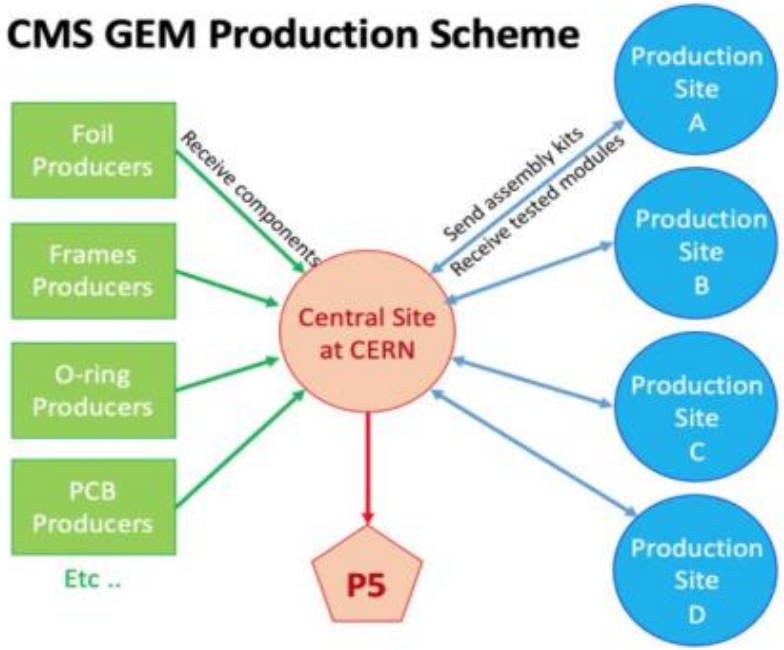




ME0 Production Scheme & Sites



- **Quality control (QC)** are key factors to ensure the delivery of fully efficient detectors yielding their best performance when installed in CMS.

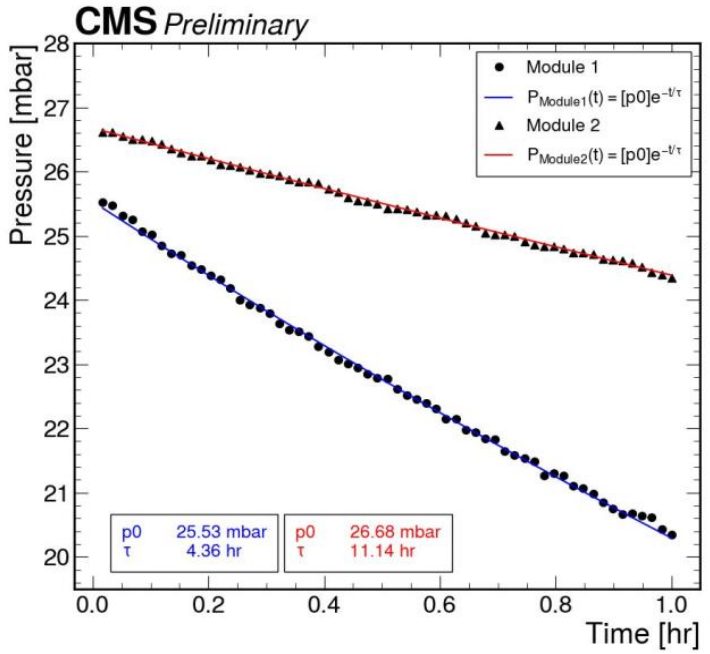


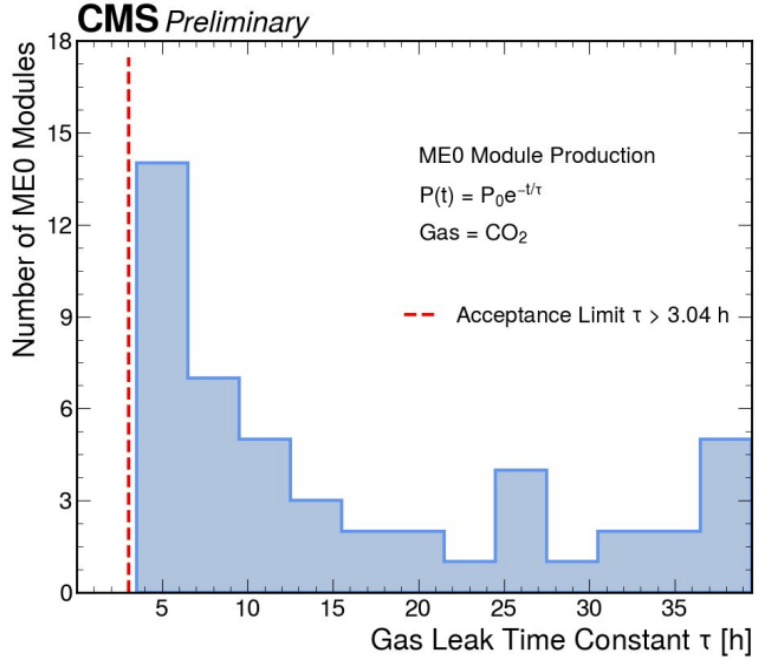
- **India (2):** Panjab Univ., Delhi Univ.
- **CERN (1):** Geneva (double capacity).
- **Europe (3):** Gent, Bari/Frascati, Aachen.
- **China (1):** PKU (Beijing).

Vendors → CERN (QC1–QC2, kit prep, logistics) → Production Sites (assembly, QC2–QC5, database).

ME0 Quality Control Results

- **Gas Leak Test:** All modules show leak rates within acceptance (τ > 3 h).
- **HV Divider Test:** Resistance deviation well below 3% acceptance limit → stable HV operation.
- **Effective Gain:** Measured with X-ray; average gain ~4.5×10^4 at 700 μA (limit ≥ 1.5×10^4).
- **Uniformity:** Gain and MPV (Most probable signal value) distributions uniform across chambers and sectors.
- **Stability:** Consistent response across modules, confirming robust production quality.





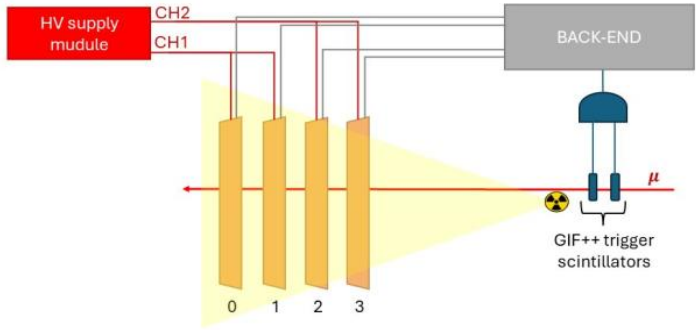
DP-2024/126

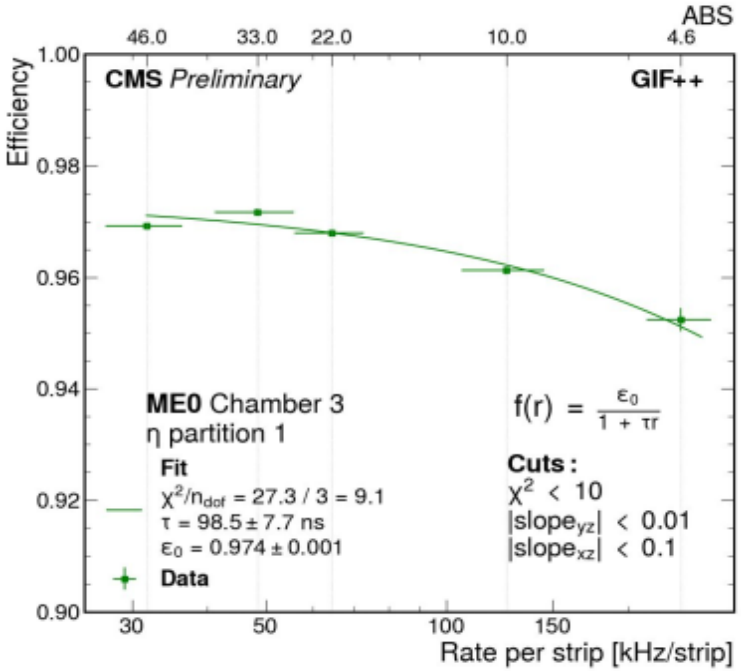
Conclusion: Initial production validated assembly procedures and confirmed readiness for large-scale ME0 construction.

ME0 Performance: Rate Capability @ GIF++ (CERN)

- 4-layer prototype with 80 GeV muons + ^{137}Cs source, VFAT3 readout.
- For global irradiation, voltage drop is successfully compensated by increasing voltage proved by testing with muon beam and gamma-rays at GIF++ (CERN).
- Efficiency vs rate follows $f(r)=\varepsilon_0/(1+\tau r)$, τ = 98–182 ns (VFAT3 dominated).
- Long flat plateau at ~97% efficiency.
- Smaller cluster size from background reduces effective dead time.

SETUP





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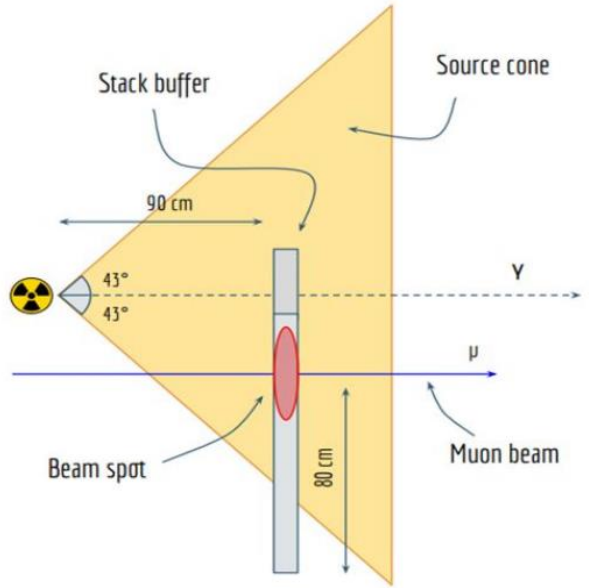
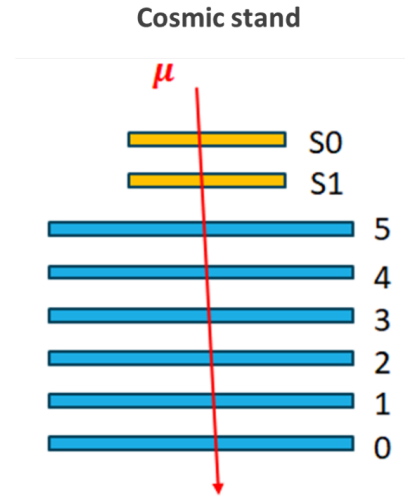
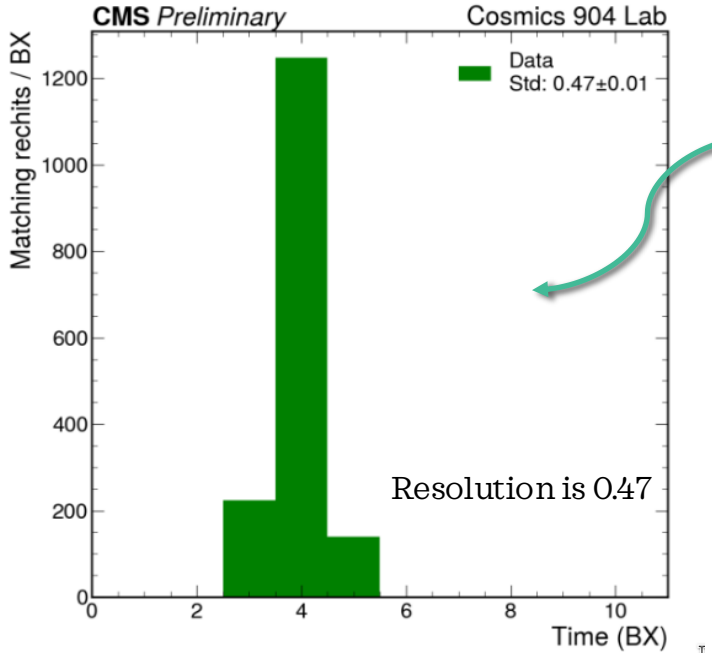


ME0 Performance : Time Resolution (1)

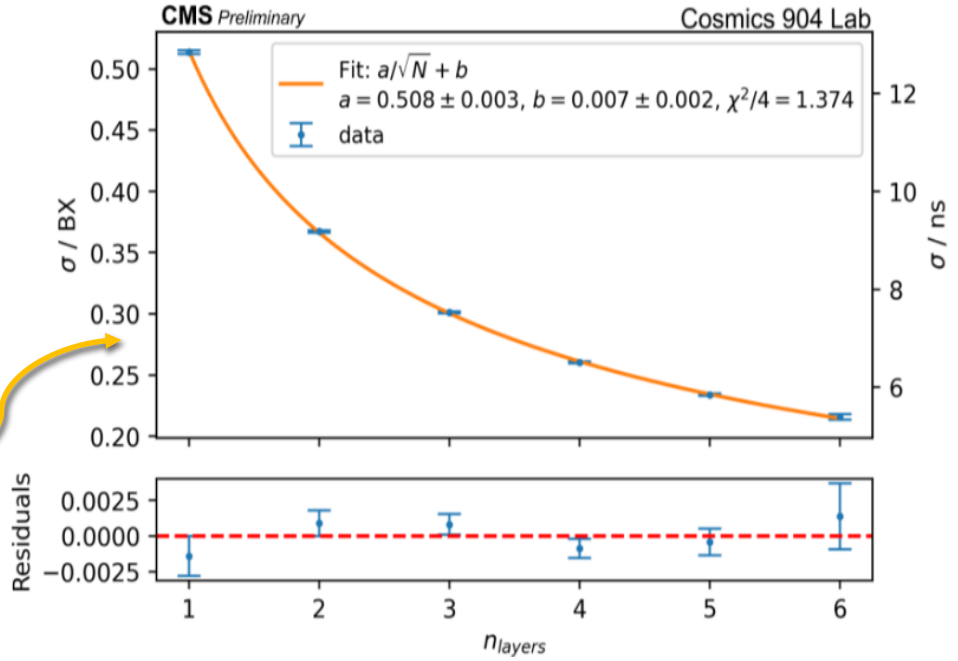
- Studied with cosmic muons (CMS 904 lab at CERN) and test beams.
- Single chamber resolution limited (~10-12ns).
- Resolution improves with number of layers: ~6 ns (5 layers), ~5.4 ns (6 layers).
- Comparable results in lab & beam tests → stable performance.
- Adequate for rejecting out-of-time backgrounds at HL-LHC.





Time Resolution of a single layer

Time Resolution of an ME0 stack

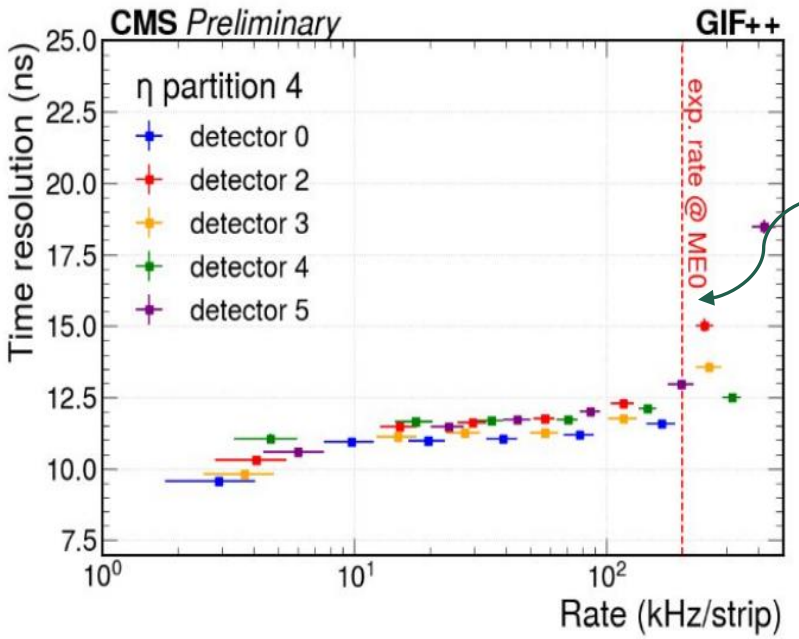


CMS DP-2024/089

ME0 Performance : Time Resolution (2)

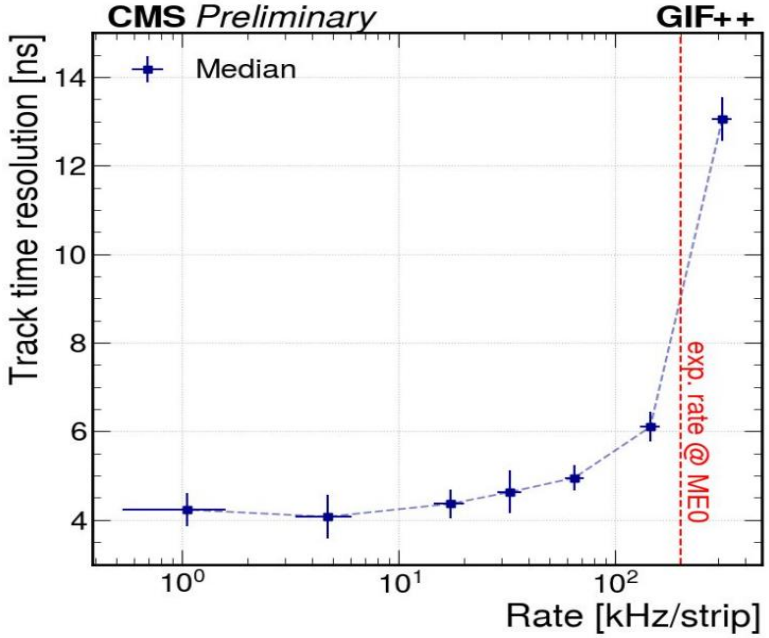
- Tested full ME0 stack at GIF++ with muons + γ background and beam
- Stable under γ background, ~95% efficiency.
- Meets HL-LHC timing requirements.
- Multi-layer design crucial for precise timing and background suppression.

CMS DP-2025/019



Dashed line indicates expected max rate (at high η)

ME0 expected range: 10 – 200 kHz/strip.

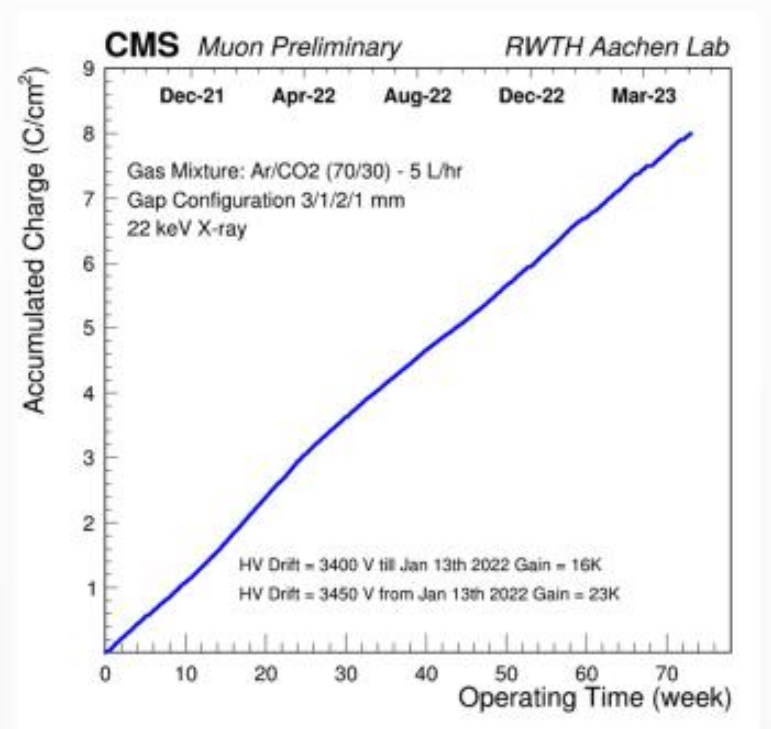


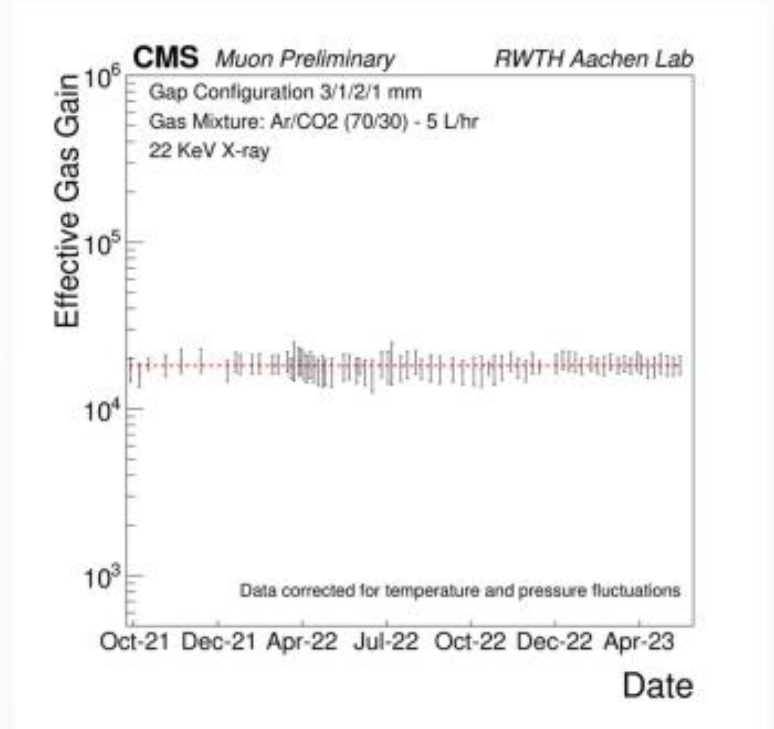
Time resolution of 5 modules at GIF++
• Slightly different rates measured in different layers of the stack due to opening angle & shielding.

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

ME0 Performance: Longevity

- Reached expected accumulated charge (safety factor = 1) at hottest point (high-η) of 8 C/cm² in ~1.5 years.
- Corrected gas gain measurement for temperature and pressure shows stable performance.





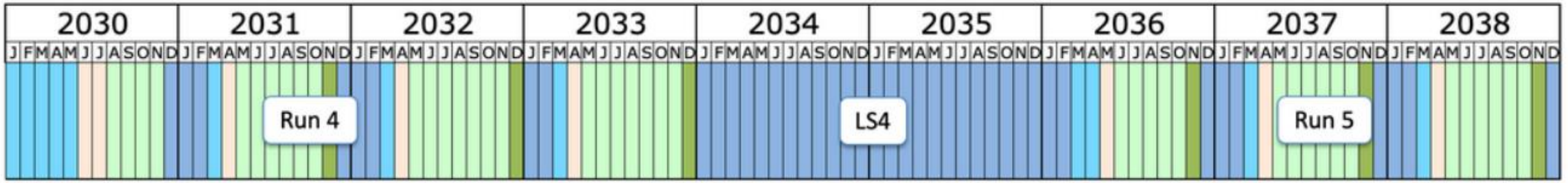
Aging Studies Public Results

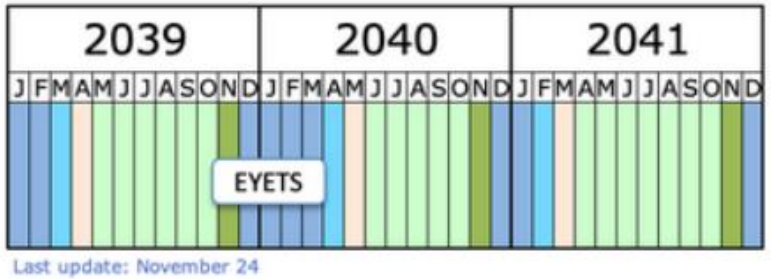
Summary

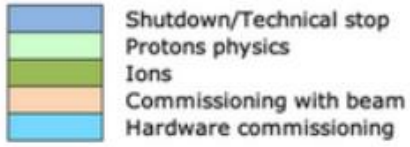
- ME0 in endcap improves muon trigger efficiency, p_T resolution, and radiation tolerance.
- ME0 (compact 6-layer GEM stack) ensures robust forward muon performance, Improves efficiency, reduces fake rate in high-rate conditions.
- Production & QC: Design validated; ~50% modules complete; QC/validation on schedule and ME0 installation planned for LS3 (2027).

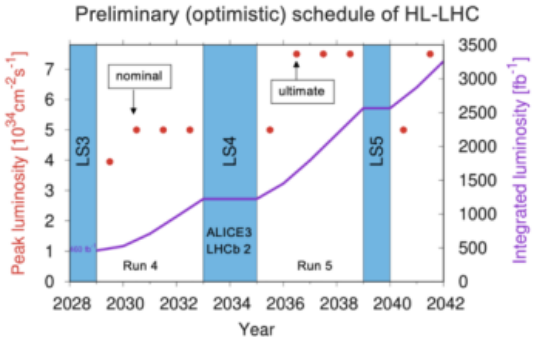
Backup...

High Luminosity timeline at LHC



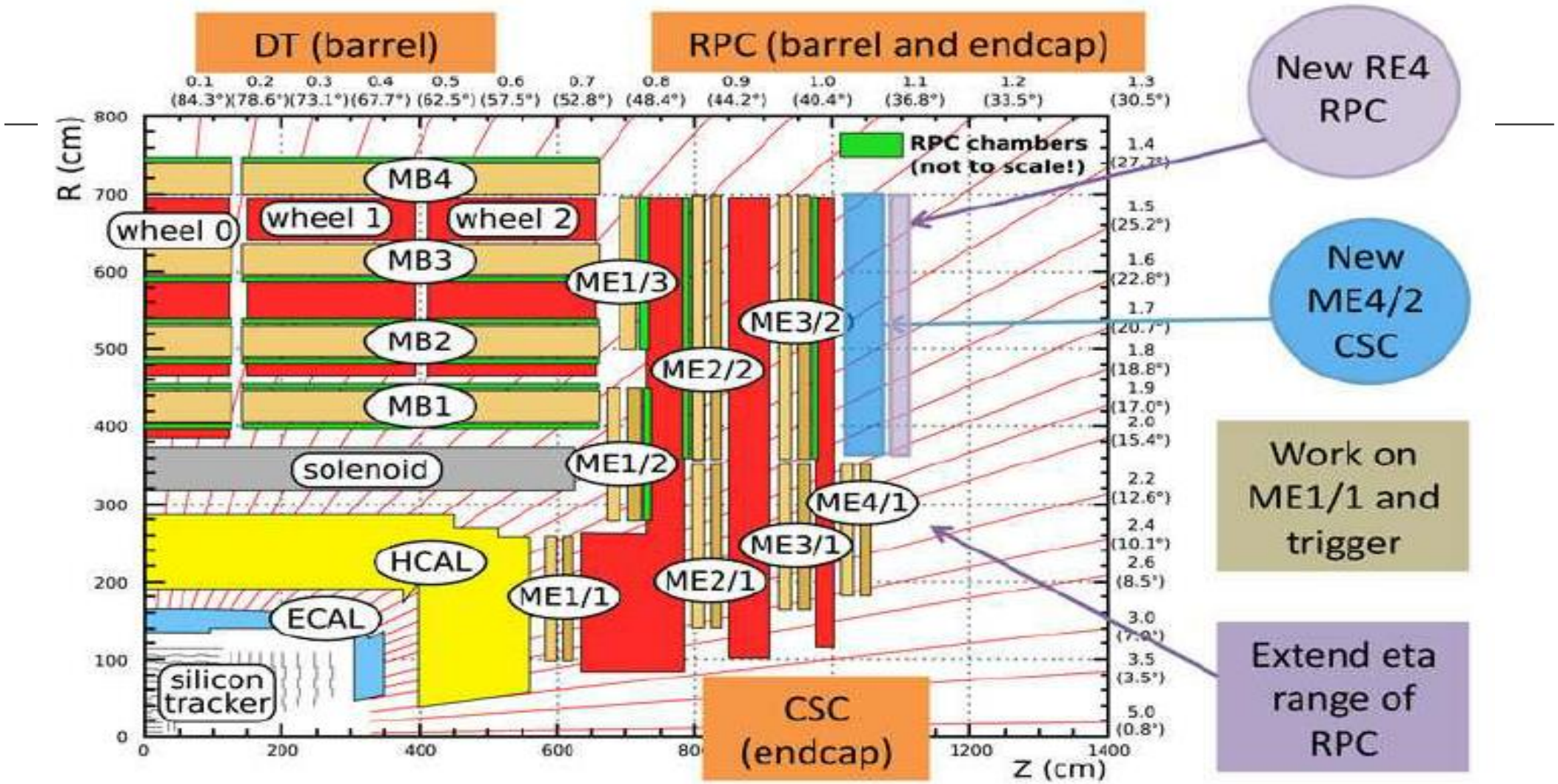




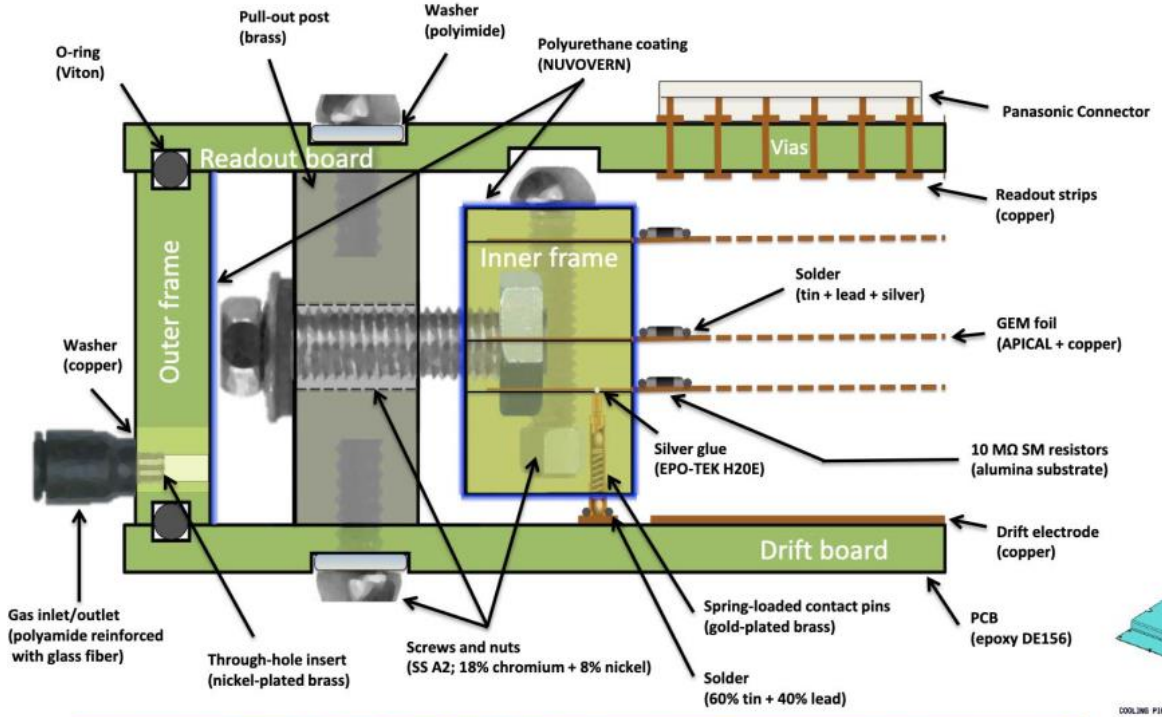


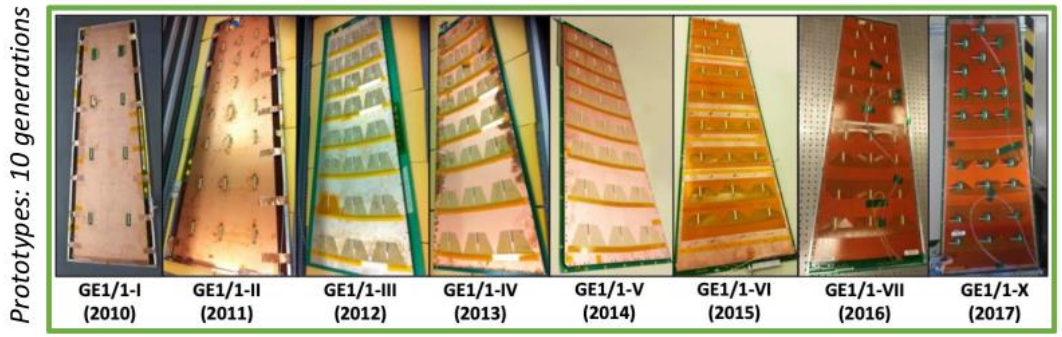
	LHC	HL-LHC baseline (ultimate)
Instant. Luminosity ($cm^{-2}s^{-1}$)	10^{34}	5 (7.5) 10^{34}
Integrated Luminosity (fb^{-1})	300	3000 (4000)
Pile- Up	30	140 (200)
	CMS Phase 1	**CMS Phase 2**
L1 trigger accept (kHz)	100	750
L1 accept latency (μs)	3.6	12.4

Schematic View of CMS Muon System

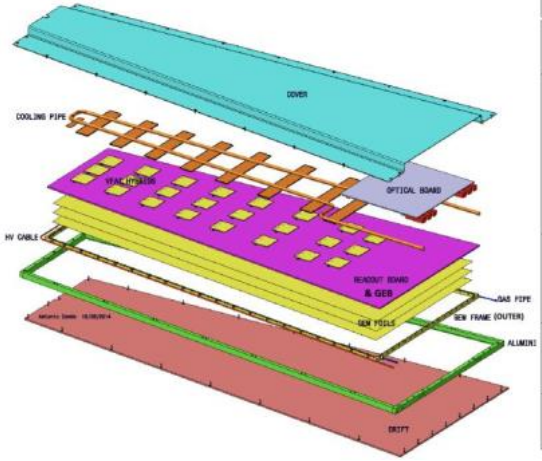


CMS GEM (GE1/1) Detector



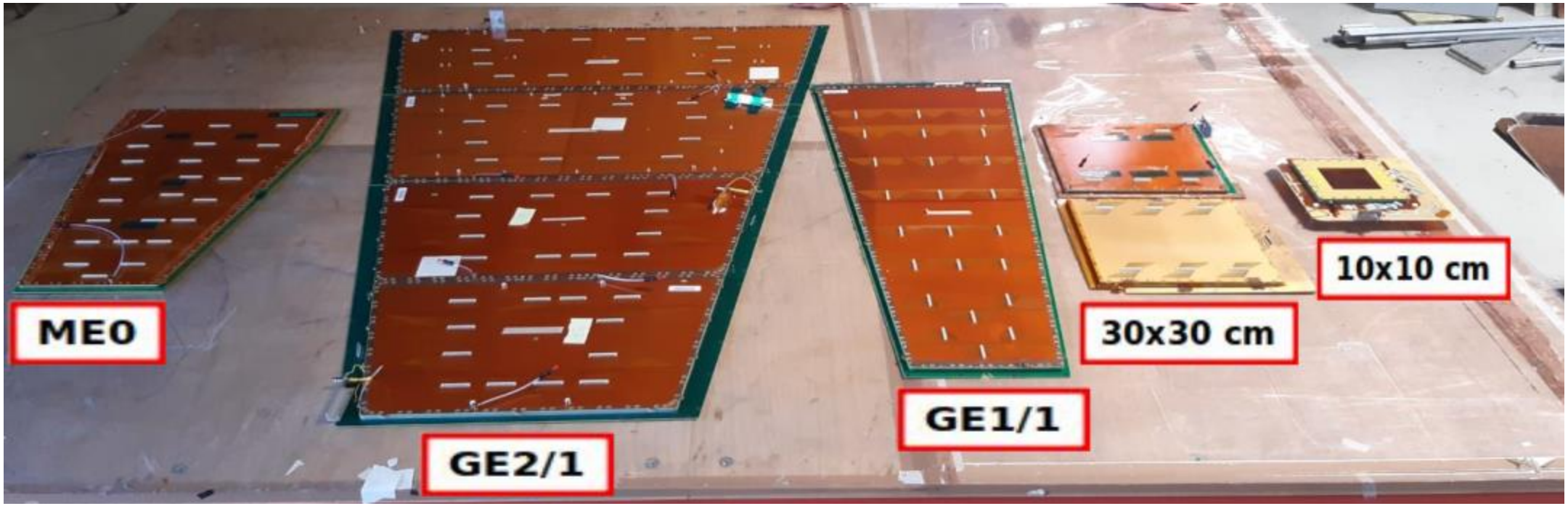


- Construction Technique: Stretching, *(NS2 = no spacer, no tretching)*
- Gap config: 3/1/2/1 mm - Ar:CO2 70/30 – Gain = 20,000
- Spatial Resolution < 300 urad
- Rata Capability up to 10 kHz/cm^2
- Two types of Chambers:
  - Long ~4000 cm^2 (l x b_1/b_2: 121cm x 23/45cm)
  - Short ~3000 cm^2 (l x b_1/b_2: 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)

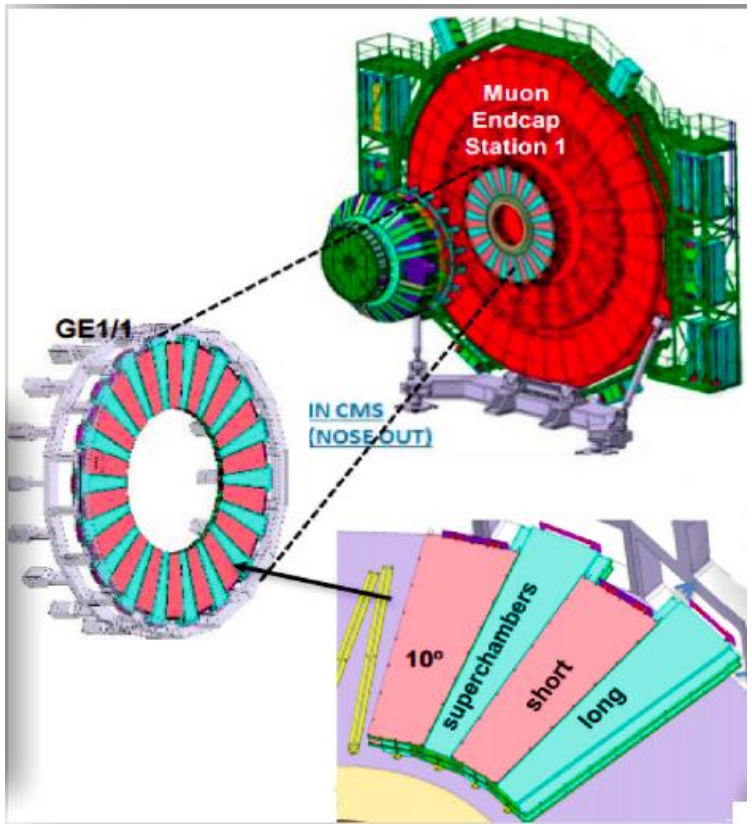


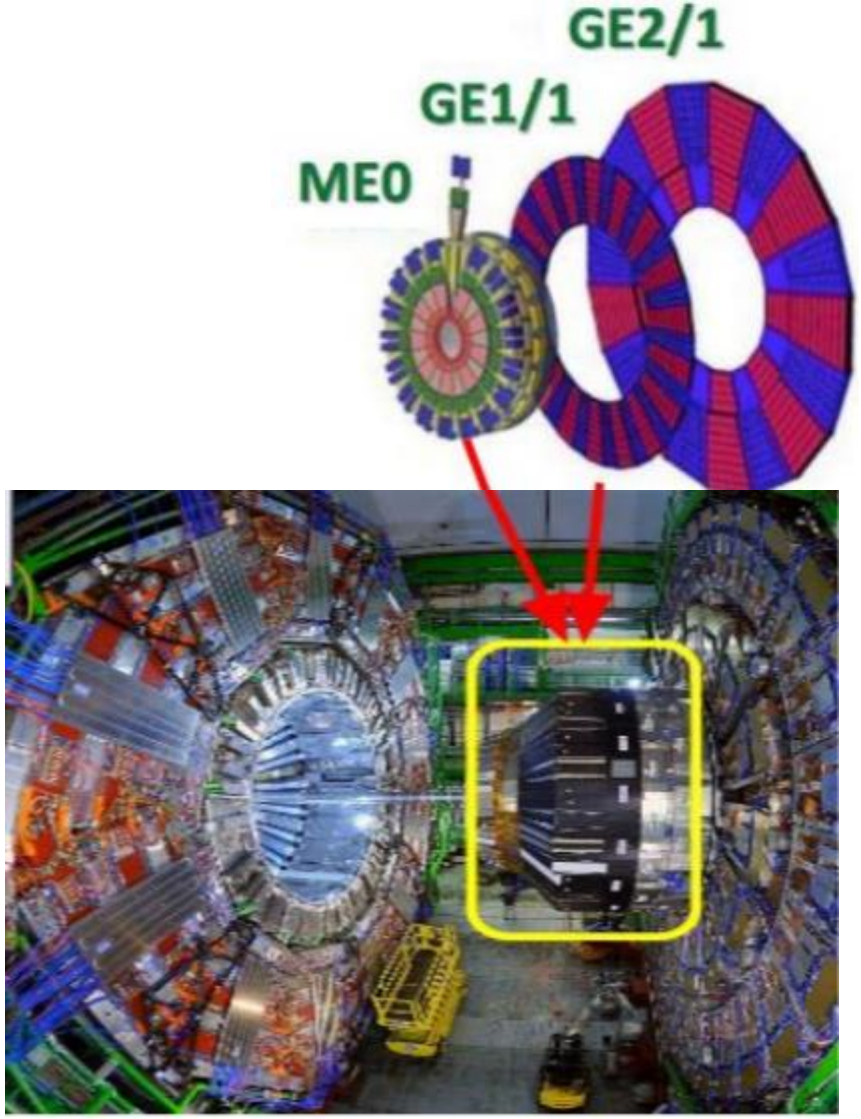
Specification / Parameter	GE1/1
Detector technology	Gaseous detector; micro-pattern gas detector (MPGD)
Charge amplification element	GEM foil (triple, cascaded, tensioned at ≈ 5 N/cm)
Number of chambers in overall system	144 (72 in each endcap)
Chamber shape (active readout area)	Trapezoidal; opening 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

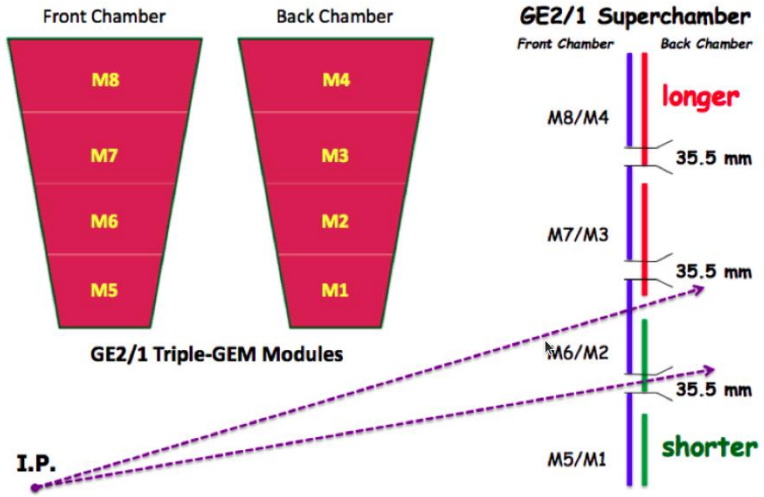
CMS GEM Detector : GE1/1, GE2/1, ME0



CMS GEM Detector : GE1/1, GE2/1, ME0



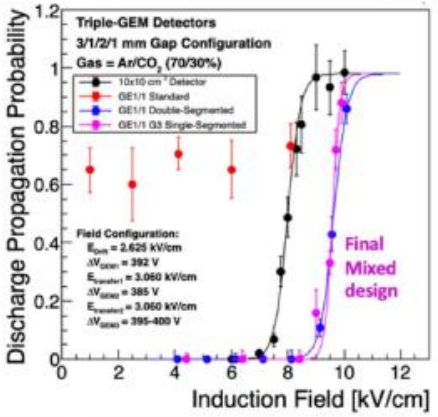


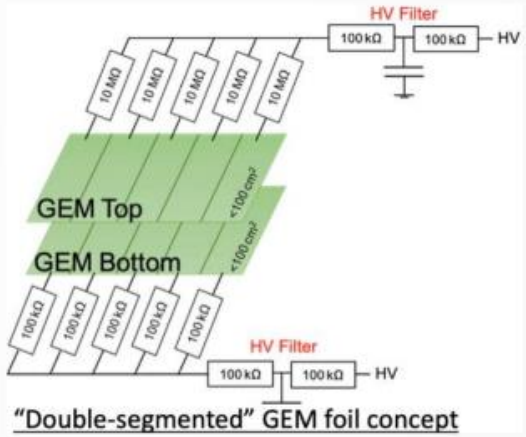


Lessons learned from GE1/1

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

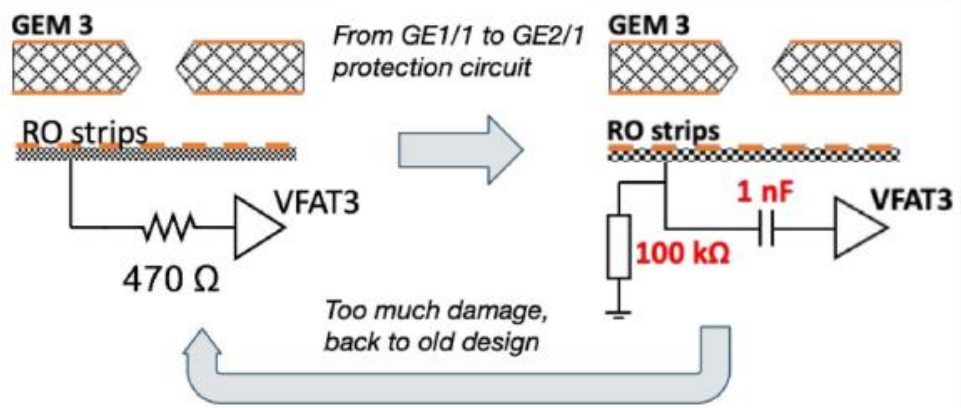




"Double-segmented" GEM foil concept

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

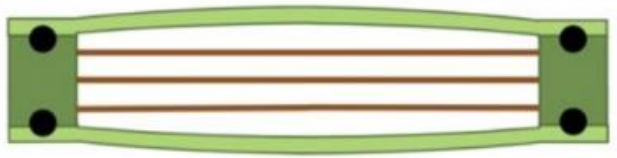


→ **resets traced back to be due to leakage current to VFAT GND**
Solution: **improved grounding** on readout board with copper bars

Lessons learned from GE1/1

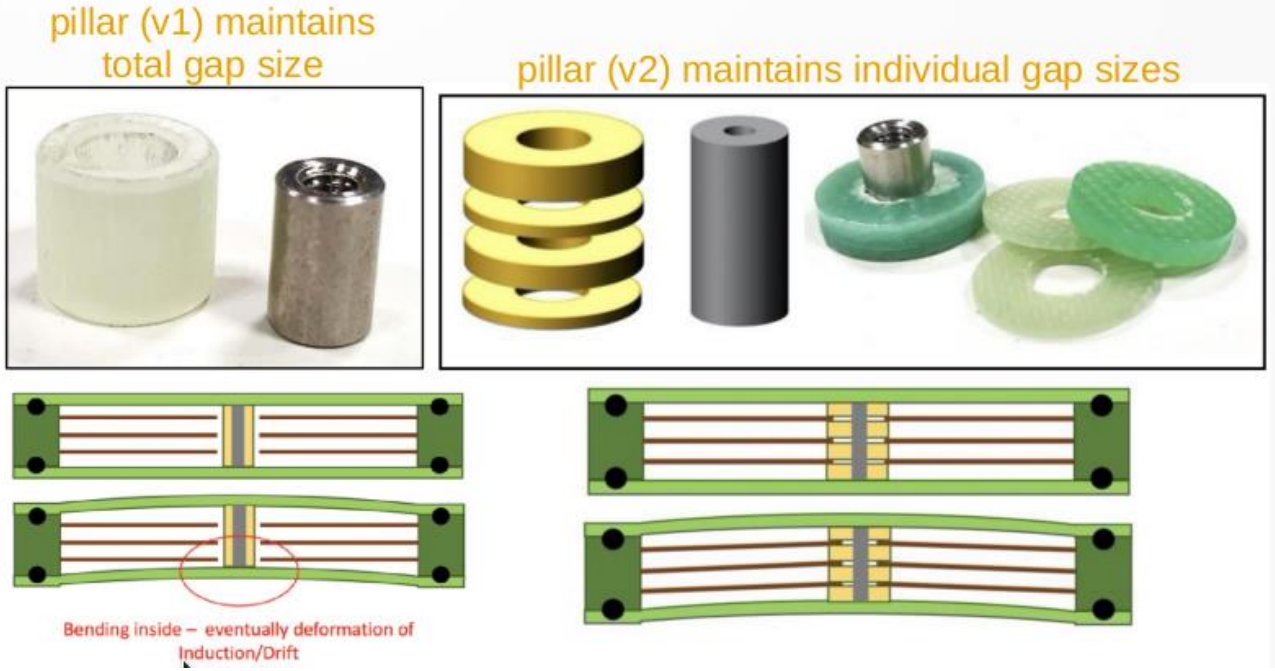
GE1/1 Basin Effect: up to 40% variation in gain measured in gain uniformity tests during mass production

drift and readout PCBs bend, deforming gas gaps inside detector



Solution:

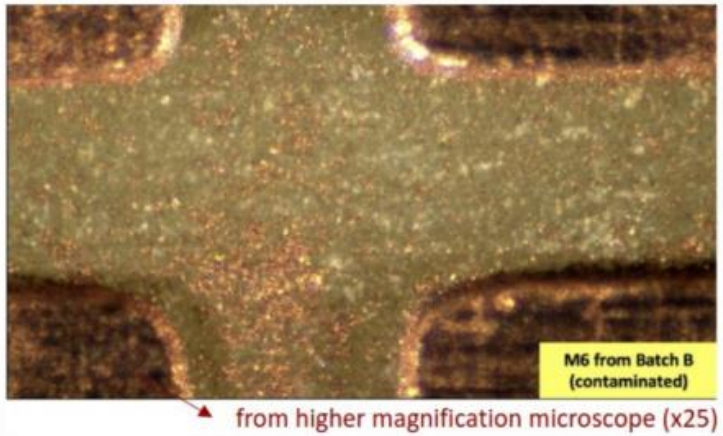
- add pillars (for GE2/1 and ME0)
- not fixed for GE1/1: requires new foil mask with holes for pillars, PCBs with holes, ...



Lessons learned from GE2/1

During summer 2023 increasing problems when closing GE2/1 modules: **shorts** forming on GEM foils

- found **copper dust** on readout PCBs
- **no passivation** applied on drift and readout PCBs to protect against oxidation



Solution for ME0:

- passivation applied on already produced ME0 PCBs
- reviewed PCB production procedure
- added microscope inspection of all boards

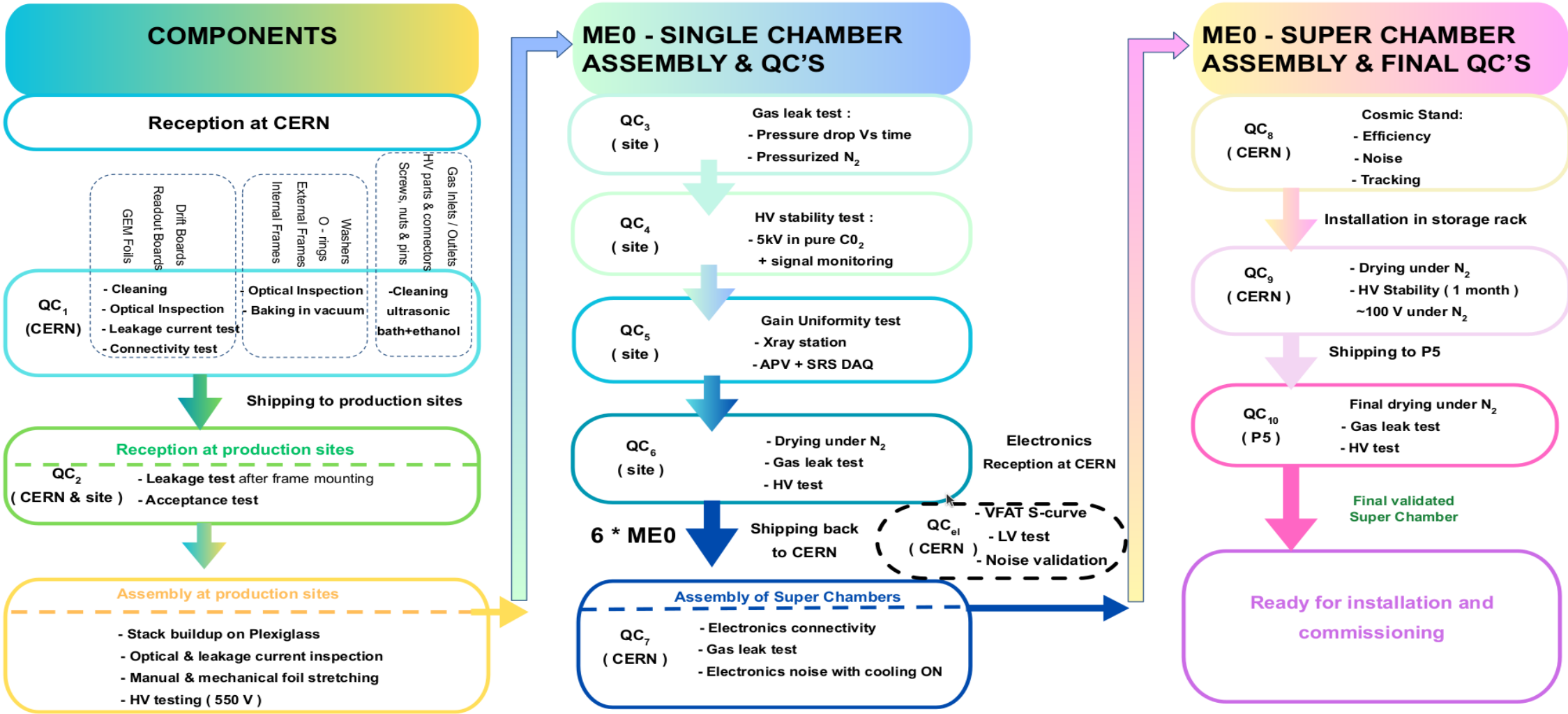
ME0 Specifications

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_2O)	8 external ⌀, 6 inner ⌀
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	~ 0.3 cm	200–340 μm	200–410 μm	160–390 μm
time resolution	1.5 ns	8 ns	8 ns	8 ns

ME0 Components & Quality Controls overview



ME0 timing studies (GIF++ test beam)

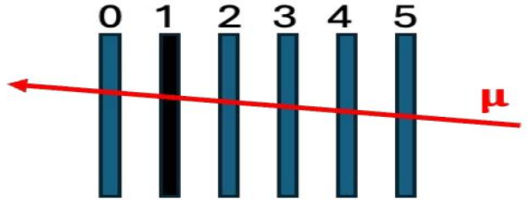
- First full ME0 stack (6 layers, 5 active) tested at **GIF++**.
- Muon beam (80 GeV) + γ background from **^{137}Cs source**.
- Readout with **VFAT3 electronics**, standard Ar/CO_2 gas.

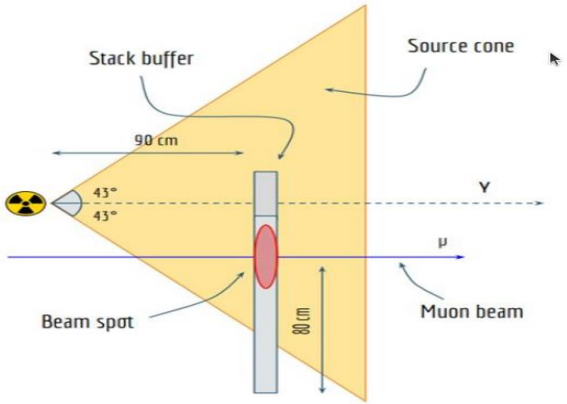
Results

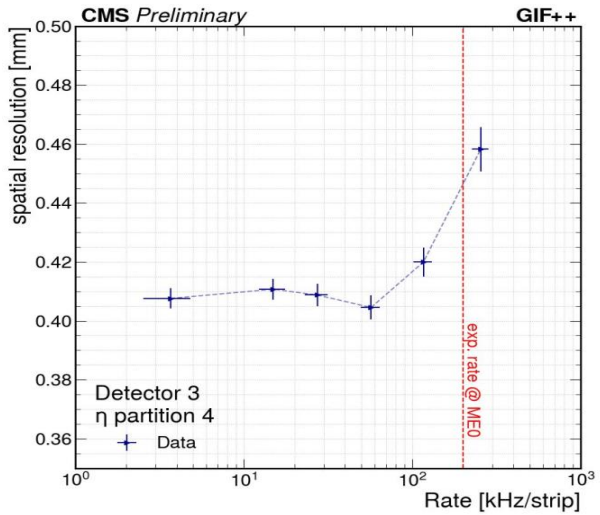
- Single-layer timing resolution: **~4–5 ns**.
- Combined 5 layers: **~2 ns resolution**.
- Stable performance with high γ background.
- Muon efficiency after BX cut: **~95%**, good background rejection.

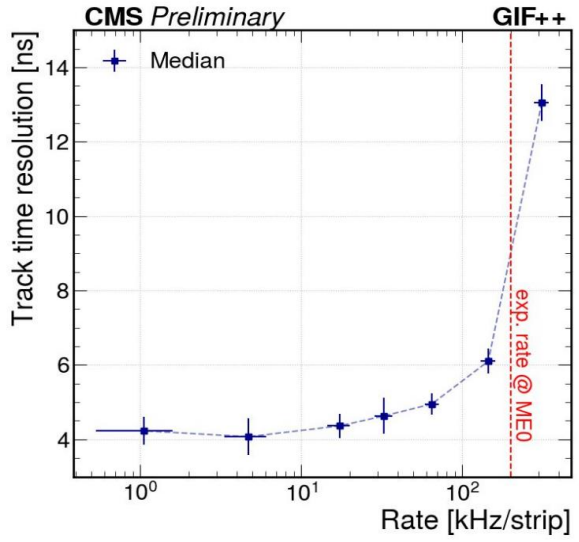
Conclusion

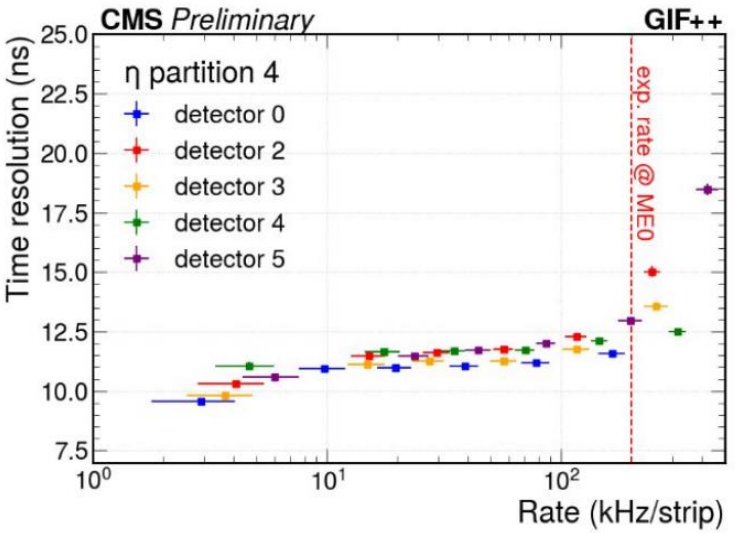
- ME0 meets HL-LHC timing requirements.
- Multi-layer design crucial for precise timing and background suppression.











QC results (ME0)