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The upgrade of the CMS muon system for the High Luminosity LHC

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To accommodate the anticipated five-fold increase in instantaneous luminosity during the High Luminosity phase of the Large Hadron Collider (HL-LHC), the CMS experiment's muon spectrometer will undergo comprehensive upgrades to its electronics and detectors. These enhancements aim to maintain the system's exceptional performance amidst the more demanding data-taking conditions of the HL-LHC. The current CMS muon system employs a combination of detector technologies, each optimized for specific regions. Drift Tubes (DT) and Resistive Plate Chambers (RPC) are deployed in the barrel, while the endcap utilize cathode strip chambers (CSC) and RPC. The electronics upgrade will focus on the existing DT, CSC, and RPC systems. The CSC electronics upgrade was largely completed during Long Shutdown 2 (LS2), while the DT electronics upgrade is scheduled for LS3. Prototypes of the new On-Board electronics for DT (OBDT) are currently undergoing testing and validation in CMS slice-test demonstrators. To address the anticipated higher background rates in the endcap, new detector stations will be installed. These stations will utilize triple gas electron multiplier (GEM) and improved resistive plate chambers (iRPC) technologies, offering enhanced time and spatial resolution and improved rate capability. The GE1/1 station, based on GEM technology, was installed in the endcap region during LS2, covering the pseudorapidity range $1.55 < |\eta| < 2.18$. Two additional GEM stations, GE2/1 and ME0, are planned for future installation to further enhance muon reconstruction in the endcap and extend the muon system's coverage up to $|\eta|$ 2.8. This presentation will provide an overview of the Muon Spectrometer upgrades, detailing the electronics developments for the DT and CSC systems. It will also present an overview of the new triple-GEM (GE2/1, ME0) and iRPC (RE3/1, RE4/1) detector stations that will be installed before Long Shutdown 3.

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1. Introduction

The High Luminosity LHC (HL-LHC) [1] program is expected to start around 2029, presents a considerable challenge due to demanding data-taking conditions. The anticipated specifications for the HL-LHC are staggering, projecting an instantaneous luminosity ranging from 5 to 7.5 x 10^{34} cm^{-2}s^{-1} and an integrated luminosity spanning from 3000 to 4000 fb^{-1}. Furthermore, the expected pile-up rates are estimated to increase significantly from 30 to 140-200. Amidst these rigorous conditions, the primary objective of the CMS Muon system upgrade [2] is to ensure its exceptional performance, maintaining a wide geometrical acceptance despite the more challenging data-taking conditions. This upgrade aims to not only meet but surpass the demands of the HL-LHC, pushing the boundaries of scientific exploration in particle physics. The Muon system upgrades are scheduled to be implemented during year-end technical stops (YETS) or during Long Shutdown 3 (LS3), crucial phases in enhancing the CMS Muon system's capabilities.

The CMS Muon Spectrometer integrates a diverse array of gaseous technologies, each serving a distinct function within the system: Drift Tubes (DT), Resistive Plate Chambers (RPC), Cathode Strip Chambers (CSC), and Gas Electron Multipliers (GEM). Currently, an ongoing upgrade plan signifies substantial improvements in electronics and the introduction of new detectors. Specifically, the upgrade predominantly focuses on enhancing electronics within the barrel of the CMS, particularly for the DT and RPC systems. Conversely, within the endcap, the upgrade involves not only electronic enhancements but also the incorporation of new detectors. The upgrade plan for the endcap's Cathode Strip Chambers (CSC) primarily focuses on electronic enhancements. In contrast, the improvement strategy for the Resistive Plate Chambers (RPC) includes not only an electronic upgrade but also the deployment of new detectors, namely improved RPCs (RE3/1 and RE4/1). Notably, a significant addition in 2020 was the installation of the 1 GEM station GE1/1. Furthermore, the introduction of additional detectors based on GEM technology, namely GE2/1 & ME0, represents a pivotal advancement, fortifying the CMS Muon Spectrometer for improved performance and expanded functionality. The upgrades for each subsystem are detailed in the sections below.

2. Drift Tubes (DT)

The MiniCrate, responsible for processing DT Front-End (FE) signals for trigger handling and readout, encounters limitations at the HL-LHC, struggling with anticipated background rates and the maximal Level-1 Trigger frequency of 750 kHz. To overcome these challenges, a new generation of electronics, primarily housed within the OBDT, has been developed. This upgraded MiniCrate brings significant enhancements: it boasts improved resolution in position, angle, and timing critical for Level-1 trigger operations, ensuring more precise and efficient data processing, reinforced to handle higher rates, even in high-background environments expected at the HL-LHC. Shifting Trigger Primitive (TP) generation to the backend streamlines signal processing, refining output for increased accuracy. The system's efficiency is augmented through the integration of multiple front-end inputs. Additionally, the introduction of two specialized OBDTs tailored for each theta and phi super-layer of the DT chamber refines precision and adaptability within the system.

During the Long Shutdown 2 phase, a rigorous assessment of the new electronics was executed with the realistic conditions. Thirteen OBDTv1 prototypes were strategically deployed within the CMS Wheel+2 Sector 12, commonly referred to as Slice Test, to establish an extensive testing environment. Both the legacy electronics chain and the upgraded counterpart were engaged to register identical events, enabling direct comparative analysis (Fig1). Data acquisition was extensively conducted throughout the Slice Test, encompassing varied operational conditions including cosmic and collision runs, thereby capturing a comprehensive spectrum of system behavior. Moreover, the successful integration of the upgraded Front End Driver (FED) into the CMS infrastructure was achieved, complemented by the implementation of a novel back-end algorithm (Analytical- method AM) tailored to improve the system efficiency.

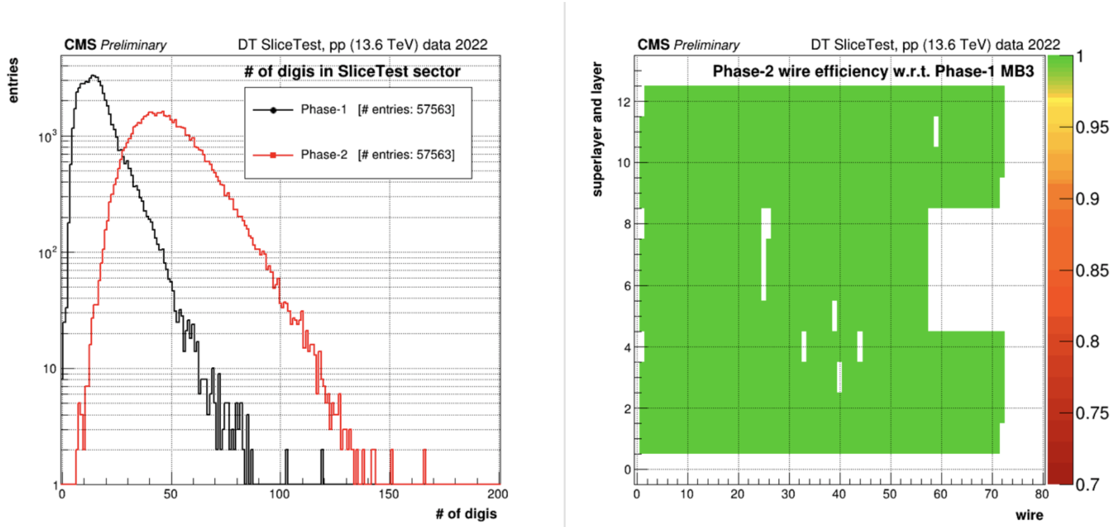

Figure 1: Left plot: Distinctive impact of Phase-2's expanded bandwidth: Notice the evident widening of readout windows, 5x broader than legacy. Right plot: the relative efficiency to detect a hit with the Phase-2 readout, when a hit is recorded by the Phase-1 readout in the MB3 station in the slice test [3].

Following the successful Slice Test in Sector 12 of Wheel+2, the evaluation expanded to include neighboring Sector 1, enhancing the test's scope. This expansion aimed to validate the latest version under realistic conditions before full-scale production, assessing the performance of the new detector, the DSS Monitoring and Safety (MONSA) system. Equipped with OBDT v2, key enhancements feature the adoption of GBT -> LpGBT for control and readout, enhancing system control and data retrieval efficiency. Additionally, the integration of SFP+/QSFP -> VTRX+ (dual) configurations bolstered data transmission capabilities. The comprehensive assessment, notably during cosmic data collection, showcased high system proficiency and success in practical operational environments.

3. Resistive Plate Chambers (RPC)

The improved RPC (iRPC) upgrade for the HL-LHC demonstrates substantial advancements, enabling it to sustain high expected rates up to 2 kHz/cm^2, ensuring a hit efficiency exceeding 95%. Notable improvements encompass a shorter recovery time for electrodes and a reduction in total charge produced during discharge, achieved through thinner electrodes and a narrowed gas gap from 2 to 1.4 mm, all while operating at lower operational HV levels. Additionally, the RPC upgrade integrates a new off-detector electronics system for RPC. In the upcoming Long Shutdown 3 (LS3), an advanced RPC Link system is slated for implementation, replacing obsolete components and an aging system with FPGAs, specifically KINTEX-7, XC7K160T – Industrial Version. The key features of this new link system include a 14-layer PCB measuring 40 × 28 cm^2, offering a Muon hit time and TDC timing resolution of 1.56 ns. Moreover, the Master Link board achieves an output data rate of 10.24 Gbps, while the Control Board facilitates communication with RPC Backend electronics at 4.8 Gbps, collectively ensuring an upgraded infrastructure for improved performance and reliability. Complementing these enhancements, a novel Front-End board (FEB) has been developed to ensure 2D measurements at centimeter space resolution, employing the TDC principle to read each strip on both sides. Specifically, the iRPC FEB incorporates 6 Petiroc2C + Cyclone V, with 2 FEBs per chamber facilitating the monitoring of 96 strips. These comprehensive upgrades collectively establish a more robust infrastructure for enhanced performance and reliability within the system. The test beam results conducted at the Gamma Irradiation Facility (GIF++) at CERN provide crucial insights into the iRPC's performance shown in Fig2.

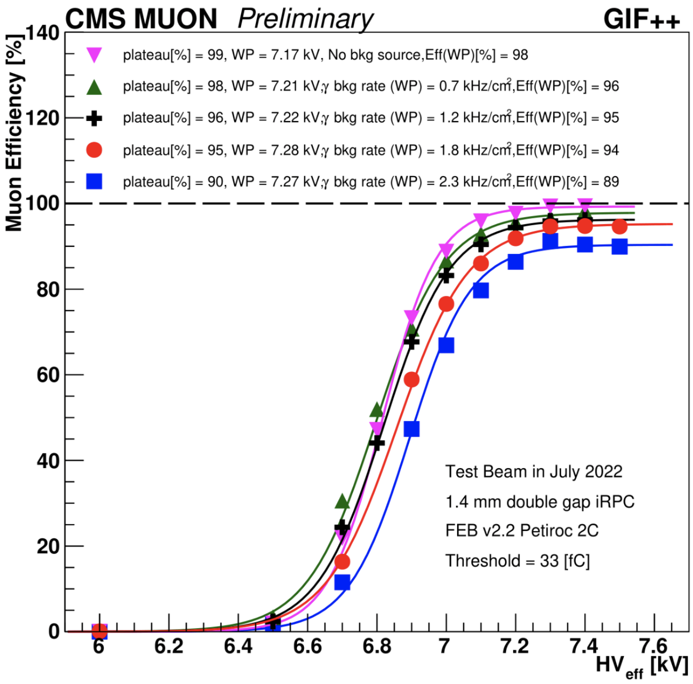

Figure 2: Efficiency at working point (WP) measured at 9% with 0.7 kHz/cm^2 (expected Phase II background rate) and 89% at 2.3 kHz/cm^2 (3 times the safe factor for background radiation) [3].

4. Cathode Strip Chambers (CSC)

The Cathode Strip Chambers (CSCs) face challenges such as increased particle rates and trigger latency at the HL-LHC, causing readout inefficiencies and event losses. To address these issues during Long Shutdown 2 (LS2), extensive upgrades targeting (O)DMBs for ME1234/1 were prioritized. LS2 focused on critical electronic enhancements, including Front-End (FE) electronics and LV & HV system improvements. Looking ahead to Long Shutdown 3 (LS3), plans involve replacing ODMB7 and ODMB5 with an upgraded FED. Meticulous pre-production efforts led to the design, production, and rigorous testing of 72 ODMB7 boards for ME1/1 and 108 ODMB5 boards for ME234/1, ensuring resilience through radiation testing. The upgrades, presented in Fig3, aim to enhance CSC capabilities for HL-LHC. Additionally, upgrades to the Backend DAQ ATCA FED enable advanced functionalities for ATCA FEDs, facilitating robust data acquisition and efficient management of TTC signals to CCBs. Continuous testing and enhancements, such as the latest X2O (rev 2), ensure improved CSC performance at the HL-LHC.

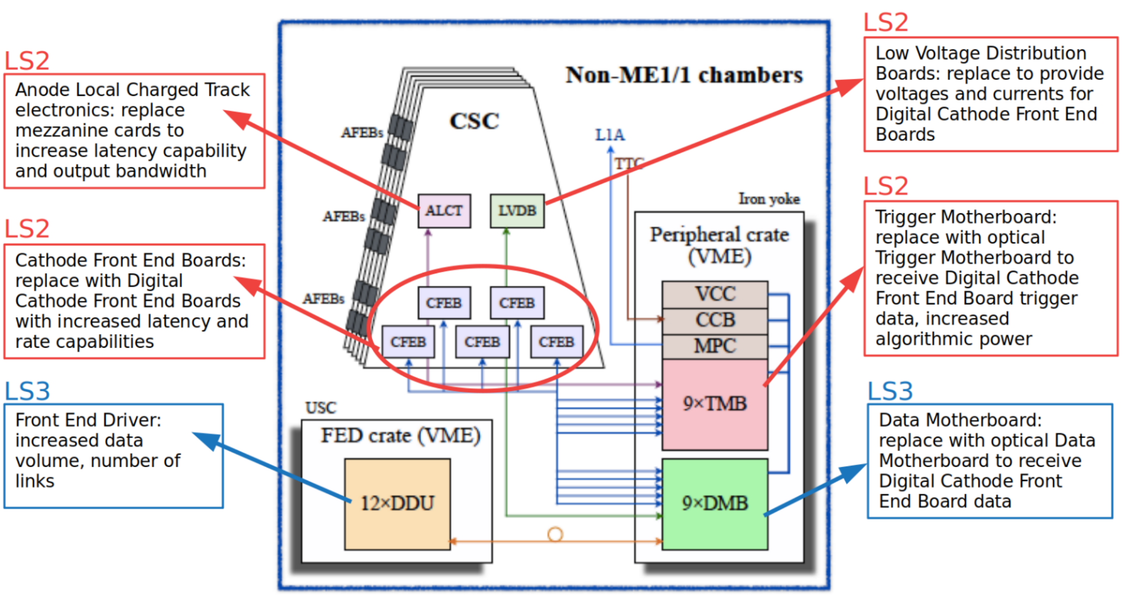

Figure 3: The CSC upgrade overview.

5. Gas Electron Multipliers (GEM)

The Gaseous Electron Multiplier (GEM) technology, utilized in GE2/1, aims to boost trigger efficiency while mitigating spikes in the trigger rate. This system consists of 72 chambers (36 per endcap) divided into 18 superchambers (SC) per endcap, each housing 2 triple GEM detectors strategically positioned at 20° in ϕ. The ongoing GE2/1 Upgrade involves six operational production sites, primarily focusing on quality control and testing. At the CERN b904 assembly site, production is nearly 50% complete, aiming for integration during LHC Run3 technical stops. The ME0 module, a technological leap with 6-layer Triple-GEM stacks, faces challenges like varied background rates and installation constraints. Scheduled production starts in 2024, with installation set for January 2027, marking significant advancements. Operating under demanding conditions, the ME0 addressed challenges of gain reduction and discharge propagation through innovative GEM foil designs, fortifying resilience against high-rate environments (Fig4).

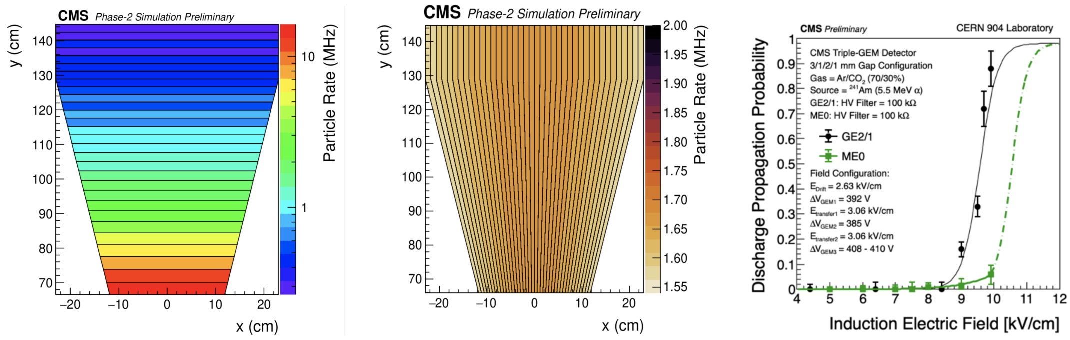

Figure 4: Left: Expected background particle rate per HV sector on an ME0 chamber with current eta segmentation. Middle:The middle plot illustrates the anticipated background rate following the implementation of the new redesign. Right: Discharge propagation probability versus the induction electric field for the GE2/1 configuration (black) and ME0 configuration (green) GEM muon detectors [3].

6. Conclusions

In summary, the upgrade of the CMS muon system for the High Luminosity LHC is a critical initiative to adapt to the anticipated demanding data-taking conditions. With enhancements in electronics and detectors like DT, RPC, CSC, and GEM, the CMS collaboration is gearing up for higher luminosity, improved tracking, and better triggering capabilities. LS2 witnessed significant progress in CSC electronics upgrades, DT electronics prototyping, and the installation of the GE1/1 GEM station. Plans for LS3 include further GEM and improved RPC station. These upgrades demonstrate CMS's commitment to optimizing the muon system for the challenges of the HL-LHC era.

References

[1] High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report, DOI:10.23731/CYRM-2020-0010

[2] The Phase-2 Upgrade of the CMS Muon Detectors, https://cds.cern.ch/record/2283189

[3] Muon DPG Results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/MuonDPGResults