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Upgrade plans of the CMS Muon System for High Luminosity LHC

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The CMS Muon System Upgrade is a significant part of the overall upgrade strategy for the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC), particularly for the High Luminosity LHC (HL-LHC) phase, which is expected to start around 2030. The HL-LHC will increase the LHC's luminosity by a factor of 5 - 7 beyond its original design, allowing it to collect more data and observe rarer processes but it also brings challenges like higher radiation levels and more pile-up events. The key goals of Muon system upgrade are to maintain high reconstruction efficiency and improve trigger capabilities, in addition to expanding muon detector coverage into the forward region (high pseudorapidity) to improve physics reach. The muon system upgrades include enhancements to both the front-end and back-end electronics for the Drift Tubes (DT) and Cathode Strip Chambers (CSC), as well as back-end electronics for the Resistive Plate Chambers (RPC). Additionally, new detectors, such as improved Resistive Plate Chambers (iRPC) and Gas Electron Multipliers (GEM), are being introduced. This talk will provide an overview of the current progress, challenges and test results, illustrating the readiness of the CMS Muon System for HL-LHC.

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1. Introduction

Muon identification and triggering play a central role in the physics program of the CMS experiment [1]. Processes such as Higgs boson decays, rare Standard Model processes, and searches for new physics rely critically on the efficient reconstruction of muons across a wide kinematic range. The HL-LHC will push the experimental conditions well beyond the original design of CMS. Pile-up values up to 200, radiation doses accumulated over a decade of operation, and significantly higher trigger and data rates demand major upgrades across the entire detector. For the muon system, the strategy is threefold: (i) extend the acceptance up to $|\eta| \approx 2.8$, (ii) improve redundancy in the forward region, and (iii) replace the electronics chain to cope with higher bandwidth, latency, and Level-1 trigger rates.

2. The CMS Muon System

The CMS muon system is based on four complementary gaseous detector technologies [2]: Drift Tubes (DT), Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC), and Gas Electron Multipliers (GEM). Together, these detectors provide muon coverage up to $|\eta| < 2.4$ with redundancy and high precision.

- DT: large rectangular cells with a central anode wire, optimized for the barrel region up to $|\eta| = 1.2$. They provide time resolution of few ns and spatial resolution of ~100 μm.
- CSC: multi-wire proportional chambers with segmented cathode readout are used in the forward region ($1.2 < |\eta| < 2.4$). They deliver a spatial resolution of 50 – 140 μm.
- RPC: double-gap bakelite detectors operated in avalanche mode. They offer excellent time resolution (~1.5 ns) and complement DT and CSC coverage.
- GEM: micro-pattern detectors with triple amplification foils, installed for the first time in 2019 in the forward region (GE1/1) to increase redundancy and cope with high hit rates.

At HL-LHC, new detectors such as GEM GE2/1 and ME0, as well as improved RPCs (iRPCs), will extend the coverage to $|\eta| \approx 2.8$. Simultaneously, the electronics chain for all muon detectors is being upgraded to handle higher data volumes and trigger rates [3].

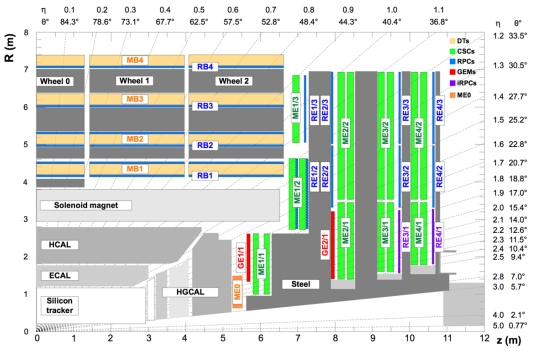

Figure 1: Schematic view, in the R-z plane, of one quadrant of the CMS detector, with the axis parallel to the beam (z) running horizontally and the radius (R) increasing upward. The different type of muon technologies, present and future, are shown.

3. Longevity and Environmental Challenges

Ensuring reliable performance of muon detectors throughout the HL-LHC lifetime requires addressing both radiation-induced aging and environmental sustainability. Since 2015, a wide-ranging experimental program has been carried out at GIF++ at CERN, where detectors are exposed to high-intensity γ-rays from a ^{137}Cs source combined with muon beams to reproduce the integrated dose and particle fluxes expected at HL-LHC.

Results indicate that Drift Tubes are the most sensitive subsystem due to their non-fluorinated gas mixture, which increases susceptibility to electrode degradation. As a mitigation measure, additional shielding has been installed around focusing magnets and the DT outer shell.

For CSCs and RPCs, the use of alternative gas mixtures with lower Global Warming Potential (GWP) is being validated. Recuperation systems have been developed and are already in operation to minimize the environmental impact of current gas usage. No performance degradation has been observed for CSCs up to accumulated charges equivalent to HL-LHC conditions.

4. The Muon Upgrades for HL-LHC

4.1 GEM Upgrades

The introduction of GEM detectors significantly enhances redundancy in the forward region. The GE1/1 stations, covering $1.55 < |\eta| < 2.18$ have been taking data during Run 3 with efficiencies above 95%. Operational experience has allowed the collaboration to address issues such as discharges, high-voltage shorts, communication problems with optical links, and PCB deformations.

The GE2/1 detectors, covering $1.62 < |\eta| < 2.43$, consist of 72 chambers per endcap arranged in 20° sectors. Installation of the full system has been postponed until after Long Shutdown 3 (LS3, 2026-2029) due to schedule constraints, but detector production is well advanced and several modules are already installed.

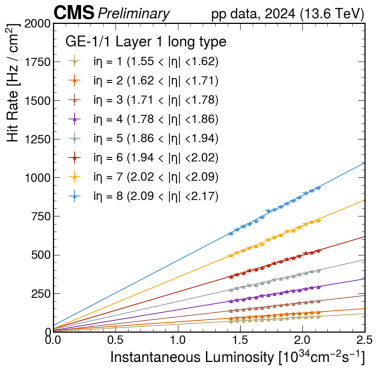

Figure 2: Hit rate as a function of instantaneous luminosity for GE1/1 negative endcap Layer 1 (long-type) using pp collision data at $\sqrt{s}$ = 13.6 TeV (Fill 10226, 816 pb^{-1} on October 15$^{\text{th}}$, 2024) [4].

The ME0 detector, located behind the High Granularity Calorimeter, will consist of six layers of GEM foils with an active area of ~2 m^2 per station. It will extend muon coverage to $|\eta| < 2.8$, providing precision tracking and timing with ~10 ns resolution and <500 μrad angular resolution.

Performance tests at GIF++ demonstrate efficiency above 97% and uniform response in high-rate environments.

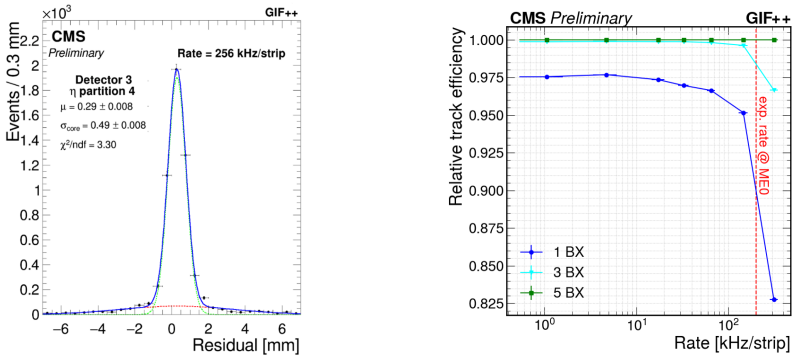

Figure 3: Left: Distribution of the residuals minima at high background rate in an ME0 chamber. The residuals are calculated as the difference between the reconstructed hit position on the module and the extrapolated position of the local track segment built using the other 4 layers in the stack [5]. Right: Efficiency of the ME0 detector as a function of the background rate with different cuts on the arrival time of the reconstructed hits. The red dashed vertical line represents the expected background rate in the ME0 station of around 200 kHz/strip [5].

4.2 CSC Upgrades

The CSC system is undergoing a staged replacement of its front-end and back-end electronics to meet HL-LHC trigger and DAQ constraints. Several on-chamber electronic boards (called DCFEBs, ALCTs, LVDB5 and OTMBs) have been replaced during LS2 (2019-2022) to accommodate latency, rate and radiation concerns. The performance of the CSC system after this replacement remains excellent as can be seen in Figure 4. Other electronic modules will be replaced in LS3, in particular the ODMB and a new backend to operate with the required data acquisition bandwidth. The production of these boards is very well advanced.

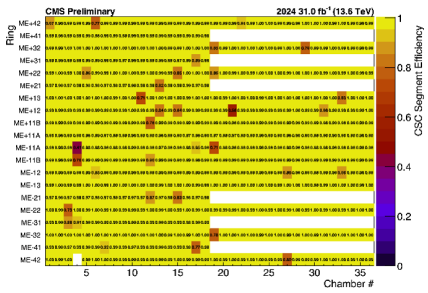

Figure 4: Measured efficiency of each CSC in the CMS endcap muon detector to provide a reconstructed muon track segment in 2024, after the upgrade of several electronic modules of the CSC chambers. The high efficiency and redundant design of the CSC detector results in no significant loss in muon trigger and reconstruction efficiency in the endcap region (98.2%) even under temporary failures [6].

4.3 RPC Upgrades

The RPC system is being upgraded with improved RPCs (iRPCs), which feature thinner High-Pressure Laminate (HPL) electrodes and reduced gas gap width (1.4 mm). This design lowers the operating voltage and significantly increases the rate capability, up to 2 kHz/cm^2, while maintaining efficiency above 95%. Half of the iRPC system was successfully installed during the 2024 – 2025 shutdown, with the remainder to follow in LS3.

The RPC readout system is also being upgraded with new Link Boards based on Kintex-7 FPGAs and providing time stamping with 1.56 ns time bin, compared to 25 ns previously.

4.4 Drift Tube Upgrades

The DT subsystem requires the most extensive electronics replacement. The entire readout and trigger chain is being modernized to cope with the HL-LHC environment.

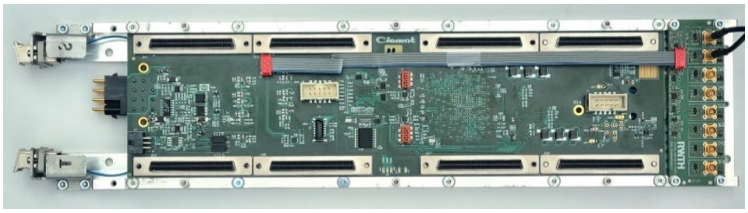

Figure 5: Image of the OBDT-theta board, responsible for the time digitization (~0.7 ns) of the CMS DT signals. The board is assembled in the cooling frame and connected to the Theta-testpulse board used for calibration.

New On-Board Digitizer and Trigger (OBDT) boards are being deployed, in two versions (ϕ and θ) to adapt to chamber geometries. They are based on Microchip PolarFire FPGAs and embed high speed serializers (10.24 Gpbs) through optical links. A novel deserialization method inside the OBDT provides time digitization with ~ 0.7 ns precision.

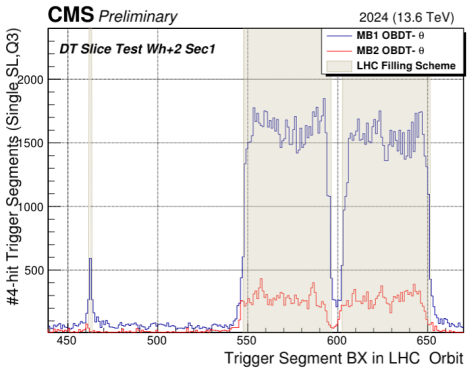

Figure 6: Distribution of the bunch crossing measurement of the DT Trigger Primitives coming from the θ view of two types of DT chambers (MB1 in blue and MB2 in red) as reconstructed by the Phase 2 trigger algorithm running on the new prototypes that have been installed in the CMS detector in the so-called Slice Test. The LHC filling scheme is indicated by shaded areas [7].

At the back-end, the Barrel Muon Track Finder Level-1 (BMTL1) is implemented on Advanced Telecommunications boards with high-speed optical connectivity. Slice tests in Run 3 demonstrated

excellent agreement between the trigger primitives reconstructed with the new system and the offline reconstruction, validating the concept in realistic collision conditions.

Production of OBDT boards is progressing satisfactorily with extensive testing. Prototypes have already been integrated into CMS readout setups, ensuring smooth commissioning ahead.

5. Summary

The CMS muon upgrade program is advancing steadily to meet the challenges of the HL-LHC. Key achievements include the successful operation of GE1/1 detectors since 2019, installation of half of the iRPC system, staged deployment of new CSC electronics, and validation of DT prototypes in realistic Run 3 conditions. Production of ME0 and GE2/1 detectors as well as DT, CSC and RPC electronics is ongoing, with installation scheduled for LS3.

Extensive irradiation studies at GIF++ confirm the longevity of the detectors, while alternative gas mixtures and recuperation systems demonstrate the feasibility of environmentally sustainable operation.

By combining new detector technologies, advanced front-end and back-end electronics, and careful integration with the CMS trigger and DAQ, the muon system will maintain high efficiency, extend acceptance, and deliver robust performance under the harshest conditions ever faced at the LHC. This ensures that CMS will fully exploit the physics potential of the HL-LHC program.

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