The RPC based trigger for the CMS experiment at the LHC

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ABSTRACT: CMS is a general purpose detector that operates at the LHC. The PACT is a Level-1, RPC based muon sub-trigger of the CMS experiment. In this paper an overview of the CMS and its muon trigger is given. The principles of the PACT system are explained. The PACT performance during the LHC Run-1 is presented, including efficiency, stability and rate. The role of the PACT in the Level-1 muon trigger system is exposed. The perspectives for the RPC system in the context of CMS modifications are discussed.

KEYWORDS: Trigger concepts and systems (hardware and software); Large detector-systems performance; Trigger algorithms
1 The CMS experiment and the RPC trigger system

The Compact Muon Solenoid (CMS) [1] is a general purpose experiment for physics discoveries at the highest luminosities of the CERN Large Hadron Collider (LHC). The LHC machine delivered about 30\,fb$^{-1}$ of proton-proton data at a center-of-mass energy $\sqrt{s} = 7\,\text{TeV}$ in 2010 and 2011, and at $\sqrt{s} = 8\,\text{TeV}$ until the end of 2012, when proton-proton collisions in LHC Run-1 ended. The CMS experiment had been successfully operated during that time. The collected data allowed physicists to perform a variety of measurements and searches, which led to the discovery of a Higgs particle [2].

The central component of the detector is a large (6 m diameter and 13 m long) superconductive solenoid. It delivers a 3.8 T magnetic field in the inner part of the CMS detector and about 1.8 T inside an iron return yoke. CMS is traditionally divided into a barrel part (with sub-detectors aligned roughly parallel to the beam pipe) and two endcaps. Next to the beam-beam interaction region, a silicon tracker system is located, surrounded by a homogeneous electromagnetic calorimeter made of lead-tungstate crystals and a sampling brass-scintillator hadron calorimeter. These subdetectors are positioned in the inner part of the CMS detector, inside the solenoid magnet. In the outer part, outside the coil, a muon system is placed. It is dedicated for muon reconstruction and identification. The muon system is equipped with gaseous detectors: Drift Tubes (DTs) in the barrel, Cathode Strip Chambers (CSCs) in the endcaps and Resistive Plate Chambers (RPCs) in both barrel and endcaps. The pseudorapidity\(^1\) coverage of the muon system extends to 2.4, but in the case of the RPC system it is restricted to $|\eta| < 1.6$.

The CMS experiment has a two-layer triggering system designed to reduce a 40 MHz LHC input rate down to a few hundreds events per second suitable for storage and offline analyses. The Level-1 Trigger is the first layer. It was build by using custom-made, partially programmable hardware devices (mostly special-purpose ASICs but also FPGAs where appropriate). It analyses coarsely segmented data only from the calorimeter and muon systems. The Level-1 Trigger selection is based on inclusive single- and multi-object triggers with a threshold relying on estimated

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\(^1\)Pseudorapidity $\eta = -\ln \tan \theta/2$, where $\theta$ is the polar angle.
(transverse) momenta and energies. It reduces the event rate below 100 kHz, which is the maximal input rate capable to be handled by the second triggering layer: the High-Level Trigger (HLT) system.

Muon reconstruction at Level-1 is performed by dedicated sub-triggers. The DT Track Finder (DTTF) and CSC Track Finder (CSCTF) reconstruct trigger candidates using pre-processed track segments delivered by DT and CSC on-detector electronics. The Pattern Comparator Trigger (PACT) reconstructs candidates directly from pattern of hits delivered by RPC chambers. Sub-trigger candidates are combined by the Global Trigger (GMT), and the resulting Level-1 muon trigger candidate is used by algorithms implemented in the CMS Level-1 Global Trigger.

The RPC based PACT system is composed of a link system, fibers, splitters, the trigger system itself and a readout system. The link system is responsible for RPC data transmission between the CMS detector cavern and the counting hall. In addition, it enables the RPC detector configuration and all data quality monitoring. The data are transmitted by Link Boards (LBs). In the LB, the signals are synchronized with the LHC clock. The synchronization is based on signal appearance in a programmable (width and delay) acceptance window. The window may be adjusted with about 0.1 ns precision. There is one setting of synchronization parameters for all LB input channels. Thus, the signal cable providing RPC detector data to a given LB must have the proper length to fix the signal propagation time. In the LB, the data are zero-suppressed and multiplexed. The initial 96 bit LB input signal is divided into 12 8-bit partitions. Only data from partitions that are not empty are selected. Data from one partition can be sent in one bunch-crossing. In the case of multiple-hit events, data are delayed up to a maximum of 8 BXs, after which the data are truncated and properly marked. Out of a total of 1232 LBs, only 444 LBs are instrumented with optical transmitters. These LBs receive data from neighbors by a front-plane, then merge and transmit them over optical fibers to the CMS counting hall. For a typical connection scheme, 1-hit cluster can be transmitted from a full RPC chamber to the trigger electronics in 1 BX.

The trigger electronics is located in the CMS counting hall. After de-multiplexing, hits are used in the trigger algorithm to reconstruct RPC PACT muon candidates. The RPC trigger algorithm (see ref [3] for a full description) is based on comparison of hit strip pattern in the event with a set of predefined, so-called valid patterns. The list of valid patterns is based on Monte Carlo calculations. Each valid pattern consists of a hit strip combination, one strip from each logical layer. In the barrel region and endcap, the logical layers match the physical ones. In the barrel-endcap transition region, the layer assignment depends on the actual chamber location. There are 6 logical layers in the barrel and only 3 in each endcap for the current (staged) version of the RPC system. Each valid pattern has a Level-1 transverse momentum ($p_T$) code assigned. The valid patterns with the same $p_T$ code are grouped in so-called energetic groups. The actual hit pattern obtained in the event is compared with each valid pattern to check their matching. The initial comparison validates the number of hit logical planes in a given energetic group. It defines a muon candidate quality. The empty layers are filled with spurious hits. If the hits from all layers exactly match a pattern in a given energetic group, a muon candidate is created. The candidate $p_T$ is given by the energetic group code and the quality by the number of logical planes with real hits. The best candidate

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2 A bunch-crossing (BX) is a time-stamp corresponding to a possible LHC collision event (i.e., proton-proton collision) and is related to the machine clock. Since collisions may occur every 25 ns, the bunch-crossing is also used to mark the 25 ns time interval between beam-beam collisions.
in terms of quality and \( p_T \) is selected as the result of the algorithm. In order to keep the rate of spurious candidates at a low level, a minimal number of hits in coincidence is required to form a muon candidate. As the baseline, in minimum of 3 hits in coincidence is required. In the barrel, to optimize trigger performance for low-\( p_T \) muons, which cannot penetrate the full muon system, a special set of patterns is introduced. Thus 3-hit high-\( p_T \) patterns which require a hit in one of the outer muon stations are supplemented with low-\( p_T \) ones based on the 4 most inner measurement layers. In the endcap region, there are currently only 3 layers available, hence coincidence of hits from all these layers is required.

The PACT algorithm is executed in the RPC Trigger Boards. The system consists of 84 Trigger Boards placed in 12 crates. The RPC trigger system is completed with a set of sorters and ghost-busters to rid the trigger response of spurious and fake candidates. The reconstructed PACT candidates are transmitted to the GMT while the RPCs input data to the CMS DAQ with a help of dedicated Data Concentrator Cards.

2 The PACT performance

Accurate timing is mandatory for the Level-1 sub-triggers. The wrong time assignment does not only dismiss a particular candidate, but in the case of candidates that appear advanced in time, it may cause detector pre-triggering and mask the proper event with the correct responses of other components. The PACT timing response is driven by the proper assignment of hits during the data transmission chain at the LB level. The distribution of hits and the resulting timing of PACT trigger are shown in figure 1. The RPC hit timing is computed by using hits spatially matched to good quality muons reconstructed offline. Only leading hits from RPC readout strips in a 6 bunch-crossing-wide event readout were taken into account when making the plot. Correct bunch crossing is identified for 99.98% of the RPC hits matched to muons. The synchronization parameters were
tuned only a few times after the LHC startup. The spread of the hit distribution is not caused by imperfect synchronization of some LBs but is rather due to a symmetric spread of hits around BX=0 at the LB level. The residual out of time hits originate from: cosmics, muons from other bunch crossings or chamber noise. During the PACT candidate reconstruction, the RPC hit signal is extended into two consecutive bunch crossings. This allows for triggering of "late arriving" exotic particles, commonly called heavy stable charged particles (HSCP). Because of this feature, in the case of a typical muon the PACT sends its muon candidates twice (in two consecutive BXs). The fake candidate in BX=-1 is vetoed during the Level-1 decision with the help of beam monitoring devices. The PACT timing analysis requires a PACT trigger candidate to match the offline reconstructed muon. The tails of the histogram are caused by cosmic muons, muons from the preceding bunch crossing and from RPC detector after-pulses. Thus the plot provides an upper limit for PACT pre- and post-triggering probability.

The PACT efficiency is presented in figure 2. The efficiency is a convolution of several components and may be decomposed. The “detector acceptance” indicates the fraction of events where a reconstructed muon crosses number of RPC chambers sufficient to provide a trigger candidate. The “hit coincidence” gives the fraction of events with a sufficient number of hits to start the trigger algorithm. This component is obtained by emulation (with data) of a trigger algorithm with a dedicated pattern covering the full geometrical region of the trigger decision. The “RPC PAC trigger efficiency” is the actual obtained efficiency of the RPC PACT system.

The other way to compute trigger efficiency used at CMS is the tag-and-probe method. This method allows us to measure trigger efficiency without a bias from the trigger selection or muon reconstruction. The method requires a well identified muon (the tag muon) which may trigger the event. It is supposed to originate from the decay of Z or J/$\psi$ particles. The second muon from such decay (the probe muon) is required to be measured in the tracker and is identified as a muon by the

\begin{figure}
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\includegraphics[width=\textwidth]{figure2.png}
\caption{Left: The RPC acceptance, detector and trigger efficiencies, computed w.r.t. good quality offline muons. The plot is made for muons with a transverse momentum above 10GeV/c, using minimum-bias data. Right: The PACT turn-on curves from the tag-and-probe method with J/$\psi$ data.}
\end{figure}
invariant mass constraint. The efficiency of the probe muon is measured as a fraction of probes and corresponding trigger answer. Since muons used for analysis are of key interest, the probe muon has to pass additional (offline) quality requirements.

The trigger performance stability is another important feature, as it must be included in various physics analyses. The PACT stability is driven by the underlying quality of RPC detector data. The RPC detector hit efficiency and the cluster size vary mainly due to changing atmospheric pressure conditions. To correct for this effect, the chamber High-Voltage (HV) tuning algorithm was developed. In figure 3 the PACT stability is presented. The trigger efficiency in a run is shown as a function of time. The last two improvements by the correction algorithm are indicated. No significant instabilities are visible. The distribution of PACT efficiency forms a sharp peak with a rms of 0.015.

3 Role of the RPC system in the Level-1 muon trigger

The muon candidates from DTTF, CSCTF and PACT sub-triggers are combined by the GMT. The GMT algorithm merges candidates and sets the transverse momentum depending on contributing candidate qualities and transverse momenta. In the baseline, the GMT \( p_T \) is the minimal \( p_T \) of the two contributing candidates, irrespective of their quality. In the endcap, however, a good quality CSCTF candidate often provides a more precise measurement than the PACT, while, in the overlap region, a low quality PACT candidate may cause momentum underestimation. In such cases, a GMT algorithm disfavors the PACT \( p_T \) measurement. The GMT efficiency and rate as a function of \( \eta \) are presented in figure 4. The efficiency plot shows the redundancy of muon the trigger system. The efficiencies of the contributing sub-systems are high. The GMT efficiency improvement related to the appearance of only one contributing sub-trigger is at the level of only a few percent. In the endcap, GMT efficiency follows that of the CSCTF because of limited PACT efficiency based on 3 layers, detectors overlap, and the coverage of the RPC trigger system \( |\eta| < 1.6 \). The GMT rate shows a relatively flat structure in the central barrel region and a rapid increase for \( |\eta| > 2 \). It is driven by decreasing bending in the magnetic field. One may note the substantial rate of events without a PACT candidate.

In figure 5, the Level-1 rate (GMT) is drawn as a function of the threshold. In this case the rate of all sub-trigger candidates, not only those used in GMT decision, is shown. The GMT rate is close to, or below, the lower rate of contributing sub-triggers. One may note the good performance
Figure 4. Left: The Level-1 muon trigger efficiency (left) and rate (right) as a function of muon pseudo-rapidity. For each GMT candidate the contributing sub-trigger candidates are marked. The tag-and-probe method is used on a Z sample for the efficiency computation. The dedicated, pre-scaled data stream with trigger information is used for the rate computation. The rate is normalized to $L = 5 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$.

Figure 5. The Level-1 muon trigger rate (GMT) as a function of threshold in the barrel (left) and endcap (right) region. The dedicated, pre-scaled data stream with trigger information is used for rate computation.
of the stand-alone RPC trigger in the barrel which, with an efficiency similar to the DTTF, leads to smaller rates. In the endcap, the PACT rate is substantially above the CSCTF. Nevertheless, the presence of PACT candidates improves the GMT response.

The Level-1 muon trigger has decreasing selectivity for the high-$p_T$ thresholds. As an example, changing the Level-1 $p_T$ threshold from 10 to 25 GeV/c decreases the rate by an order of magnitude, but a reduction by another factor of 10 is not possible without harder quality cuts and efficiency reduction. This effect is even more important for higher pseudorapidities. It is one of the reasons for the Level-1 trigger upgrade in LHC Phase-I, discussed below.

### 4 RPC and CMS Phase-I upgrades

The LHC Run-1 ended in the beginning of 2013 and LHC entered Long Shutdown I (LS1). During the period of LS1 the LHC is improving the magnet interconnections. These improvements and the dipole magnet training program will allow LHC to provide proton-proton collisions at an energy of $\sqrt{s} = 13$ TeV. Until the end of LHC Phase-1, planned for 2022, LHC will collect over $300 \text{fb}^{-1}$ of proton-proton data.

The modernizations of the LHC machine will be accompanied by necessary upgrades [4] of the CMS apparatus to deal with more difficult experimental conditions, radiation, detector aging, but also to improve the detector performance.

In the ongoing LS1, an important modification to the detector geometry is the upscope of the muon system. This will provide an additional, 4th muon station in the endcaps, equipped with RPC and CSC detectors. This is especially important for the PACT sub-trigger, which is currently working with limited efficiency. The additional measurement will improve efficiency, but also further constrain muon trajectory patterns, improving Level-1 triggering.

The increase in accelerator energy and luminosity impose high purity triggering already at Level-1. Otherwise, to keep the Level-1 rate within the design bandwidth of 100 kHz, a substantial increase of trigger thresholds is required, affecting physics performance. To improve purity, the Level-1 system will be rebuilt with a modern electronics [5] to enable more advanced algorithm execution. On the muon side the transverse momentum resolution should be improved.

The muon trigger will undergo major logic changes. Currently the trigger response is generated independently by muon sub-triggers and trigger candidates are combined by a GMT. Within the new Muon Track Finder the underlying detector signals will be delivered to one data processing unit and the resulting muon candidate will take into account all the available information from RPC, DT and CSC. The new Muon Track Finder will ultimately replace the current PACT trigger.

Since triggering is a vital aspect of an experiment, CMS cannot put data at risk. Hence, after LS1, a part of detector data will be split and delivered both to the legacy and new system. The new system will thus coexist with the current one for commissioning purposes during data taking. The full replacement is targeted for the winter shutdown 2015/16.

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