The Compact Muon Solenoid Experiment
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The CMS muon system status and upgrades for LHC run-2 and performance of muon reconstruction with 13 TeV data

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Abstract

The CMS muon system has played a key role for many physics results obtained from the LHC Run-1 and Run-2 data. During the Long Shutdown (2013-2014), as well as during the last year-end technical stop (2015-2016), significant consolidation and upgrades have been carried out on the muon detectors and on the L1 muon trigger. The algorithms for muon reconstruction and identification have also been improved for both the High-Level Trigger and the offline reconstruction. Results of the performance of muon detectors, reconstruction and trigger, obtained using data collected at 13 TeV center-of-mass energy during the 2015 and 2016 LHC runs, will be presented. Comparison of simulation with experimental data will also be discussed where relevant. The system's state of the art performance will be shown, and the improvements foreseen to achieve excellent overall quality of muon reconstruction in CMS, in the conditions expected during the high-luminosity phase of Run-2, will be described.

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The CMS muon system: status and upgrades for LHC Run-2 and performance of muon reconstruction with 13 TeV data

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ABSTRACT: The CMS muon system has played a key role for many physics results obtained from the LHC Run-1 and Run-2 data. During the Long Shutdown (2013-2014), as well as during the last year-end technical stop (2015-2016), significant consolidation and upgrades have been carried out on the muon detectors and on the L1 muon trigger. The algorithms for muon reconstruction and identification have also been improved for both the High-Level Trigger and the offline reconstruction. Results of the performance of muon detectors, reconstruction and trigger, obtained using data collected at 13 TeV centre-of-mass energy during the 2015 and 2016 LHC runs, will be presented. Comparison of simulation with experimental data will also be discussed where relevant. The system's state of the art performance will be shown, and the improvements foreseen to achieve excellent overall quality of muon reconstruction in CMS, in the conditions expected during the high-luminosity phase of Run-2, will be described.

KEYWORDS: Gaseous detectors, Muon spectrometers, Trigger concepts and systems (hardware and software), Performance of High Energy Physics Detectors

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1 Introduction

The Compact Muon Solenoid (CMS) is a general purpose detector operating at the LHC collider at CERN. A significant fraction of the CMS physics programme is characterised by signatures whose event topologies contain muons with transverse momentum spanning a range from few GeV/ c to approximately 1 TeV/ c . For this reason, highly performing muon identification and reconstruction capabilities are crucial tools for the experiment.

The CMS muon system [1] consists, at present, of three different detector technologies and equips the outermost layers of the detector. It ensures efficient muon identification, improves the measurement of the p_T of muons in the regime of O(100) GeV/ c and provides a robust standalone trigger. The latter is able to identify the bunch-crossing (BX) originating a prompt muon with a mis-assignment rate lower than 1%, at the LHC machine BX frequency of ~ 40 MHz.

2 The CMS Muon System in the LHC Run-2

A schematic view of CMS is given in Fig. 1. Muon reconstruction is performed both using the inner tracker, located at the centre of the detector and immersed in a 3.8 T solenoidal magnetic field, and four station layers of gaseous detectors, located inside the steel return yoke surrounding the magnet.

The inner tracker consists of pixel and strip silicon detectors and covers up to a pseudorapidity range of $|\eta| < 2.5$. The barrel region ($|\eta| < 1.2$) of the muon spectrometer is equipped with Drift Tube (DT) chambers, whereas Cathode Strip Chambers (CSC) cover the end-cap regions ($0.9 < |\eta| < 2.4$). In addition, Resistive Plate Chambers (RPC) complement DTs and CSCs up to a pseudorapidity of $|\eta| < 1.8$.

Figure 1. Longitudinal cross section of a quadrant of the CMS detector. The interaction point is located at the lower left corner of the figure.

2.1 Drift Tube Chambers (DT)

Drift Tube Chambers are used as tracking and triggering devices in the barrel region of the muon spectrometer. A total of 250 chambers is equally distributed among 5 barrel wheels. Each wheel hosts four concentric rings of stations segmented in 12 contiguous sectors. The basic DT detector element is a rectangular drift cell with a transversal size of $4.2 \text{ cm} \times 1.3 \text{ cm}$, filled with a 85/15% Ar/CO_2 gas mixture. Cells are arranged parallelly to form detection layers, stacked half-staggered in groups of four to form super-layers (SL). Each DT chamber is equipped with two SLs measuring the coordinate in the CMS bending plane ($r - \phi$), whereas a single SL measures the coordinate along the beam line (z) in the 3 innermost station rings. The CMS DTs design resolution, for single reconstructed hits, is expected to be around $\sim 250 \text{ } \mu\text{m}$, for a final resolution of $\sim 100 \text{ } \mu\text{m}$ for offline segments reconstructed in the $r - \phi$ view.

During the first LHC long shutdown (LS1) the DT underwent a relocation of the first level trigger (L1T) electronics from the experimental cavern to the service one. Later, during the 2015 year-end run break, new trigger electronics, able to combine information of DT trigger segments with the one of the nearby RPC layers was deployed, as part of a major upgrade of the CMS L1T. The former upgrade ensures more freedom to intervene on a critical component of the system at running time, whereas the latter is aimed at improving the performance of the L1T by means of an early combination of DT spatial resolution with RPC timing response.

Finally, during LS1, the algorithm used to perform offline DT segment reconstruction was also improved [2]. The *Mean-Timer* property, holding for half-staggered layers of cells characterised by almost-constant drift velocity, is now exploited to include the particle crossing time as parameter in the reconstructed segment fit, on par with spatial coordinates. This improves the rejection of hits from δ -rays, increasing both spatial and time segment resolution. It also allows for more performing reconstruction of segments from out-of-time muons (e.g. from neighbouring crossings), improving the capability to tag and reject them when muon identification is performed.

2.2 Cathode Strip Chambers (CSC)

Cathode Strip Chambers serve as tracking and trigger detector in the muon system end-cap regions. They are organised in trapezoidal detector chambers arranged, within four disks in each end-cap, in 2 or 3 concentric rings, according to the disk position. The full CSC system presently consists of 540 chambers, 72 of which were installed in the outermost disk layers during LS1, completing its design layout.

Each chamber is made of 6 layers of 9.5 mm-thick arrays of anode wires enclosed between cathode planes. One of the cathodes is segmented with strips of variable width (8.4 to 16 mm) which allow precise position measurement in $r - \phi$. Anode wires, placed perpendicular to the strips, are used to measure the radial coordinate and their fast response is exploited to perform BX identification in the L1T. Chambers are filled with a 40/50/10% $Ar/CO_2/CF_4$ gas mixture. The CSC strip design resolution for single reconstructed hits is expected to vary between roughly 75 and 150 μm .

A triple readout ganging was applied in Run-1 to the chambers equipping the innermost rings of the first CSC disks in $2.1 < |\eta| < 2.4$. It was removed during LS1 with the refurbishment of the CSC readout electronics in the high- $|\eta|$ region. Such an upgrade allows to exploit the full detector granularity, improving the resolution of offline and trigger segments above $|\eta| > 2.1$.

2.3 Resistive Plate Chambers (RPC)

Resistive Plate Chambers equip the CMS muon system both in barrel and end-caps. Due to their good timing resolution, they are mainly used in the trigger. They also participate to offline muon tracking, though with limited resolution.

A total of 480 (576) chambers, arranged similarly to the DT (CSC) ones, presently equip the muon spectrometer barrel (end-caps). CMS uses double gap RPC chambers working in avalanche mode, filled with a 96.2/3.5/0.3% $C_2H_2F_4/Iso - C_4H_{10}/SF_6$ gas mixture. Strips allow to measure the $r - \phi$ coordinate with a precision around 1 cm, while the hit timing resolution is around 2 ns.

The equipment of the fourth end-cap layers with RPCs was completely carried out during LS1, with the addition of 144 chambers. Such improvement brought redundancy, allowing to increase L1T efficiency during the 2015 run and to tighten trigger quality cuts with the aim of keeping reasonably low thresholds.

2.4 Muon detectors performance

Figure 2 shows some highlights of the muon detector performance, as measured during the LHC 2016 run [3]. A chamber-by-chamber map of CSC segment reconstruction efficiency, computed by means of a *Tag-and-probe* method exploiting $Z \rightarrow \mu\mu$ decays, is presented in Fig. 2(a). Performance is, in general, very good ($\langle \epsilon \rangle \sim 97\%$). The few inefficient spots are mostly due to malfunctioning of chamber electronics, either occasional (corrected along the run) or that requires access to the chambers for intervention. Similar conclusions hold for the RPC system, whose hit efficiency is shown, for the detector barrel region, in Fig. 2(b). In this case, the efficiency is measured by extrapolating linearly DT reconstructed segments to close-by RPC chamber layers and looking for matching with RPC reconstructed hits. Finally, Fig. 2(c) summarizes the DT hit resolution, computed as residual with respect to local reconstructed segments, for each station ring of the

five barrel wheels. Results are in good agreement with design expectations (Sec. 2.1) and Run-1 ones [1]. Worse resolution is expected for hits reconstructed in the θ view of external wheels due to the large impact angles of prompt muons with the DT chambers, whereas the lower resolution of MB4 stations comes from their lack of θ SLs, which cannot then be used to determine the particle crossing coordinate in z and correct for effects due to signal propagation of along DT wires in $r-\phi$ SLs.

Figure 2. Chamber-by-chamber map of CSC segment reconstruction efficiency computed with the tag-and-probe method (a). Efficiency distribution for RPC chambers equipping the CMS muon spectrometer barrel (b). Summary map of DT hit resolution for both $r-\phi$ and θ SLs computed with respect to offline reconstructed DT segments (c).

3 Online and offline muon object reconstruction

The standard CMS offline muon reconstruction is documented in detail in [4]. It starts from single detector elements (i.e. pixel and strip hits in the inner tracker, or RPC hits in the muon system) or segments (reconstructed within single DT/CSC chambers). Out of these, tracks are built in parallel both in the inner tracker (*inner tracks*) and in the muon spectrometer (*standalone tracks*). For each standalone track, matching with nearby inner tracks is then attempted by propagating them onto

a common surface, testing the compatibility of their parameters and retaining the best pairing. In case of success, a *Kalman-filter* based approach is exploited to perform a combined track fit to form a *global-muon track*. Besides this *outside-in* muon reconstruction algorithm, an *inside-out* muon identification approach also exists. Inner tracks above a minimal momentum threshold are propagated, accounting for multiple-scattering and energy loss effects, to each station layer of the muon spectrometer and the potential matching with DT or CSC segments is checked. If at least one (CSC or DT) segment is found to be compatible with the extrapolated inner track, a *tracker-muon* is generated.

The CMS trigger [5] is based on a two-staged approach. Firstly a L1T system, built using custom electronics, reconstructs object candidates exploiting information from muon spectrometer and calorimeters, coarsely estimates a candidate's energy (or momentum) and identifies its BX of origin. Up to 100 kHz of events passing the L1T selection criteria are then processed by an High-Level-Trigger (HLT), consisting in a computer farm running a streamlined versions of the algorithms used for offline reconstruction, which exploits the full information available from the detector. Up to 1 kHz of events are stored by the HLT for offline analysis.

Reconstruction of standalone muons at the HLT proceeds through the same steps of the offline one, the most significant difference between the two being the request for HLT standalone muon tracks to be geometrically matched with L1T muon candidates. After that, to cope with the more stringent CPU timing requirements imposed to online reconstruction, a dedicated logic is exploited at HLT to perform global muon tracking. It consist of two outside-in and one inside-out algorithms for seeding and pattern recognition which are run in *cascade* from the fastest to the slowest and stop as soon as a muon combined track is built.

Furthermore, muon isolation at HLT is also computed with the aim of discriminating muons from QCD processes. Both the sum of p_T from inner tracker tracks and/or energy deposits measured in the calorimeters, computed within geometrical cones surrounding HLT muon candidates, can be exploited for this purpose.

3.1 Improvements for the LHC Run-2

The simultaneous increase in centre-of-mass energy (from 8 to 13 TeV) and instantaneous luminosity (from approximately $7.7 \cdot 10^{33}$ to $1.48 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ¹) led to an increase of physics rates of about a factor four compared with the ones reached during the LHC Run-1. The latter, together with the increment of collision frequency (reduction of BX spacing from 50 to 25 ns), also represents a challenging scenario in terms of overlap of signal and pile-up collisions (both in-time and from neighboring crossings), especially within the innermost detectors (i.e. tracker and calorimeters).

Already at the end of the first LHC run, a pile-up dependent inefficiency of the order of 5-10% was observed for single muon HLT triggers. The issue was traced to originate within the online global muon reconstruction. In particular, tracks from the cascade were found to often fail the typical quality cuts (e.g. a 1-2 mm cut on the transverse muon impact parameter with respect to the beam-spot) used to keep under control the rate increase with growing luminosity. In preparation for Run-2, the pattern recognition logic used for the cascade tracking was improved, replacing a

¹ Instantaneous luminosity peak limit recorded by CMS during the 2016 run at the moment the results presented in this document were collected.

simple geometrical matching criterion with a χ^2 one. Moreover track quality cuts have been added at the end of the first two cascade steps, preventing faster algorithms to stop the reconstruction in case they build a “poor quality” candidate. The impact of these two improvements, shown for MC simulations in Fig. 3(a), indicates that the stability of efficiency versus pile-up is completely restored.

Figure 3. Efficiency of global muon reconstruction at HLT, as function of the number of reconstructed vertices, computed using $W \rightarrow \mu\nu$ simulated events (a). Tight muon identification efficiency computed with tag-and-probe using Run-1 data. Results compare the performance of the Run-1 and Run-2 CMS muon reconstruction algorithms (b).

The general HLT tracking was also improved in term CPU timing and scalability at higher pile-up. This allowed, for the first time, to deploy single muon trigger algorithms based on an approach similar to the one used for offline tracker-muon identification, improving overall efficiency and robustness.

The use of isolation at HLT was also revisited in preparation for the new run period [6]. Mild, tracker-only isolation cuts have been applied to both legs of the general-purpose double muon triggers, bringing a rate reduction of approximately a factor 2. The muon isolation logic used at the end of the LHC Run-1 by single muon triggers, based on a single cut applied on the combination of information from inner tracker and raw calorimetric energy deposits, was also updated. Better performance was achieved by clustering calorimetric deposits according to the particle-flow event reconstruction [7, 8], and applying individual cuts on the isolation (relative to the muon p_T) computed in sequence exploiting information from the electromagnetic calorimeter, the hadronic calorimeter, and the inner tracker.

Offline muon reconstruction has also undergone a set of important improvements. One example is the addition of two muon-specific iterations to the general CMS tracking. This update was aimed at curing a small, pile-up dependent, loss of tracking efficiency observed at the end of Run-1. The change consists in the deployment of an additional inside-out and an additional outside-in reconstruction sequences. The former runs tracking a second time, with relaxed cuts, on objects identified as tracker muons, with the aim of improving hit efficiency. The latter uses standalone

muons as seeds for tracking to recover inefficiencies from reconstruction algorithms solely based on the inner tracker. The impact of this update, in terms of identification efficiency for the standard Tight muon selection used in CMS [10], is presented as a function of reconstructed muon η in Fig. 3(b) [9]. Results, computed with tag-and-probe and exploiting data from the end of LHC Run-1, show an overall improvement up to $\sim 2\%$.

3.2 Performance with 13 TeV data

Results about the offline and online muon reconstruction performance with 13 TeV data are documented in [11]. Figure 4 shows muon reconstruction, identification and isolation efficiencies, computed with tag-and-probe, on the basis of the dataset collected by CMS during the 2015 run. Measurements from real data are also compared with simulation predictions.

Figure 4. Tag-and-probe muon identification and isolation efficiency for muons of $p_T > 20$ GeV/c and within $|\eta| < 2.4$ computed: as a function of reconstructed muon η for the Loose (a) and Tight (b) identification criteria; with respect to muons selected by the Tight identification and presented as a function of reconstructed p_T , for the Tight isolation working point (c).

In particular, Figs. 4(a) and 4(b) show results for the standard Loose and Tight muon identification criteria [10] computed as a function of reconstructed muon η . Loose identification includes all muons from particle-flow that are reconstructed as either tracker or global muons. The efficiency of this selection criteria is measured to be almost 100%, both in data and simulation. Additional cuts are used to define Tight muons. They are based on: (i) the number of muon station layers with segments matched to the inner-track, (ii) the number of tracker (muon system) hits used to form the muon inner-track (global-track), (iii) the χ^2 of the global-track fit and (iv) the proximity of the muon impact parameter to the reconstructed primary vertex of the hard interaction. The overall efficiency of such a selection is, in general, above 95%, with the only exception of the $0.2 < |\eta| < 0.3$ region, corresponding to the cracks between the central and wheel of the muon system barrel and the neighboring ones. Simulation is found to reproduce the behaviour observed in data with differences between 1% and 3%.

Finally Fig. 4(c) shows the efficiency of a cut on combined isolation, computed relative to muon p_T and exploiting information from the particle flow reconstruction. Results, referring to a working point tuned to have an efficiency of approximately 95% and presented as function of reconstructed muon p_T , show remarkable agreement between data and simulation.

The performance of the muon trigger, computed using method and dataset mentioned above, is presented in Fig. 5. The figure reports the efficiency of firing either of two isolated single muon triggers, built using the global-muon or the tracker-muon online reconstruction algorithms. Results are reported as function of reconstructed muon η (Fig. 5(a)) and p_T (Fig. 5(b)). Data and simulation are in overall good agreement and the efficiency is measured to be around 90% or more, in all the muon spectrometer coverage. Efficiency was also measured to be rather stable with respect to pile-up, with a variation of approximately 2% in a range between 5 and 25 offline reconstructed primary vertices.

At the moment the results presented in this document were collected, CMS was deploying lowest-unprescaled single-isolated (double) muon triggers with threshold of 24 (18-7) GeV/c, to operate at instantaneous luminosity values up to $\sim 1.5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Such p_T cuts are identical to the one used at the end of Run-1 [5] and reflect the impact of different factors: (i) the improvements in the algorithms, (ii) an updated strategy for the allocation of the bandwidth at HLT and (iii) an improvement in the offline reconstruction, capable of processing an higher rate of events stored by HLT with respect to the end of Run-1.

4 Conclusion

Significant upgrades involving muon detectors, trigger and reconstruction algorithms, have been carried out during LS1. Redundancy has been added to the system and muon tracking has been made more robust against pile-up, resulting in an overall increase of the CMS muon identification efficiency. The CMS muon trigger algorithms have been improved as well. Thresholds of the general purpose triggers were kept as the ones of Run-1 despite an increase of physics rate by a factor about four, preserving high acceptance for many signatures including muons. Overall, the CMS muon detection and reconstruction are performing remarkably, retaining their crucial role in fulfilling the experiment physics programme.

Figure 5. Tag-and-probe muon HLT efficiency for muons of computed with respect to muons reconstructed offline and passing the Tight identification and isolation criteria. Results are presented: (a) as a function of reconstructed muon η , for $p_T > 22$ GeV/c; (b) as a function function of reconstructed muon p_T within $|\eta| < 2.4$.

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