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Upgrade of the CMS Muon system with triple-GEM detectors: performance of the GE1/1 station and detector design and testing of the ME0 station

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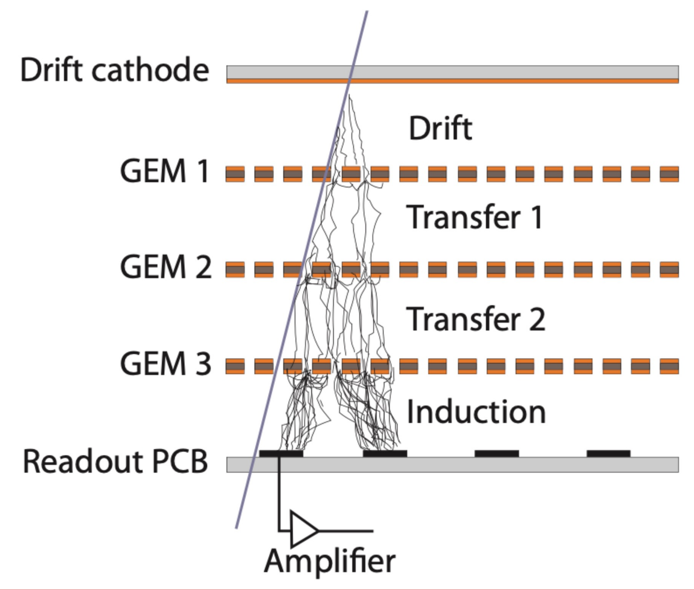
Principle of operation

Triple GEM:

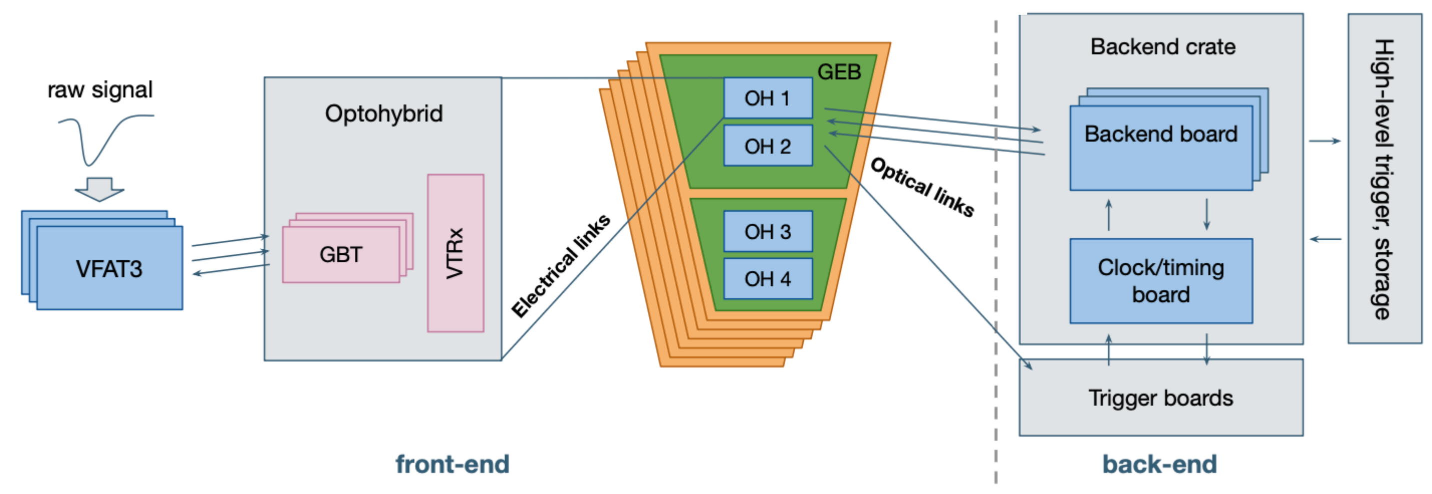
- Three GEM foils in cascade

Main Features:

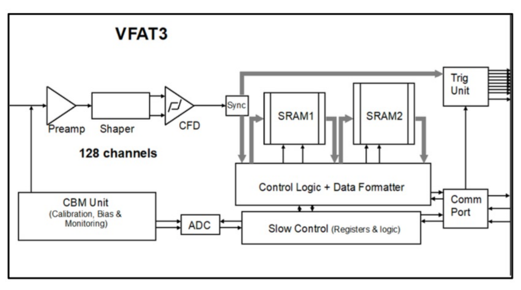
- Gain ~ 10^4
- Spatial Resolution O(100μm)
- Intrinsic rate capability > 1 $\mathrm{MHz/mm^2}$
- Timing 8-10 ns
- Longevity at integrated charges $\leq 8\ \mathrm{C/cm^2}$



Readout Electronics

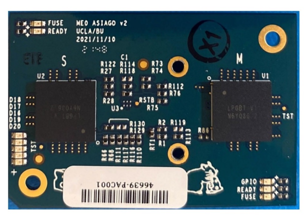


Front-end chip: VFAT3



- 128 analog channels (with preamplifier, shaper, discriminator)
- Digital paths for trigger and DAQ

VFAT readout: OptoHybrid

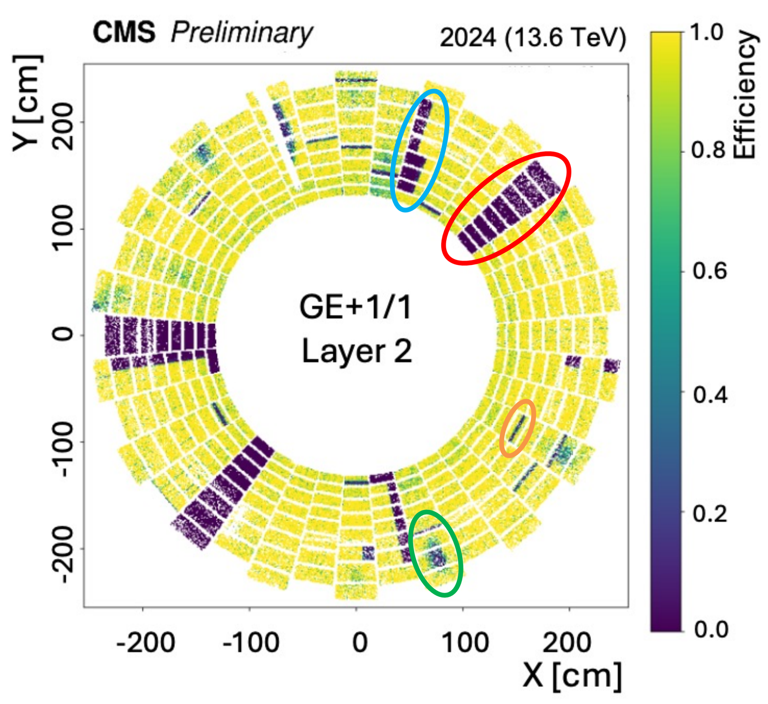


- Electrical links to VFAT (320 Mb/s)
- Optical links for readout and trigger (10.24 / 2.56 Gb/s)
- No FPGA in ME0 due to high radiation

Back-end Electronics

- ACTA crate with X2O back-end board
- Manages L1 trigger and send data streams to the CMS DAQ system
- Monitor front-end data

GE1/1 Performance



Measure of **high-resolution efficiency** for GE+1/1 layer 2 [3]

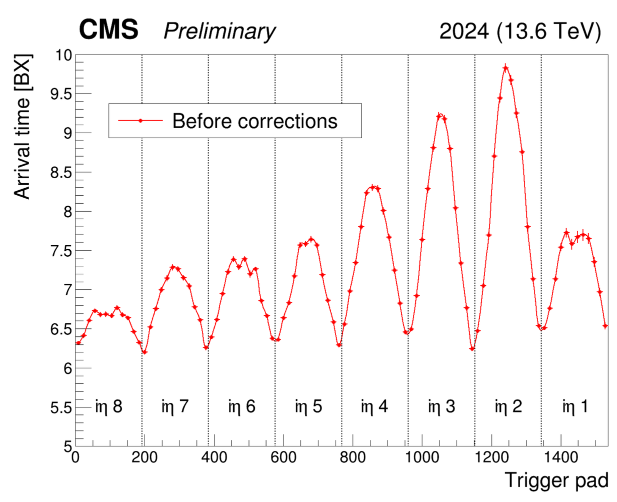
Main sources of inefficiency:

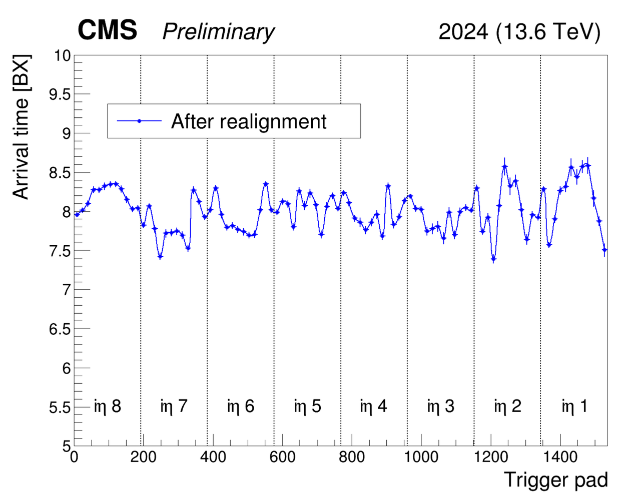
- HV (short circuits)
- Chambers with communication issues
- Electronics (VTRx outgassing) — Solved in ME0 moving to VTRx+
- Bending of the PCBs

Solved in ME0 inserting pillars [8]

Measure of **average arrival time** for a long GE1/1 chamber [3]

- Arrival times span 4 BXs (of 25 ns)





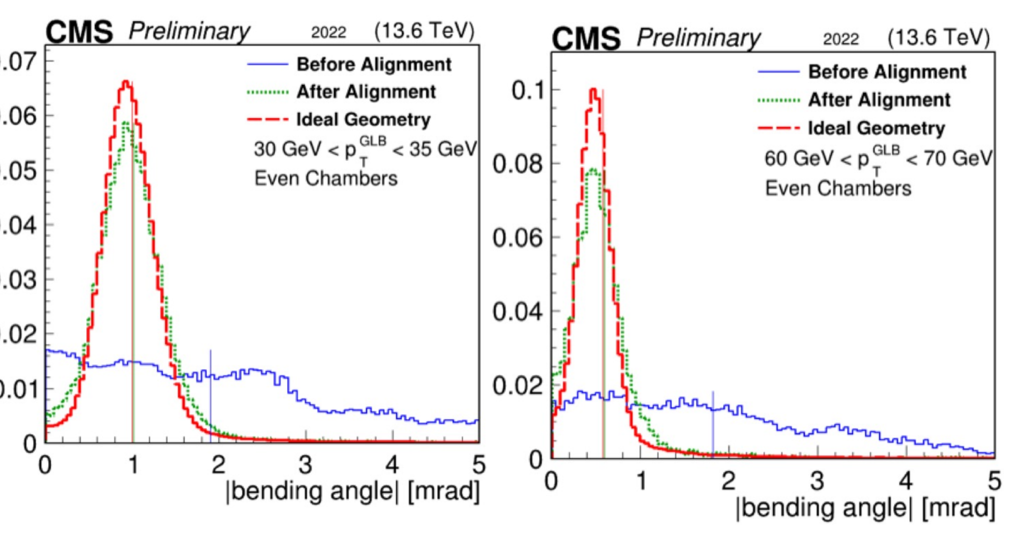
- Due to bending of the PCBs that change the electric field
- Applied strip-by-strip delays to make the chamber time response uniform

Measure of **Muon Bending Angles** in the CMS GE1/1-ME1/1 System [4]

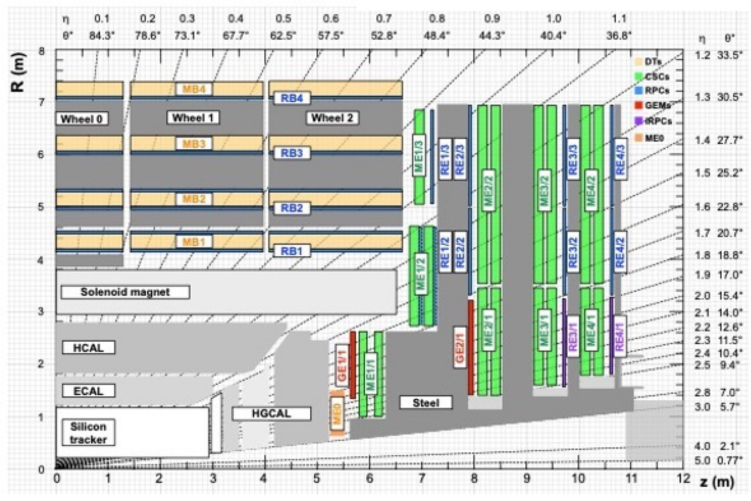
- Clear dependence of the muon p_T from the bending angle after the alignment.

Where:

- $\phi_{bending} = \phi_{ME1/1\ segment} - \phi_{GE1/1\ RecHit}$
- p_T^{GLB} is global muon track p_T



The CMS Phase-2 GEM upgrade

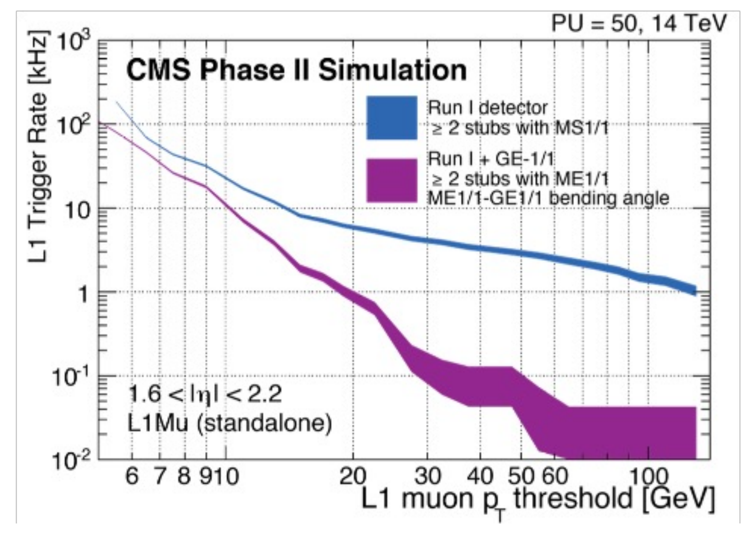


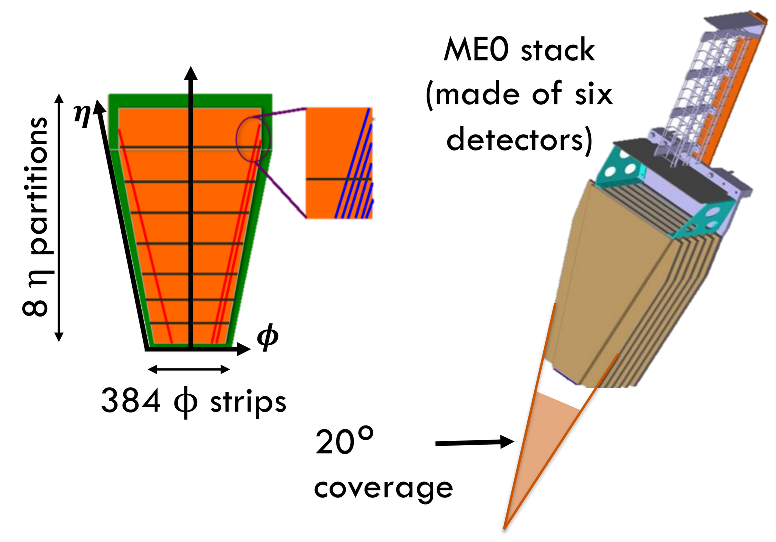
In view of the High-Luminosity LHC upgrade, exp. lumi. of 5-7.5×10^{34}cm^{-2}s^{-1}, CMS is upgrading its muon spectrometer with three new **stations of triple-GEM detectors** [1]:

- GE1/1 was installed in LS2 (2019-2020), commissioned with cosmic rays and proton-proton collisions, and is currently taking data in Run 3.
- ME0 will be installed in LS3.

Motivation for GE1/1

- Complementary to nearby CSC stations, ME1/1 and ME2/1 in the region $1.6 < |\eta| < 2.4$
- Trigger L1 rate reduced ×10
- Improved p_T resolution at the trigger level
- Larger lever arm for measuring the bending angle of muons





Motivation for ME0

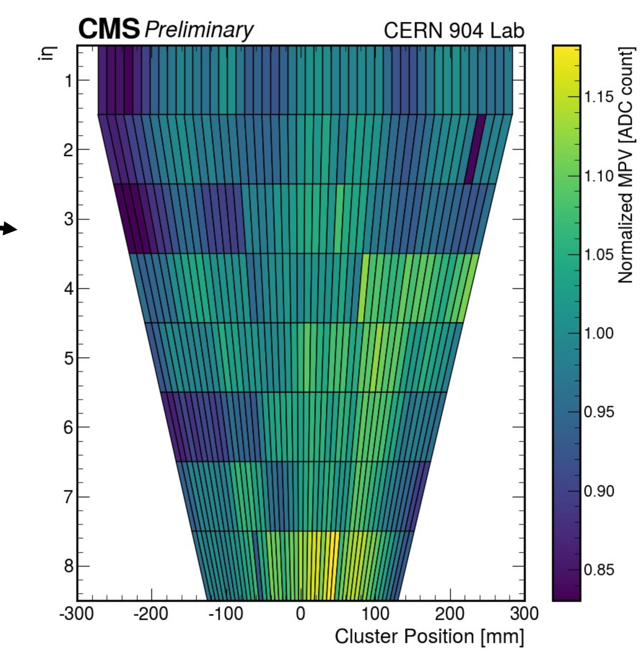
- Nearest muon station to LHC beam line: $2 < |\eta| < 2.8$
- Improve muon reconstruction complementing CSC stations in $2 < |\eta| < 2.4$
- Extending the acceptance of the muon system and complementing the inner tracker in $2.4 < |\eta| < 2.8$

ME0 Performance

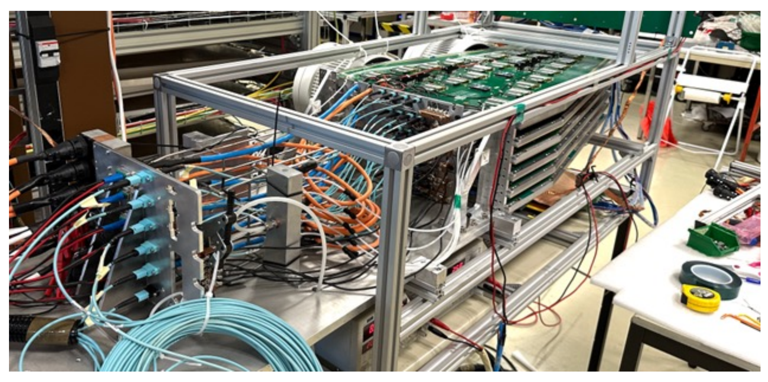
Detector Performance Requirements

- Efficiency > 95 % per detector
- Space Resolution in ϕ O(100 μrad)
- Temporal Resolution ~ 10 ns
- Background particle flux up to 250 $\mathrm{kHz/cm^2}$
- Longevity: Up to an integrated charge of 7.9 $\mathrm{C/cm^2}$

ME0 Production started in 2024 at 8 sites, so far 76 (over 216) modules have been produced.
Several **quality tests** ongoing [5]. Example:
Gain Uniformity (study gain variation across a ME0 module)

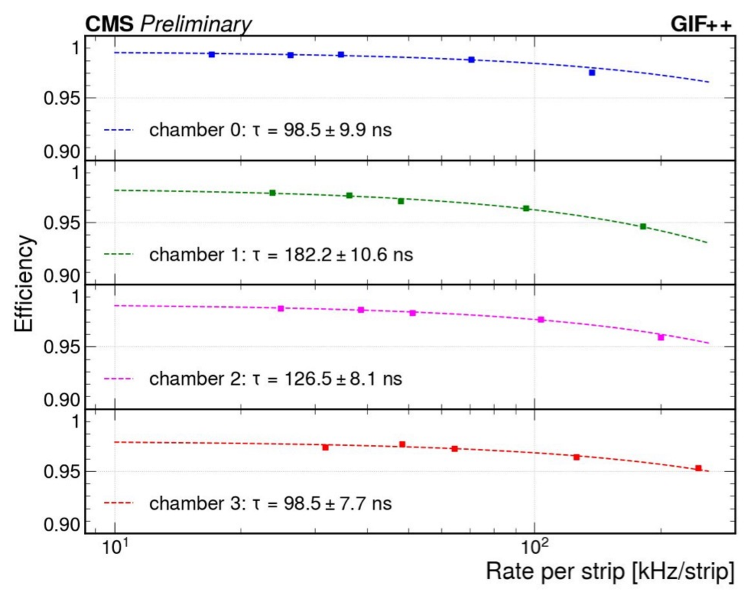


Full 6-layer stack performance studied



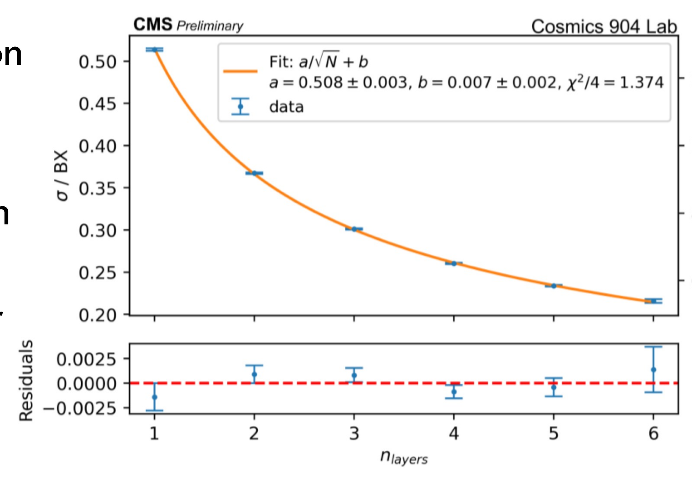
Efficiency study: test beam at GIF++ [6] using 80 GeV muons + low energy gamma bkg (from ^{137}Cs).

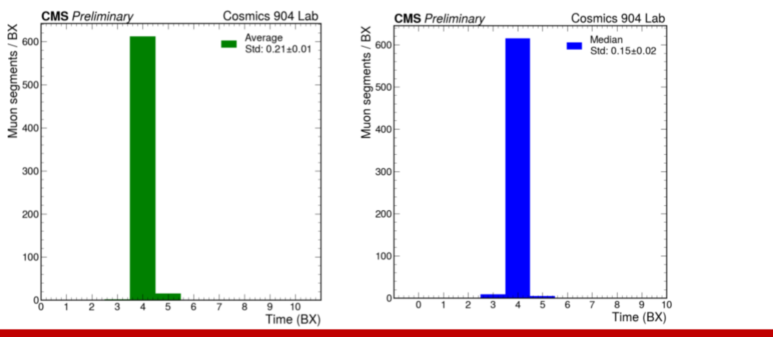
- The GEM foil is segmented to allow for good gain up to rates of 2 MHz/sector.
- Efficiency under irradiation limited by dead time of front-end electronics (400 ns per readout strip).
- Expected efficiency loss in highest eta region: 2.5% per chamber.
- Will be mitigated (1%) by the redundancy of the six chambers per stack.



Time Resolution: measured with Cosmic Rays [7]

- Average time resolution of track segments as a function of the number layers used to reconstruct the segment.
- Arrival time of the segment is calculated as the average of the arrival times of the matching rechits on the chambers
- "average" will be substituted with "median" for better performance and easier computation at a firmware level





For 6-layer segments the time resolution is **0.21 BX** (~ 5.4 ns)
The time res. measure in an environment like the one expected in ME0 is ongoing

Conclusions

The status of the GEM stations was discussed focusing on **GE1/1** and **ME0**.

CMS is currently taking data with the full GE1/1 detector and its performance was validated measuring efficiency, arrival time and muon bending angle. The integration in the Level-1 trigger and the evaluation of the trigger performance are ongoing.

ME0 is in the final stages of development. Its electronics was finalized and tested showing an efficiency compatible with the expectations. The ME0 production is ongoing and is scheduled to be completed by the end of Run 3 in 2026.

Scan Me!

Poster Digital Version

[1] A. Colaleo et al., *CMS Technical Design Report for the Muon Endcap GEM Upgrade*, CMS-TDR-013
[2] A. Datta et al., Development of Readout Electronics for the CMS ME0 Muon Detector, DOI: 10.1016/j.nima.2022.167872
[3] CMS Collaboration, GE1/1 Operation Plots, CMS-DP-2024-125
[4] CMS Collaboration, First Measurements of Muon Bending Angles in the CMS GE1/1-ME1/1 System. CERN-CMS-DP-2022-069
[5] CMS Collaboration, ME0 Quality Control Results from Initial Productions, CMS-DP-2024-126
[6] CMS Collaboration, Rate capability of CMS ME0 stack at the GIF++, CMS-DP-2024-119
[7] CMS Collaboration, Time resolution of ME0 Triple GEM stack, CMS-DP-2024-089
[8] F. Fallavollita 2020 JINST 15 C08002, doi: 10.1088/1748-0221/15/08/C08002