LEVEL-1 MUON TRIGGER OF THE CMS EXPERIMENT*

Rafał Komuda

on behalf of the CMS Collaboration

University of Warsaw, Faculty of Physics, Warsaw, Poland
rafal.komuda@cern.ch

Received 24 March 2024, accepted 23 June 2024, published online 5 August 2024

The CMS detector at the LHC has implemented a two-stage trigger system in order to cope with a huge event rate given by the accelerator. In the article, the Level-1 Muon Trigger is presented, providing insights into its essential components with an emphasis on the Overlap Muon Track Finder (OMTF) reponsible for Level-1 muon reconstruction in the detector pseudorapidity region of $0.83 < |\eta| < 1.24$. The OMTF algorithm as well as its performance are discussed and a recent development is described.

DOI:10.5506/APhysPolBSupp.17.5-A31

1. Introduction

Due to the finite amount of time and storage space available, it is impossible to gather and analyse all events occurring from proton collisions at the LHC. In response, the CMS experiment [1, 2] has developed a robust triggering system adapted to challenging luminosity conditions. The CMS trigger system must swiftly identify interesting physical phenomena, such as the production of high transverse momentum particles, or signatures associated with the search for new particles. It must ensure high triggering efficiency to avoid missing any such interesting events and simultaneously effectively reject background processes.

2. Division of the muon system

The outermost part of the CMS experiment is the muon system, consisting of gaseous chambers interlaced in a magnet return yoke. It has been divided into three regions in terms of pseudorapidity: barrel — the central

* Presented at the 30$^{\text{th}}$ Cracow Epiphany Conference on *Precision Physics at High Energy Colliders*, Cracow, Poland, 8–12 January, 2024.

part of the detector, endcaps — detector covers, and the overlap — the area where detectors are positioned both vertically and horizontally (non-trivial geometry) and the magnetic field is particularly not uniform. The muon system division is shown in figure 1. Based on this division in Phase-I upgrade which took place in year the 2016, a new enhanced Level-1 Muon Trigger (L1T) system [3] was implemented in the CMS experiment, replacing the old detector-based subtriggers. It is still in use today. In particular, the Warsaw Group was responsible for the development and implementation of the trigger in the overlap region, which covers the pseudorapidity of $0.83 < |\eta| < 1.24$.

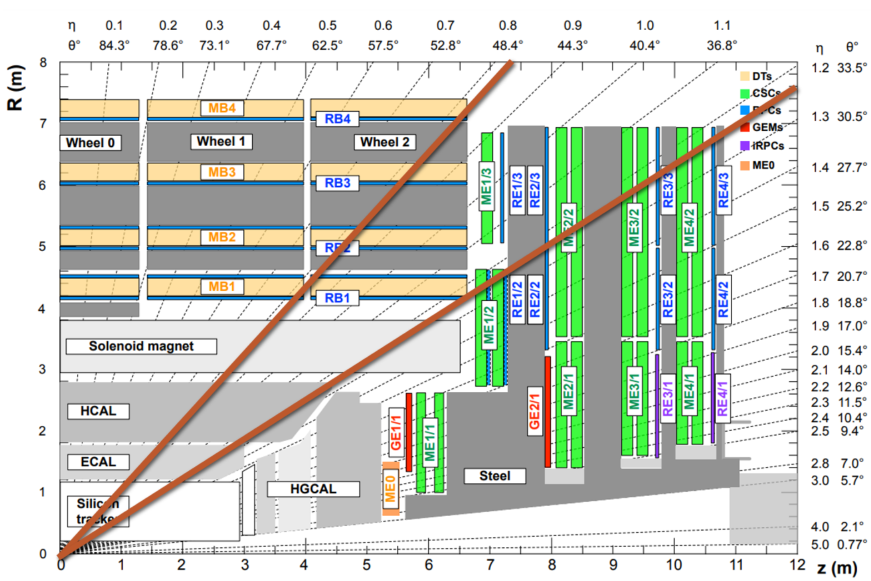

Fig. 1. (Colour on-line) One-quarter of the axial cross section of the CMS detector (longitudinal view) divided into regions (from left to right): barrel, overlap, and endcap indicated by the straight orange/grey lines [4].

3. Triggering system

3.1. Level-1 trigger

The purpose of L1T, which is the first stage of the CMS trigger, is to perform an initial event selection and reduce the data-saving frequency from 40 MHz to approximately 100 kHz. Decision-making is based solely on coarse input data. L1T operates on dedicated trigger boards, meaning all processing occurs in hardware. It has access to data from the calorimeters and muon system, but not from the tracker, and thus is divided into two parts: muon and calorimetric. This article will focus on the former.

Figure 2 illustrates the muon trigger architecture at L1T used during Run 2 (2015–2019) and Run 3 (2022–2026). Initially, data is recorded by gaseous chambers (Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers), and then splitted and preprocessed by concentrators (CPPF-Concentration PreProcessing and Fan-out, TwinMux). Subsequently, it progresses to regional MTF (Muon Track Finder) trigger boards [5]: BMTF (Barrel MTF), OMTF (Overlap MTF), EMTF (Endcap MTF) for L1T muon reconstruction. The muon data is then sorted and cleaned in the Global Level-1 Muon Trigger before reaching the Global Level-1 Trigger, where the final decision regarding abandoning or transferring an event to the HLT (High Level Trigger) is made.

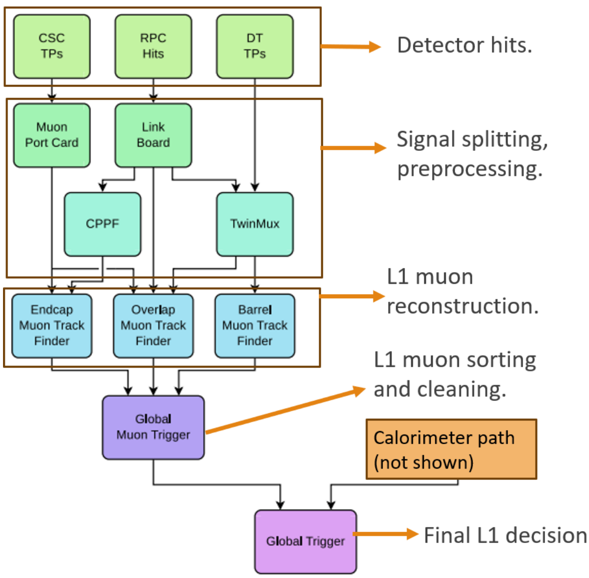

Fig. 2. Diagram of the upgraded CMS Level-1 trigger system [6].

3.2. High level trigger

The second step of CMS triggering occurs in software, as the HLT [7] is implememnted in a large computer farm equipped with CPUs and GPUs. It has access to full granularity data from the whole detector, including the tracker. A decision of whether to save an event is based on fully reconstructed events. The HLT reconstruction is similar to the one done offline but with simplified algorithms optimised for fast processing. A standard stream of the HLT reduces data saving frequency from 100 kHz to above 1 kHz. There are also two other HLT streams: parking (storing more data but the analysis is postponed) and scouting (storing more data but each event takes less storage space — only selected reconstructed information is saved).

4. Golden Pattern Algorithm

The complexity of the overlap region has pushed the Warsaw Group to develop an algorithm based on a probabilistic approach. The algorithm reconstructs muon tracks and determines their momenta by evaluating the probabilities of matching detector hits for multiple predefined transverse momentum hypotheses [8]. It can be considered as a naive Bayes classifier.

The detector is treated as a set of 18 logical layers with measurements of a certain type. Some of those layers have low noise and good resolution — they will be called reference layers. The algorithm computes the bending angle, with respect to a given reference hit, between a given layer and a reference layer.

Figure 3 provides a sketch plot illustrating how the algorithm operates. The resulting bending for all layers is compared to a set of pre-computed "Golden Patterns" (GP). Every one of them is made for a specific momentum hypothesis and they handle information about average muon track propagation and hit spread in the form of a probability density function (PDF). Thus each hit provides a single value based on probability, which describes its matching to a given layer in GP. For each GP, the logarithms of probabilities from each layer are summed, and the GP with the highest sum will be the best-fitting one, allowing for the determination of the transverse momentum of the muon.

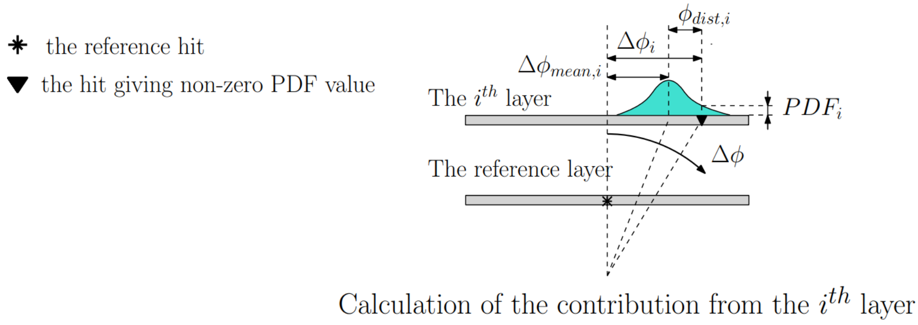

Fig. 3. The principle of operation of the OMTF algorithm. Description in the text [9].

The OMTF algorithm underwent several modifications during its runtime, partially due to changes in the quality of detectors. These modifications include: improving patterns, constraining individual layers and requirements for signal quality (particularly in DT and RPC chambers). Recently, an improvement supplementing the algorithm with the ability to reconstruct muons originating from displaced vertices has been implemented. One of the key features of the Level-1 trigger is proper timing. If the trigger fires too early or too late, it may lead to the loss of a potentially interesting event. Thus, a study was performed to understand sources of early triggering (pre-firing) in the OMTF region. This effect is marginal but can be further reduced. The study has shown that pre-firing is caused by duplication of reconstructed muon candidates in two consecutive bunch crossings caused by input signals from DT chambers. The duplicates were found to be reconstructed as of good quality, which of course contradicts the truth. According to this information, a veto for two consecutive bunch crossings has been developed: if a muon from the first bunch crossing has only DT hits and a muon from the second bunch crossing has DT hits and at least one other hit (RPC or CSC), the event gets vetoed. Emulation of OMTF response has confirmed that the veto may effectively suppress the pre-firing rate by a significant factor and has a very minor impact on OMTF trigger efficiency. Now, a modification for the trigger in the overlap region aimed at improving its response to this issue is being considered.

5. OMTF trigger performance

In the Phase-I trigger upgrade, the new system based on regional MTFs replaced old detector-based subtriggers that operated during Run 1 and until 2015. In the OMTF, an algorithm called the "Golden Pattern Algorithm" was implemented to improve the identification of the transverse momentum of muons. One of the significant features of the Level-1 Muon Trigger is its efficiency. A comparison of the efficiency of the old (legacy) and current (upgraded for Phase-I) trigger in the overlap region is shown in figure 4. The efficiencies were calculated using the tag and probe method [10].

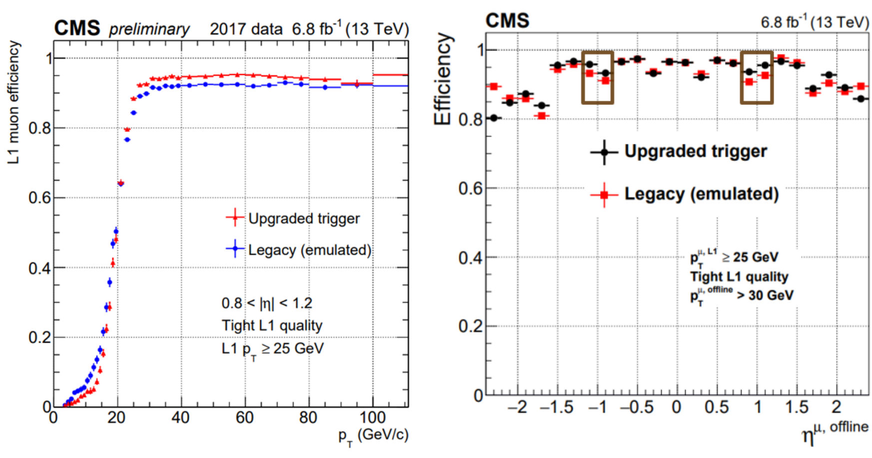

Fig. 4. (Colour on-line) Level-1 Muon Trigger efficiency in the overlap region (left) dependent on the muon transverse momentum ($p_{\rm T}$), (right) dependent on the pseudorapidity (overlap region is marked with two brown/grey boxes) [11].

As one can observe, the results on both figures are consistent and satisfactory — an increase in efficiency is observed both in terms of transverse momentum and pseudorapidity. Therefore, the OMTF trigger performs very well. For Phase-II of CMS, another upgrade of the L1T, including the OMTF, is planned [4, 12].

6. Conclusions

The Level-1 Muon trigger of the CMS experiment is one of the crucial components of the detector. Its Phase-I upgrade significantly increased the performance due to new regional triggers, including OMTF. Currently, the CMS muon trigger is stable and working efficiently. Further muon trigger upgrades are planned for Phase-II of the LHC.

This contribution is partly supported by the Ministry of Science and Higher Education (Poland) grant No. 2022/WK/14.

REFERENCES

[1] CMS Collaboration (S. Chatrchyan *et al.*), *J. Instrum.* **3**, S08004 (2008).

[2] CMS Collaboration, «Development of the CMS detector for the CERN LHC Run 3», accepted by *J. Instrum.*, 2023.

[3] CMS Collaboration (V. Khachatryan *et al.*), *J. Instrum.* **12**, P01020 (2017).

[4] CMS Collaboration, «The Phase-2 Upgrade of the CMS Level-1 Trigger», CERN-LHCC-2020-004; CMS-TDR-021, 2020.

[5] CMS Collaboration (A.M. Sirunyan *et al.*), *J. Instrum.* **16**, P07001 (2021).

[6] CMS Collaboration (A.M. Sirunyan *et al.*), *J. Instrum.* **15**, P10017 (2020).

[7] CMS Collaboration, «Commissioning of the CMS High-Level Trigger with Cosmic Rays», CMS PAPER CFT-09-020, 2010.

[8] K. Bunkowski, «The algorithm of the CMS Level-1 Overlap Muon Track Finder trigger», CMS CR-2018/073, 2018.

[9] M. Bluj *et al.*, *Acta Phys. Pol. B Proc. Suppl.* **9**, 181 (2016).

[10] A. Jales, T. Gaehtgens, «Measurement of muon efficiencies in CMS open data Tag and Probe method», 2020.

[11] CMS Collaboration, «Level-1 muon trigger performance in 2017 data and comparison with the legacy muon trigger system», CMS DP-2017/041, 2017.

[12] CMS Collaboration, «The Phase-2 Upgrade of the CMS Muon Detectors», CERN-LHCC-2017-012; CMS-TDR-016, 2017.