Development and validation of the Overlap Muon Track Finder for the CMS experiment

J. Dobosz[a], P. Miętki[a,b], K. Zawistowski[a], and G. Żarnecki[a]

[a]University of Warsaw, Faculty of Physics, Pasteura 5, 02-093 Warsaw, Poland
[b]Gdansk University of Technology, Faculty of Applied Physics and Mathematics, Narutowicza 11/12, 80-233 Gdansk, Poland

ABSTRACT

Present article is a description of the authors contribution in upgrade and analysis of performance of the Level-1 Muon Trigger of the CMS experiment. The authors are students of University of Warsaw and Gdansk University of Technology. They are collaborating with the CMS Warsaw Group. This article summarise students' work presented during the Students session during the Workshop XXXVIII-th IEEE-SPIE Joint Symposium Wilga 2016.

In the first section the CMS experiment is briefly described and the importance of the trigger system is explained. There is also shown basic difference between old muon trigger strategy and the upgraded one.

The second section is devoted to Overlap Muon Track Finder (OMTF). This is one of the crucial components of the Level-1 Muon Trigger. The algorithm of OMTF is described.

In the third section there is discussed one of the event selection aspects - cut on the muon transverse momentum p_T. Sometimes physical muon with p_T bigger than a certain threshold is unnecessarily cut and physical muon with lower p_T survives. To improve p_T selection modified algorithm was proposed and its performance was studied.

One of the features of the OMTF is that one physical muon often results in several muon candidates. The Ghost-Buster algorithm is designed to eliminate surplus candidates. In the fourth section this algorithm and its performance on different data samples are discussed.

In the fifth section Local Data Acquisition System (Local DAQ) is briefly described. It supports initial system commissioning. The test done with OMTF Local DAQ are described.

In the sixth section there is described development of web application used for the control and monitoring of CMS electronics. The application provides access to graphical user interface for manual control and the connection to the CMS hierarchical Run Control.

Keywords: Muon Trigger, OMTF

1. COMPACT MUON SOLENOID AND EVENT SELECTION

Compact Muon Solenoid (CMS)[1] is an experiment at the Large Hadron Collider (LHC) at European Organisation for Nuclear Research (CERN). During the Run-I of the LHC (taking data from 2009 to 2013) the CMS and ATLAS collaborations discovered Higgs boson (that was officially announced in July 2012). Because of the very high rate of proton-proton collisions inside the CMS detector and limited ability of gathering data it is necessary to use trigger system which automatically selects part of the events for further analysis. Selection is done in two steps - in the Level-1 Trigger and the High Level Trigger. One of the crucial components of the Level-1 Trigger is the Level-1 Muon Trigger - its development is currently one of the main tasks of the CMS Warsaw Group. Good muon trigger is expected to reconstruct muon tracks efficiently and select events which are interesting for current studies.

There are three types of muon chambers in the CMS detector: Drift Tubes (DTs), Cathode Strip Chambers (CSCs) and Resistive Plate Chambers (RPCs). In the old muon trigger there were three parallel systems providing muon candidates. Each system was using data from different type of muon chambers. The Level-1 Muon Trigger is being upgraded for the LHC Run-II (taking data since 2015) and the new strategy is introduced. It is based on track finders working in different geometrical regions of the CMS detector: the Barrel, the Endcap and the Overlap. In upgraded trigger system track finders should combine signals from all available types of chambers.

2. THE MUON SELECTION IN THE DETECTOR OVERLAP REGION

The algorithm of the Overlap Muon Track Finder (OMTF) was designed to reconstruct muon tracks in the Overlap region at the Level-1 Muon Trigger. The algorithm is based on comparing measured hits with precomputed track patterns, so-called Golden Patterns (GPs). Each GP corresponds to the muon track with a certain charge (i.e. μ^+, μ^-) and transverse momentum. GP comprises information about track's average azimuthal angle bending $\Delta\phi_{mean}$ between reference layer and every other layer caused by CMS magnetic field. There are also included Probability Density Function (PDF) values of possible deviations from $\Delta\phi_{mean}$ values (due to stochastic effects: multiple scattering and energy losses).

Constant set of 8 reference layers is foreordained. In the beginning of the algorithm, up to 4 reference hits in reference layers are chosen (among all physical hits in the event) to make finding multiple muon candidates possible. Then for every signal from the event there is calculated the azimuthal angle difference $\Delta\phi_i$ between certain reference hit and each hit laying in acceptable logic region. In order to compare this with certain Golden Pattern algorithm calculates difference between average azimuthal angle track bending for given GP and actual track bending ($\phi_{dist} = \Delta\phi_{mean} - \Delta\phi_i$)for every hit. For each layer hit with the smallest ϕ_{dist} value is chosen and corresponding PDF value is taken. If the PDF value is bigger than 0, the processed layer is counted as an *active layer*. Subsequently the PDF values from all layers are added up. In the end for each reference hit there is chosen one Golden Pattern fitted best to event hits. The basic criterion for that choice is the number of *active layers* corresponding to each GP - the pattern with more *active layers* is favoured. If that number is the same for a few GPs then the pattern with the biggest sum of PDF values is selected. As this procedure is followed for up to 4 reference hits, on the output there are up to 4 candidates in the Overlap region per one event.

Described algorithm was developed on the grounds of Monte Carlo simulations and is implemented in dedicated electronics as a FPGA firmware.[2]

3. OPTIMISATION OF EVENT SELECTION

In the CMS experiment there are many proton-proton beams collisions which produce lots of detected events data. Since there is a huge rate (40MHz) of bunch crossings, it is impossible to save and analyse all of the data. The event selection is an essential stage in the OMTF and it is being done by a trigger. The reduction of rate is achieved by rejecting these events that are unattractive in experiment. So the trigger has to reconstruct muon tracks in each event to make a so-called cut. The cut consists in rejecting muons with transverse momentum lower than a specified threshold value and accept that events with a bigger one.

In the Fig. 1 there is a plot of efficiency of trigger for a momentum cut set on 16 GeV/c vs transverse momentum of muons. The efficiency is defined as a ratio of number of accepted muons to number of all muons. The ideal efficiency curve should look like a step function changing the efficiency value from 0 to 1 in the threshold value point.

There were performed tests of optimisation of event selection. In this study were used data samples with simulated single muon events The current event selection algorithm is based on quality and PDF value. The improved one takes into consideration diversity of efficiency of each reference layer and adds different relevance to PDF sub-values that depends on detector type. The RPC detectors was devalued because of their poor spatial resolution, the weight for DT detectors was increased due to their excellent spatial resolution. For CSC detectors there were no changes. In the Fig. 1 there is plot of these two options of muon selection in OMTF - actual and improved. They are compared with the best possible efficiency for that case that is known because it is plotted on simulated Monte Carlo data.

The selection in the range below the momentum cut is essential because it improves the purity of the trigger. It is important since low-energetic muons increase a difficulty of data analysis. In the Fig. 2 there is a plot of ratio of previous efficiencies that shows some improvement in range of low transverse momentum.

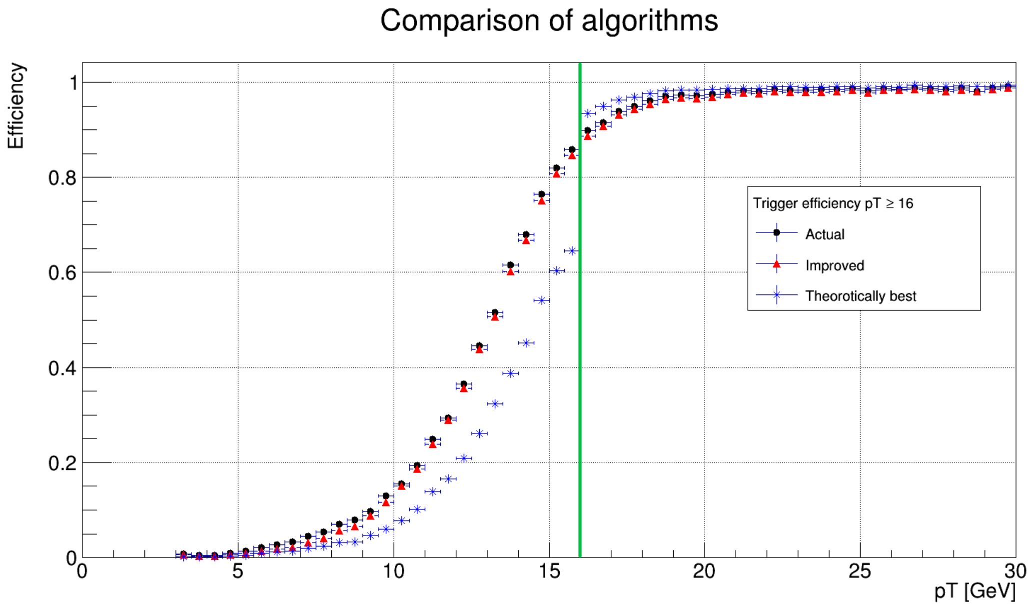

Figure 1. Efficiency of different algorithms of events selection vs muon transverse momentum

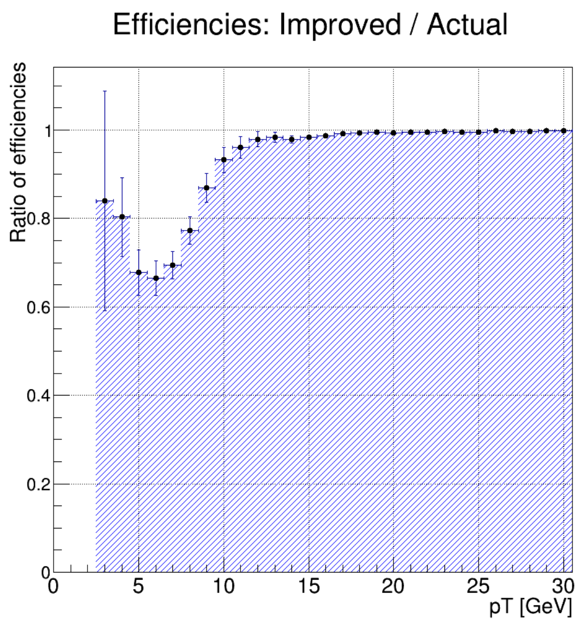

Figure 2. Ratio of improved efficiency and actual efficiency. Muons with momentum in the range from 3 to 12 GeV are rejected in a better way.

4. TEST OF GHOST BUSTER ALGORITHM

During the step of muon track reconstruction it is common that one physical muon causes a few muon candidates with similar track parameters. The additional candidates are often called *ghosts*. The step of eliminating *ghosts* is called Ghost-Buster. Ghost-Buster takes the input set of muon candidates and produces the output set of selected candidates. The algorithm of Ghost-Buster is based on comparing azimuthal angle of muon candidates. Sometimes two or more physical muons appear in Overlap region per one event. Well working Ghost-Buster is expected to select the same number of muon candidates as the number of physical muons. For the present article performance of Ghost-Buster emulator was studied.

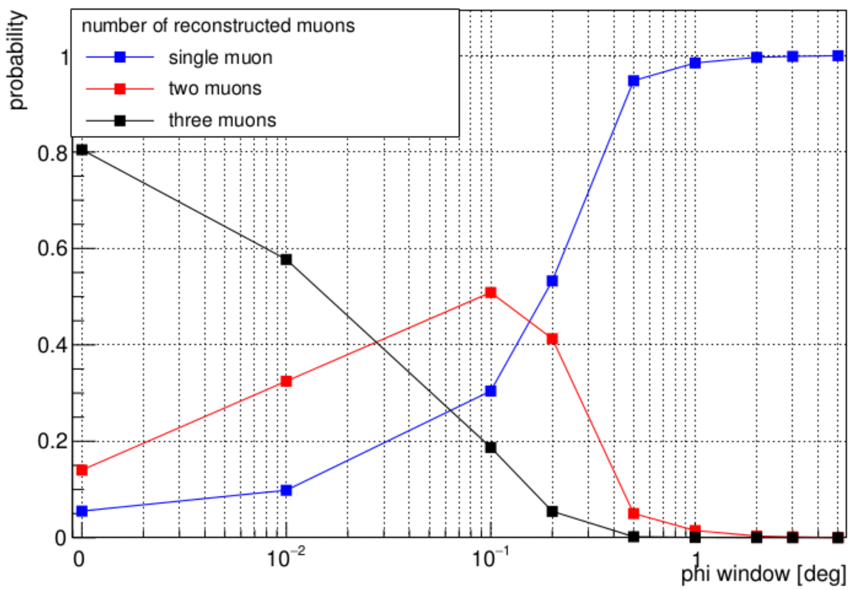

Figure 3. Results obtained for sample with single muon events. Probability of multiple muon reconstruction on the output of Ghost-Buster vs ϕ *window* width. Points on the left edge of plot refer to *window* width set to 0°.

In the beginning the input set of candidates is taken and they are sorted by quality. Then all candidates are checked in a loop whether their azimuthal angle is close to the azimuthal angle of candidates which are already in the output set (that is performed in a nested loop). If the angle difference is smaller than veto *window* (set to 5°) then the candidate from the input set is recognised as a *ghost* and is not passed to the output set. Consequently input candidate with the best quality is always forwarded to the output set.

Chance for finding and eliminating *ghosts* successfully depends significantly on the width of the veto *window*. To study this dependency data samples with simulated single muon events were used. In the Fig. 3 there is a plot of probability of getting certain number of candidates at the Ghost-Buster output set with respect to veto *window* width. This plot was done for events with both generated muons propagating into the whole Overlap region, that is with pseudorapidity $0.83 < \eta < 1.24$. For the very small values of veto *window* width Ghost-Buster's performance is degenerated - in most cases single physical muon will be reconstructed as multiple candidates. For 0.5° and 1° Ghost-Buster is clearly much more effective and for 5° probability of receiving single candidate on the output set is bigger than 99.9%.

Good *ghosts* selection has however its price. For high transverse momenta Ghost-Buster decreases efficiency of the $\mu^+\mu^-$ pairs reconstruction. This effect was studied on data samples with simulated single $J/\Psi \rightarrow \mu^+\mu^-$ decay events. In the Fig. 4 there is a plot of efficiency of the $\mu^+\mu^-$ pairs reconstruction vs J/ψ generated transverse momentum. This plot was done for events with both generated muons propagating into the middle Overlap region, that is with pseudorapidity $0.9 < \eta < 1.15$. For J/ψ transverse momentum bigger than 40 GeV/c efficiency drops from $(92.4 \pm 0.5)\%$ (when cut on azimuthal angle is disabled) to $(86.2 \pm 0.6)\%$ (when 5° cut is used). This is a consequence of fact that for high J/ψ momenta the decay resulting in muons propagating into narrow ϕ *window* is more probable.

5. SYSTEM TESTS WITH LOCAL DATA

For further (offline) event reconstruction and data analysis CMS is equipped with Data Acquisition System (DAQ), which saves events selected by trigger. Regardless of it, OMTF introduced ability to read data directly from memory buffers. This readout set was called Local Data Acquisition System (Local DAQ) and it is a kind of *spy module*, which means it allows to snapshot some raw data collected by OMTF for further prompt feedback analyses.

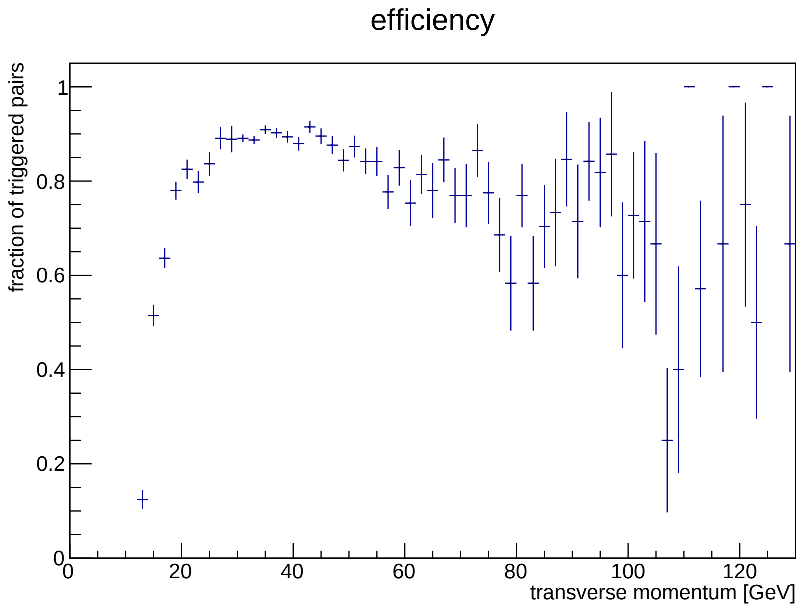

Figure 4. Efficiency of reconstructing two muon candidates vs J/ψ transverse momentum.

Local DAQ returns 3 steps of data acquisition and analysis - raw hits collected by detectors (AlgoHits), data after selection by hardware-built-in algorithm (AlgoMuons) and data after ghost-busting (CandMuons). There is too much data being processed by hardware at one point of time, so Local DAQ reads it with limited bandwidth.

Data collected from Local DAQ can be analysed to check the angular distribution of hits from all types of detector and out-coming muons. It is expected to be roughly uniform, with some fluctuations in the chamber overlapping region due to chamber acceptance. If expectations are met, it indicates that detectors work properly and give CMS statistically correct data.

Other important things to check are the correlations of hits between chambers. Due to the geometry of OMTF, some chambers are placed directly next to others (RPC and DT in barrel region or RPC and CSC in endcap region). This allows to quickly check whether detectors work properly by data correlation analysis. If AlgoMuons data is included, hardware algorithm work may be checked either.

The next step in local data analysis is to compare results of hardware-built-in algorithm with outcome of emulation of algorithm work. To do this the events from simulation (test pulses) are injected into electronics, processed and read-out. The results must exactly match the expectations.

The Local DAQ and simplified analysis performed with collected data played a key role in initial commissioning of OMTF. The readout of memory buffers will be further used for online OMTF monitoring.

6. SYSTEM CONTROL AND MONITORING

A dedicated web application is used for the monitoring and control of CMS electronics. As the new Level-1 Trigger uses standardised electronics designs and standard communication protocol, significant effort has been made to provide shared implementation of low level functionalities that are common across different Level-1 subsystems. This gave rise to SWATCH, a specialised web container for upgraded Level-1 Trigger control application, and MicroHAL, a high-level hardware control library. The structure of the OMTF Control Software is defined by the usage of these components, as it comprises two basic modules: OMTF System, a SWATCH-based web application, and OMTF Hardware Control.

OMTF System was built upon SWATCH-based abstractions of the system, the state of the system, operations executed on the hardware, and large scale hardware components. It provides access to many features granted by SWATCH framework, such as graphical user interface for diagnostics, monitoring and manual control, the connection to the CMS hierarchical Run Control allowing the subsystem to be operated automatically with the rest of Level-1 trigger and standardised configuration using relational database provided by ORACLE.

OMTF Hardware Control contains implementations of various hardware routines required to operate the system. It makes use of detailed tree-like firmware description provided by MicroHAL library and wraps it in it's own object oriented description, to provide compile-time validation, integration with the code analysis engine provided by the integrated development environment and additional order and convenience. The object reflection is split into two parts: blueprint base classes, generated automatically from the firmware description used by MicroHAL, and the subclasses containing needed implementations.

Both aforementioned components are written in C++ and compiled to dynamical shared libraries with use of the standardised Make scripts used normally by the majority of CMS online processing software.

As the OMTF hardware makes use of firmware blocks and hardware designs developed for other Level-1 subsystems, the components of supplied software were integrated into OMTF software when possible.

ACKNOWLEDGMENTS

Work supported by National Science Centre, Poland, grant 2013/11/B/ST2/04202.

REFERENCES

[1] Chatrchyan, S. et al., "The CMS experiment at the CERN LHC," *JINST* **3**, S08004 (2008).

[2] Zabołotny, W. M. et al., "FPGA Implementation of Overlap MTF Trigger – preliminary study," *Proc. SPIE Int. Soc. Opt. Eng.* **9290**, 929025 (2014).