Available online at www.sciencedirect.com

ScienceDirect

Nuclear and Particle Physics Proceedings 273–275 (2016) 2509–2511

www.elsevier.com/locate/nppp

Muons in the CMS High Level Trigger System

Piet Verwilligen

For the CMS Collaboration
INFN Sezione di Bari, Via E. Orabona n. 4, 70125 Bari, Italy

Abstract

The trigger systems of LHC detectors play a fundamental role in defining the physics capabilities of the experiments. A reduction of several orders of magnitude in the rate of collected events, with respect to the proton-proton bunch crossing rate generated by the LHC, is mandatory to cope with the limits imposed by the readout and storage system. An accurate and efficient online selection mechanism is thus required to fulfill the task keeping maximal the acceptance to physics signals. The CMS experiment operates using a two-level trigger system. Firstly a Level-1 Trigger (L1T) system, implemented using custom-designed electronics, is designed to reduce the event rate to a limit compatible to the CMS Data Acquisition (DAQ) capabilities. A High Level Trigger System (HLT) follows, aimed at further reducing the rate of collected events finally stored for analysis purposes. The latter consists of a streamlined version of the CMS offline reconstruction software and operates on a computer farm. It runs algorithms optimized to make a trade-off between computational complexity, rate reduction and high selection efficiency. With the computing power available in 2012 the maximum reconstruction time at HLT was about 200 ms per event, at the nominal L1T rate of 100 kHz. An efficient selection of muons at HLT, as well as an accurate measurement of their properties, such as transverse momentum and isolation, is fundamental for the CMS physics programme. The performance of the muon HLT for single and double muon triggers achieved in Run I will be presented. Results from new developments, aimed at improving the performance of the algorithms for the harsher scenarios of collisions per event (pile-up) and luminosity expected for Run II will also be discussed.

1. The Muon High Level Trigger Algorithms

The main algorithms to reconstruct muons at the HLT consist of two steps: Level-2 (L2), where the muon is reconstructed in the muon spectrometer only, and Level-3 (L3), which is a global fit of tracker and muon hits. Separately, also Tracker Muons can be reconstructed.

The **L2 Muon reconstruction** starts with the reconstruction of the local hit positions within the different muon detectors. Hits inside the multi-layer DT and CSC chambers are combined in “track segments”. The segments are used to create an intial state (seed), used as the starting point for the Kalman filter that fits a track through the muon spectrometer. Finally the L2 candidates are filtered on the track quality and p_T^{L2}.

The **L3 Muon reconstruction** starts with reconstructing the hits inside a small volume of the tracker pointed by the L2 Muon. This is followed by the seeding step that initiates the Kalman filter. The track reconstruction needs to balance quality with speed. Therefore different seeding algorithms are used, depending on whether the seeding is Outside-In or Inside-Out and whether only tracker or muon system information is used. Three different seeding algorithms are run in a cascade: if the first (fastest) algorithm fails to reconstruct a L3 Muon, then the next algorithm is used. The L3 candidates are again filtered on quality, p_T^{L3} and a beamspot constraint before the event is accepted or rejected.

The **Tracker Muon** is used in some double muon triggers after having reconstructed a L3 Muon to reduce the trigger rate. The track reconstruction is performed in the whole tracker volume, after which matches are

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.441

sought between tracks and DT/CSC segments.

Finally a **relative isolation** requirement can be added to reduce the rate and to allow for lower p_T^{L3} threshold. The track-p_T in tracker and energy deposits in calorimeters in a cone of size $\sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} = 0.3$ around the muon are summed and corrected for pile up using the average energy density in the event (ρ).

During Run-I the **trigger menu** dedicated to muons consisted among other of single and double lepton triggers, listed in Table 1. *Mu40* was the inclusive trigger with lowest p_T threshold, while the p_T was lowered for *IsoMu24*, by including a relative isolation requirement (Iso < 0.15). There were two main double muon triggers, one made of two L3 Muons (*Mu17Mu8*), the other of one L3 Muon and one Tracker Muon (*Mu17TkMu8*). At the end of 2012 both triggers applied a **dZ-Filter** to ensure that the muons originate from the same *pp*-collision: the difference of the z-coordinates at the points of closest approach with the beamline must be < 0.2 cm.

Table 1: Lowest unprescaled Muon triggers used in 2012.

	p_T^{L3}	p_T^{Tk}	p_T^{L1}	Rate [$\mathcal{L} = 7E33$]	
Mu40	40	-	16	25 Hz	
IsoMu24	24	-	16	49 Hz	Iso
Mu17Mu8	(17,8)	-	(10,0)	11 Hz	dZ-Fltr
Mu17TkMu8	17	8	(10,0)	17 Hz	dZ-Fltr

2. Performance of Single Muon Triggers

The measurement of the trigger efficiency requires a source of pure and unbiassed muons. By selecting muons from Z-decay, requiring one muon to be tightly identified and matched to the Single Muon trigger (tag-muon), one can use the second identified muon, as an unbiassed probe to test whether the muon passed the trigger requirement. This technique is named “tag-and-probe” [2].

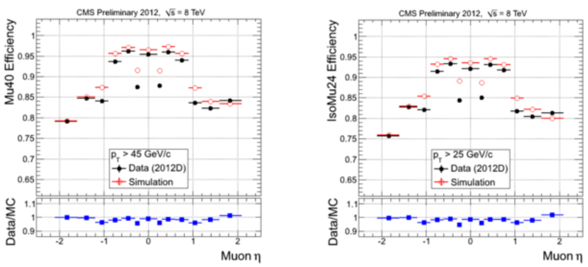

Figure 1: Efficiency of Mu40 (left) and IsoMu24 (right) at the end of 2012 as function of η for tightly identified muons. [1]. An additional 1% systematic uncertainty (not shown) has to be added.

Figure 1 shows the efficiencies of *Mu40* and *IsoMu24* at the end of Run-I: ~95% in the central region of CMS ($|\eta| < 0.9$) and 75–85% elsewhere ($0.9 < |\eta| < 2.1$). The shape is mainly due to the L1 (*SingleMu16*) trigger efficiency which is lower in the overlap and endcap region ($0.9 < |\eta| < 2.1$) and the efficiency of *IsoMu24* is slightly lower due to the isolation requirement.

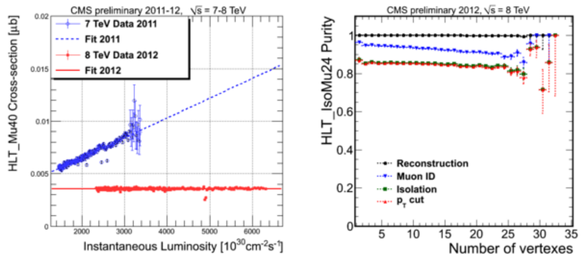

Figure 2: Left: Cross section of the Mu40 trigger in 2011 (blue) and 2012 (red). Right: Purity of the IsoMu24 trigger in 2012.

Figure 2 shows the cross section of Mu40 (left) and the purity of IsoMu24 (right). In 2011 the Mu40 trigger cross section (σ = Trigger Rate/$\mathcal{L}$) increased with higher luminosities. Tighter muon identification cuts restored a constant trigger cross section in 2012, while keeping a stable purity of ~ 85%.

3. Performance of the Double Muon Triggers

The efficiency of the double muon triggers can not be measured by a tag-and-probe method, since both muons of the Z-decay are under study. Therefore several techniques have been developed and their results agree within 1%. The method that is most precise is detailed here. Figure 3 shows the phase space for events with double muon topology. The dark-colored area is the triggerable area, while the light-colored area is inaccessible.

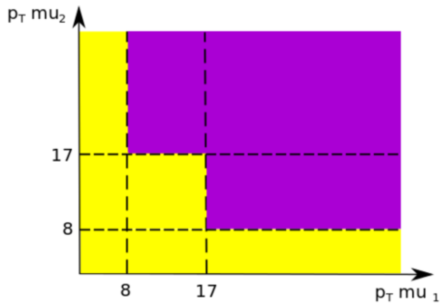

Figure 3: Phase space of double muon events. Indicated are the lower and higher thresholds of the double muon trigger used during Run-I.

The efficiency of the double muon trigger can then be calculated using the single muon leg efficiencies and the dZ-Filter efficiency as input:

$$\epsilon = \text{dZ} \cdot \Big(\text{Mu17}(\mu_1)\text{Mu8}(\mu_2) + \text{Mu17}(\mu_2)\text{Mu8}(\mu_1) - \text{Mu17}(\mu_1)\text{Mu17}(\mu_2)\Big). \quad (1)$$

The efficiencies of the Mu17 and Mu8 legs are calculated using the tag-and-probe technique. Figure 4 shows the efficiency of the Mu17 leg of the double muon trigger at the end of the datataking in 2012. The efficiency is above 90% in the barrel, and overall well described by the simulation (ratio data/simulation ∼ 1).

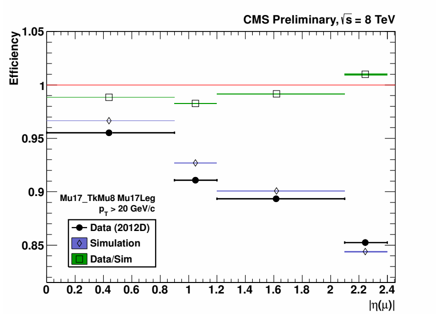

Figure 4: Efficiency of the Mu17 leg of the Mu17TkMu8 trigger at the end of the datataking in 2012, for loosely identified muons [3] with $p_T > 20\,\mathrm{GeV}/c$. Only statistical uncertainties are shown.

The efficiency of the dZ-filter is calculated from a sample of prompt muons from the Z-decay collected using prescaled Mu17 and Mu8 triggers:

$$\mathrm{dZ} = \frac{\text{Mu17Mu8 trigger fires}}{\text{Mu17leg fired \& Mu8leg fired}}. \quad (2)$$

The final efficiencies for the double muon trigger are shown in Figure 5 for the asymmetric case where one muon has $10 < p_T < 20\,\mathrm{GeV}/c$ and the other muon has $p_T > 20\,\mathrm{GeV}/c$ (top) and for the symmetric case where both muons have $p_T > 20\,\mathrm{GeV}/c$ (bottom).

The efficiency is higher than 90% for events with both muons in the barrel and is higher than 85% for events with both muons in the endcap, with the exception of the extreme case where both muons are in the forward part of the muon spectrometer ($2.1 < |\eta| < 2.4$), which is due to the low leg efficiency (see Figure 4) and the reduced performance of the dZ-filter at high η.

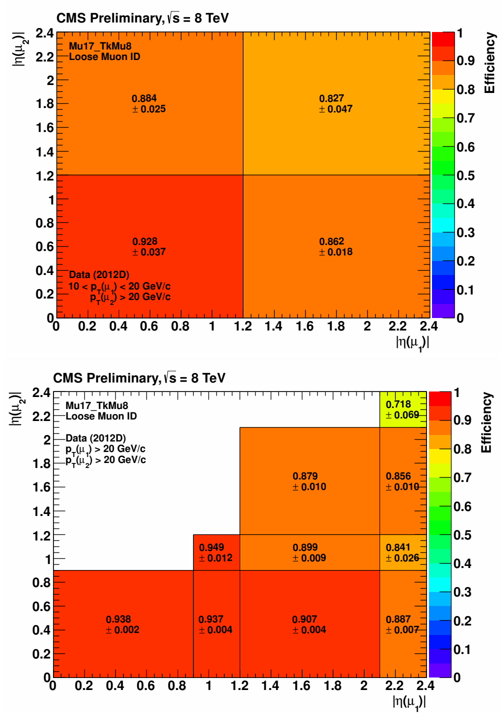

Figure 5: Efficiency of the Mu17TkMu8 trigger at the end of the datataking in 2012, for loosely identified muons [3] with $10 < p_T(\mu_1) < 20\,\mathrm{GeV}/c$ and $p_T(\mu_2) > 20\,\mathrm{GeV}/c$ (top) and for loosely identified muons with $p_T > 20\,\mathrm{GeV}/c$ (bottom). The statistical ⊕ systematic uncertainties are shown.

4. Improvements for Run-II

Several improvements in the Muon HLT algorithms have been implemented in the light of data taking at higher luminosities in 2015. In 2012 we observed an efficiency degradation of the single muon triggers at high pile-up that was traced back to low quality L3 Muons. Significant improvements in the performance arise from better track reconstruction in the tracker (pattern recognition based on χ^2 of candidate hits within trajectory instead of geometrical matching). Along with this also the cascade algorithm has been improved: the condition to switch from a faster to a slower algorithm has been changed from *the failure to reconstruct a track* to *the reconstructed track failing to pass certain quality requirements* (e.g. transverse impact parameter w.r.t. the beamspot, track fit quality). This allows to use slower, but more precise algorithms to obtain higher quality tracks, which is beneficial exactly at high pile-up when the track reconstruction is more complicated. Furthermore the double muon trigger rate will be reduced (and hence it will be possible to maintain reasonably low p_T thresholds) by requiring a loose track-based relative isolation on the muon legs. The isolation requirement reduces the contribution of background muons while keeping high efficiency for prompt isolated muons.

Acknowledgements

I would like to thank the CMS Muon Community, in particular D. Trocino, I. Mikulec, S. Goy Lopez, G. Abbiendi, H. Brun and C. Battilana for the fruitful collaboration.

References

[1] CMS Collaboration, Single Muon efficiencies in 2012 Data.
[2] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, JINST 7 (10) P10002.
[3] CMS Collaboration, Measurement of the properties of a Higgs boson in the four-lepton final state, Phys.Rev. D89 (2014) 092007. arXiv:1312.5353, doi:10.1103/PhysRevD.89.092007.