CMS muon system towards LHC Run 2 and beyond

Luigi Guiducci for the CMS collaboration

Dipartimento di Fisica e Astronomia - Università e INFN di Bologna

Abstract

The CMS muon system has played a key role for many physics results obtained from the LHC Run 1 data. The LHC will increase the beam energy as well as progressively increase the peak instantaneous luminosity in Run 2 and in the following years. Significant consolidation and upgrade activities are ongoing, in order to improve the CMS muon detectors and trigger performance and robustness. With LHC and then HL-LHC running beyond 2030, the large accumulated radiation dose, the high pileup environment, and the ageing of several detector and electronics components become challenges that can only be met with further development and upgrade work. We will introduce the CMS muon system and present the consolidation work in preparation for LHC Run 2. We will then describe the main constraints and the solutions proposed for the upgrade of the muon detector system towards HL-LHC.

Keywords: LHC, CMS, muon detectors, upgrade, HL-LHC

1. Introduction

The Compact Muon Solenoid (CMS) [1] is a multi-purpose particle physics detector built at the CERN Large Hadron Collider (LHC) [2]. The CMS basic design element is a super-conducting solenoid that produces a 3.8 T magnetic field: the tracker, the electromagnetic and hadron calorimeters are within the field volume. The iron yoke is instrumented with a muon spectrometer for muon identification, and for momentum measurement and assignment of the parent bunch crossing for triggering. A longitudinal section of the CMS detector is shown in Fig. 1. The muon spectrometer is divided into 5 separate wheels in the barrel, containing 4 concentrical layers of detectors, and 4 independent disks both in the positive and negative endcaps. The detectors for the 4th disk were installed during the LHC Long Shutdown 1 (LS1) in 2013-2014. Three different gaseous detector technologies are employed: Drift Tube (DT) chambers in the barrel region to detect muons up to pseudo-rapidity |η| < 1.2; Cathode Strip Chambers (CSC) to handle the higher rates and non-uniform magnetic field in the endcap region 0.9 < |η| < 2.4; Resistive Plate Chambers (RPC) located in both barrel and endcap regions, up to |η| < 1.6. Details about the muon detectors are given in [3].

LHC Run 1 operations started in March 2010, with proton-proton collisions at a center-of-mass energy of

Figure 1: Schematic view of one quadrant of the CMS detector in the Rz plane, in Run 1 configuration. The z-axis is coincident with the beam axis, while R measures the distance from it. The RPC chambers are marked in red, DT in yellow and CSCs in green.
7 TeV and commissioning of the machine through the year; in 2011 the instantaneous luminosity reached up to $3.5 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$, setting a new world record for beam intensity at a hadron collider. In 2012, LHC has been operating at the increased energy of 4 TeV per beam, reaching a maximum of instantaneous luminosity of $7.7 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$.

After the proton-lead ion run at the beginning of 2013, the LHC stopped circulating protons or ions and entered the LS1 [4], devoted to a campaign of consolidation of the interconnections between the dipole magnets in order to provide increased beam energy in Run 2 [5].

2. Run 1 operations and performance of the CMS muon system

The operation of the CMS detector during LHC Run 1 has been smooth with data taking efficiencies above 92%. The contribution of muon detectors to the CMS downtime was below 1.5%. At the end of Run 1, the fraction of active channels was 97.4% for CSCs, 98.4% for RPCs and 98.6% for DTs. The most common reason for the loss of channels was the failure of components of on-detector electronics, not accessible since 2009.

2.1. Performance results from Run 1

The performance of the muon systems has been evaluated using prompt muons from proton-proton collisions at increasing luminosity and was found to be stable with respect to the number of collisions per beam crossing [6, 7].

The efficiency for reconstructing chamber track segments at the trigger level was found to be around or above 95% in DT (see Fig. 2) and CSC detectors. The resolution was measured from offline data and found to be 200 $\mu$m for hits and below 100 $\mu$m for track segments, in good agreement with simulations (see Fig. 3) [8]. The RPC system also proved a very high hit efficiency, around 95%, and low noise: about 0.1 Hz/cm$^2$ in average (Fig. 4 and 5) [9]. The Level-1 and high level trigger systems achieved a good control of the rate of selected events and high purity with respect to muon object selection implemented in offline analyses [10].

---

Figure 2: Efficiency of the DT trigger track segments with respect to reconstructed tracks, for the four muon stations, versus the muon transverse momentum.

Figure 3: The DT resolution, computed from the width of the distribution of the distance between hits and the muon tracks reconstructed in CMS data. Red points correspond to the hits in the transverse view, blue points correspond to hits in the longitudinal view.

Figure 4: Efficiency of the RPC detector in 2012 run.
2.2. Background rate measurements

In order to understand the expected performances of the detectors when the LHC will collide beams at even higher luminosity, the trend of background rates with respect to the instantaneous luminosity was investigated. The main sources of background in the system are thermal neutrons populating the cavern, which are captured by the nuclei in the detector material and result in the emission of photons within the active volume; and prompt background, mostly punchthrough and fly-through hadrons escaping the calorimeters.

As it can be seen in Fig. 6, where the measurement of rates in the DT detector is shown for a particular LHC fill, neutron background induces the highest rates in the outer chambers and in the top sectors of the detector, due to the lack of shielding effect provided by the walls and the floor of the cavern. Prompt background is larger in the chamber closer to the beamline and at larger pseudorapidities. All measured rates, in different regions and from different detectors, show a linear dependence on the instantaneous luminosity [11, 9]. This is shown for example for the RPC measurements in Fig. 7. It is thus assumed safe to perform a linear extrapolation and then take into account a safety factor in order to predict the background rates that the detectors will have to sustain at the HL-LHC.

3. Consolidation of the muon system in preparation for Run 2

During the LS1 the CMS detector was accessible to allow interventions to the detectors and the electronics. The interventions were of three main types: i) reparations and recovery of dead channels in the detectors and in the electronics (all detectors) ii) consolidation of the electronics systems and improvements in their granularity (DT, CSC) iii) completion of the endcap muon detectors in the 4th disk (RPC, CSC).

All three DT, CSC and RPC systems engaged in an extensive campaign of reparations, in order to recover dead channels due to the electronics or the high voltage system. The fraction of active channels in the muon systems is now close to 100 %. In the following sections, more details about other consolidation and upgrade activities will be given.

3.1. DT Consolidation

The main intervention in the DT system during the Long Shutdown 1 was the relocation of the Sector Collector (SC) electronics, a system of VME crates for data concentration and optical transmission installed inside the CMS cavern, on the towers surrounding the detector. The SC was considered an important single point of failure due to access limitations to the experimental cavern. As shown in Fig. 8, a simpler copper-to-optical (CuOF)
converter has been installed within CMS detector towers and 3500 optical links were routed to the counting room, where optical-to-copper converters (OFCu) feed the relocated SC [12]. The full DT system was then recommissioned with cosmic ray muons. The main advantage of this approach is that no data concentration happens in the experimental cavern and the full DT data is available on optical links in the counting room, paving the way for further Level-1 trigger upgrade in 2016.

Furthermore, the algorithm of the DT frontend trigger ASIC, called Bunch-and-Track-Identifier (BTI), was implemented in FPGA and new trigger boards were installed in two (out of five) of the DT wheels. This allowed the stock of spare BTI ASICs, which suffered of high infant mortality, to be refurbished.

3.2. CSC ME1/1 electronics upgrade

During Run 1, the innermost part of the ME1/1 chamber, covering the pseudorapidity range 2.1 < η < 2.4, was equipped with low granularity trigger and frontend electronics. This impacted the precision of the reconstructed position and direction of the trigger primitives from such chambers, resulting in a degradation of the \( p_T \) measurement performed by the Level-1 trigger. During Long Shutdown 1, the electronics was replaced and the full granularity restored.

3.3. Completion of endcap detectors

The production and installation of CSC and RPC chambers in the fourth endcap disk (ME4/RE4 stations) represent the completion of the original CMS muon system design [13, 14]. The increased redundancy will allow the trigger performance to be improved at high luminosity, in terms of better \( p_T \) resolution and better rejection of background and fake muons. In Fig. 9, the trigger rate from the CSC system is evaluated at a luminosity of \( 2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \) for two configurations, with and without the ME4/2 station. For the same target rate of 5 kHz, the \( p_T \) threshold can be reduced from 40-50 GeV down to less than 20 GeV.

In Fig. 10, the muon identification efficiency versus the muon transverse momentum in the range 1.2 < |\( \eta \) | < 1.8 is shown for the two configurations: the addition of ME4 and RE4 detector stations allow an increase of about 2% across the \( p_T \) range.

4. CMS muon upgrade plans for LHC and High Luminosity LHC

The LHC program will continue with Run 2, when the center of mass energy will reach the nominal value of 14 TeV and the luminosity will reach \( 10^{34} \text{cm}^{-2}\text{s}^{-1} \). After the LS2, in 2018, the luminosity will possibly reach \( 2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \), with a pileup of 50-60 events per crossing, and a total integrated luminosity of about 300 fb\(^{-1} \) will be collected before the LS3.

The CMS “Phase 1” upgrades, performed before or during the LS2, include the replacement of the pixel detector [15], the upgrade of HCAL electronics [16] and a new Level-1 trigger system [17].

During LS3 the LHC will be upgraded, initiating the High Luminosity LHC phase (HL-LHC), with the goal of collecting an integrated luminosity of 3000 fb\(^{-1} \). The instantaneous luminosity will raise up to 5 \( \times \)
Figure 10: Muon identification efficiency in the region $1.2 < |\eta| < 1.8$, as obtained from CMS simulation using the configuration with (red) and without (blue) the ME4/RE4 stations.

$10^{34} \text{ cm}^{-2}\text{s}^{-1}$, with a very high pileup value, about 140 collisions per crossing.

4.1. HL-LHC physics

Among the goals of the HL-LHC program are precision Higgs and VV spectrum measurements, where final states with muons and forward jets play a key role. The Higgs decaying into WW and ZZ boson pairs will allow the measurement of bosonic couplings, while the decay $H \rightarrow \tau\tau$, with one tau fermion decaying into a muon, will provide the best measurement of fermionic couplings. Also the branching fraction of the rare decay $H \rightarrow \mu\mu$ will be measurable with an integrated luminosity of $3000 \text{ fb}^{-1}$. In this scenario, it will be necessary to trigger on leptons with low thresholds, around 20 GeV, in order to keep a high efficiency for electroweak physics. The search for new physics, like SUSY and Exotica scenarios, is also demanding very high performance of the CMS muon system. High mass objects implies very high $p_T$ leptons in the final state. The search for heavy stable charged particles will benefit of improved timing resolution to distinguish slow-moving particles. Other particular signatures are non-pointing muons and collimated muon "jets". Thus, it will be important to maintain a good muon standalone trigger capability, with enhanced ability to resolve multiple tracks.

4.2. CMS muon upgrade plans

In order to achieve the physics goals for the HL-LHC program, the CMS detector will be required to maintain or improve the excellent performances demonstrated at relatively low pileup. A “Phase 2” upgrade plan for CMS is forming and a Technical Proposal is in preparation. The studies include the replacement of the tracking system, with an embedded track-based trigger (TT), new endcap calorimetry, further Level-1 trigger and DAQ system upgrades, and improvements to the muon systems.

A key element of CMS Phase 2 upgrade plan is to introduce a tracker based trigger. In such architecture, the tracker electronics will push into the trigger system track candidates with very good momentum resolution. Such tracks will be matched to calorimeter and muon trigger objects to improve the trigger decision, and, ultimately, achieve much lower trigger rates. In order to achieve a good purity and efficiency in the matching process, muon systems will have to improve the standalone determination of the track spatial parameters and of its momentum.

In order to increase the redundancy and trigger capability of the muon system, new detectors and the consolidation of the existing ones are proposed. In addition, muon system acceptance will be increased, together with pixel tracking and calorimetry acceptances, to $|\eta| < 3.0$. This extension will be beneficial for yields and/or the signal to noise ratio of final states with muons, especially multi-muon final states. It will also improve the identification of top and W events and the missing transverse energy determination.

There are three types of upgrades proposed for the Phase 2 CMS muon system: $i)$ actions that ensure the longevity of the present muon detectors; $ii)$ additional muon detectors to increase redundancy and enhance the trigger capabilities in the forward region $1.6 < |\eta| < 2.4$; and $iii)$ extension of the muon coverage to $|\eta| > 2.4$ in the rebuilt endcap calorimeter, to take advantage of pixel tracking coverage extension.

4.3. Longevity of existing muon detectors

Within the HL-LHC program, original CMS detectors and electronics components will be required to be still performant after approximately 30 years of operation and an integrated luminosity of 3000 fb$^{-1}$. Past irradiation tests, measured background rates, and the history of problems with electronics components during Run 1 allow to identify critical actions needed to ensure long term operation of the detector and electronics. It is expected that the muon detectors will stand the integrated dose foreseen at HL-LHC, with minimal impact on the performances. This will be verified with extended irradiation tests, planned in the new GIF++ facility. Several electronics systems, instead, were not
Figure 11: Schematic view of one quadrant of the CMS detector in the Rz plane, highlighting the forward muon detector configuration proposed for Phase 2 upgrades. The z-axis is coincident with the beam axis, while R measures the distance from it. The original CSC chambers are marked in green and original RPC chambers in light blue. Proposed GEM detectors are marked in red and proposed iRPC detectors in dark blue.

qualified for large irradiation and/or their operation throughout HL-LHC is not recommended due to the impact of aging and the possibility of entering a wear-out phase.

Additional constraints arise from other changes proposed for Phase 2, in particular to the DAQ and trigger system. In order to cope with the extremely high instantaneous luminosity, and profiting of improved data transmission technologies and computing resources, it is planned to increase the Level-1 trigger latency (from 3.2 to 10 μs) and the overal readout rate (from 100 kHz to 0.5-1 MHz). In such conditions, and depending on actual background rates, DT and CSC readout electronics will start to suffer significant data losses and will need to be rebuilt. In case of DT, the proposed on-detector electronics for Phase 2 will only perform time digitization and transmission of the raw hits: latest high speed optical link and radiation tolerant FPGAs technologies provide sufficient bandwidth and processing power. The complexity and the power consumption of the on-detector electronics will be greatly reduced. The track fitting and the trigger primitive generation will be performed in custom processors in the counting room. The availability of full resolution hits in the trigger algorithm will allow the matching with the tracking trigger to be improved.

4.4. New muon detectors for the Phase 2 upgrade

A sketch of the proposed new muon detector for the Phase 2 upgrade of the CMS muon system is shown in Fig.11. GEM chambers are proposed for the endcap stations one and two, covering the pseudorapidity range 1.5 < |η| < 2.4 [20]. They will improve the redundancy in the muon system, for robust tracking and triggering, and the Level-1 and high level trigger momentum resolution, in order to reduce or maintain the trigger rate through high pileup conditions. Improved RPC (iRPC) chambers are proposed for the endcap stations three and four, in order to extend the present RPC system up to |η| < 2.4. This will also increase the redundancy of the muon system with a detector offering excellent time resolution, which will allow the neutron background and pileup effects to be reduced, as well as precision timing for the searches of Heavy Stable Charged Particles. Finally, an extension of the acceptance of the muon system up to |η| < 3 is proposed by means of a new muon station, installed in the space left by the new compact endcap calorimeter, based on GEM chambers. This detector will allow the tagging of muons in the extended pseudorapidity region covered by the Phase 2 pixel detector.

New muon detectors for HL-LHC will need high rate capability: about 1 kHz/cm² in the iRPC region, and up to 10-100 kHz/cm² in the most forward regions, up to |η| < 3. In addition, exceptional performances are needed: a spatial resolution down to 100 μm, rejection of uncorrelated neutron hits, possibly a very good timing resolution O(100 ps), the use of eco-friendly gases. Given such figures, the choice of the optimal detector is driven by physics performance, robustness, cost, simplicity, etc.

4.5. Improved RPCs

The main limitation to the maximum rate sustainable by detectors based on RPC technology is given by the limited voltage drop in the resistive electrode. Possible improvements can follow two complementary
Figure 13: Operational principles of a GEM detector. Left: equipotential and field lines in the region of the perforated kapton foil. Center: simulation of the paths of electrons and ions across the amplification region. Right: the triple GEM configuration used for CMS GEMs.

approaches: reducing the electrode resistivity (below $10^{10} \Omega \text{cm}$), and reducing the charge generated per particle, by means of using improved amplification electronics and a better rejection of detector noise. New detector configurations can improve the ratio of the signal to the charge in the gas gap: low resistivity bake-lite, multi-gap RPC (Fig. 12) [18], and glass-RPCs [19], where the smoother electrode surface result in lower noise. The definition the appropriate configuration will require R&D in order to understand the robustness of the proposed solution, expecting an integrated charge of $1-1.5 \text{C/cm}^2$ from the HL-LHC program. GIF++ facility, starting in 2015, will allow to study the rate capability and the radiation-induced aging effects of the prototypes.

4.6. GEM detectors

GEM chambers for CMS [21, 22] are in a triple-GEM configuration, with three amplification steps provided by perforated 50 $\mu$m kapton foils with 5 $\mu$m copper metalization on both sides. A sketch of this configuration is shown in Fig. 13. This configuration allows an amplification factor up to $10^4$ to be achieved and present

Figure 14: Left: sketch showing the principle of combining the GEM measurement point with the CSC segment to improve the determination of the muon trajectory and thus its bending in CMS magnetic field. Right: the distribution of the bending angle measured by the GEM-CSC combination is shown for muon of $p_T = 5 \text{ GeV}$ (red) and 20 $\text{GeV}$ (blue).

a rate capability up to $10^5 \text{Hz/cm}^2$. The production is based on a relatively low cost industrial process. Non flammable gases are needed, such as a mixture based on Ar/CO$_2$/CF$_4$. There is already a large experience with GEMs in particle physics, in experiments such as Compass [23], Totem [24], LHCb [25]. Nevertheless, R&D will be needed to replace the CF$_4$ with a gas with lower greenhouse-effect index.

The use of GEM chambers in endcap stations one and two is beneficial mainly because they will provide a further high resolution measurement point along the trajectory of a muon. CSC chambers, present in the endcap stations, have a good spatial resolution but are relatively thin (11 cm) thus providing a limited resolution on the trajectory direction. The combination of the GEM measurement and the CSC segments allows an increased level arm, as it is shown in Fig. 14, and thus a better measurement of the bending of the muon in the magnetic field, resulting in improved resolution for the determination of the muon transverse momentum. In Fig. 15 the trigger rate from the pseudorapidity range corresponding to the proposed GEM in the first endcap station is shown as a function of the threshold on the muon transverse momentum. The red curve shows the results of a combined GEM-CSC algorithm, while. the red curve, and the measurement from the trigger configuration available for Run 2 in the green curve. As it can be noticed, a reduction factor of about 10 can be
achieved in the relevant $p_T$ region, 20 to 40 GeV.

4.7. Pseudorapidity extension

The muon tagging in the high pseudorapidity region will be based on a single detector, covering the range $2 < |\eta| < 3$. The space for the installation of the new chambers will be available in the back of the Phase 2 endcap calorimeter, as sketched in Fig. 16. The proposed muon station, called ME0, will be based on six layers of triple-GEM chambers, to suppress individual hits from neutron background. The background will be reduced also using borated poliethylene and lead shielding. The feasibility of muon tagging is shown in Fig. 17, where the uncertainty in matching between the Phase 2 pixel detector tracks and the ME0 hits is shown, separating the contribution from multiple scattering and from track reconstruction uncertainty.

5. Conclusions

After the very successful LHC Run 1, the CMS detector is being continuously consolidated and upgraded for the next LHC runs. The CMS muon system, which played a key role for many physics results from CMS, including the discovery of the standard model scalar boson, has undergone a large repairation and consolidation effort during the Long Shutdown 1, being now ready for the increase of beam energy and luminosity at LHC Run 2, and for the Level-1 trigger upgrade, foreseen in 2016. With HL-LHC, starting around 2023, unprecedented luminosity (up to $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$) and harsh pileup and background conditions will set severe constraints for the successful operation of CMS muon detectors. A Phase 2 CMS upgrade campaign, which is now being defined, will allow to successfully face the challenges of the reconstruction of the events in high pileup while mitigating the effects due to ageing of the detectors and the large integrated radiation dose. The plans for the muon detectors, including the consolidation of the existing detectors, the installation of new detectors in the endcaps and the extension of the pseudorapidity reach of muon tagging in CMS, were outlined.

References