PROCEEDINGS OF SCIENCE

Upgrades of the CMS muon system in preparation of HL-LHC

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The present CMS muon system operates three different detector types: barrel drift tubes (DT) and resistive plate chambers (RPC), along with cathode strip chambers (CSC) and another set of RPCs in the forward regions. In order to cope with increasingly challenging conditions, various upgrades are planned to the trigger and muon systems. In view of the operating conditions at the High Luminosity LHC (HL-LHC), it is vital to assess the detector performance under high luminosity. New irradiation tests had to be performed to ensure that the muon detectors will survive the harsher conditions and operate reliably. The new CERN GIF++ (Gamma Irradiation Facility) allowed aging tests to be performed on these large muon detectors. We present results in terms of system performance under high backgrounds and after accumulating charge through an accelerated test to simulate the expected dose. New detectors will be added to improve the performance in the critical forward region: large-area triple-foil gas electron multiplier (GEM) detectors will be installed in LS2 in the pseudo-rapidity region $1.6 < |\eta| < 2.4$, aiming at suppressing the rate of background triggers while maintaining high trigger efficiency for low transverse momentum muons. For the HL-LHC operation, the muon forward region will be enhanced with another large area GEM-based station called GE2/1, and with two new generation RPC stations called RE3/1 and RE4/1, having low resistivity electrodes. These detectors will combine tracking and triggering capabilities and can stand particle rates up to a few kHz/cm^2. In addition to taking advantage of the pixel tracking coverage extension, a new detector, the ME0 station, will be installed behind the new forward calorimeter, with coverage up to $|\eta| = 2.8$.

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1. The High-Luminosity LHC and the CMS Muon System

The HL-LHC, planned to start in 2026, will deliver an instantaneous luminosity up to $7.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, a pileup of up to 200 at CMS, with the aim of an integrated luminosity of up to 4000 fb^{-1}. Background rates and total doses will be well beyond LHC specifications [1]. In figure 1 the time profiles of the instantaneous and integrated luminosities obtained during the LHC operation and expected for HL-LHC are shown.

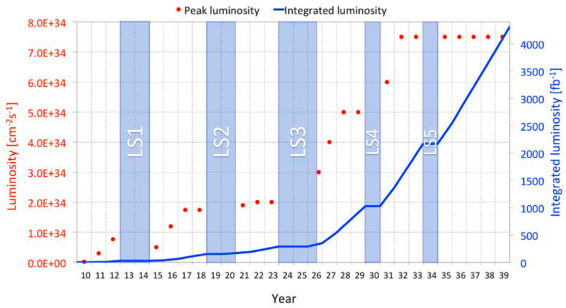

Figure 1: Instantaneous and integrated luminosity versus operational year at LHC and HL-LHC.

The present CMS muon system is based on three detector technologies to ensure muon trigger and reconstruction: Drift Tubes (MB) in $|\eta|$<1.2, Cathode Strip Chambers (ME) in 0.9<$|\eta|$<2.4, and Resistive Plate Chambers (RB/RE) in $|\eta|$<1.9. The goal of the "Phase2" muon system upgrade is to maintain optimal performance in the harsh HL-LHC conditions [2]. Consolidation and electronics upgrade of existing muon detectors is foreseen, as well as new endcap chambers (namely, gas-electron-multipliers (GEM) and improved-RPC (iRPC)): *i)* Double triple-GEM in two stations (GE1, GE2) in 1.6<$|\eta|$<2.4; *ii)* iRPC in two stations (RE3, RE4) for coverage up to $|\eta|$<2.4; and *iii)* six layers of triple-GEM (ME0) extending acceptance to $|\eta|$<2.8. The longitudinal cross section of one quadrant of the CMS detector is shown in figure 2 , highlighting present and planned muon chambers.

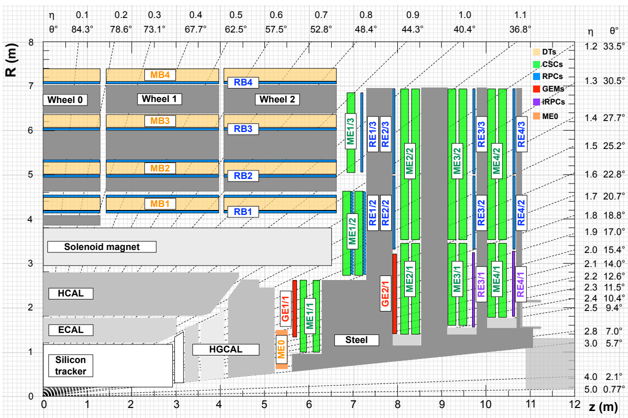

Figure 2: Longitudinal view of one quadrant of the CMS muon detectors, including the new stations planned for the Phase2 upgrade.

2. Longevity of detectors and electronics

Aging in the presence of radiation affects both gaseous detectors and electronics components. Longevity of both present and new muon detectors is studied by exploiting the GIF++ irradiation area at CERN (14 TBq ^{137}Cs source emitting 662 keV photons) [3]. The existing chambers will be able to operate until the end of Phase2 with no or little degradation, and mitigation measures are now implemented. Several electronics components are predicted to fail, and they will require replacement. In table 1, the integral radiation dose, hit rate, and accumulated charge for the most affected elements of each CMS muon detector technology are shown, as obtained from simulations performed assuming an instantaneous luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Table 1: Integral radiation dose, hit rate, and accumulated charge for the CMS muon detectors after Phase-2 upgrades, at the end of HL-LHC running, assuming an instantaneous luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

	DT	CSC	RPC	iRPC	GE1/1	GE2/1	ME0
$\lvert\eta\rvert$ range	0-1.2	0.9-2.4	0-1.9	1.8-2.4	1.6-2.15	1.6-2.4	2.0-2.8
neutron fluence (10^{12} n/cm^2)	0.4	40	1	7	20	12	200
total ionization dose (kRad)	0.12	10	2	3	3	7	490
hit rate (Hz/cm^2)	50	4500	200	700	1500	700	48000
charge per wire (mC/cm)	20	110	-	-	-	-	-
charge per area (mC/cm^2)	-	-	280	330	6	3	280

The electronics of exisiting muon detectors will be upgraded. DT will replace complex on-detector trigger and readout system with TDCs streaming hits to a new integrated backend. CSC Front-end boards will be replaced to mitigate saturation at high rate. RPC electronics will be upgraded improving the time resolution.

3. Muon trigger performance

New muon detectors in the forward region will provide additional hits along a muon's trajectory. A new L1 trigger architecture will ensure that information from different subdetectors will be integrated and matched with tracker information; tracking algorithms will rely on powerful processors receiving signals from multiple stations.

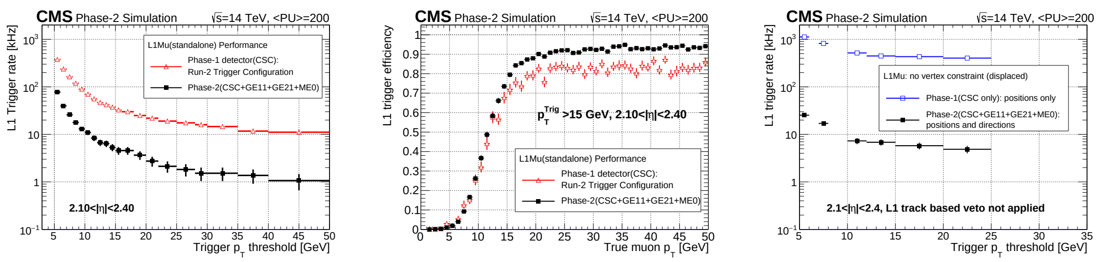

Figure 3: Selected performance results from the simulation of the upgraded muon trigger. The inclusion of new GEM detectors allows new trigger algorithms to achieve higher efficiency and lower trigger rates, and displaced muon trigger algorithms resulting in low rates are possible.

Several simulation results are shown in figure 3. Integration of RPC and future iRPC in the trigger system of the forward region will improve efficiency with respect to the CSC-only trigger. Availability of high-resolution GEM hits will help to significantly reduce the standalone muon trigger rate by improving the momentum resolution, and will increase the efficiency. Algorithms for displaced muon triggering are being developed and are improved by the availability of new detectors. Improved time resolution enabled by the new RPC/iRPC electronics will allow efficient triggers dedicated to slow-moving particles.

4. Offline muon reconstruction performance

Offline muon reconstruction was evaluated for Phase2 geometry and several pileup conditions using simulated Drell-Yan dimuon events to measure signal efficiency and ttbar events to measure background muon yelds. The displaced muon reconstruction algorithm, which does not require

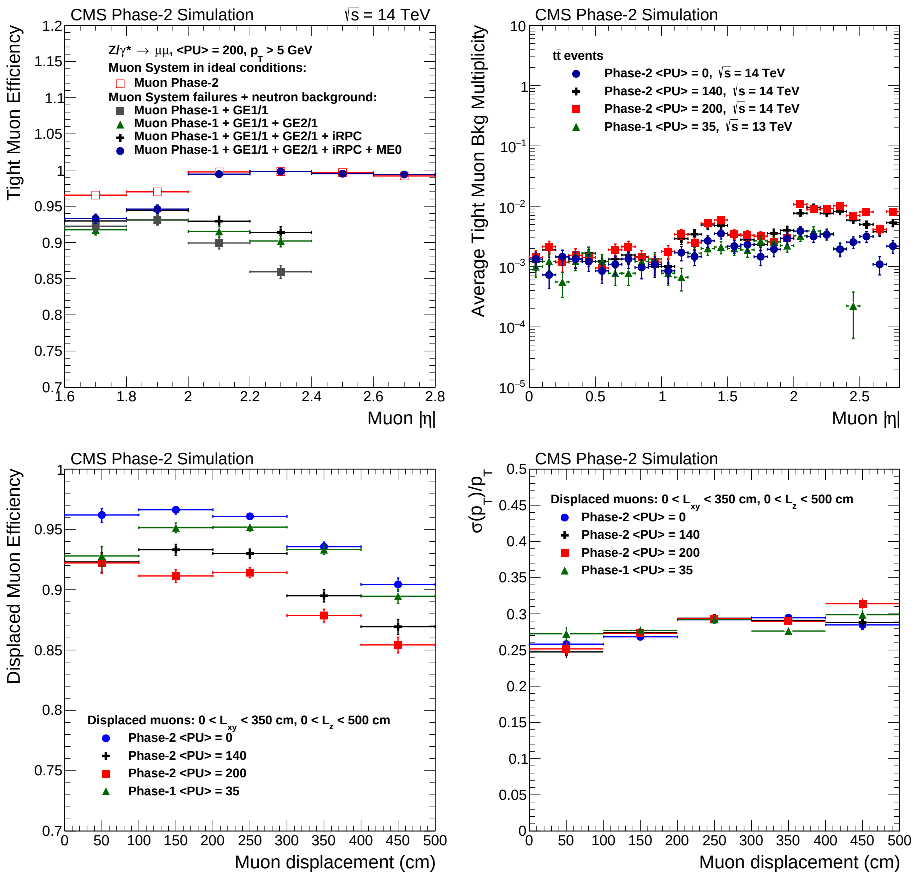

Figure 4: Offline muon reconstruction performance. Top: muon reconstruction efficiency versus the pseudorapidity in several detector scenarios at pileup 200, and background muon multiplicity in Phase2 detector, stable across a large range of pileup conditions. Bottom: displaced muon reconstruction efficiency and momentum resolution is shown to be robust against pileup.

tracks to point to the interaction vertex, was also evaluated using a simulated sample of muons with transverse impact parameter up to 50 cm.

Results from simulation, shown in figure 4, indicate that the Phase2 detector efficiency will remain high and background yelds will stay under control in HL-LHC data taking conditions, as well as preserving the displaced muons standalone efficiency and momentum resolution.

5. Conclusions

The high radiation level and track and hit densities foreseen at High Luminosity LHC require a comprehensive upgrade plan for the CMS muon system. Consolidation of existing detectors, electronics upgrades, and installation of new detectors in the forward region will allow the excellent physics performance achieved by CMS during LHC data taking to be maintained or improved.

References

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

[3] D. Pfeiffer et al., *The Radiation Field in the Gamma Irradiation Facility (GIF++) at CERN*, *Nucl. Instrum. Meth.* **A866** (2017) 91, doi:10.1016/j.nima.2017.05.045.