Muon Reconstruction Software in CMS

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Abstract

The CMS detector has a sophisticated muon system made up of tracking chambers and dedicated trigger chambers. A powerful muon reconstruction software has been developed which reconstructs muons in the stand-alone muon system, using information from all three types of muon detectors, and links the resulting muon tracks with tracks reconstructed in the silicon tracker. The software is designed to work for both, offline reconstruction and for online event selection within the CMS High-Level Trigger (HLT). Since the quality of the selection algorithms used in the HLT system is of utmost importance the software has been designed using modern object-oriented software techniques and is implemented within the CMS reconstruction software framework. The design, implementation and performance of the CMS muon reconstruction software is presented.

INTRODUCTION

The CMS (Compact Muon Solenoid) experiment is one of the two general purpose experiments that will study proton-proton and heavy ion collisions at the Large Hadron Collider (LHC). With a center-of-mass energy for proton collisions of 14 TeV and a design luminosity of $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, the LHC is a machine of unprecedented complexity and potential. The accelerator is currently under construction at CERN, and is scheduled to start delivering collisions from mid 2007.

The CMS design is based on the choice of an intense magnetic field, obtained by using a large superconducting solenoid which accommodates a silicon tracker, a crystal electromagnetic calorimeter and a sampling hadron calorimeter. The 4 T magnetic field ensures high momentum resolution for charged particles and reduces the pile-up from soft hadrons in the four-station muon system. The tracking system is based on silicon strip and silicon pixel detectors for the vertex reconstruction. The electromagnetic calorimeter is made of $PbWO_4$ crystals and the hadron calorimeter is made of copper absorber plates interleaved with 4 mm thick plastic scintilator tiles. Finally, the muon system consists of tracking and trigger chambers and is embedded in the iron of the magnet return yoke. The CMS detector has a length of 21.6 m, a diameter 14.6 m and a total weight of ~ 12500 tons.

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THE CMS MUON SYSTEM

Three types of gaseous detectors are used to identify and measure muons [1]. The choice of the detector technologies has been driven by the very large surface to be covered and by the different radiation environments. In the barrel region ($|\eta| < 1.2$), where the neutron induced background is negligible, the muon rate is low and the residual magnetic field is low, Drift Tube (DT) chambers are used. In the two endcaps, where the muon rate as well as the neutron background is high, and the magnetic field is high as well, Cathode Strip Chambers (CSC) are employed and cover up to $|\eta| < 2.4$. Finally, Resistive Plate Chambers (RPC) are used in both barrel and endcaps, up to $|\eta| < 2.1$.

The layout of one quarter of the CMS muon system is shown in Fig. 1. In the barrel region, four stations of detectors are arranged in cylinders interleaved with the iron yoke. Each muon station has a DT and a RPC, plus one additional layer of RPC in each of the first two stations, to improve the low p_T trigger efficiency. The segmentation along the beam direction follows the five wheels of the yoke. In each of the endcaps, the CSCs and RPCs are arranged in four disks perpendicular to the beam, and in concentric rings around the disks, three in the innermost, and two in the others.

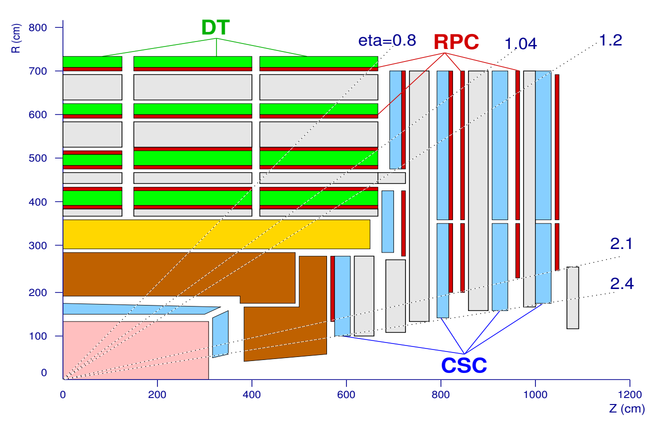

Figure 1: Layout of the CMS muon system.

THE CMS HIGH-LEVEL TRIGGER

The High-Level Trigger (HLT) [2] is the second step of the CMS online selection chain. Its goal is to reduce the event rate from the maximum Level-1 output rate of 100 kHz to a rate of $\mathcal{O}(100)$ Hz. The HLT is fully implemented in software running on a single farm of commercial processors, each one processing one full event at a time. This system incorporates the functionality of the Level-2 and Level-3 trigger hardware of a more conventional trigger design.

This design of a fully programmable system allows complete flexibility of the algorithms, which are only limited by the maximum available CPU time and data bandwidth. This flexibility will allow to adapt the system to unforeseen conditions or developments. The use of standard software techniques and languages will make it possible to benefit from the continuous improvements in the reconstruction software.

While the HLT runs on a single processor farm and does not have an internal architecture of separate trigger levels, uninteresting events should be discarded as soon as possible. It is therefore useful to organize the selection in a chain of logical steps that consist of progressively more sophisticated and CPU-time consuming algorithms. Selection criteria are applied at the end of each step, in order to reduce the event rate to a level acceptable for the following one. For muons there are two logical steps: Level-2, where only data from the calorimeters and muon detectors are used, and Level-3, which also utilizes the information from the silicon tracker. Additional rate rejection is obtained at both levels by the use of isolation algorithms.

The HLT reconstruction algorithms are implemented according to the principle of regional reconstruction, that is the ability to reconstruct an object using only the information coming from a limited region of one (or more) subdetectors. This leads to significant CPU savings and allows to discard uninteresting events even without reading out the full event data. Regional reconstruction requires prior identification of the object to be reconstructed; therefore each trigger level uses the candidates reconstructed at the previous level as seed. Regional reconstruction also implies that HLT algorithms are designed to be executed on-demand, i.e. they are performed only when they are explicitly requested.

MUON RECONSTRUCTION

A software package based on a Kalman filter technique [5] has been developed, which performs muon reconstruction in the muon system and the silicon tracker. The software has been designed using the concept of regional reconstruction in order to allow the application in both offline reconstruction and the HLT (online event selection).

The muon reconstruction algorithm used by the HLT is seeded by the muon candidates found by the Level-1 muon trigger, including those candidates that did not necessarily lead to a Level-1 trigger accept. These seeds define a region of interest in he muon system, in which local reconstruction is performed.

In case of offline reconstruction a different seed generation has been developed, which performs local reconstruction in the whole muon system and uses patterns of segments reconstructed in CSC and/or DT chambers as initial seeds.

Muon reconstruction is performed in three stages: Local reconstruction (local pattern recognition), stand-alone reconstruction and global reconstruction. Starting from a seed, the chambers compatible with the seed are identified, and local reconstruction is performed only in these chambers. Stand-alone muon reconstruction uses only information for the muon system, while global muon reconstruction uses also silicon tracker hits. In case of HLT stand-alone and global reconstruction are called Level-2 and Level-3 reconstruction respectively.

Local Reconstruction

The first step is local reconstruction in the multi-layer chambers (DT and CSC), which attempts to associate aligned hits and builds track segments [3].

In the DT chambers, hits in the three superlayers (four layers of drift tubes) are independently reconstructed in the two different projections, bending ($R\phi$) and along the beam axis (Rz). First, the hits in the drift cells are reconstructed using a linear time-space conversion. A single cell has an intrinsic left-right ambiguity which can be solved only by associating hits from different layers. In order to get the best cell resolution, the drift velocity in the gas, the magnetic field and the impact angle in the cell have to be taken into account. As they are not available at the first step of the hit reconstruction, an iterative process is applied. For each projection, two-dimensional segments are built, performing a linear fit. The left-right ambiguities are solved with a best χ^2 criterion. In the $R\phi$ projection, hits in the two superlayers are used. A correction for the impact angle is applied on the hits forming the segments, and the fit is repeated. Finally, the two projections are associated and a three-dimensional segment is built. The resolution of the reconstructed track segments amounts to $\sigma_x \sim 100\ \mu$m for position and $\sigma_\theta \sim 1$ mrad for direction.

In the Cathodes Strip Chambers each of the six layers is able to provide two coordinates. The measurement in the bending coordinate is obtained by clustering together adjacent strips with signals, and by fitting the charge distribution with a Gatti function [4] to get the cluster centroid and width. The resolution of this measurement is $\sim 100\ \mu$m for the innermost CSCs, where the strip pitch is smaller, while it is $\sim 200\ \mu$m for the other chambers. The other coordinate is obtained from the wire signal, discriminated and read out after grouping several wires together. The resolution is therefore $w/\sqrt{12}$, where w is the width of wire group, and is of the order of ~ 0.5 cm. The two projections are associated using a time coincidence of the hits. Finally, the three-dimensional hits are used to create three-dimensional track segments with a linear fit. The pattern recognition starts with two hits in the first and last layers. Hits in other layers are searched for and chosen according to a χ^2 compatibility. No hit sharing is allowed between different segments.

Stand-alone and Level-2 Muon Reconstruction

The stand-alone/Level-2 muon reconstruction uses only data from the muon detectors, without usage of the silicon tracker. Both tracking detectors (DT and CSC) and RPCs participate in the reconstruction. In spite of the poor spatial resolution, the latter complement the tracking chambers, especially where the geometrical coverage is problematic, mostly in the barrel-endcap overlap region.

The starting point are reconstructed track segments from the muon chambers obtained by local reconstruction. The state vectors (track position, momentum and direction) associated with the segments found in the innermost chambers are used to grow the muon trajectories, working from inside out, using a Kalman filter technique [5]. The predicted state vector at the next measurement surface is compared with existing measurements and updated accordingly. In the barrel DT chambers, reconstructed track segments are used as measurements in the Kalman filter procedure. In the endcap CSC chambers, where the magnetic field is inhomogeneous, it is the individual reconstructed constituents (three-dimensional hits) of the segments that are used. Reconstructed hits from RPC chambers are also included. A suitable χ^2 cut is applied in order to reject bad hits, mostly due to showering, delta rays and pair production. In case no matching hits (or segments) are found, e.g. due to detector inefficiencies, geometrical cracks or hard showering, the search is continued in the next station. The state is propagated from one station to the other using the GEANE package [6], which takes into account the muon energy loss in the material, the effect of multiple scattering, and the non-constant magnetic field in the muon system. The track parameters and the corresponding errors are updated at each step. The procedure is iterated until the outermost measurement surface of the muon system is reached. A backward Kalman filter is then applied, working from outside in, and the track parameters are defined at the innermost muon station. Finally, the track is extrapolated to the nominal interaction point (defined by the beam spot size: $\sigma_{xy} = 15$ μm and $\sigma_z = 5.3$ cm) and a vertex constrained fit to the track parameters is performed.

Global and Level-3 Muon Reconstruction

The global/Level-3 muon reconstruction consists of extending the muon trajectories to include hits in the silicon tracker system. Starting from a stand-alone reconstructed muon, the muon trajectory is extrapolated from the innermost muon station to the outer tracker surface, taking into account the muon energy loss in the material and the effect of multiple scattering. The GEANE package is currently used for the propagation through the iron and calorimeters. Silicon layers compatible with the muon trajectory are then determined, and a region of interest within them is defined to perform regional track reconstruction. The determination of the region of interest is based on the track parameters and uncertainties of the extrapolated muon trajectory, obtained with the assumption that the muon originates from the interaction point as described in the previous section. This has a strong impact on the reconstruction efficiency, fake rate, and CPU reconstruction time: well measured muons are reconstructed faster and with higher efficiency than poorly measured ones.

Inside the region of interest, initial candidates for the muon trajectory (regional seeds) are built from pairs of reconstructed hits. The two hits forming a seed must come from two different tracker layers, and all combinations of compatible pixel and double-sided silicon strip layers are used in order to achieve high efficiency. In addition, a beam spot constraint is applied to muon candidates above a given transverse momentum threshold to obtain initial trajectory parameters.

Starting from the regional seeds, a track reconstruction algorithm based on the Kalman filter technique, is used to reconstruct tracks inside the selected region of interest. The track reconstruction algorithm consists of the following steps: trajectory building (seeded pattern recognition), trajectory cleaning (resolution of ambiguities) and trajectory smoothing (final fit). In the first step, the trajectory builder transforms each seed into a set of trajectories. Starting from the innermost layer, the trajectory is propagated to the next tracker layer that is reachable, and updated with compatible measurements found on that layer. In the second step, the trajectory cleaner resolves ambiguities between multiple trajectories that may result from a single seed on the basis of the number of hits and the χ^2 of the track fit. In the final step, all reconstructed tracks are fit once again with reconstructed hits in the muon chambers included from the original stand-alone reconstructed muon, and selected on the basis of a χ^2 cut.

PERFORMANCE

Figure 2 shows the transverse momentum resolution for muons determined by the stand-alone reconstruction as expressed by the distribution of the quantity $(1/p_T^{\rm rec} - 1/p_T^{\rm gen})/(1/p_T^{\rm gen})$, where $p_T^{\rm gen}$ and $p_T^{\rm rec}$ are the generated and reconstructed transverse momenta, respectively. Muons from $\mathrm{W} \to \mu\nu$ decays at LHC design luminosity are used as reference sample. The distributions are broken up into three pseudorapidity intervals: barrel ($|\eta| < 0.8$), overlap ($0.8 < |\eta| < 1.2$) and endcap ($1.2 < |\eta| < 2.1$). Figure 3 shows the same distributions for muons reconstructed with the global muon reconstruction algorithm. The improvement in resolution over the stand-alone muon reconstruction is substantial (factor 10).

The stand-alone muon momentum precision is essentially determined by the measurement in the transverse plane of the muon bending angle at the exit of the 4 T coil, taking the beam spot as the origin of the muon. This measurement is dominated by multiple scattering in the material before the first muon station up to p_T values of $200\mathrm{GeV}/c$, when the chamber space resolution starts to dominate. For low momentum muons the momentum resolution is given by the resolution obtained in the silicon

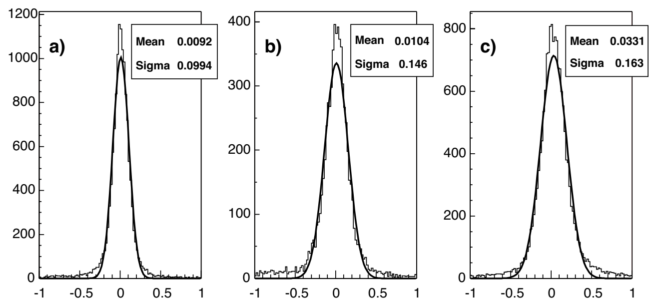

Figure 2: $1/p_T$ resolution for stand-alone reconstructed muons, shown in three pseudorapidity intervals: a) $|\eta| < 0.8$, b) $0.8 < |\eta| < 1.2$, c) $1.2 < |\eta| < 2.4$.

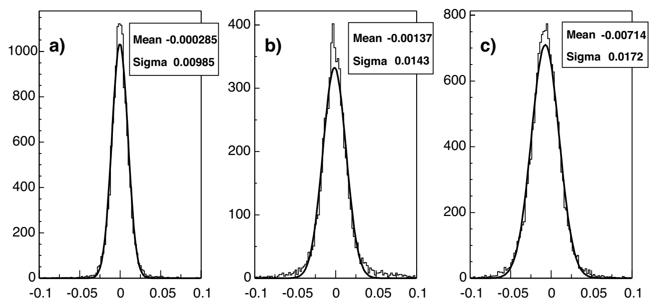

Figure 3: p_T resolution for muons reconstructed with the global muon reconstruction algorithm, shown in three pseudorapidity intervals: a) $|\eta| < 0.8$, b) $0.8 < |\eta| < 1.2$, c) $1.2 < |\eta| < 2.4$.

tracker.

The achieved stand-alone reconstruction efficiency is everywhere larger than $\sim 99\%$. The efficiency of the global muon reconstruction algorithm relative to the stand-alone reconstruction is typically 99%.

Figure 4 shows the inclusive muon rate after each trigger level as a function of the p_T threshold for a luminosity of $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. All relevant physics processes, i.e. minimum bias, heavy flavor generation, W, Z and $\mathrm{t\bar{t}}$ production, have been included in order to simulate the inclusive single muon production. With the described Level-2 reconstruction algorithm a rate reduction of about a factor of 10 is achieved for a threshold of 20 GeV/c. At Level-3, due to the improved resolution, the reconstructed p_T spectrum follows nicely the generated spectrum.

Because the HLT algorithms are executed on an on-line farm, the CPU time needed to reconstruct muons is a crucial issue. With the current implementation most of the time spent (in the Level-2 reconstruction) is consumed in propagating across the iron of the return yoke. Work is underway to replace GEANE with an optimized propagation package customized for the CMS geometry, which should result in a significant speed-up of propagation.

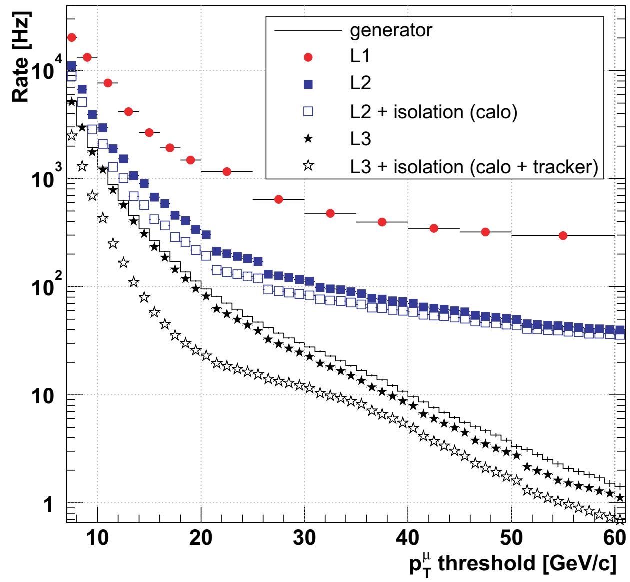

Figure 4: Single-muon trigger rates as a function of the p_T threshold for a luminosity of $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

CONCLUSIONS

The CMS detector has been designed to provide robust, flexible and redundant muon reconstruction and identification. A sophisticated muon reconstruction package was implemented which exploits much of these feature. The implementation of the muon reconstruction algorithms, both stand-alone and with the silicon tracker, have been discussed. The performance of the muon reconstruction and selection algorithms has been shown. It has been demonstrated that offline code with little modifications can be used in the HLT system, by making use of the concepts of regional and conditional reconstruction. The next step to improve the performance of the software will be the development of a new propagation package to replace GEANE.

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