Reconstruction of Cosmic and Beam-Halo Muons with the CMS Detector

N. Neumeister and C. Liu

Purdue University, W. Lafayette, IN 47907, USA

The powerful muon and tracker systems of the CMS detector together with dedicated reconstruction software allow precise and efficient measurement of muon tracks originating from proton-proton collisions. The standard muon reconstruction algorithms, however, are inadequate to deal with muons that do not originate from collisions. We present the design, implementation, and performance of a dedicated cosmic muon track reconstruction algorithm, which features pattern recognition optimized for muons that are not coming from the interaction point, i.e. cosmic muons and beam-halo muons. To evaluate the performance of the new algorithm, data taken during Cosmic Challenge phases I and II as well as beam-halo muons recorded during the first LHC beam operation were studied. In addition, a variety of more general topologies of cosmic muons and beam-halo muons were studied using simulated data to demonstrate some key features of the new algorithm.

1. INTRODUCTION

The efficient and accurate detection of muons and the reconstruction of their momenta with high precision over a large range of muon energies are crucial for the LHC physics program. The Compact Muon Solenoid (CMS) experiment [1] at the LHC provides excellent muon identification and reconstruction capabilities. A large superconducting solenoid with a 4 T magnetic field provides strong bending power, allowing a precise measurement of the momentum. A complex muon system has been designed that consists of 3 different types of detectors, sandwiched between layers of the iron return yoke. Centrally-produced muons are detected in the silicon tracker, the calorimeters, and the muon system.

In addition to centrally-produced muons, particles that do not originate from $p-p$ collisions, such as cosmic muons and beam-halo muons, can be recorded by the CMS detector. However, the detection and reconstruction of cosmic and beam-halo muons are different from that of muons from $p-p$ collisions. Cosmic muons are the most abundant particles originating from cosmic rays at sea level [2]. Beam-halo muons are machine-induced particles that travel along the beam line. Although in physics analyses these types of muons are generally considered as sources of background, they can be used for detector alignment, calibration, and detector performance validation. The efficient reconstruction of cosmic and beam-halo muons is especially important for the commissioning phase of the detector.

Since the standard muon reconstruction software has been optimized to identify and reconstruct muons originating from $p-p$ collisions, a different optimization must be carried out to reconstruct effectively the muons coming from outside the detector. A dedicated cosmic muon reconstruction software was developed and the performance was tested with real data taken during the CMS Magnet Test and Cosmic Challenge (MTCC) [3]. Unlike muons from collisions, which are moving radially outward, cosmic muons arrive at the detector from random directions and at random times. They can traverse either both hemispheres or only a small part of the detector depending on their energy and direction. Figure 1 illustrates the different topologies of muons coming from outside and from $p-p$ collisions. In some cases, as indicated in Figs. 1(b) and (c), the standard muon reconstruction algorithm can reconstruct a cosmic muon, but the muon will be recognized as 2 separate tracks. Cosmic muons arriving at the detector in coincidence with $p-p$ collisions are a potential background for the physics processes. Distinguishing them from real muon events is crucial for many physics analyses. In addition, reconstructing such muon trajectories provides an important tool for aligning detector components and studying trigger and reconstruction efficiencies, especially during the initial data taking period [4].

Muon reconstruction as implemented in the official CMS software framework is performed in 3 stages: local pattern recognition within each muon chamber, standalone reconstruction that builds tracks within the muon system, and global reconstruction that builds tracks using data from the muon system and the silicon tracker. Already at the level of local reconstruction in the muon system, cosmic muons and beam-halo muons should be treated differently. For
example, in the barrel drift tube muon system, drift times are recorded and transformed to local positions for further reconstruction. The latencies of different drift tube chambers and readout electronics are different and depend on the location of the muon track and on its time of arrival within the (arbitrary, in the case of cosmic muon) bunch crossing (BX) window defined by the trigger. Since cosmic muons arrive randomly in time, a specific calibration process is carried out as discussed in [5, 6]. In this article, we focus on the standalone and global muon reconstruction steps by presenting the limitation of the standard reconstruction algorithms and proposing an alternative reconstruction algorithm for cosmic and beam-halo muons. The standard algorithms are designed with the assumption that muons are coming from the interaction point and the direction of the energy flow of trajectories is always out-going from the center of the detector. Pattern recognition based on this assumption is not suitable for the reconstruction of muons coming from outside the detector, except for some special cases when the direction of cosmic muons is pointing to the interaction point. To correctly and efficiently reconstruct cosmic muons and beam-halo muons, the cosmic muon reconstruction algorithm assumes that muons are coming from outside, and is optimized by utilizing properties of cosmic muons and beam-halo muons as discussed below.

The new cosmic muon reconstruction software [7] has been released and is available to the CMS community as a part of the official CMS software releases. During the MTCC the new cosmic muon reconstruction software was employed successfully to reconstruct cosmic muons traversing a full slice of the CMS detector. Although the initial motivation of the design was to reconstruct cosmic muons, the reconstruction algorithm can also be applied to beam-halo muons.

2. THE CMS MUON SYSTEM

The CMS muon system [8] is composed of 3 independent subsystems. In the barrel region (|η| < 0.8), drift tube (DT) detectors are installed, while cathode strip chambers (CSC) are used in the endcap regions (1.2 < |η| < 2.4). In the intermediate (“overlap”) region (0.8 < |η| < 1.2), chambers of both detectors are crossed by a muon track from the interaction point. Resistive plate chambers (RPC) are installed in the |η| < 1.6 region, covering both the barrel and the endcaps. RPCs have limited spatial resolution, but good time resolution, thus can provide excellent bunch crossing identification. The barrel muon system is arranged in 5 wheels along the z-axis, where each wheel is divided into 12 sectors and 4 stations called (from innermost to outermost) MB1, MB2, MB3, and MB4. Each station consists of 12 chambers, except for MB4, which has 14 chambers. The endcap muon system is arranged in 4 stations at each end of the detector. They are numbered from ME1 to ME4 in order of their absolute values of z-position. The innermost CSC stations are composed of 3 concentric rings, while the other stations are composed of 2 rings only. Each ring consists of 18 or 36 trapezoidal chambers.

3. RESULTS

The performance of the new cosmic muon reconstruction algorithm was studied using simulated data from a dedicated Monte Carlo cosmic muon generator [5] as well as data taken during MTCC. Fig. 2 shows an event display of a reconstructed cosmic muon in a 3.8 T magnetic field.

It is possible to observe muons that traverse the whole CMS detector, as illustrated in Fig. 1(b). With the algorithm described here, all hits from both hemispheres of the detector can be used in a single trajectory, which in turn allows for a more precise momentum measurement and provides an excellent tool for alignment.

The efficiency to reconstruct traversing muons is defined as the number of events containing a track passing through 2 hemispheres divided by the number of events containing 2 separate standalone tracks in the 2 hemispheres. The measured efficiency is about 85%. Because more hits over a larger distance are included in traversing trajectories, the $p_T$ resolution of traversing tracks is better than for muons reconstructed only in one hemisphere.
Figure 1: Illustration of the differences among muons from $p$-$p$ collisions, different types of cosmic muons, and beam-halo muons. (a) Muons from collisions always propagate from the center to the outside and the pattern is well-defined; (b) Cosmic muons can penetrate the detector and leave signals in opposite hemispheres of the muon system; (c) Cosmic muons can leave signals in the tracker system and opposite hemispheres of the muon system; (d) Cosmic muons can enter the detector and leave without passing through all muon detector layers; (e) beam-halo muons can penetrate the detector and leave signals in both endcap regions; (f) Cosmic muons can enter the endcap region and leave from the barrel region of the detector (or vice versa, in the upper part of the detector).
3.1. Global Cosmic Muon Reconstruction

The first reconstructed muon trajectory passing through the Tracker, DTs, and CSCs was reported shortly after the MTCC phase I. The efficiency of global cosmic muon reconstruction is defined as the number of events with the global cosmic muon track built successfully over the number of events with 1 standalone cosmic muon track and 1 tracker track. The measured efficiency by this definition was to be about 46%.

3.2. Strategy and Performance of Beam-Halo Muon Reconstruction

Beam-halo muons are machine-induced particles that travel along the beam line from outside of the detector. In CMS software, beam-halo muons can be reconstructed by the same software package and configuration used for cosmic muons. When the $|\eta|$ value of the momentum of a trajectory seed in the endcap region exceeds a given threshold, it is identified as a beam-halo muon. In this case, all barrel layers are skipped when asking for compatible layers in the navigation step, because beam-halo muons will pass through the entire sensitive zone of the barrel DT and RPC chambers, which creates a large amount of charge to be deposited and decreases the chamber efficiency [8]. Although not all beam-halo muons arrive at the second endcap, the layers in the second endcap are still chosen as compatible layers. The compatible layers are ordered as outside-in on one end and inside-out on the other. The navigation direction is flipped from outside-in to inside-out when the endcap region changes during building trajectory.

Fig. 3 shows a reconstructed beam-halo muon recorded during the LHC beam operation in September 2008. The reconstruction efficiency, defined as the number of events with track reconstructed successfully divided by number of
events with 2 or more track segments built in the CSC system, is about 99%.

4. CONCLUSIONS

We have described a new algorithm designed to reconstruct cosmic muons and discussed the different reconstruction strategy compared to the standard muon reconstruction algorithm. The new cosmic muon reconstruction algorithm works efficiently for both cosmic muons and beam-halo muons. A full detector simulation and reconstruction analysis was carried out to validate the performance. In addition, data taken during the MTCC were compared to simulated cosmic data, and good agreement between simulated and reconstructed results was observed. The presented cosmic muon reconstruction software provides a powerful tool to utilize cosmic and beam-halo muons for synchronization and alignment during the commissioning of the CMS detector and the initial data taking period at the LHC.

References

[1] CMS Collaboration, Technical Proposal, CERN/LHCC 94–38.
[2] Particle Data Group, W. M. Yao et al., J. Phys. G, 33, 1 (2006).
[3] CMS Collaboration, CMS NOTE 2007/005.
[4] V. Drollinger, CMS NOTE 2005/012.
[5] P. Biallass et al., CMS NOTE 2007/024.
[6] N. Amapane et al., CMS NOTE 2007/034.
[7] C. Liu et al., Eur. Phys. J. C (2008) 56; 449–460.
[8] CMS Collaboration, CMS Physics TDR, Volume 1, CERN/LHCC 2006-001.