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

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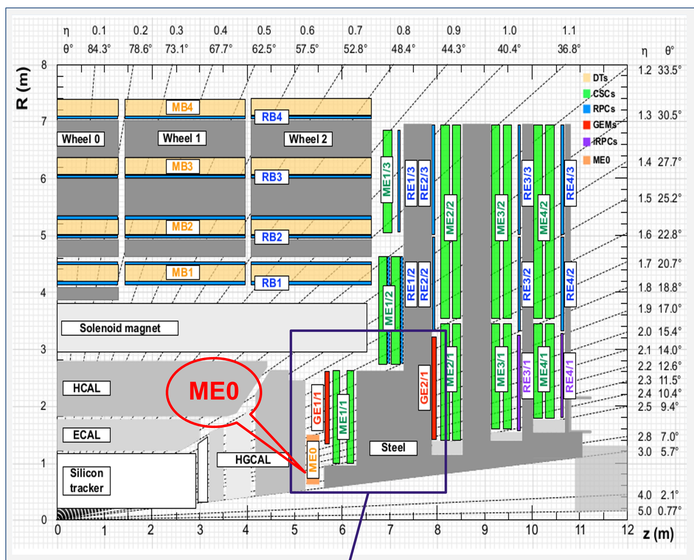
Abstract : The High-Luminosity LHC will increase proton-proton collision rates to 5.0 -7.5 times the nominal LHC luminosity, resulting in 140-200 pp-interactions per bunch crossing. To ensure effective muon triggering and reconstruction in this high-rate environment, the forward Muon spectrometer of the CMS experiment will be upgraded with Gas Electron Multiplier (GEM) detectors. The ME0 station will consist of six-layer stacks of triple-GEM detectors, designed to extend the muon system's pseudorapidity coverage up to $|\eta| < 2.8$. The operating environment for ME0 will be characterized by extremely high rates, with simulations predicting approximately 150 kHz/cm². To guarantee optimal performance in this challenging setting, a thorough study of its rate capability and timing performance is essential. This poster provides an overview of the ME0 project and its current progress. 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 (GIF++). Our findings confirm that the ME0 design meets the Phase-2 CMS muon system upgrade requirements.

Motivation for ME0 GEM Detector



GEM Phase-2 upgrade: three new stations GE1/1, GE2/1 and ME0.

CMS (Compact Muon Solenoid) Detector

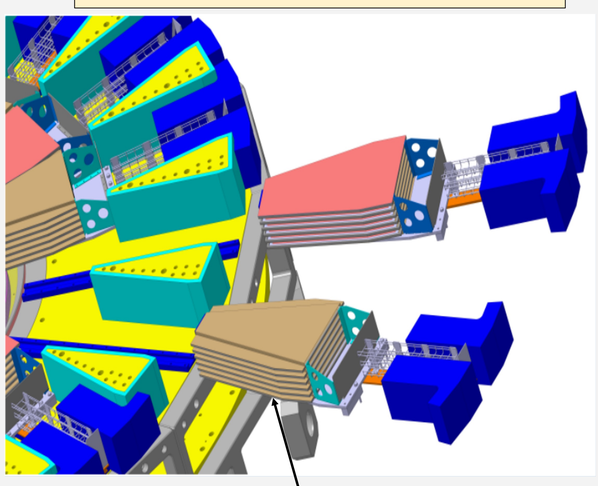
- A general purpose experiment measuring proton-proton and heavy-ion collisions at the Large Hadron Collider (LHC) at CERN.
- Running at p-p energies 13.6 TeV, with an LHC luminosity exceeding 1-2 x 10^{34} cm^{-2} s^{-1}. **HL-LHC (High Luminosity LHC);** Integrated luminosity will increase 10 fold w.r.t. LHC's design value.
- **GEM detectors in CMS:** To improve the forward muon triggering and reconstruction.
- **Phase-2 Upgrade:** ME0 GEM detectors will extend the acceptance of the muon system which will improve muon identifications.

Description of the new ME0 stations

- Coverage extends from $|\eta|$ = 2.0 to 2.8. Each stack covers $\delta\varphi$ = 20°.
- Install behind the new Endcap HGCAL.
- Radial distance from beam line: 63 cm.
- The ME0 detector station comprises 36 ME0 stacks (18 per endcap).
- Total 216 ME0 modules; Each stack of 6 ME0 triple GEM detectors.

ME0 will provide enough redundancy to reject neutron-induced backgrounds and to form muon track segments in the L1 trigger

Where will be the ME0 GEM detector?



3D drawing of the insertion of two adjacent stacks of six ME0 modules (pink/brown) into the muon system.

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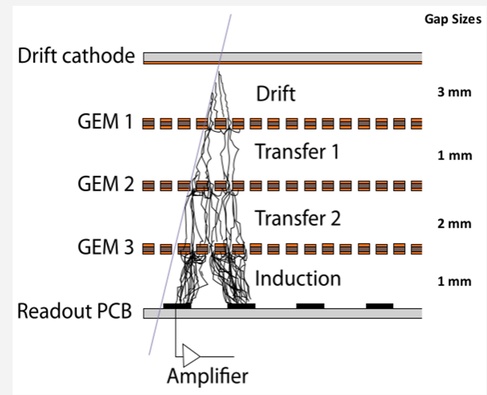
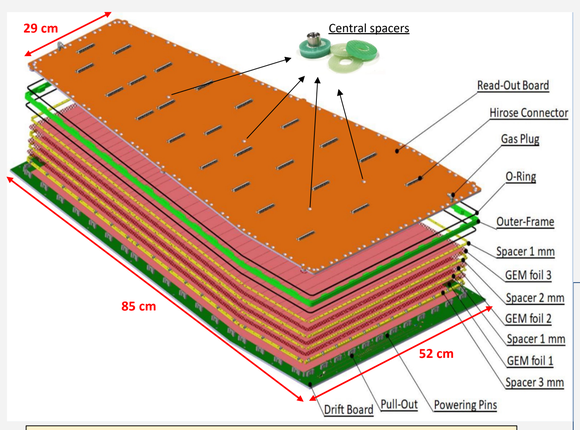
ME0 Detector Mechanical Design

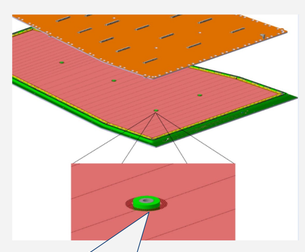
ME0 GEM detector working

- ME0 module is a **Triple layer GEM Detector**, based on micro-pattern gas detector (MPGD) technology.
- Consists of three foils with 3/1/2/1 mm gaps in Ar:CO_2(70:30).
- The segmentation of each ME0 module is 8 partitions in η and 3 sectors in φ. Each φ sector contains 128 radial strips.
- Single-module efficiency of > 97%.
- Rate Capability>150 kHz/cm².
- Time resolution 8–10 ns for single layer.
- Radiation hardness> 7.9 C/cm².



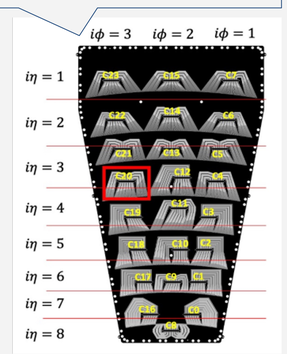


The layout of ME0 GEM detector



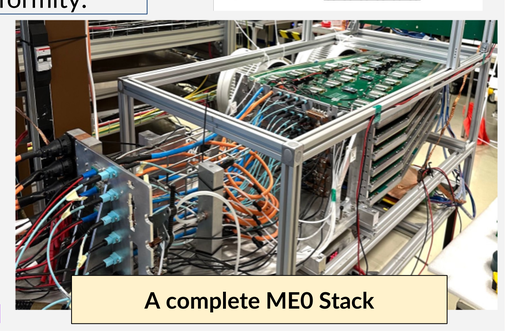
- **Internal distance holders (Pillars);** Placing central pillars at the 4 positions of the active area which improves the gain uniformity.

Segmentation of ME0 module; Each φ sector contains 128 radial strips.



ME0 stack design

- 1 ME0 stack consists of 6 ME0 modules capable of detection of charged particle trajectories with excellent φ resolution.
- Thickness of one ME0 detector = 16 mm. and total thickness occupied by a six-layer stack ~ 226 mm.
- Each stack is mounted on a 15 mm thick aluminium plate which supports the stack mechanically.



A complete ME0 Stack

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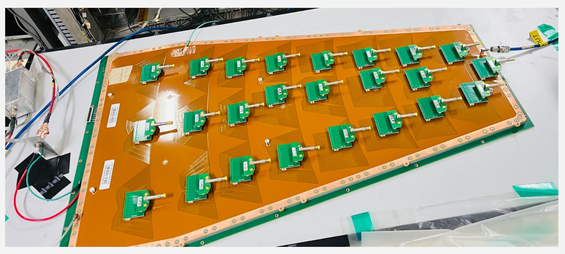
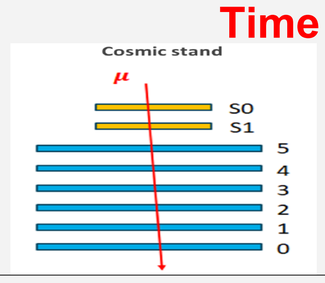
QCs, Reconstruction, and Timing Studies of ME0 Stack at The GIF++ and Using Cosmic Rays

Quality Controls (QCs) ensure the delivery of fully efficient



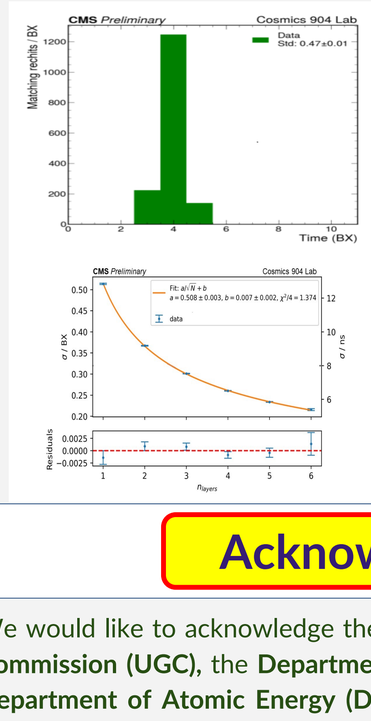
QC Step	QC procedure
Before Assembly of module	**QC1:** Initial inspection of the chamber components.
	QC2: Electrical cleaning of the GEM foils and impedance check.
After Assembly of module	**QC3:** Leak test of closed detector volume.
	QC4: Linearity test of high voltage divider and intrinsic noise rate measurement.
	QC5: I. Effective gas gain measurement. II. Response uniformity measurement.
Module with electronics	**QC6:** Long term high voltage stability test.
	QC7: Front end electronics connectivity test.
Complete stack	**QC8:** Cosmic ray test of 6 layer of ME0 modules.

Time Resolution Using Cosmic Rays

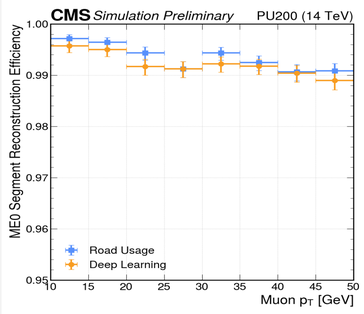


- Cosmic ray in 904 Lab in May 2024.
- Trigger: Two 30 x 30 cm^2 Scintillators S0 and S1; Used Ar:CO_2 (70:30) and VFAT3
- Five ME0 detector used to fit segment.
- Find rechit matching the propagated position of the track on the chamber not used in segment finding.
- Time of matched rechit is used to calculate time resolution.

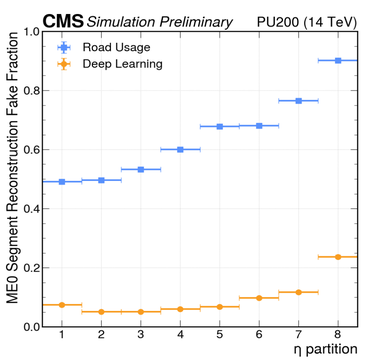
- Example distribution of arrival times of matching rechits for one of the six chamber in the stack.
- The time is expressed in BX where each BX correspond to 25 ns.
- The matching window is defined the five times the sigma of the residual distribution within the same readout partition.
- Average time resolution of track segments as a function of number of ME0 chambers used in stack.
- For 6 layers (ME0) the time resolution is about 5.4 ns.
- For 5 layers (ME0) the time resolution is estimated to be 6 ns.
- At GIF++, similar results are obtained.



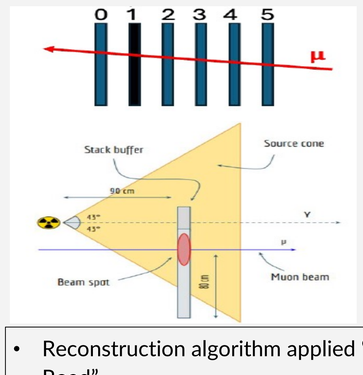
Segment Reconstruction Efficiency with Deep Learning



- ME0 hits: Formed by clustering adjacent fired strips within the same BX. Cluster size is the total strips in a ME0 rechits.
- Segmentation reconstruction: Road Usage (RU) Algorithm.
- CNN Based deep learning mode; Input: Centre strip, BX, Cluster size, *iη*-sector, layer strips.
- Sim. dataset: pT:10-50 GeV, |η|:2.0 - 2.8
- Efficiency: Ratio of simulated muon match to reconstructed segments.

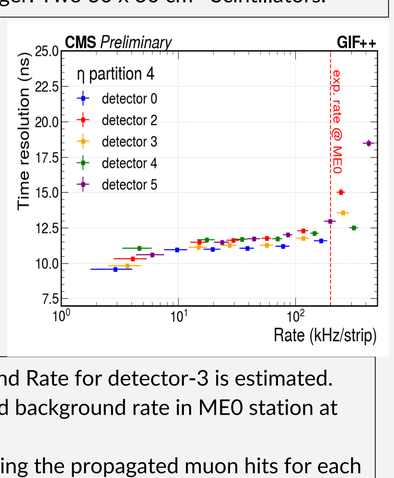


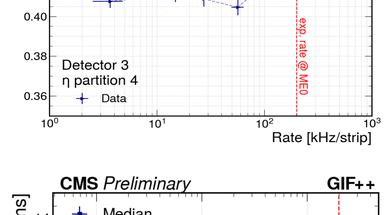
Timing Studies at GIF++

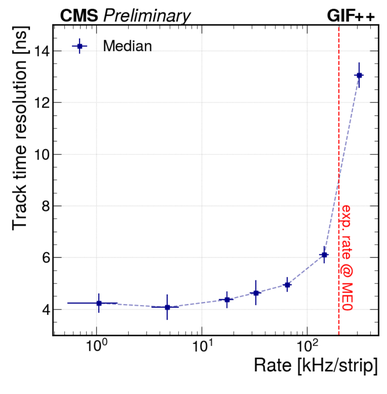


- Reconstruction algorithm applied "Based-Road".
- Reconstruction from hits that arrives within 5 BX around the peak of arrival time distribution.
- The background rate depends on the three absorber placed in front of the source.

- Data taken with 80 GeV Muon+ ^{137}Cs in GIF++ (July 2024).
- ME0 Stack: 6 Triple ME0 detector. (One detector was excluded due to error).
- Ar:CO_2 (70:30)
- VFAT3: Final Front End Electronics.
- Trigger: Two 30 x 30 cm^2 Scintillators.







- Spatial resolution as a function of Background Rate for detector-3 is estimated. The RED vertical line represent the expected background rate in ME0 station at 200 kHz/strip.
- Time resolution of reconstructed hits matching the propagated muon hits for each ME0 detector in the stack is computed
- Time resolution of reconstructed track from the stack is studied. The arrival time of the track is computed as the medians of the arrival time of reconstructed hits.

Summary and Future Works

- The GEM technology is selected for the upgrade of the CMS muon Endcap. Three projects: GE1/1(already installed at CMS in LS2), GE2/1 (ongoing), and ME0 (ongoing).
- ME0 installation is planned in 2026 and 2027 during LS3.
- Time resolution from Cosmic Rays and GIF++ are found to be about 6 *ns* for 5 layers in a stack.

Acknowledgement

We would like to acknowledge the funding agencies, **University Grants Commission (UGC),** the **Department of Science and Technology (DST), Department of Atomic Energy (DAE), Govt. of India** for providing the financial support. We would also like to thank all members of the CMS Muon group including GEM production team for their valuable suggestions during making this poster.

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EPS-HEP 2025: European Physical Society Conference on High Energy Physics 2025, 7-11 July 2025, Marseille (FRANCE)