The CMS Muon Reconstruction Software

Daniele Trocino
on behalf of the CMS Collaboration

Università di Torino, Dip. Fisica Sperimentale & INFN Torino, 10125 Torino, Italy

Abstract. Muonic final states will provide clean signatures for many physics processes at the LHC. One of the main goals of the Compact Muon Solenoid (CMS) design is thus to ensure efficient and accurate identification and reconstruction of muons. A sophisticated muon system is used for muon identification and stand-alone reconstruction and the inner silicon tracker exploits the high magnetic field to ensure a very precise transverse momentum resolution. The global reconstruction algorithms combine muons reconstructed in the dedicated spectrometer with tracks reconstructed in the inner detector. The CMS reconstruction software is well suited for both offline reconstruction and online event selection (HLT) and its performance has been studied in detail using Monte Carlo simulations. The muon reconstruction has also been employed successfully to reconstruct cosmic muons traversing the CMS detector. The design of the CMS muon identification and reconstruction is presented, as well as its performance on simulated and cosmic data.

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INTRODUCTION

One of the main goals of the Compact Muon Solenoid experiment [1] at the LHC is an efficient reconstruction of muons and a precise measurement of their momenta over a large range of energies. The tracking is based on an intense (3.8 T) magnetic field provided by a superconducting solenoid which allows to measure the bending coordinate independently inside and outside the coil. Muons are detected in the inner *silicon tracker* [2] and in the *calorimeters* [3] [4], located inside the magnet coil, and in a hermetic *muon system* [5], embedded in the return yoke of the magnet.

The muon system is composed of three types of gaseous detectors, used both for tracking and for trigger purposes. Drift Tube (DT) chambers are used in the barrel region and Cathode Strip Chambers (CSC) in the endcaps. For redundancy both the barrel and the endcaps are instrumented with Resistive Plate Chambers (RPC), which also provide a good time resolution.

The muon reconstruction is also crucial for the trigger selection. The CMS trigger is designed in only two physical levels: the *Level-1* [6], implemented on dedicated hardware, and the *High Level Trigger* (HLT) [7], fully implemented in software. In order to optimize the CPU-time consume, the HLT is organized in a sequence of logical steps.

MUON RECONSTRUCTION SOFTWARE

The muon track reconstruction is performed in three steps [8]: reconstruction of hits and segments inside each muon chamber (*local reconstruction*); track reconstruction in the muon system alone (*stand-alone reconstruction*); reconstruction of the final track using the whole CMS Tracking System (*global reconstruction*).

The same algorithms are used both for the off-line and the HLT muon recostruction. The muon HLT is organized in two steps: the *Level-2*, based on the stand-alone reconstruction, and the *Level-3*, based on the global reconstruction.

The tracking of a muon candidate is based on a *Kalman filter* [9] technique and starts from a *seed* state, provided by the L1 trigger in the HLT reconstruction and built from the DT/CSC segments in the off-line reconstruction.

Local Reconstruction

In each DT chamber, the measured drift times are converted into positions with respect to the wires, thus obtaining *1D points* either in the ϕ (up to 8) or in the θ (up to 4) coordinate. These are used to build *2D segments* (in the R-ϕ or R-θ plane), which are finally combined to form a *3D segment*, with a position resolution of 150-200 μm.

In the CSC's, *2D points* are built combining the ϕ coordinate, measured by strips, and the R coordinate, measured by wires. The *3D segments* are determined fitting such 2D points from the 6 layers of each chamber. The position resolution is about 100-240 μm.

The RPC's measure the ϕ coordinate using a clusterization algorithm. These points are used in the track fit, even though the RPC's have been designed mainly for trigger purposes.

Stand-Alone and Level-2 Reconstruction

The trajectory is built with a Kalman Filter technique, starting from the seed state and proceeding iteratively through all the muon system. At each step, the *state vector* (track position, direction and momentum) is extrapolated to the next layer of chambers and here the most compatible *segment* is chosen on a χ^2 basis (*pattern recognition*). If the new measurement satisfies a χ^2 cut, the trajectory parameters are updated including the new information: either the whole segment or its single hits can be used in the fit. This iterative procedure is performed twice: once from inside out (*pre-filter* or *forward filter*) to eliminate possible biases from the seed; the second time from outside in (*filter* or *backward filter*). Finally, the track is extrapolated to the point of closest approach to the beam line and a vertex constraint is applied to improve the momentum resolution.

Global and Level-3 Reconstruction

The stand-alone track is used to define a *region of interest* (ROI) within the silicon layers of the tracker. At this point, two strategies are available. One assumes that the tracks in the tracker are already built and tries to match them with the stand-alone track. The other performs a prompt reconstruction of the tracks only in the ROI and then performs the matching with the muon system. In both cases, the tracker tracks are built using a Kalman Filter procedure. The latter method is better suited for the HLT.

Once the two compatible tracks are found, the whole set of hits in the tracker and muon system is fitted and the final track is extrapolated to the vertex.

TRACKER MUON RECONSTRUCTION

The algorithm described in the previous section works well if a high quality muon track exists in the muon detector. In some cases, especially for muons with transverse momentum below 6-7 GeV/c, the hit and segment information in the muon system is minimal and stand-alone muon reconstruction fails. The geometrical acceptance of the muon system also causes inefficiencies, as can be seen in Fig. 1.

A complementary approach consists in considering all the tracker tracks and identifying them as muons by looking for compatible signatures in the calorimeters (energy depositions) and in the muon system (compatible hits and segments). This method is called "Muon Identification" and the muons identified with this method "Tracker Muons".

PERFORMANCE

Detailed studies of the performance have been done using full detector simulation, pile-up events and realistic detector misalignment scenarios. The following figures show the reconstruction efficiency (Fig. 1) and the transverse momentum resolution (Fig. 2) for stand-alone and global muons. Fig. 2 shows that the transverse momentum resolution for global reconstruction is dominated by the tracker component up to about 200 GeV/c, while at higher p_T the contribution from the muon system improves significantly the global resolution.

The muon reconstruction software has also been commissioned reconstructing cosmic muons traversing the CMS detector (Fig. 3), with excellent results.

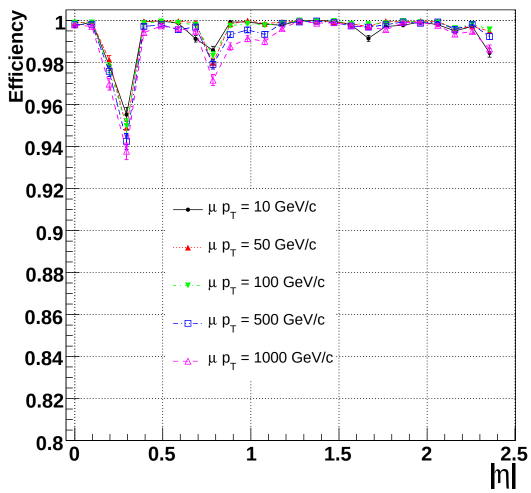

FIGURE 1. Stand-alone (*left*) and global (*right*) muon reconstruction efficiency as a function of pseudorapidity and for several p_T values. The dips are due to the geometrical acceptance of the muon chambers.

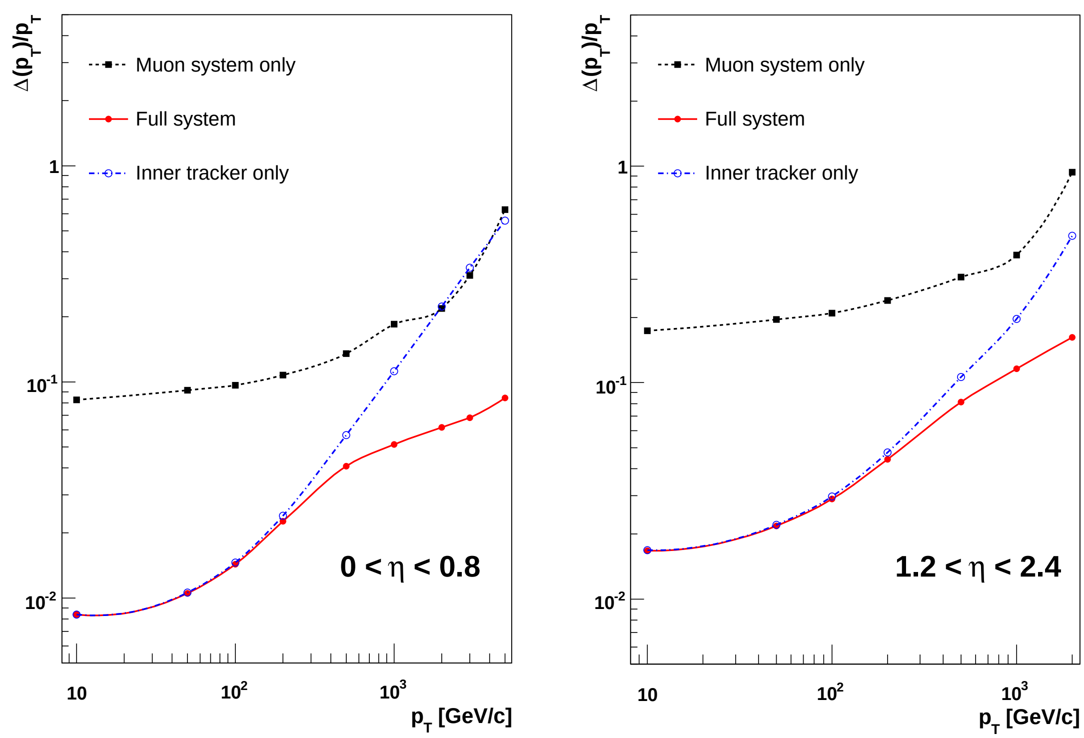

FIGURE 2. Transverse momentum resolution of stand-alone (*black*), tracker (*blue*) and global (*red*) muons as a function of p_T, in the central region $|\eta| < 0.8$ (*left*) and forward region $1.2 < |\eta| < 2.4$ (*right*).

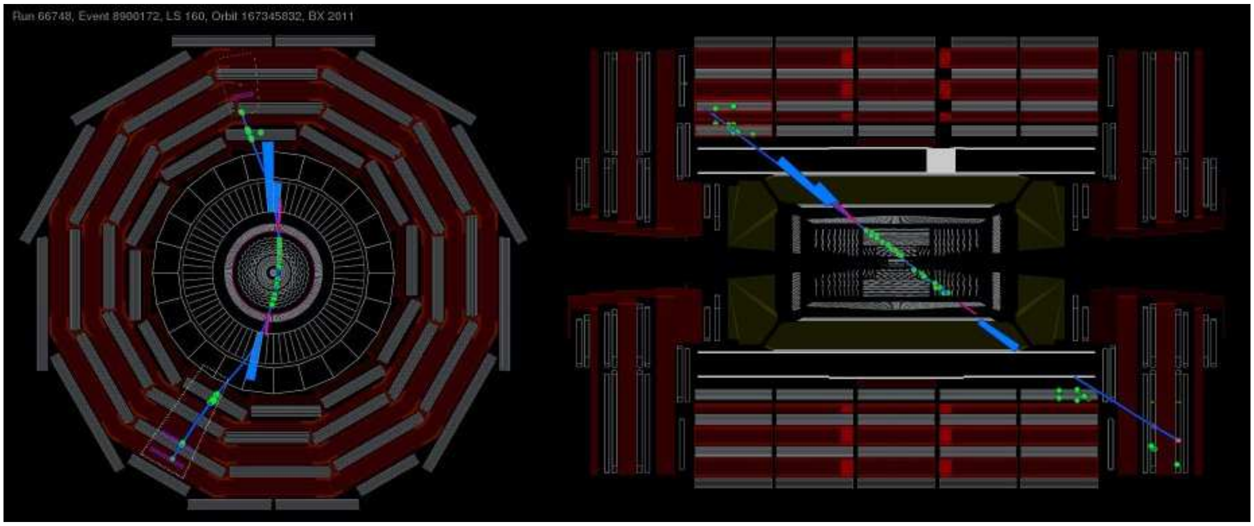

FIGURE 3. Visualisation of a cosmic muon traversing the CMS detector.

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