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Triple GEM Detectors for the ME0 System of the CMS Phase-2 Upgrade

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These proceedings provide an overview of gas electron multiplier (GEM) detectors for the muon endcap station (ME0) project. Specifically, we present the integration of a final-design prototype for a six-layer ME0 stack and share performance measurements related to muon segment reconstruction efficiency and timing. We discuss results from cosmic ray measurements as well as rate capability tests conducted under high-rate gamma background conditions at the CERN Gamma Irradiation Facility.

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1. Introduction

The High-Luminosity LHC (HL-LHC) will increase proton collision rates to 5.0 -7.5 times the nominal LHC luminosity, resulting in 140-200 proton-proton interactions per bunch crossing (i.e. pileup). To ensure effective muon triggering and reconstruction in this high-rate environment, the forward Muon spectrometer of the CMS experiment will be upgraded with Gas Electron Multiplier (GEM) detectors. The muon endcap station (ME0) will consist of six-layer stacks of triple-GEM detectors as shown in Fig. 1(centre), designed to extend the pseudorapidity coverage of the muon system up to $|\eta| = 2.8$ as shown in Fig. 1(left). The operating environment for ME0 will be characterised by extremely high rates, with simulations predicting approximately 150 kHz/cm^2. To guarantee optimal performance in this challenging setting, a thorough study of its rate capability and timing performance is essential. A complete description of CMS experiment and GEM detectors is given in [1–3].

2. ME0 Detector Mechanical Design

A single ME0 chamber or module is a triple-layer GEM detector, based on the Micro Pattern Gas Detector. Figure 1(right) shows its working principle. It consists of 3 foils placed at 3/1/2/1 mm gap and filled with Ar:CO_2 gas mixture with 70:30 ratio, which is ionized by incident muons. The foil consists of a 50 micron-thick insulating polymer (i.e. polyimide) surrounded on the top and bottom with copper conductors. Throughout the foil, microscopic holes are etched in a regular hexagonal pattern and provide the necessary drift to charges produced in a gas mixture to create an avalanche. Each chamber contains on-board front-end electronics (VFAT3 ASICs) and opto-hybrid boards to connect to the data acquisition and trigger systems. The ME0 detector station comprises of 36 ME0 stacks (18 per endcap). Here, each stack consists of 6 ME0 triple-GEM modules, i.e, a total of 216 ME0 triple-GEM detectors. Each stack covers a $\Delta\phi = 20^o$ (where ϕ is azimuthal angle) and they will be installed behind the new endcap high-granularity calorimeter. The readout module is 8 partitions in η and 3 sectors in ϕ, where each ϕ sector is further divided into 128 radial strips. Here each sector is read out by a single VFAT3. The mechanical design incorporates aluminium plates for mounting and stability. Figure 2(left) and (centre) show the various components of a single ME0 triple-GEM detector, and a completed ME0 stack, respectively.

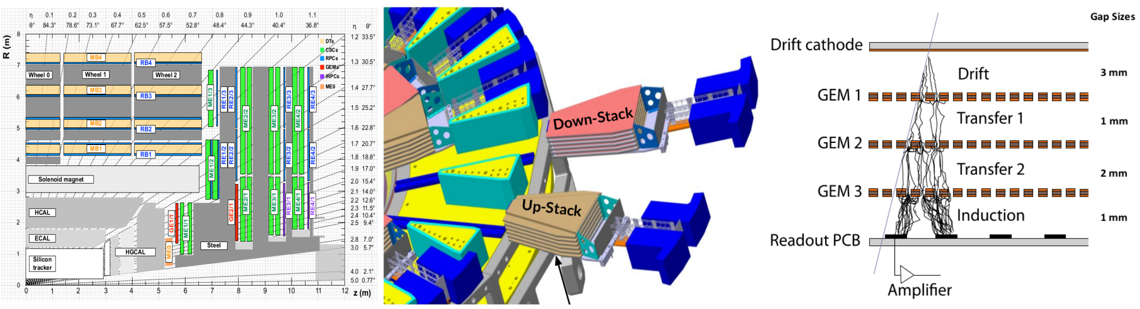

Figure 1: (Left) An R-z cross-section of a quadrant of the upgraded CMS detector. (Centre) Representative diagram showing the stack position in CMS detector. (Right) Working principle of the triple-GEM detector.

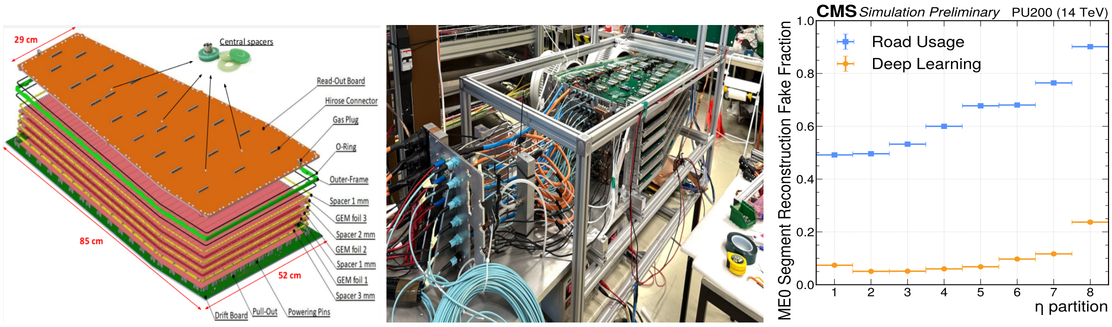

Figure 2: (Left) Layout of the ME0 detector. (Centre) A complete stack consisting of 6 ME0 chambers. (Right) Comparison of the fake segment reconstruction between deep learning and *Road Usage* algorithm using a simulation sample with pileup around 200 (PU200).

3. Quality Controls and Reconstruction

Once the ME0 chamber is assembled, it is subjected to various Quality Control (QC) checks to ensure optimal performance as per the expected design. This ensures long-term stability, electrical safety and operational efficiency of these detectors. These tests are done in multiple phases; some of them are done at the raw material level, some during the assembly and a few others post-assembly of a single ME0 triple-GEM detector, as well as after ME0 stack formation [4]. The QC1 steps ensure that all components are as per CMS design specifications before entering the assembly procedure. The QC2 is dedicated to verifying the electrical integrity of GEM foils before their assembly. It includes a sequence of high-voltage insulation measurements and discharge monitoring. The gas tightness of the assembled chamber is verified in the QC3 test, as a stable and gas leak-free volume is necessary for the efficient working of the GEM detector. The next step, QC4, evaluates the robustness of the electrical components of the fully assembled ME0 chamber under nominal operating voltage. It helps to find the sectors with electric shorts and degraded insulation. The next step assesses the gain performance of the chamber and is called the QC5 test. This test ensures that the detector operates with the designed amplification and detector has signal uniformity across all η-ϕ sectors. The QC6 and QC7 tests ensure the long-term high voltage stability and electronics connectivity, respectively. The global signal processing is tested using a cosmic ray setup under the QC8 test before they are installed at the CMS experiment.

The offline reconstruction of tracks in a high pileup environment, such as expected at HL-LHC, will be challenging to maintain a high accuracy and efficiency. The reconstructed hits (rechits) of ME0 are formed by clustering adjacent fired strips that share the same bunch crossing (BX) [5], where each BX corresponds to 25 *ns*. The cluster size is defined as the number of strips contributing to the rechits formation. The baseline algorithm used in offline segment reconstruction is known as "*Road Usage*" algorithm [6], and originally used for the Cathode Strip Chambers (CSC) subsystem, and a modified version is used for GEM. The algorithm is based on selecting a pair of seeds on the outer layers, and then finding compatible hits on the interior layers. Then a linear fit is performed to choose a segment with the lowest χ^2 error. The disadvantage of this algorithm is that the fake segment reconstruction becomes very high at HL-LHC luminosities; to reduce this fake fraction, a convolutional neural network (CNN), a class of deep learning algorithms, has been constructed and tested for segment reconstruction. The CNN-based deep learning model takes 3-channel (centre strip position, BX, cluster size of rechits) 3-Dimensional (3D, i.e. η partitions, layer, strips) images as input, matching the geometry of the stack. The inputs are thus represented by an array of 4 dimensions with the size (3x8x6x384) for the 3 channels, 8 η partitions ($i\eta$), 6 layers, and 384 strips. The model output is also a 3D image with a single channel. Each pixel in this image represents a strip, and the value indicates whether the strip was fired due to a muon passing through the detector. Muon segments are formed by connecting muon hits across layers. The connected hits on adjacent layers are required to satisfy $|\Delta i\eta| \leq 1$ and $|\Delta strips| \leq 2$. Figure 2(right) shows the comparison of fake segment fraction based on the CNN-deep learning model and "*Road Usage*" algorithm as a function of η partitions. Here, the fake fraction is defined as the ratio of reconstructed muons that are unmatched to simulated muons, where a match requires at least four GEM rechits from the simulated muon, and those hits must account for at least 60% of the total rechits in the segment. Clearly, the CNN-deep learning model reduces the fake segment fraction nearly a factor of 4 across all η partitions without altering the segment reconstruction efficiency in a significant manner (not shown here).

4. Timing Studies of ME0 using Cosmic Ray and GIF++ Setup

The forward region of the CMS experiment is very challenging due to high background radiation. To enhance the overall performance of the ME0 detector, a good time resolution (few ns) is required as per design expectation. The time resolution of assembled detectors, before installation, could be measured either using cosmic rays or using a muon beam at the CERN Gamma Irradiation Facility (GIF++).

Figure 3(left) shows the cosmic ray test setup at CERN lab-904, consisting of 6 triple-GEM ME0 detectors (referred to as a ME0 stack). The trigger consists of two layers of 30×30 cm^2 scintillators (S0 and S1) placed before the stack. The segment finding procedure involves fitting a track segment using 5 layers and then searching for a rechit matching the propagated position of the track on the chamber not used in segment finding. Certain quality selections are also applied to matching hits to ensure high quality of tracks. The arrival time of the matched hits is then used for the time resolution measurement [7]. The arrival time of the matched rechits is chosen as one of the

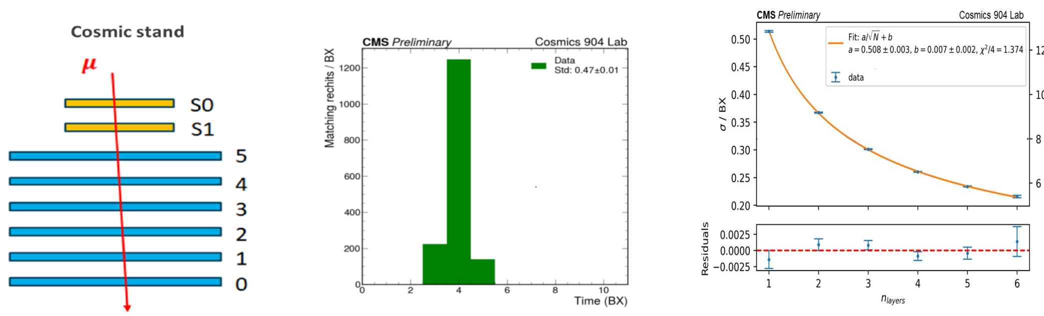

Figure 3: (Left) Representative cosmic stand setup. (Centre) Arrival time distribution for one of the matching rechits for a single chamber in the stack. (Right) Average time resolution of track segments as a function of the number of ME0 chambers used to reconstruct the segment in the cosmic ray test.

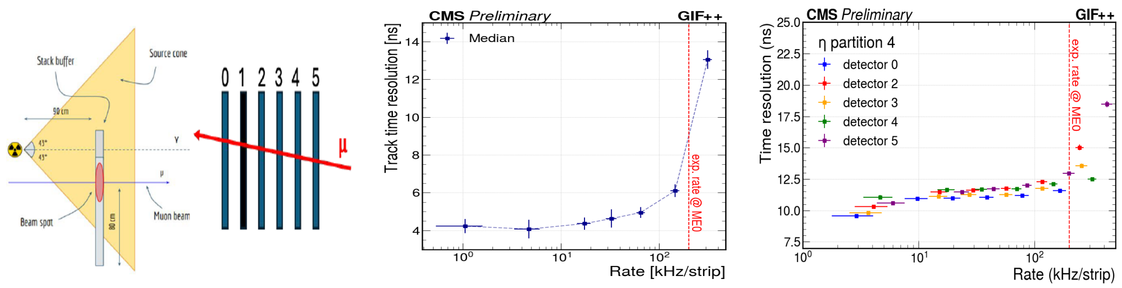

Figure 4: (Left) Representative GIF++ test setup. (Centre) Time resolution of the track reconstructed by the stack as a function of background rate. (Right) Time resolution of hits matching the propagated muon hits.

last firing strips in the cluster. Figure 3(centre) shows the example arrival time distribution for one of the six chambers used in the stack. Here, the time is expressed in units of BX. This data is fitted with a Gaussian distribution, and a matching window is defined as 5 times the standard deviations (σ) of the residual distribution within the same readout partition. Figure 3(right) shows the average time resolution of track segments as a function of the number of ME0 chambers used to reconstruct the segment. The arrival time of the segment is calculated as the average of the arrival times of matched rechits on the chambers. A time resolution of 0.21 BXs corresponding to 5.4 (6.0) ns is achieved for a 6- (5-)layer segment.

The test beam setup at GIF++ is similar to the one used in cosmic rays in terms of the number of layers and the triggers for muons. The ME0 stack was exposed to 80 GeV muons and also to a radioactive γ source ^{137}Cs as background. It is to be noted that the background rate at the GIF++ depends on the configuration of three absorbers placed in front of the source [8]. Once the configuration is set, the irradiation field is inhomogeneous along the stack, resulting in different rates measured by the detectors in the stack. Hence, the σ is used for the lowest rate points, while a Gaussian fit is employed for the highest rates.

Here, the track reconstruction algorithm ("*Road Usage*") takes those hits that arrive in a window of 5 times BXs around the peak arrival time distribution [9]. The timing resolution of the track reconstructed by the stack as a function of the background rate is shown in Fig. 4(centre). Here, the arrival time of the track is computed as the median of the arrival times of the reconstructed rechits along the track. The expected background rate in the ME0 station of around 200 kHz/strip is also shown (vertical Red dashed line). The time resolution for the individual chambers for $i\eta$=4 partition is shown in Fig. 4(right), and is expected to be lower than the one from the complete stack. A time resolution of ~6 ns is measured from the ME0 stack at the expected background rate of 200 kHz/strip and is consistent with the measurement from the cosmic ray setup.

5. Conclusions

The triple gas-electron-multiplier detector in the CMS muon endcap station (ME0) has a time resolution of 6ns, measured using cosmic rays and the CERN gamma irradiation facility, and found to be consistent with the design expectations. Simulation studies show that the fake segment reconstruction in ME0 could be reduced with the help of a deep learning model based on the convolutional neural network.

Acknowledgments

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References

[1] CMS Collaboration, “The CMS Experiment at the CERN LHC", JINST **3** (2008) S08004.

[2] CMS Collaboration, “Development of the CMS detector for the CERN LHC Run 3", JINST **19** (2024) P05064.

[3] CMS Collaboration, “The Phase-2 Upgrade of the CMS Muon Detectors", CERN-LHCC-2017-012.

[4] CMS Collaboration, “ME0 Quality Control Results from Initial Productions", CMS Detector Performance Note CMS-DP-2024-126, 2024.

[5] CMS Collaboration, “ME0 Offline Reconstruction Study with Deep Learning", CMS Detector Performance Note CMS-DP-2025-021, 2025.

[6] V. Palichik and N. Voytishin, “New CSC segment builder algorithm with Monte-Carlo TeV muons in CMS experiment", Phys. Part. Nucl. **48** (2017) 786.

[7] CMS Collaboration, “ME0 Quality Control Results from Initial Productions", CMS Detector Performance Note CMS-DP-2025-089, 2025.

[8] D. Pfeiffer et al., “The radiation field in the Gamma Irradiation Facility GIF++ at CERN", Nucl. Instrum. Meth. A **866** (2017) 91.

[9] CMS Collaboration, “Timing studies with the ME0 stack at the GIF++ irradiation facility", CMS Detector Performance Note CMS-DP-2025-019, 2025.

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