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The First-Level and High-Level Muon Triggers of the Compact Muon Solenoid Experiment at CERN

H. Sakulin

Institute for High Energy Physics of the Austrian Academy of Sciences, Vienna, Austria

CMS Collaboration

Abstract

High transverse momentum muons are expected to play a crucial role in the discovery of the Standard Model Higgs, precision Standard Model measurements, as well as in the discovery of new physics such as Supersymmetry at CERN's new Large Hadron Collider. In order to provide efficient and precise muon detection, three muon systems are utilized in the Compact Muon Solenoid (CMS) experiment: Drift Tubes in the barrel, Cathode Strip Chambers in the endcaps and Resistive Plate Chambers throughout for trigger information complementary to the high-precision tracking measurements of the first two systems. The CMS trigger has to reduce the event rate from the LHC bunch-crossing rate of 40 MHz to a rate of approximately 100 Hz, the maximum that can be recorded for offline analysis. This enormous reduction is achieved in several subsequent levels: while the first level trigger reduces the initial rate to a maximum of 100 kHz employing fully pipelined custom-built electronics, the following higher trigger levels will run on a high-performance farm of commercial processors allowing for full flexibility. Muon-trigger algorithms employed at the first and higher trigger levels are discussed. Special emphasis is given to the First-Level Global Muon Trigger, which increases efficiency and considerably improves rate reduction by optimally combining trigger information of all three muon systems. Detailed Monte-Carlo simulations of expected trigger rates and trigger efficiencies are presented.

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The First-Level and High-Level Muon Triggers of the Compact Muon Solenoid Experiment at CERN

Hannes Sakulin, on behalf of the CMS Collaboration

Abstract--High transverse momentum muons are expected to play a crucial role in the discovery of the Standard Model Higgs, precision Standard Model measurements, as well as in the discovery of new physics such as Supersymmetry at CERN's new Large Hadron Collider. In order to provide efficient and precise muon detection, three muon systems are utilized in the Compact Muon Solenoid (CMS) experiment: Drift Tubes in the barrel, Cathode Strip Chambers in the endcaps and Resistive Plate Chambers throughout for trigger information complementary to the high-precision tracking measurements of the first two systems. The CMS trigger has to reduce the event rate from the LHC bunch-crossing rate of 40 MHz to a rate of approximately 100 Hz, the maximum that can be recorded for offline analysis. This enormous reduction is achieved in several subsequent levels: while the first level trigger reduces the initial rate to a maximum of 100 kHz employing fully pipelined custom-built electronics, the following higher trigger levels will run on a high-performance farm of commercial processors allowing for full flexibility. Muon-trigger algorithms employed at the first and higher trigger levels are discussed. Special emphasis is given to the First-Level Global Muon Trigger, which increases efficiency and considerably improves rate reduction by optimally combining trigger information of all three muon systems. Detailed Monte-Carlo simulations of expected trigger rates and trigger efficiencies are presented.

I. INTRODUCTION

CERN's new Large Hadron Collider (LHC) will provide proton-proton collisions with a center-of-mass energy of 14 TeV, roughly 7 times that of the current most powerful machine, the Tevatron II. At an instantaneous luminosity of $L=10^{34} \text{ cm}^{-2}\text{s}^{-1}$, the LHC will operate with a bunch crossing frequency of 40 MHz. Typical event sizes of around 1 MB in the general purpose experiments CMS [1] and ATLAS [2] limit the event rate that can be recorded for offline analysis to approximately 100 Hz. The enormous rate reduction from 40 MHz to 100 Hz has to be performed on-line by the trigger system of the experiment.

CMS has chosen to perform this rate reduction employing only two physical layers as illustrated in Fig. 1: the first step of reduction is performed by the Level-1 Trigger [3], a large system of fully pipelined custom-built electronics which processes data from every bunch crossing without dead-time. Based on coarsely segmented data from the calorimeters and muon system, the Level-1 Trigger reduces the rate below 100 kHz while the full high-precision data are kept in front-end pipelines. Triggered events are passed to the readout buffers in order to be analyzed by High-Level Trigger [4] algorithms running on a farm of commercial processors. High-level trigger algorithms are optimized to reject events as early as possible using as little CPU resources as possible. Reconstruction therefore proceeds in virtual trigger levels: virtual "Level-2" algorithms select events using fast algorithms based on the muon system and calorimeters. Only after this step tracker data are included in order to perform a finer selection.

Muons of high transverse-momentum (p_T) play a very important role in triggering since they are part of the signature of many of the processes to be studied at the LHC. The penetrating nature of muons simplifies their identification and occupancies in the muon detectors are generally low. At low transverse momenta muons from decays of K and π and from decays of b- and c-quarks constitute a large background (Fig. 2). Precise measurement of muon p_T will be the most important tool in reduction of this background. Since muons from K, π , b, c are produced inside jets, isolation criteria based on the energy deposited around the muon in the calorimeter or tracker can help to further reduce the background.

In order to provide precise and efficient muon measurement, CMS includes three muon systems (Fig. 3): four stations of Drift Tube (DT) Chambers with bunch-crossing identifying capabilities provide precision tracking measurements throughout the barrel region, each station consisting of twelve (eight in the outermost station) staggered layers of drift tubes. Four disks of Cathode Strip Chambers (CSCs) cover each of the two endcaps, each disk consisting of

Manuscript received October 29, 2003. Hannes Sakulin is with the Institute for High Energy Physics of the Austrian Academy of Sciences, Nikolsdorferg. 18, A-1050 Vienna, Austria. (e-mail: Hannes.Sakulin@cern.ch).

6 layers of chambers. Six layers of Double-Gap Resistive Plate Chambers (RPCs) mounted on the DT stations and four layers mounted on the CSC stations provide additional complementary information with superior timing resolution. All three muon systems are used both in the First-Level and the High-Level Muon Trigger.

II. FIRST LEVEL TRIGGER

The First-Level Trigger analyzes coarsely segmented data of the calorimeters and muon systems for every bunch crossing without dead-time. Employing pipelined electronics, it finds its L1-Accept decision within a latency of only 3.2 μ s including signal propagation from the detector to the underground counting room and back. The implementation of the trigger logic is based on two main technologies: Application Specific Integrated Circuits for the on-chamber electronics and Field Programmable Gate Arrays for the electronics in the underground counting room.

The overall structure of the CMS Level-1 Trigger is shown in Fig. 4. It consists of three main systems: the Calorimeter Trigger, the Muon Trigger and the Global Trigger. While more conventional Level-1 triggers are based on counting trigger objects that pass certain programmable transverse energy or momentum thresholds, in CMS a novel, very flexible triggering concept will be employed. The Calorimeter Trigger and the Muon Trigger identify as trigger objects: electrons/photons, isolated electrons/photons, forward, central and τ -jets and muons. Up to four trigger objects of each type are forwarded to the Global Trigger [5], each including a measurement of its transverse momentum or energy its coordinates in the detector (ϕ, η) and its quality. Only at the Global Trigger are thresholds applied and are trigger algorithms evaluated. Trigger algorithms can consist of arbitrary combinations of trigger objects passing certain thresholds and can even include topological correlations between any of the trigger objects. Up to 128 trigger algorithms can be run in parallel and a crossing is accepted if either of the conditions is fulfilled. It is also possible to pre-scale certain trigger algorithms i. e. to accept only a certain fraction of events that trigger the algorithm.

In the Muon Trigger, muon candidates are independently identified by regional triggers and then combined by the Global Muon Trigger (GMT). In the DT and CSC Trigger, local trigger electronics identify track segments at the muon stations based on the signals of multiple layers of chambers. Besides precise position information, the track segments also include information on the track direction and quality. Track finders then perform extrapolations between pairs of track segments and connect them into tracks compatible with muons originating from the interaction region. A transverse momentum is assigned to the tracks based on the

ϕ -coordinates of the track segments. Tracks further include the sign of charge, the position ϕ and η at the muon system and an indication of quality. The DT Track Finder finds tracks separately in the r - ϕ plane and the r - z plane while the CSC track finder uses a three-dimensional road finding technique. Up to four tracks may be found by the DT Track finder in the barrel region and by the CSC Track finder in the Endcap regions. In the region of overlap between barrel and endcap muon systems, track segments from several chambers are shared between the two track finders in order to keep efficiency high. Possible double counting of muon candidates in this region is later resolved at the Global Muon Trigger.

The RPC trigger independently identifies muon candidates employing a pattern-finding algorithm. In the barrel, different combinations of layers are used to detect low- p_T and high- p_T muons. Based on the track pattern a pre-calculated transverse momentum is assigned. Candidates further contain sign of charge, position and quality measurements. Up to four candidates for the barrel region and up to four candidates in the endcap regions are forwarded to the Global Muon Trigger.

The Global Muon Trigger combines the muon candidates found by the regional triggers and identifies the best four candidates in the detector. By exploiting the complementarity of the muon systems, the GMT reduces trigger rates with respect to the standalone trigger rates of the regional triggers while at the same time increasing efficiency. Candidates of complementary systems are matched on the basis of their spatial coordinates. Candidates that are only detected by one of the muon systems can be tagged in order to be suppressed in certain trigger algorithms based on their quality information and position in the detector. For muons detected by two systems the GMT attempts to assign the better measurement of transverse momentum and of the coordinates. Duplicate candidates in the region of overlap between barrel and endcaps are cancelled out on the basis of their proximity in space. The GMT further correlates muon candidates with regions in the calorimeter in order to check them for isolation or to confirm them. For this purpose the Calorimeter Trigger sends for each region ($\Delta\eta \times \Delta\phi = 0.35 \times 0.35$ rad) a quiet bit indicating that the energy deposit was below a certain threshold and a MIP bit indicating that the energy deposit was compatible with the passage of a Minimum Ionizing Particle such as a muon. One calorimeter region is checked for the MIP bit while multiple regions can be checked for in order to determine isolation of a muon candidate. Finally, the best four muon candidates are determined based on sort ranks which depend on p_T , quality and detector region.

The Level-1 Muon Trigger reaches an overall efficiency of 97 % including the geometric acceptance for muons of flat transverse momentum distribution between 2.5 and 100 GeV/c generated in the nominal range of acceptance.

III. HIGH-LEVEL TRIGGER

The CMS data acquisition system processes events accepted by the first-level trigger at a maximum input rate of 100 kHz. Event data are read out from the detector and stored in readout buffers at a total rate of 1 Terabit/s. The event-builder then assembles event fragments into full events employing a large switching network. The high-level trigger algorithms run on a farm of $O(10^3)$ commercial processors. Each event is processed by a single processor, which has access to the full raw event data. High level-trigger reconstruction code will be as close as possible to the full offline analysis code, the main differences resulting from limited processing time and the possible lack of precise calibration constants. The following three key features of HLT software guarantee minimal processing time:

Reconstruction on demand: trigger objects are only reconstructed if needed in the trigger decision. Unnecessary calculations are avoided by rejecting events as early as possible using fast algorithms. The reconstruction and selection therefore takes place in several stages (virtual trigger levels), which roughly correspond to the functions of traditional second and third trigger levels. There is no limitation to the number of virtual trigger levels or to the algorithms employed except for CPU time. For historic reasons the terminology "Level-2" is used for a first high-level trigger stage based on data from the muon systems and calorimeters while "Level-3" refers to algorithms including tracker data.

Partial/Region reconstruction: only parts of detector information are analyzed guided by the trigger objects found in the preceding trigger levels.

Conditional reconstruction: reconstruction is aborted if further calculations would not alter the result (for example when reconstructing additional tracks in an isolation algorithm) or if the condition arises that resulting trigger object would not be relevant to the trigger decision.

Prototype high level trigger algorithms have been developed and tested. Muon reconstruction at "Level-2" is guided by the position and transverse momentum information of Level-1 muon candidates. Segments and hits are reconstructed at the muon system chambers in regions defined by the Level-1 candidates. Starting from the innermost chambers, the state vectors corresponding to the segments are propagated outwards. The predicted state vector at the next measurement surface is compared to measured points and updated using a Kalman filter technique. The measurements used in the Kalman filter procedure are the segments for the barrel chambers and the reconstructed hits in the endcaps, where the magnetic field is inhomogeneous. Reconstructed RPC hits are also included. After measurements at all stations have been added, a fit to the track parameters is performed from the outside-in under the assumption that the muon originated

from the interaction region ($\sigma_y=15$ mm, $\sigma_z=5.3$ cm). The track parameters are evaluated at the vertex and used to accept events for further processing at "Level-3". The $1/p_T$ resolution at Level-2 lies between 10 % and 16 % depending on pseudorapidity.

At "Level-3" the track found at Level-2 is propagated to the outermost surface of the tracker defining a region of interest in the tracker in which regional track reconstruction proceeds. The uncertainties of the Level-2 measurement have a large impact on the performance of the "Level-3" reconstruction since they define the size of the region of interest. Within the region of interest, pairs of tracker hits compatible with a muon coming from the beam spot and exceeding a certain minimum p_T are used as seeds for the regional reconstruction. Starting from these seeds, regional track reconstruction is performed using a Kalman filter technique, adding compatible hits starting from the innermost layer. Multiple trajectories may be found for each seed so that ambiguities have to be resolved based on the number of hits and chi-squares of the fits. In a final step, reconstructed tracks are fitted together with the reconstructed hits in the muon system and selected on the basis of a chi-square cut. The $1/p_T$ resolution after including tracker information is improved by a roughly a factor of 10 with respect to Level-2: resolutions between 1.0 % and 1.7 % can be achieved depending on pseudorapidity.

Isolation criteria can further reduce the background of muons from K, π , c and b quark decays. At "Level-2" a muon is considered to be isolated if the sum of energies deposited in the calorimeters in a cone around the muon direction at vertex is below a certain threshold. Cone sizes and thresholds vary with pseudorapidity. They are optimized to get maximum rejection of background muons for a given efficiency on a reference signal.

At "Level-3", an additional isolation algorithm based on tracks in the pixel tracker can be applied. Tracks are reconstructed regionally in the pixel tracker in a cone around the muon direction at vertex. A muon is considered isolated if the sum of reconstructed track transverse momenta in the cone is below a given threshold. In contrast to the Level-2 isolation algorithm, the Level-3 algorithm is insensitive to pile-up since only particles from the same vertex as the muon are considered. Processing time in the Level-3 isolation algorithm is minimized by conditional tracking: reconstruction of further tracks is aborted as soon as the sum of reconstructed p_T 's exceeds the isolation threshold.

IV. SIMULATED PERFORMANCE

Simulation studies using large sets of Monte-Carlo generated minimum bias events and a detailed description of the entire detector have been performed based on GEANT 3.21 [6]. The simulation includes pile-up in the signal bunch crossing as well as from bunch crossings before

and after the signal crossing. Due to excessive computing time requirements, neutron background is not included in the simulation. The simulation includes an emulation of all the components of the Level-1 trigger system.

Level-1 trigger rates as a function of applied transverse momentum threshold are shown in Fig. 5 for the initial low-luminosity phase of LHC operation ($L=2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$). The Level-1 GMT can achieve a rate reduction by a factor of 5 to 10 with respect to the standalone rates of DT/CSC and RPC Triggers while at the same time increasing efficiency and reducing ghosting. A typical working point of the level-1 muon trigger compatible with the available bandwidth as defined by the level-1 trigger table could consist of thresholds of 14 GeV/c in the single muon trigger and 3 GeV/c in a symmetric di-muon trigger.

The evolution of the single muon trigger rates at the prototype higher trigger levels is shown in Fig. 6. As a result of excellent p_T -resolution, the Level-3 rates before applying isolation algorithms are close to the generated rates. The Level-3 isolation algorithm provides powerful rejection of the components from K, π , b and c decays if muon p_T and corresponding jet energy are sufficiently high. Events containing isolated muons from heavy objects are retained with high efficiency. They dominate the resulting Level-3 muon rates at thresholds above 18 GeV/c. A possible working point compatible with the available output bandwidth could consist of a single-muon threshold of 19 GeV/c and a symmetric di-muon threshold of 7 GeV/c. Simulation of important signals to be triggered by muonic triggers show that the CMS First-Level Muon Trigger and the prototype high-level muon trigger algorithms meet the requirements for discovery physics at the above working points.

V. SUMMARY

The CMS experiment requires powerful on-line event selection. Starting from the LHC bunch-crossing rate of 40 MHz, the event rate has to be reduced to of the order of 100 Hz. The CMS trigger system will perform this enormous rate reduction using only two physical layers, the first level trigger electronics and the high level trigger algorithms running on a farm of commercial processors. Muon triggers of both layers have been discussed. Prototypes of trigger hardware and algorithms have been developed and the final system is currently being constructed. Detailed simulation studies of both the first and the high-level muon triggers have shown that the system can achieve the required rate reduction while yielding high efficiency for the signals to be studied at the LHC.

VI. REFERENCES

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Fig.1. Principle of the CMS Trigger and Data Acquisition system.

Fig. 2. Integrated generated muon rates per muon parent for low LHC luminosity $L = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ within a geometric acceptance of $|\eta| < 2.1$. Rates are dominated by K and π decays up to a threshold of 5 GeV/c. Above, up to 25 GeV/c muons from c and b-quark decays dominate the rates.

Fig. 3. The CMS detector and its three muon systems.

Fig. 5. Level-1 single muon trigger rates as a function of applied transverse momentum threshold at low LHC luminosity $L = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ within a geometric acceptance of $|\eta| < 2.1$.

Fig. 4. The CMS Level-1 Trigger.

Fig. 6. Trigger rates at the higher trigger levels as a function of applied transverse momentum threshold at low LHC luminosity $L = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ within a geometric acceptance of $|\eta| < 2.1$.