Proceedings of CTD 2020
PROC-CTD2020-15
August 31, 2020

A muon tracking algorithm for Level 1 trigger in the CMS barrel muon chambers during HL-LHC

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ABSTRACT

The electronics of the Compact Muon Solenoid (CMS) Drift Tube (DT) chambers will need to be replaced for the High Luminosity LHC (HL-LHC) operation due to the increase of occupancy and trigger rates in the detector, which cannot be sustained by the present system. New electronics are being designed that will forward asynchronously the totality of the chamber signals to the counting room, at full resolution. The new back-end system will be in charge of building the trigger primitives of each chamber out of this asynchronous information, aiming at achieving resolutions comparable to the ones of the offline reconstruction. The new improved functionality will help to improve the resilience to potential ageing situations. An algorithm for the trigger primitive generation that will run in this new back-end system has been developed and implemented in firmware. The performance of this algorithm has been validated through different methods: from a software emulation approach to hardware implementation tests. The performance obtained is very good, with optimal timing and position resolutions, close to the ultimate performance of the DT chambers. One important validation step was including the implementation of this algorithm in a prototype chain of the HL-LHC electronics, which has been operated with real DT chambers during cosmic data taking. The new trigger primitive generation has been implemented in the so-called AB7, spare uTCA boards from the present DT system which host Xilinx Virtex 7 FPGAs. The performance of this prototyping system has been verified and will be presented in this contribution, showing the feasibility of the design for the expected functionality during HL-LHC.

PRESENTED AT

Connecting the Dots Workshop (CTD 2020)
April 20-30, 2020

1 Introduction

CMS is one of the two general purpose detectors at the LHC. It has been designed with a two-level trigger system: the Level 1 trigger (L1), implemented in custom-designed electronics, and the High Level Trigger (HLT), a streamlined version of the CMS offline reconstruction software running on a computer farm. Muon trigger and reconstruction are provided by the DT chambers in the barrel and the cathode strip chambers (CSC) in the endcap, both complemented by a system of resistive plate chambers (RPC). A more detailed description of the CMS detector can be found in [1].

The basic element of the CMS drift tube detector is the drift cell, described in [2]. Four staggered layers of parallel cells form a superlayer (SL), which allows for solving single-hit ambiguities and provides the measurement of two-dimensional segments. A chamber is composed of two superlayers measuring the r-φ coordinates (SL1, SL3), with the wires parallel to the beam line and separated by 23.5 cm, and an orthogonal superlayer measuring the r-z coordinates (SL2).

For the HL-LHC operation, also called Phase 2, the full DT electronics will be replaced with a new system and trigger primitive algorithms will be implemented in powerful FPGAs, resulting in a substantial improvement of the physics performance comparable to the current offline reconstruction system.

We present here an algorithm, called 'Analytical Method' (AM), to perform trigger primitive (TP) generation for the DT trigger system upgrade.

2 The Analytical Method. Performance evaluation

The **Analytical Method** is an algorithm for trigger primitive generation in the DT chambers in HL-LHC. It profits from the better electronics time binning in Phase 2 (1 ns instead of 12.5 ns at present). The algorithm is capable of computing a trigger primitive's crossing time, both in ns (t_0) and bunch crossing (BX) units, together with muon track position and local direction.

The algorithm has been implemented both in software as an emulator and in firmware. The inputs to this algorithm are the time and cell number of all signals detected in a superlayer and can be described in three steps: grouping, fitting and correlation.

The grouping step selects patterns of 3 or 4 fired DT cells compatible with a straight line in a single superlayer and their sub-patterns of 3 over 10 cells at a time in order to reduce combinatorics. All these patterns with their corresponding possible hit laterality (whether the signal was produced right or left of the cell wire) combinations are forwarded to the fitting step.

In the fitting step, once the group of hit cells is identified, thanks to the meantimer [5] property it is possible to compute unambigously the bunch crossing corresponding to every subset of 3 hits within the group. For cases with 4 hits the BXs of each possible triplet are combined using an arithmetic mean, giving a unique BX for the 4-cells group. For the 3-cells groups, every laterality assumption providing a physical solution is considered. Finally, track parameters are computed using exact formulas from χ^2 minimisation.

As a final step, a correlation between the fits in both φ superlayers is attempted when the fitted times agree within $\pm 25\,\text{ns}$. If a match is found, the track parameters are recalculated in order to benefit from the larger lever arm given by the distance between SL1 and SL3. If no match is found, all per-SL primitives are kept.

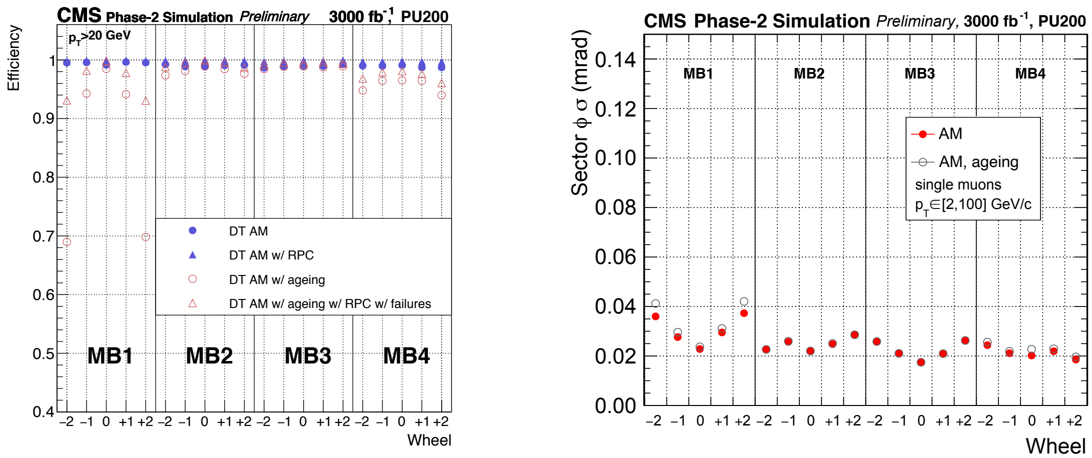
After building the AM DT primitives and clustering the RPC hits, the information from both subdetectors can be combined into a Super-primitive (SP), exploiting the redundancy and complementarity of the two subsystems and combining DT spatial resolution and RPC time resolution.

2.1 Performance evaluation in simulation

The algorithm's performance has been evaluated in a 200 average pile-up simulated sample produced for the L1 Trigger Phase 2 Upgrade TDR [3]. In this sample, two prompt back to back muons are generated, with flat φ and p_T distributions, in a range of p_T between 2 GeV and 100 GeV.

In order to compute efficiencies, the denominator is defined as all the offline segments geometrically matched with a generated muon and the numerator as the trigger primitives reconstructed in the good BX that match these segments. Figure 1 (a) shows the Barrel Muon Phase 2 trigger primitives efficiency with and without the RPC inclusion and considering the DT and RPC ageing scenarios predicted at the end of HL-LHC [3]. DT-only efficiency is in general very high except for some drops related to regions very affected by the DT ageing. The inclusion of RPC improves efficiency in these most affected regions.

Figure 1 (b) shows *sector* φ resolution (position in global coordinates) computed with respect to the simulated hits in the muon chambers. *Sector* φ resolution is < 0.05 mrad for every chamber, improving a factor ~ 6 with respect to the Phase 1 trigger primitives.



(a) (b)

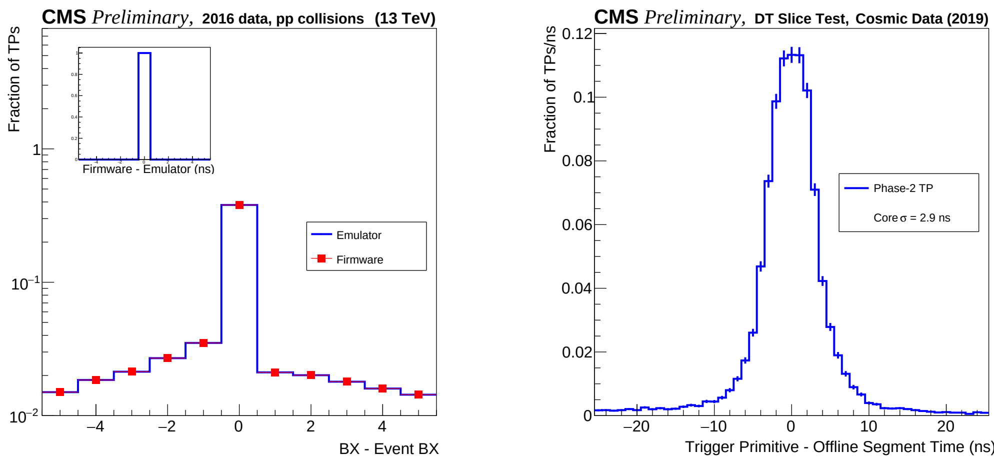
Figure 1: (a) Barrel Muon Phase 2 trigger primitives efficiency with respect to offline segments and (b) position (*sector* φ) and core resolutions with respect to the simulated hits in the muon chambers. Both figures show results with and without the ageing scenario. More details can be found in [3].

2.2 Performance evaluation in data

The AM has been implemented in VHDL code in order to estimate its performance in real time conditions inside prototyping FPGAs. This activity is critical to estimate the resources required on the final back-end electronics that needs to be designed for HL-LHC. The first implementation of this algorithm has been performed in a Virtex 7 FPGA, in particular, the XC7VX330T-3FFG1761E, where the most occupied resources are the Slice LUTs (around 30%).

Tests of firmware-emulator comparison have been performed in a dedicated test stand at CIEMAT. DT hits from 10000 reconstructed $Z \to \mu\mu$ events in the 2016 collision data sample coming from all DT chambers in the CMS detector are provided as input. Using these hits, AM firmware generates the trigger primitives, which can be then compared to the ones obtained by the software emulator. Figure 2 (a) shows the level of agreement in BX when comparing the primitives obtained by the firmware and the emulator with the same hits and lateralities. The insert shows an agreement in the fitted time value at the level of Least Significant Bit (1 ns). This agreement is also reached in fitted position and local direction.

During the Long Shutdown 2 (currently ongoing) a complete exercise was made to instrument one sector (wheel +2 sector 12) of the CMS detector with the HL-LHC DT electronics front-end and back-end prototypes. This way, both Phase 1 and Phase 2 electronics can be run in real conditions inside the CMS infrastructure. One of these back-end boards (the so-called AB7) runs the AM firmware, so it can be validated using real cosmic muons. Figure 2 (b) shows the difference between the crossing time of incoming cosmic muons computed by the DT offline reconstruction and the primitives obtained by the Analytical Method firmware. The core resolution of this distribution is of few ns, while for the Phase 1 system the trigger output time is given in BX units (25 ns step).



(a) (b)

Figure 2: (a) Difference in BX assignment between emulator primitives and event BX (blue) and firmware primitives and event BX (red) and (b) difference between the crossing time of incoming cosmic muons computed by the DT offline reconstruction and the Phase 2 AM DT local trigger in the Slice Test set-up. More details can be found in [3].

3 Conclusions

We have proposed a new algorithm for CMS DT trigger primitive generation for Phase 2. Studies in simulation show a performance comparable to the offline reconstruction system. The firmware implementation has been tested injecting DT hits from collision data, showing a good level of agreement with the software emulation. A sustained campaign of cosmics-muon data taking in one CMS sector has already shown the large improvement in time resolution that can be achieved for Phase 2 trigger primitives with respect to the present system.

ACKNOWLEDGEMENTS

The Spanish Ministry of Science and Innovation supported this research via FPA2017-84260-C3-3-R, FPA2017-84260-C3-2-R, FPA2017-84260-C3-1-R and FPA2017-84502-R

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