Available on CMS information server **CMS CR -2016/419**

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

24 November 2016 (v2, 05 December 2016)

Design and Performance of the Phase I Upgrade of the CMS Global Trigger

Johannes Wittmann, Gregor Aradi, Bernhard Arnold, Herbert Bergauer, Manfred Jeitler, Takashi Matsushita and Claudia-Elisabeth Wulz for the CMS Collaboration

Abstract

The Global Trigger is the final decision stage of the Level-1 Trigger of the CMS Experiment at the LHC. Previously implemented in VME, it has been redesigned and completely rebuilt in microTCA technology, using the Virtex-7 FPGA chip family. This allows implementing trigger algorithms close to the final analysis selection, combining different physical objects. The flexible and compact new system is presented, together with performance tests at a proton-proton centre-of-mass energy of 13 TeV. Firmware and software developments for the operation and validation of the Global Trigger will also be discussed.

Presented at *TWEPP-16 Topical Workshop on Electronics for Particle Physics*

Preprint typeset in JINST style - HYPER VERSION

Design and Performance of the Phase I Upgrade of the CMS Global Trigger

J. Wittmann[a*], G. Aradi[a], B. Arnold[a], H. Bergauer[a], M. Jeitler[a], T. Matsushita[a] and C.-E. Wulz[a] for the CMS Collaboration

[a]*HEPHY Vienna - Institute of High Energy Physics of the Austrian Academy of Sciences, Nikolsdorfer Gasse 18, A-1050 Vienna, Austria*
E-mail: johannes.wittmann@oeaw.ac.at

ABSTRACT: The Global Trigger is the final decision stage of the Level-1 Trigger of the CMS Experiment at the LHC. Previously implemented in VME, it has been redesigned and completely rebuilt in MicroTCA technology, using the Virtex-7 FPGA chip family. This allows implementing trigger algorithms close to the final analysis selection, combining different physical objects. The flexible and compact new system is presented, together with performance tests at a proton-proton centre-of-mass energy of 13 TeV. Firmware and software developments for the operation and validation of the Global Trigger will also be discussed.

KEYWORDS: Trigger concepts and systems (hardware and software); Modular electronics; Trigger algorithms.

*Corresponding author.

Contents

1. Introduction

The Global Trigger is the final decision stage of the Level-1 Trigger of the CMS Experiment at the LHC. Previously implemented in VME, it has been redesigned and completely rebuilt in MicroTCA technology, using the Virtex-7 FPGA chip family. This allows implementing trigger algorithms close to the final analysis selection, combining different physical objects received from the calorimeters and muon detectors. Electrons or photons, muons, jets, taus, as well as energy sums can be combined. Topological conditions (angular correlations between objects) can be applied. It is also possible to trigger on the invariant or transverse mass calculated for pairs of objects. The number and complexity of the algorithms making up the trigger menu are substantially increased compared to the VME-based “legacy" design used in Run I of the LHC. The new system is based on a single principal type of board, the MP7 module, which performs the logic calculations. It was developed for the CMS calorimeter trigger by Imperial College, London, the University of Bristol and Rutherford Appleton Laboratory. Auxiliary boards developed at HEPHY Vienna are used to receive external signals from subdetectors other than the calorimeters and the muon systems and to manage the simultaneous operation of several MP7 boards running in parallel to enable using a large number of complex algorithms. Performance evaluations undertaken in parallel operation with the legacy system during the initial months of Run II of the LHC and during data taking in 2016 at a proton-proton centre-of-mass energy of 13 TeV are presented. Firmware and software developments necessary for the setup, control, monitoring and validation of the Global Trigger are also discussed.

2. CMS Level-1 Trigger

The upgrade performed during the first long shutdown (LS1) of the LHC accelerator to increase its energy and luminosity required also adaptations and upgrades of the CMS Level-1 Trigger and its subsystems to take full advantage of the higher collision rates. Especially the high luminosity

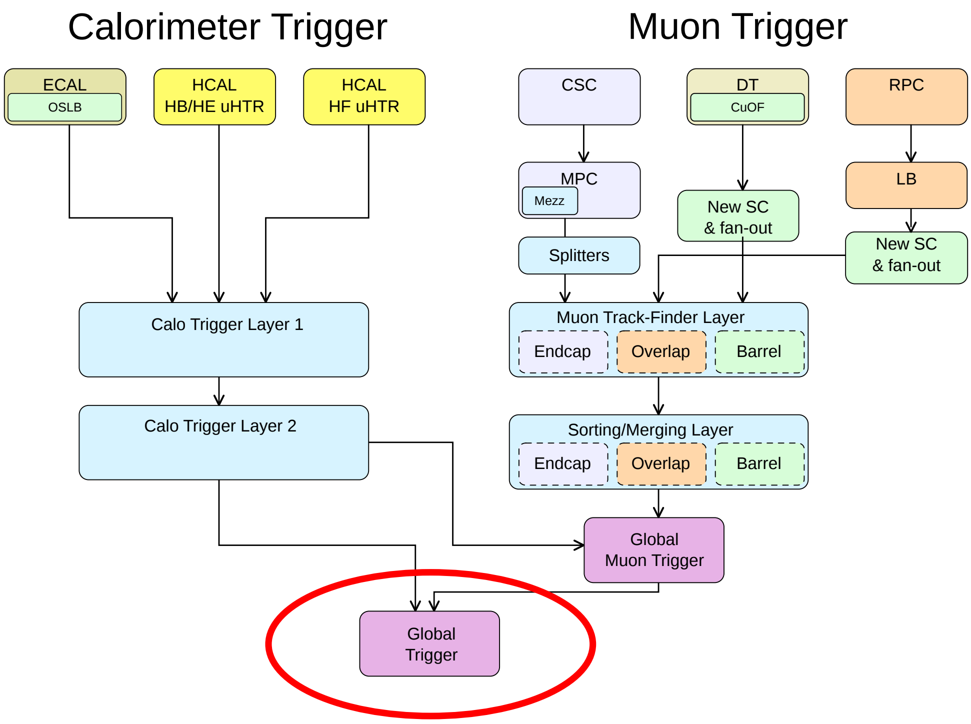

Figure 1. The upgraded Level-1 Trigger.

which leads to a higher pile-up of events in the CMS detector is a challenge for the Level-1 Trigger. The goal of this upgrade was to improve the resolution and, as a consequence, allow for efficient data taking at higher collision rates while keeping the Level-1 Trigger rate at a manageable level of up to 100 kHz. The upgraded system took over the full trigger functionality at the beginning of 2016. The architecture of the Level-1 Trigger systems is shown in Figure 1. It shows the calorimeter trigger systems and the muon trigger path. The Global Trigger is at the end of the path and combines the information provided by both branches [1].

3. The CMS Global Trigger

The upgraded Global Trigger system is designed to deal with the conditions of Run II of the LHC explained in Section 2. It considers the inputs of the muon and the calorimeter systems which are provided via fast optical fibres. In addition, there are also data from other sources (the LHC beam detector “BPTX", the special “CASTOR” calorimeter and others) that can be used in the Global Trigger. These so-called “External Conditions" are received via electrical connections and merged with the muon and calorimeter data to use them in the trigger algorithms. Over 500 trigger algorithms can be calculated in parallel, thus allowing physicists to use optimized triggers for each expected physics signal and scenario. The Global Trigger system builds upon the modern MicroTCA standard and powerful Virtex-7 Field Programmable Gate Arrays (FPGAs) from Xilinx company. The main processing unit, the MP7 module is also used in several other subsystems of the Level-1 Trigger [2]. Auxiliary boards developed at HEPHY Vienna are used to receive External

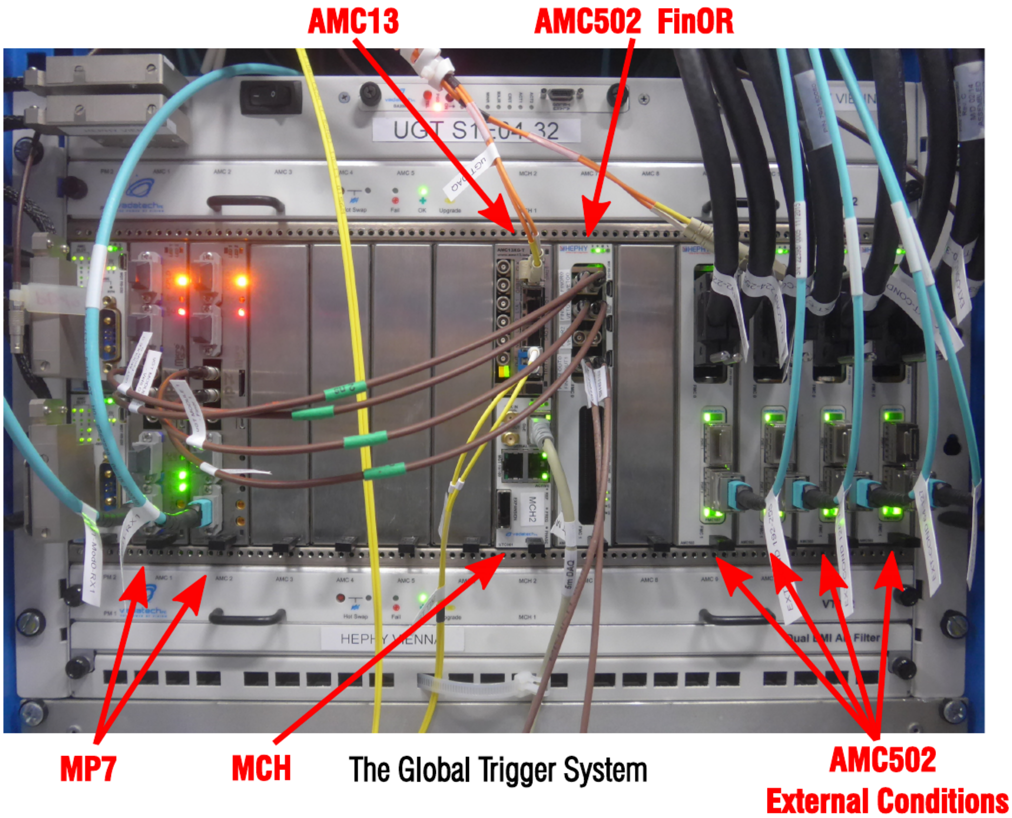

Figure 2. The Global Trigger uTCA Crate at the CMS Experiment during 2016 data taking.

Conditions and to merge the trigger requests from several MP7 boards running in parallel.

The Global Trigger system used during physics data taking in 2016 is shown in Figure 2. The MicroTCA crate from Vadatech company is equipped with two MP7 boards containing the centrepiece of the Global Trigger - the trigger algorithms. These algorithms are compiled in a so-called “trigger menu”. During the 2016 data taking the physics algorithms implemented in the trigger menu exceeded the chip resources of one MP7 module. Therefore, trigger algorithms were distributed over two boards - doubling the capabilities of the Global Trigger system. To collect the trigger decisions of several MP7s and to calculate a final trigger signal (FinOR) for the CMS experiment, an auxiliary AMC502 board designed by HEPHY Vienna and built by Vadatech company is used. This type of board is also used to convert and forward the External Condition data received from other detector sources. Four of these modules are used to receive up to 256 different External Condition signals. The AMC13 board built by Boston University is responsible for distributing the timing information and sending data to the Data Acquisition System (DAQ). The MCH module from Vadatech company manages the MicroTCA crate functions and the communication between the modules [3].

Fast optical fibres operating at a rate of 10 Gbps are used to transmit the data within and from the muon and the calorimeter trigger systems. Optical patch panels allow for uppermost flexibility

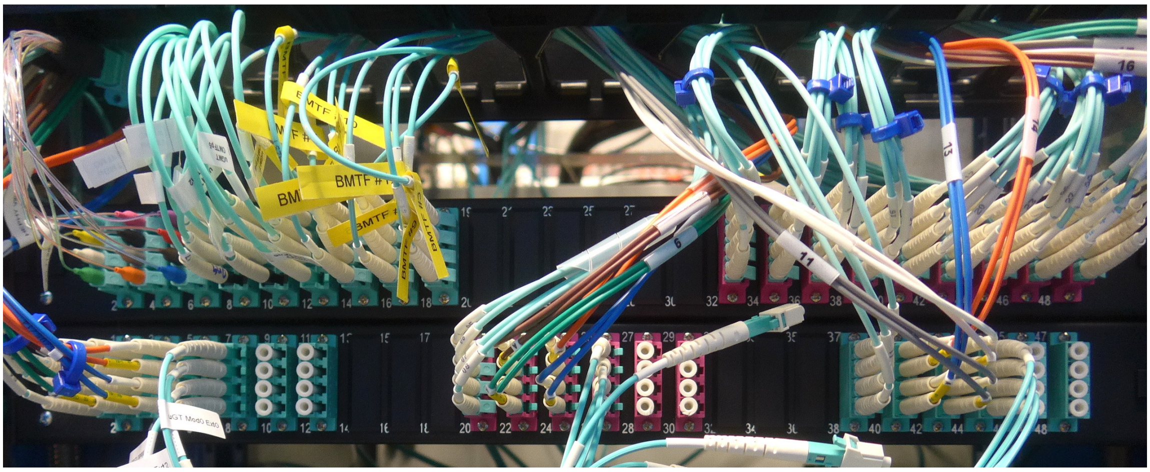

Figure 3. Optical patch panels guarantee the connections between the different subsystems.

in these interconnections. The patch panels used at the Global Trigger and Global Muon Trigger (GMT) system is shown in Figure 3. The top module is used to connect the muon track finders to the GMT. The lower patch panel merges data from the GMT and the calorimeter trigger together with the converted External Conditions to the Global Trigger. Each block of 16 fibres represents the inputs for one MP7 board. The structure of the patch panels allows engineers to quickly add or change optical fibre connections.

4. Run 2016

CMS recorded more than 37 fb^{-1} during p-p collisions at 13 TeV centre-of-mass energy in 2016 using the upgraded Level-1 Trigger system as shown in Figure 4. The peak luminosity in 2016 delivered to CMS during stable beams for p-p collisions was above $1.5 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$, as shown in Figure 5. The increasing luminosity is a challenge for the Level-1 Trigger system and the whole of CMS. Without the introduction of sophisticated new algorithms, in order to stay below the Level-1 Trigger rate limit of 100 kHz acceptable to CMS trigger thresholds would have to be raised to a level that would result in serious loss of physics data. Section 5 shows up some ideas on how new types of algorithms in the Global Trigger could contain trigger rates while maintaining a high level of efficiency.

The first Level-1 Trigger menu which was used at the beginning of 2016 p-p physics data taking was composed of 201 trigger algorithms, roughly 50 % more than the legacy Run I Global Trigger was able to use: the system which was operating until the end of 2015 was limited to 128 algorithms. The number of algorithms used increased to 267 at the end of the p-p collisions run, i.e. to more than twice the number possible in the legacy system. This shows that one important feature of the upgrade trigger system, the increase in the maximum number of physics algorithms, was badly needed. Table 1 shows an overview of the main Level-1 Trigger menus used for p-p data taking in 2016 and a breakdown of the different trigger groups.

Object type / menu version	v1	v2	v3	v4	v5	v6	v7	v8	v9	v10
Muon algorithm triggers	32	33	33	33	33	34	34	34	34	34
E/gamma algorithm triggers	37	37	37	37	43	44	44	44	44	44
Jet algorithm triggers	25	25	25	25	25	25	25	25	25	28
Tau algorithm triggers	10	10	10	10	10	11	11	12	12	12
Energy Sums algorithm triggers	29	29	28	28	28	31	31	34	34	34
Cross algorithm triggers	52	54	67	69	69	72	76	76	82	82
Correlation algorithm triggers	2	2	8	8	13	12	12	12	12	12
Invariant-mass triggers	0	0	0	0	0	0	0	4	4	4
External Condition triggers	14	37	31	31	31	31	16	16	17	17
Total number of algorithms	201	227	239	241	252	260	249	257	264	267

Table 1. List of the main p-p trigger menus in 2016.

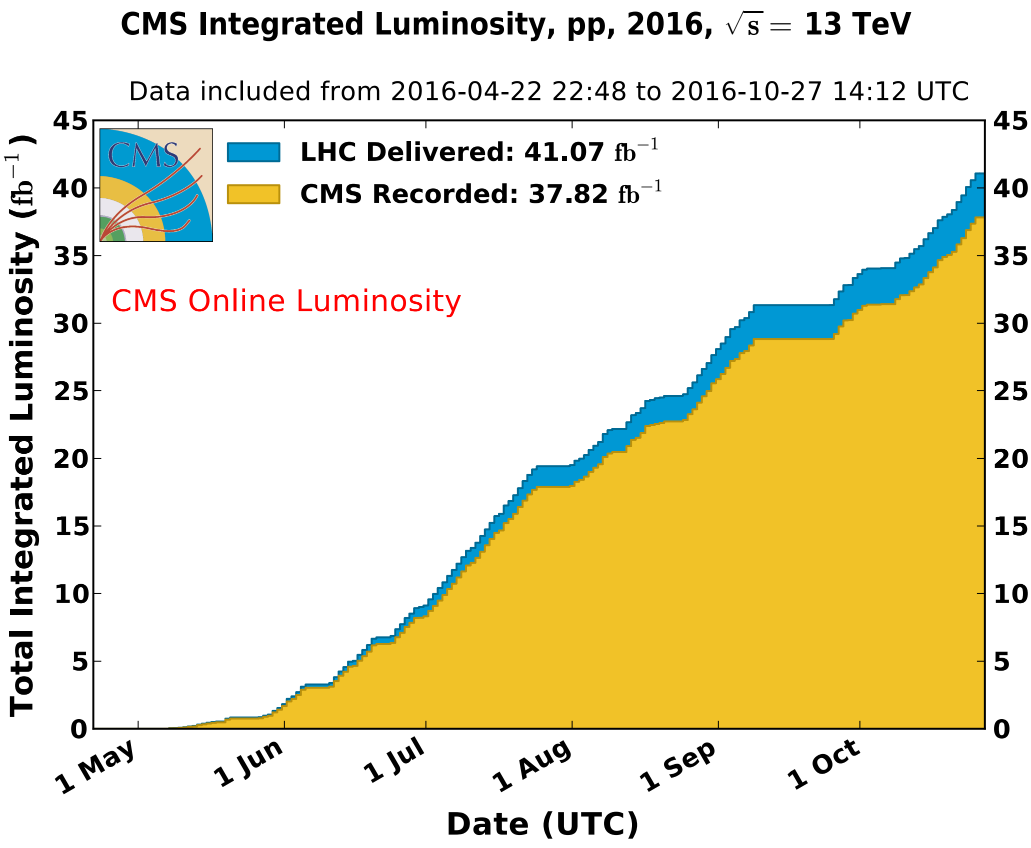

Figure 4. Total Integrated Luminosity in 2016.

The 2016 run started with only one MP7 module in the Global Trigger system. In spite of the large logic resources of the Virtex-7 FPGA one module soon turned out to be insufficient because the number and the complexity of physics algorithms used in the Level-1 Trigger menus increased very fast. This limited the introduction of additional algorithms during summer 2016. Therefore,

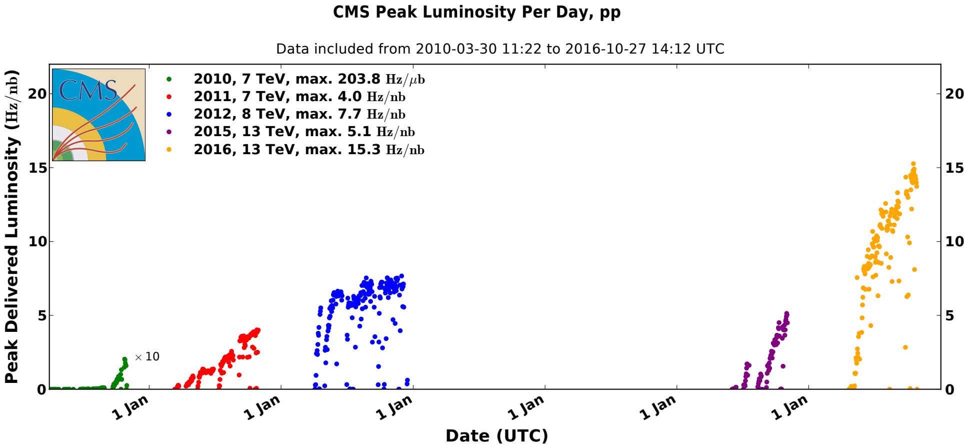

Figure 5. Peak Luminosity versus time for 2010, 2011, 2012, 2015 and 2016 (p-p data only).

a second MP7 module was installed in September when the trigger menu v7 was deployed. Four invariant-mass trigger algorithms were then included to study the performance of these new trigger types in the CMS experiment.

An important feature of the Global Trigger system is its flexibility in adding new trigger objects. During 2016, several new calorimeter objects were introduced. So, while so far the calculation of missing transverse momentum did not include data from the Hadronic Forward calorimeter (HF), an additional version of this trigger object where the HF data are also used was deployed during the 2016 run. Another object type introduced at short notice was a minimum-bias trigger for Heavy-Ion running, which consists of a few dedicated bits calculated in the Hadronic Calorimeter of CMS and forwarded via the calorimeter trigger chain.

5. Outlook

A number of improvements and additional features are foreseen for the next year of running and will be introduced during the annual LHC shutdown at the end of 2016 and in early 2017. Additional MP7 modules (eventually up to six) will be installed to provide chip resources for a large number of complex algorithms. New trigger objects such as jet sums (so-called “wide jets”, taking care of further decays of particles producing several closely-spaced jets) will be created in the calorimeter trigger and used in the Global Trigger. The azimuth coordinate of muons will be corrected for magnetic-field effects in the Global Muon Trigger to enable a more accurate calculation of the invariant mass in $\mu\mu$ decays in the Global Trigger. In the Global Trigger itself, an overlap removal procedure will be introduced for cases in which the same physical object is interpreted as several different trigger objects (so, a τ object can sometimes also appear as a jet, a jet can at the same time be labelled as an e/γ event and so on). Measures are also planned to improve the ease of use of the system. A preview mechanism will allow to accurately predict the trigger rate that will be observed when switching to a different set of trigger prescales (due to trigger overlaps, this is not trivial). In order to prepare firmware changes and upgrades during running without jeopardising the physics data taking, all modifications will first be test in a “test crate”, which is a fully equipped, redundant copy of the Global Trigger system used in physics production.

Acknowledgments

The Institute of High Energy Physics of the Austrian Academy of Sciences would like to thank the Austrian Federal Ministry of Science, Research and Economy for funding the Austrian contribution to this project. Also, we would like to thank all our colleagues from the CMS collaboration for the great cooperation in the Level-1 Trigger project.

References

[1] M. Jeitler, *The upgrade of the CMS trigger system*, 2014 *JINST* **9** C08002.

[2] A. Rose et al., *The MP7 and CTP-6: multi-hundred Gbps processing boards for calorimeter trigger upgrades at CMS*, 2012 *JINST* **7** C12024.

[3] J. Wittmann et al., *The upgrade of the CMS Global Trigger*, 2016 *JINST* **11** C02029.