PROCEEDINGS OF SCIENCE

The CMS Level-1 muon triggers for the LHC Run II

Papavergou Ioanna
National and Kapodistrian University of Athens
E-mail: ioanna.papavergou@cern.ch

The CMS experiment implements a sophisticated two-level triggering system composed of Level-1, instrumented by custom-design hardware boards, and a software High Level Trigger. A new Level-1 trigger architecture with improved performance is now being used to maintain high physics efficiency for the more challenging luminosity conditions experienced during Run II. The CMS muon detector contains complementary and partially redundant muon detection systems: the Cathode Strip Chambers, Drift Tubes and Resistive Plate Chambers. The upgraded L1 muon trigger combines information from these three detectors to reconstruct muons and obtain a better efficiency and lower rates. Algorithms for the selection of events with muons, both for precision measurements and searches for new physics beyond the Standard Model, are described in detail. The performance of the upgraded muon trigger system will be presented, based on proton-proton collision data collected in 2017.

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1. The CMS Level-1 muon trigger upgrade

The CMS Level-1 (L1) trigger is the custom-made hardware-based first trigger stage of the CMS detector. Its main goal is to perform physics selection with maximum possible efficiency and as a result to reduce the bunch crossing rate of 40 MHz, delivered by LHC, down to 100 kHz. After 2016 the L1 muon trigger underwent major upgrades in order to cope with the increasing instantaneous luminosity (from 1×10^{34} cm^{-2} s^{-1} to 2×10^{34} cm^{-2} s^{-1} after the upgrade) of the LHC while maintaining high efficiency in event selection for physics analysis carried by the CMS collaboration. The L1 muon trigger moved from a sub-detector centered approach, where each of the three detectors provides muon candidates to the Global Muon Trigger (GMT), to a regional based approach where information from the different sub-detectors are combined within the three track finders (TF) and are then sent to the GMT (see Figure 1).

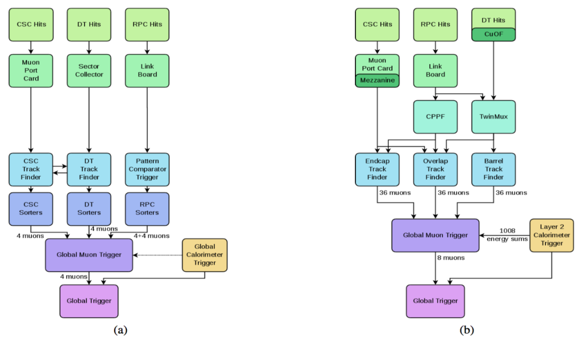

Figure 1: The legacy muon trigger (a) and the upgraded muon trigger (b). In the legacy system CSCs, DTs and RPCs hits are sent to the TF. The tracks are sorted before being sent to the GMT which also receives calorimetric information (not used in Run I). The 4 best candidates were sent to the global trigger. In the upgrade, hits from CSC are sent to the EMTF and OMTF, RPC hits are sent to the OMTF through the CPPF and to the BMTF through the TwinMux concentrator cards together with DT hits.

The three track finders are: the Barrel Muon Track Finder (BMTF) covering pseudorapidity (η) region of $0-0.8$ combining information from the drift tubes (DT) and the resistive plate chambers (RPC), the Overlap Muon Track Finder (OMTF) covering η region of $0.8-1.24$, combining information from the DTs the RPCs and the cathodic strip chambers (CSC) and the Endcap Muon Track Finder (EMTF) in the η region of $1.24-2.4$, using the CSCs and RPCs hits. The best 36 muon candidates from every regional track finder are selected and sent to the GMT, where the candidates are sorted based on p_T and quality criteria and duplicates are removed. The 8 best muon candidates are sent to the Global Trigger.
Figure 3 shows a quadrant of the CMS detector where the η coverage of the three track finders is picketed

2. The Level-1 muon trigger algorithms

2.1 The BMTF algorithm

The muon barrel architecture groups the muon detectors in 12 wedges. Each wedge has five sectors and each sector four DT stations and three RPC planes. The DT and RPC hits are sent to the

BMTF through the concentrator system TwinMux. TwinMux forms trigger superprimitives which contain information of the bending angle, the ϕ and the quality of the hit. The superprimitives are then sent to the BMTF.

There are three steps for the muon track reconstruction in the BMTF. Firstly the *extrapolator unit* receives inputs from a station and its two neighboring stations. It uses the ϕ and the quality information of the superprimitive to form a window of acceptance to the next station. If there is a superprimitive inside the window, a pair of superprimitives is formed. The next step of the BMTF trigger algorithm is the *track assembler unit* where pairs of superprimitives are sent from the extrapolator units and the track segments are combined for the track reconstruction. At the end, a quality bit is assigned to every track based on its length. The last step of the algorithm is called *assignment unit* and it uses look-up tables in order to assign p_T, η, ϕ and quality to a muon candidate's track. The tree steps of the BMTF muon track reconstruction are presented in Figure 2

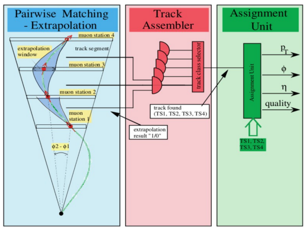

Figure 2: The three steps of the BMTF algorithm.

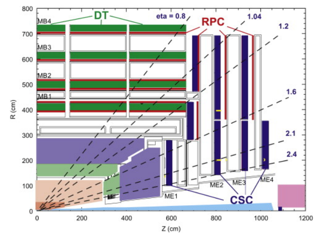

Figure 3: The CMS detector quadrant, showing the three sub -detector systems in their η coverage.

2.2 The OMTF algorithm

The OMTF algorithm uses all the available CSC and DT track segments and the RPC hits for muon recognition and p_T and sign estimation. Due to the very complicated geometry of the detector in this region the algorithm uses 53 predefined Golden Patterns (GP) for specific p_T-sign hypothesis. As a result, there are 26 p_T bins per sign hypothesis. The algorithm calculates the $\Delta\phi$ between hits in all the detector's layers and a selected reference hit and uses it in every GP to calculate the log-likelihood of a given p_T-sign hypothesis. The log$-$likelihood is calculated as sum of log-likelihoods for each layer's $\Delta\phi$. The best GP is found based on the highest number of non-zero layers log-likelihoods and on the biggest sum of the log-likelihoods. For each event, the algorithm is repeated four times for different reference hits in the same layer in order to find more than one muon in each event. Figure 5 shows a representation of a hit passing through the OMTF detector layers of RPCs and CSCs

2.3 The EMTF algorithm

The end-cap is divided into 6 trigger sectors in ϕ. The CSCs and RPCs send Local Charged Tracks (LCTs) while the concentrator pre-processor and fan-out (CPPF) card sends clustered RPC hits with coordinates to the EMTF. The first step of the EMTF algorithm is the LCT primitive conversion into hits with θ/ϕ coordinates information. Each LCT is assigned to one or two zones based on θ value where the algorithm checks for patters, matching the ϕ values of the LCT trigger primitive across the station. After the patterns based on ϕ information have been formed, only the three highest in quality patterns are kept. The quality is defined by the straightness of the formed pattern. The next step of the algorithm is the track building where the RPC hits are matched (based on the ϕ) to to the LCTs patterns in order to build the track candidates. After this step, LCTs that are too scattered in θ (not in $\Delta\theta < 0.15$ to at least one LCT in another station) are removed and duplicate tracks are discarded. Only the three highest quality tracks per sector are kept and the p_T, charge, η and ϕ are assigned to them using look-up tables. The information of the muon track candidates is then sent to the Global Muon Trigger. Figure 4 shows the consecutive steps of the muon track reconstruction in the EMTF.

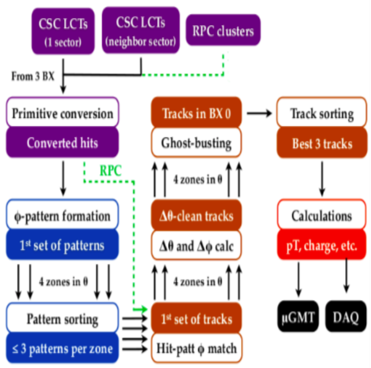

Figure 4: The EMTF algorithm cycle.

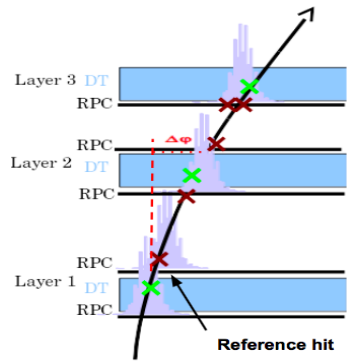

Figure 5: Hit passing through the OMTF detector layers of RPCs and CSCs. There are 8 reference layers based on high ϕ resolution, low noise and good ϕ and η coverage.

3. The Level-1 muon trigger performance with the data collected in 2017

The L1 muon trigger performance for 2017 was measured using the tag and probe method, implementing an invariant mass cut of $71 - 111$ GeV, $\Delta R_{(\mu_{reco} - \mu_{L1})} \leq 0.2$ for matching and the L1 muon track extrapolation to the vertex for muon angle correction after passing the CMS magnetic field. The efficiency plots in Figure 6 were made using the full 2017 SingleMuon data sample of 41.0 fb^{-1} integrated luminosity.

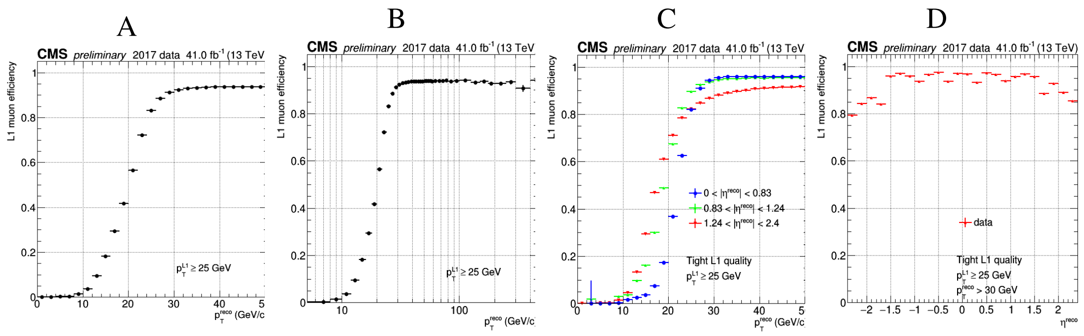

Figure 6: *A,B,C*: Efficiency vs. p_T for all muons ($-2.4 < \eta < 2.4$). The full single muon dataset from 2017 was used. *(A)*: Zoom in the region p_T<50 GeV Efficiency vs. p_T. *(B)*: Full p_T range. *(C)*: Efficiency vs. p_T for all TFs. Blue BMTF, green OMTF, red EMTF. *(D)*: Efficiency vs. η for muons passing $p_T > 25$ GeV at L1 and $p_T > 30$ GeV in the offline reconstruction.

The Global Muon trigger is able to extrapolate the muon track reconstruction to the collision vertex by using a programmable look up table that has been optimized for 2017 data taking. This upgrade resulted in improvement of the L1 muon trigger resolutions in p_T, η, ϕ and in the L1 dimuon invariant mass. For the invariant mass spectrum shown in Figure 7, part of the MuOnia sample collected in 2017 was used. The result presented in Figure 7 was used by a lot of heavy flavor physics triggers.

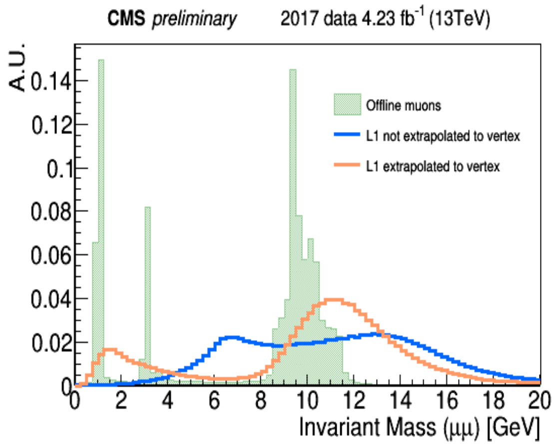

Figure 7: The M_{offl} spectrum compared to the M_{L1} spectrum with and without L1 track extrapolation to the vertex. M_{L1} appears shifted compared to M_{offl} due to p_T offsets designed to make the L1 muon trigger 90% efficient at any given p_T threshold.

4. Conclusions

The L1 muon trigger algorithms upgrades that took place after the 2016 upgrade of the CMS detector, led to very efficient data taking in 2017. The efficiency of the L1 muon trigger was measured using the tag and probe method and found to be greater than 90% for all the Muon Track Finders. The muon track extrapolation at the vertex allowed for dimuon invariant mass reconstruction at L1 stage. The results were used by heavy flavor-physics triggers applying more sophisticated offline event selection criteria (mass windows) already at the online level.

References

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[3] CMS collaboration, Level-1 muon trigger performance with the full 2017 dataset, CMS-DP-2018-008