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Published by IOP Publishing for Sissa Medialab

Received: *November 2, 2024*
Accepted: *January 30, 2025*
Published: *March 18, 2025*

Topical Workshop on Electronics for Particle Physics
University of Glasgow, Scotland, U.K.
30 September–4 October 2024

# Triggering on muon showers

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Abstract: In view of the HL-LHC, the Phase-2 CMS upgrade will replace the entire trigger and data acquisition system. The readout electronics will be upgraded to allow a maximum L1 accept rate of 750 kHz and a latency of 12.5 µs. The muon trigger is a multilayered system designed to reconstruct and measure the momenta of the muons by correlating information across muon chambers using muon track finders. This is achieved with sophisticated pattern recognition algorithms that run on FPGA processors. The Layer-1 Barrel Muon Filter is the second layer of this system, it concentrates the stubs and hits from the barrel muon stations and runs dedicated algorithms to refine and correlate the information of multiple chambers before sending the information to the track finders. In this paper we describe the first version of an algorithm designed to detect and identify muon showers. The algorithm has been demonstrated in firmware and the physics performance is also assessed.

Keywords: Trigger algorithms; Trigger concepts and systems (hardware and software); Wire chambers (MWPC, Thin-gap chambers, drift chambers, drift tubes, proportional chambers etc)

2025 JINST 20 C03024

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https://doi.org/10.1088/1748-0221/20/03/C03024

## Contents



# 1 Introduction

Building upon Phase-1's achievements, CMS Phase-2 Upgrade introduces advanced technologies such as highly granular silicon tracking detectors, innovative timing detectors, and upgraded calorimeters with improved granularity and precision. These enable enhanced particle identification, improved resolution in momentum measurement, and increased sensitivity to rare processes and new physics phenomena.

These improvements come with an increase in the amount of data to be processed, reaching 40 TB/s. To cope with this increased rate in the muon system, CMS is developing a new filter for Phase 2 trigger that will be implemented in dedicated FPGA boards for simultaneous readout of the Drift Tube (DT) and Resistive Plate Chamber (RPC) system. Matching segments within a 25 ns window achieves 99% efficiency. It will allow cross-chamber cleaning, reconstruction of Heavy Stable Charged Particles, Particle shower identification for high momentum muon tagging and hadronic shower reconstruction, while reducing the data volume.

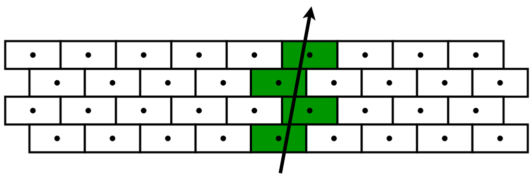
The current algorithm for track reconstruction in the Level 1 Trigger (L1T) is the "Analytical Method" (AM) [1]. The generated Phase-2 Trigger Primitives (TPs) are expected to provide a measurement of the time of the collision generating the muon with a 1 ns granularity, much finer than the 25 ns bins needed for bunch crossing (BX) identification. The muon segment parameters (position and direction) will have a resolution comparable to what is achievable using the present offline reconstruction software.

In [2], a study explored the relationship between L1T efficiency and muon transverse momentum ($p_T$ ), revealing that L1T efficiency declines for muons with higher $p_T$ . This efficiency drop is particularly concerning since high-$p_T$ muons are of special interest for analysis. As muon energy increases, so does the likelihood that these high-$p_T$ muons will radiate: at energies above 600 GeV, at least one in five muons emits radiation. This radiation causes a 10% drop in the trigger efficiency (see figure 13 of [2]).

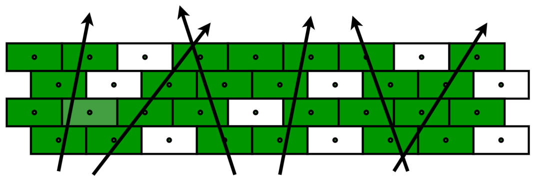
Another physics signature that can produce showers in the DTs is the presence of Long-Lived Particles (LLPs) [3], which travel significant distances from the interaction point before decaying into jets beyond the calorimeters. By using a system capable of triggering on these signatures [3], one could enhance sensitivity to several new-physics models by several orders of magnitude compared to the current trigger system. In the current trigger strategy, muon showers in the barrel are not reconstructed at trigger level and thus compromising the sensitivity of the CMS experiment.

### 1.1 Triggering in the Drift Tubes (DTs)

As explained before, the algorithm used for track reconstruction in the DTs is the “Analytical method”. Taking into account the maximum drift time of the DTs, 400 ns or 16 BXs, the algorithm stores the data during 16BXs and uses groups of 3 or 4 active cells compatible with a straight line to calculate all the possible positions and slopes of the crossing muon (figure 1(a)).



(a) Non-radiating muon crossing a DT superlayer, produces a single TP



(b) Radiating muon produces multiple activations and multiple TPs

**Figure 1.** Comparison of muon interactions in a DT superlayer.

In the case of a muon radiating, the amount of active cells in a small portion of the subdetector will be high (figure 1(b)). As the AM tries to calculate all the possible combinations, it looses time building TPs that will not correlate to a muon, producing spurious data. As the amount of particles close-by increases, the number of spurious TPs increases exponentially.

## 2 Trigger algorithm

The proposed algorithm represents the initial version of a shower identification and reconstruction algorithm. Taking into account that the hits need to be stored for 16BXs and then deleted, a representation of the active hit count in a given super layer (SL) can be shown in figure 2. First 4 events represented a muon crossing a SL producing a clean signal of 4 active cells during 16BXs before being deleted.

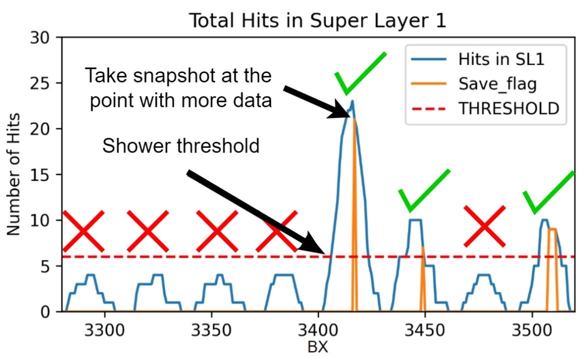



**Figure 2.** Non-radiating muon hit count remains below threshold.

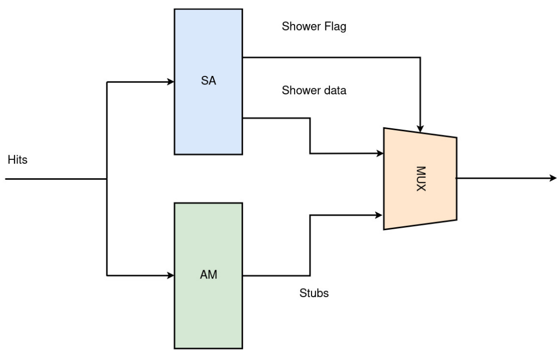



**Figure 3.** Algorithm working scheme.



2025 JINST 20 C03024

In the case of a particle shower, the amount of hits produced with respect to time will increase. This can be seen in figure 2 where the fifth event produced over 20 hits. By defining a threshold, we can tag an event as a shower if the count surpasses this threshold. Multiple thresholds and qualities can be defined to decide what to do with the AM output. This algorithm runs in parallel to the AM as shown in figure 3 and identifies showers faster than the AM, allowing the algorithm to determine whether the AM primitives should be kept or discarded and thus reducing the production of spurious data. For events with moderate hit multiplicities (i.e. below 10 hits per SL) the output of the AM might be worth keeping and sending to later stages of the trigger chain.

To restore as much information from the shower as possible, a simple peak detector waits to trigger a "snapshot" of the detector near the peak of the data, that will be used to reconstruct the main parameters of the shower event. The reconstructed information from the shower algorithm, together with the segments that could potentially be reconstructed by the AM, will then be sent to a multiplexer for disambiguation.

### 2.1 Hardware implementation

The hardware implementation was performed for the FPGA board XCVU13P, using less than 1% of the resources for both LUTs and CLB, see table 1. It uses 8 dual port Block RAMS per SL used as circular buffers to store the incoming hits. By using an array of "valid" we can keep track of the hits from the previous 16BXs. After the peak finder produces a trigger, data can be read from the 8 RAMs in parallel, increasing speed.

**Table 1.** FPGA implementation results.

| Site Type | Used | Available | Util% |
|---|---|---|---|
| CLB LUTs | 7038 | 1728000 | 0.41 |
| CLB Registers | 9995 | 3456000 | 0.29 |
| CARRY8 | 180 | 216000 | 0.08 |
| F7 Muxes | 72 | 864000 | <0.01 |

Future work will extend the current algorithm not only to identify a shower, but to assign it to a given bunch crossing and derive an approximate position of the shower.

## 3 Validation and truth definition

In order to assess the performance of the algorithm, we need to define what a "true" shower is. This definition cannot rely on the number of hits as this will introduce a bias in the performance measurements. We have simulated a DT station in Geant4, incorporating an equivalent thickness of iron to replicate real DT station conditions. This setup enables the identification of single hits produced by muons and by the electrons originated in the shower of the radiating muon. A total of 1000 events were generated, with primary muons set at an energy of 2 TeV.

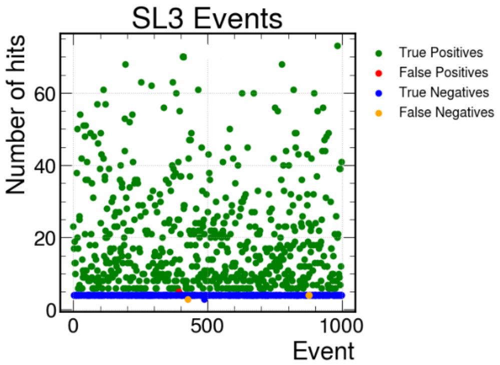
### 3.1 Algorithm results

Results from the algorithm can be seen in figure 4 and table 2. From the 1000 events generated, only 14 events at SL level were misidentified. The rate of false positives is well below 1%, meaning that the

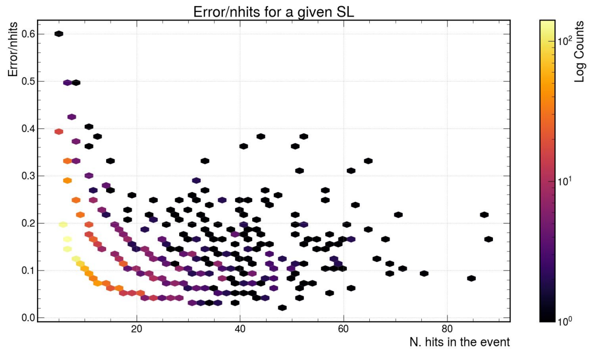


2025 JINST 20 C03024

algorithm will not interfere significantly with the AM while there isn't a shower. These false positive events occur for low hit-multiplicity (below 10 hits per SL) and in these cases, the output AM will still be kept and sent to further stages of the trigger. For the false negatives, also well below 1%, the amount of hits in the SL is low, meaning that the AM will be able to process them without compromising speed.




(a)




(b)

**Figure 4.** (4(a)) Confusion matrix as a function of the number of hits in a SL. (4(b)) Relative error on the number of recovered hits on a given SL as a function of the number of simulated hits.

**Table 2.** Algorithm identification results.

| | SL1 | SL2 | SL3 |
|---|---|---|---|
| True positives | 607 | 614 | 621 |
| False positives | 0 | 4 | 1 |
| True negatives | 390 | 379 | 375 |
| False negatives | 3 | 3 | 3 |

| | SL1 | SL2 | SL3 |
|---|---|---|---|
| Accuracy(%) | 99,7 | 99,3 | 99,6 |
| Precision(%) | 100 | 99,4 | 99,8 |
| Recall(%) | 99,5 | 99,5 | 99,5 |
| F1(%) | 99,7 | 99,5 | 99,6 |

For the reconstruction efficiency, some hits from the shower are lost due to the peak detector. An average of 88% of the hits corresponding to a shower are recovered. Figure 4(b) shows the distribution of the relative error on the number of reconstructed hits with respect to the total amount of hits in a given shower. Most of the events are reconstructed with relative errors smaller than 20% which is an acceptable range to ensure shower identification yet leaving some room for future improvements of the algorithm.

## 4 Conclusions

This work addresses the detection challenges posed by muon showers, which naturally arise in events involving high-momentum muons and can lead to significant trigger inefficiencies. These showers may also indicate the presence of long-lived particles decaying at significant distances from the primary interaction point. The current trigger systems in the barrel region, as well as the planned Phase-2 algorithms, demonstrate limited efficiency in capturing such events. To address this, we propose a novel algorithm designed to identify and capture muon showers within the barrel muon system which is capable of identifying more than 99% while 0.07% are mis-tagged. On average, the algorithm recovers 88% of the hits corresponding to a shower. This algorithm represents a promising advancement of existing algorithms and could allow the detection of new physics signatures at the HL-LHC.

2025 JINST 20 C03024

## Acknowledgments

This work and the authors are partially supported by ERC grant (INTREPID, 101115353) and the Ministerio de Ciencia e Innovación (Spain) with the project PID2020-113341RB-I00. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

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