CMS Muon detector and trigger performance

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Abstract

In the CMS experiment at the LHC proton-proton collider a key role will be played by the muon system that is embedded inside the iron yoke used to close the magnetic flux of the CMS solenoid. The Muon system of the CMS experiment performs three main tasks: triggering of muons, identifying muons, and assisting the central tracker in order to measure the momentum and charge of high-pt muons in the pseudo-rapidity region $|\eta| \leq 2.4$. The system is composed by a central barrel and two closing endcaps. Three independent technologies are used to reconstruct and trigger muons: Drift Tubes (DT) in the barrel, Cathode Strips Chambers (CSC) in the endcaps and Resistive Plate Chambers (RPC) in both barrel and endcap regions. All the detectors will contribute to the tracking and triggering of muons. Towards the end of 2008 and in 2009 the CMS experiment was commissioned with many millions of cosmic rays. These data have been fundamental to check the performance of the three sub-detectors and of the trigger response. In this paper the results in terms of the detection and trigger performance at the level of each sub-detector and at the level of the full muon system will be reported.

Key words: LHC, CMS, muon

1. Introduction

The Compact Muon Solenoid (CMS)[1] is one of the two multi-purpose detectors installed at the Large Hadron Collider (LHC)[2], which is being commissioned at the European Organization for Nuclear Research (CERN). The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing a magnetic field of 3.8 T. The silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass-scintillator hadronic calorimeter (HCAL) are located within the solenoidal field volume. Muons are measured in gas ionization detectors embedded in the steel return yoke. From the geometrical point of view the muon system is composed by a barrel and two closing endcaps. Three different technologies are used for muon track reconstruction and triggering. Drift Tubes (DT) are used to reconstruct muon tracks in the barrel for pseudorapidity $|\eta| < 1.2$, Cathode Strip Chambers (CSC) in the endcaps in the range $0.9 < |\eta| < 2.4$ while Resistive Plate Chambers (RPC) are used both in barrel and endcaps up to $|\eta| = 1.6$.

The three different sub-detectors were independently installed and commissioned until 2006. Between August 2006 and August 2009 the CMS experiment was tested by recording cosmic rays with magnetic field off and at the nominal value.

During dedicated data taking periods called CRAFT (Cosmic Run At Four Tesla) more than 600M of Cosmic Ray events have been collected allowing to commission the apparatus, to test the full Data Acquisition and Trigger chain and to calibrate the detector with high accuracy before the start-up of LHC collisions operation. Finally at the end of 2009 the first LHC collisions were recorded by the full experiment.

In this paper a more detailed description of the muon system in terms of detectors and trigger layout is given in section 2. Section 3 deals with the performance of the three subsystem detectors and triggers obtained from the analysis of the recorded Cosmic Rays. Finally the conclusions will be outlined in section 4.

2. The CMS Muon system

Detection of muons is fundamental in the understanding of several physics processes produced by proton-proton collisions. Muons provide clear signatures and are relatively easy to reconstruct and to trigger on.

The CMS experiment is based on a compact muon spectrometer embedded in the iron plates used to close the solenoidal magnetic field flux of about 4 Tesla. The main purpose of the muon detector is to identify the muons for $|\eta| < 2.4$ and to measure the transverse momentum of the particles with an accuracy of about 9 % at 200 GeV/c and less than 40 % at 1 TeV/c. The momentum resolution is pushed down to 1 % for low momentum muons and 5 % at 1 TeV/c when the results coming from the standalone muon system are combined with tracker measurements.

One of the goals of the muon system is also to trigger with high efficiency muons without dead time and to identify correctly the bunch crossing of the event.

All these performance parameters have to be reached in a hostile environment where the rate of background induced by the LHC machine can be as high as 1 kHz/cm^2 in the endcaps.

In order to fulfill the expected requirements a hermetic and redundant muon system has been constructed. Three different technologies of gaseous detectors have been choosen for this

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purpose: Drift Tube Chambers (DT)[3] are used in the barrel ($|\eta| < 1.2$), Cathode Strip Chambers (CSC)[4] in the endcap regions ($0.9 < |\eta| < 2.4$) and Resistive Plate Chambers (RPC)[5] are used both in the barrel and endcaps up to $|\eta| = 1.6$. All these detectors participate both in reconstruction and triggering of the muon tracks.

Figure 1 shows the cross section of the muon system and the angular regions covered by the different sub-detectors. From the construction point of view the muon detector consists of a barrel and two closing endcaps. The barrel is divided into five wheels placed at different positions along the beam line. Each endcap is composed of 4 disks on each side of the system. In the following we report the details of the three different sub-detectors.

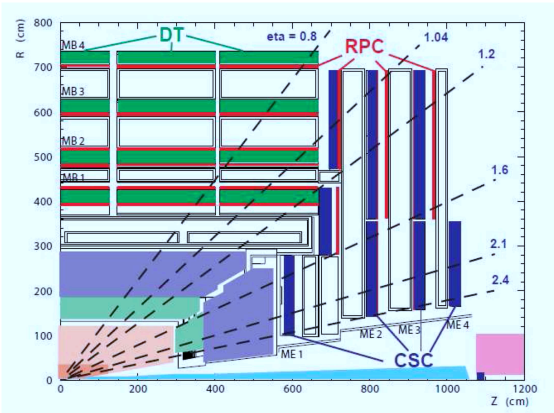

Figure 1: Cross section of the muon system of the CMS detector

2.1. Drift Tube Chambers (DT)

The Drift Tube Chambers ae used as tracking and triggeing devices in the barrel system. There are 250 chambers (50/wheel) distributed over five wheels, with 12 sectors per wheel and four stations per sector. Each of the four DT stations (called MB1, MB2, MB3 and MB4 going from the innermost position up to the outermost) is composed by three "SuperLayers" (SL) with four staggered layers each; the innermost and outermost SL measures the coordinate in the CMS bending plane (r-ϕ plane) while the central one measures the coordinate along the beam line (r-z plane). The outermost station (MB4) just measures the r-ϕ coordinates.

The distance between the anode wires of consecutive cells is 4.2 cm and cells in different contiguous layers are staggered by the same amount allowing left-right ambiguity resolution. The chamber works with gas mixture of Ar/CO_2 in the ratio of 85/15 %. The anode wires are put at 3.6 kV while electrode strips at 1.8 kV are used to shape the electric field lines. Cathode planes are set at -1.2 kV. With this electric configuration a good linearity of the cell behavior is guaranteed over almost the entire drift volume, and a constant drift velocity of 54.3 μm/ns, corresponding to a maximum drift time of 380 ns, is achieved.

The chamber electronics produces trigger primitives containing information about the reconstructed track segments in the DT "SuperLayers" for each Bunch Crossing. Trigger primitives from a given sector are sent to the sector collector electronics located outside the detector. The signals from each station, after having been synchronized, are forwarded to the Drift Tube Track Finder (DTTF), which matches trigger primitives coming from different stations and assigns a quality code, ϕ, η, charge and transverse momentum.

2.2. Cathode Strip Chambers (CSC)

Due to the higher magnetic field component and to the high background rate, tracking in the endcap region is made by Cathode Strip Chambers. A total number of 468 chambers is distributed over four disks per endcap with 1, 2 or 3 rings, according to the disk position. Every ring consists of 18 or 36 chambers covering the full azimuthal range. CSCs are multiwire proportional chambers with a cathode strip readout. Each chamber consists of six layers with 9.5 mm thick gaps filled with a gas mixture of $Ar/CO_2/CF_4$ in the proportion 40/50/10%. Anode wires are placed in the middle of the gap and permit a fast response for bunch crossing identification and the reconstruction of the radial coordinate. One of the two cathode planes is segmented into strips with a pitch varying from 8.4 to 16 mm that reconstruct the bending coordinate (ϕ) by measuring the centroid of the signal induced on three adjacent strips with an accuracy ranging from 80 μm to 450 μm.

Front end electronic boards reconstruct track segments in the cathode and anode view separately, requiring that they point to the interaction point with an angular acceptance of about one radian depending on the station location. Track segments from each view are combined into a 3-dimensional track representing the CSC trigger primitives. Trigger primitives are sent to the CSC Track Finder (CSCTF) that matches together 3D segments coming from different stations to form a complete track and assigning a transverse momentum, ϕ, η, charge and a quality bit.

2.3. Resistive Plate Chambers (RPC)

Resistive Plate Chambers are used as dedicated trigger detectors for both barrel and endcap regions. Their fast response and readout segmentation make them ideal for triggering purposes. They also participate in the track reconstruction but due to the coarse segmentation their contribution to the precision of the coordinate measurement is limited.

The RPCs used in CMS are double gap chambers working in avalanche mode with a gas mixture of $C_2H_2F_4$/Iso-C_4H_{10}/SF_6 with a ratio of 96.2/3.5/0.3%. Copper strips placed in the middle between the two gaps measure the bending coordinate (ϕ) with a resolution of the order of 1 cm. The good RPC timing ($\sigma \sim 2$ ns) permits a precise bunch crossing identification. A total number of 480 chambers is distributed over five wheels, 12 sectors per wheel and six layers per sector in the barrel region. In the endcaps 362 chambers are distributed over three disks per side with two rings per disk and 36 chambers per ring. The innermost ring and outermost disk of the endcaps are not instrumented at the moment. So the RPC system just covers the geometry region up to $|\eta|$=1.6.

From the trigger point of view, the RPC system is segmented into 33 towers covering the full $|\eta| \leq 1.6$ region. In each tower coincidences of RPC hits in the same bunch crossing and consistent with pre-defined hit patterns are searched for in order to find muon candidates. In the barrel the RPC trigger requires a coincidence of at least four out of six layers in the pre-defined patterns for high momentum muons and a coincidence of three of the innermost four layers for low momentum muons. In the endcap a coincidence of three out of three layers is required.

3. Muon detector and trigger performance

The large sample of cosmic muons collected by CMS allowed a detailed analysis of the performance of each muon subsystem.

The average efficiency of DT cells has been evaluated to be about 98.4% with negligible variation for runs with magnetic field on and off. Figure 2 shows the efficiency as a function of the distance from the anode wire for one MB1 station. The drift velocity has been measured with the use of the mean timer method, using the drift times coming from three consecutive and staggered layers. A constant drift velocity is found for all the stations and it is almost uniform along the wire direction. A more accurate analysis makes use of the track fit method in which the effect of a non-uniform magnetic field along the anode wire is taken into account. The only visible effect is a reduction of about 3% at the edge of the innermost station of the external wheels where the component of the magnetic field is not negligible. Cosmic rays have been used to measure the residual distribution for horizontal sectors. In order to get the best resolution the random arrival time of the cosmic rays in the bunch crossing time interval has to be taken into account. After proper corrections a resolution ranging between 200 and 260 μm has been obtained, which is in reasonable agreement with MC simulations.

The CSCs chambers, being installed vertically, have been illuminated by cosmic rays with larger inclination with respect to the detector plane. Special selections have been applied in order to define data samples of muons crossing the CMS detector closer to the interaction point and with a slope not too large with respct to the CSC plane. Despite the lower statistics available after these cuts, it has been possible to measure the single hit efficiency to be above 99.3 % and the track segment efficiency above 99 %. The segment track inefficiency is driven by events where, due to noise, a large number of hits is present in the chamber, which affects the reconstruction algorithm. The overall chamber resolution has been measured to be about 160 μm for most of the chamber types and 50-55 μm in the special case of the chambers at lower distance from the beam axis (ME1/1 chambers). Finally the CSCs chambers also recorded many beam halo muons coming from the LHC operation in September 2008 and December 2009 (Figure 3). These events have been used to study the overlap regions between the edges of the chambers for alignment purposes.

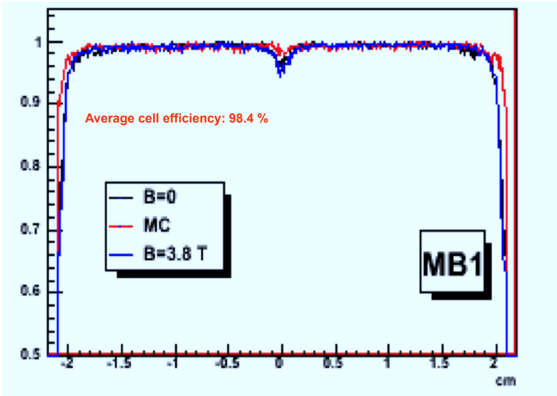

Figure 2: DT cell efficiency as a function of the distance from the anode wire for the MB1 stations

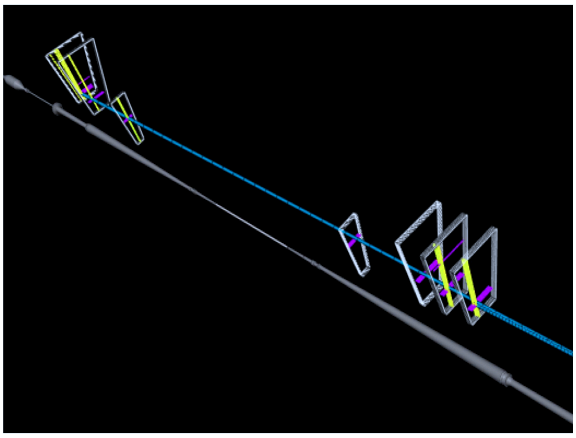

Figure 3: Display of Beam halo event reconstructed in the CSCs

The Resistive Plate Chambers have been analyzed making use of the redundancy of the muon system. Each Cosmic Ray is reconstructed independently by DTs and RPCs in the barrel and by CSCs and RPCs in the endcap. The segments reconstructed by DTs and CSCs and extrapolated to the RPC surface permit to study the RPC performance at the local level. An average efficiency of the order of 95% in the barrel and of 90% in the endcaps has been measured for the working voltage used during the Cosmic Data taking. The noise level at the level of 0.1 Hz/cm^2 and detector currents of the order of 1 μA/m^2 have been found to be very stable during the operation.

Cosmic Rays have also been used to check the trigger performance [6]. The timing of the trigger objects has been studied by comparing the bunch crossing identification coming from different muon sub-detectors. The random arrival time of the cosmic rays makes them not ideal for timing studies but still a good synchronization between different parts of the muon system has been found. The efficiency of the local trigger objects has been studied and shows that the performance is in good agreement with the expectations.

The large amount of Cosmics collected has also been used to align the muon chambers with high precision [7] and to cross-check the magnetic field map [8].

The final goal of the muon system is to merge the information from the different sub-detectors, reconstruct the muon track and assign it the correct charge and transverse momentum. The muon is reconstructed independently in the muon system and in the inner tracker. The inner tracker dominates the resolution up to 200 GeV/c due to multiple scattering in the iron. Above 200 GeV/c, the combined muon-tracker fit improves the resolution. Fig.4 shows the resolution as a function of the track momentum measured in Cosmic Data by comparing the top and bottom leg of the Cosmic Muon track. The resolution is in good agreement with the results coming from MC studies.

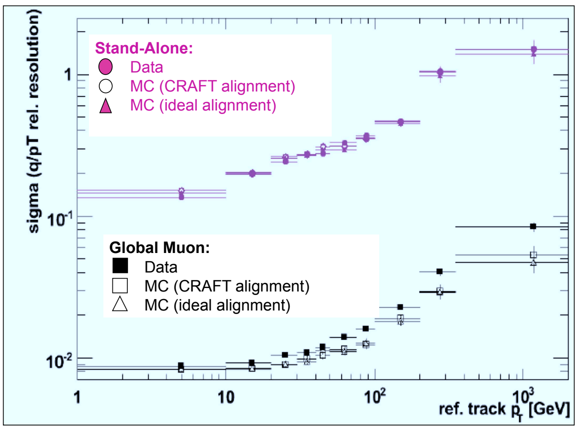

Figure 4: Transverse momentum resolution as a function of p_t for muons reconstructed by the muon system standalone and by the combined muon-tracker fit. Data before and after having applied alignment constants extracted from CRAFT data are compared to MC expectations

4. Conclusions

The CMS muon system is a key feature of the CMS experiment. The large amount of data collected in Cosmic Ray runs during 2008 and 2009 has permitted to check the muon subsystem performance at a detailed level. The performance of the system has been found to fulfill the design expectations. The alignment precision reached is comparable to that coming from 10 pb^{-1} of LHC data. The acquisition chain has been tested and all the algorithms to reconstruct the data have been verified and tuned.

At the end of 2009 the first LHC collisions taken at a center of mass energy of 900 GeV and of 2.36 TeV have proved that the muon system was able to correctly reconstruct the first muons produced and is ready for the 2010 LHC data taking.

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