Available on CMS information server **CMS CR 2004/024**

CMS Conference Report

28 June 2004

The performance of the CMS tracking

Nicola De Filippis

Dipartimento interateneo di Fisica dell'Università e Politecnico di Bari, INFN Sezione di Bari,
Via Amendola 173, I-70126 Bari, Italy

CMS collaboration

Abstract

Track and vertex reconstruction in the CMS detector use the information from the silicon pixel and the silicon strip detectors. The track and vertex fitting algorithms are based on the Kalman filter approach. The performance of the tracking procedure is evaluated in terms of efficiency and parameter resolution. The vertex reconstruction performance is reported in terms of primary vertex resolution. Some results obtained with a partial/conditional track reconstruction, used for High-Level Trigger algorithms are also given.

Presented at the *9th topical Seminar on Innovative Particle and Radiation Detectors*,
Siena (Italy), May 23-26, 2004

1 Introduction

High-energy-physics experiments demonstrated, over the past years, that the tracking system plays an important rôle in the reconstruction of events containing leptons and jets. The CMS tracker is designed to reconstruct high-$\mathrm{p_T}$ isolated charged particle tracks with a $\mathrm{p_T}$ resolution better than $\delta\mathrm{p_T}/\mathrm{p_T} \simeq 15 \times \mathrm{p_T}\%$ ($\mathrm{p_T}$ in $\mathrm{TeV/c}$) and to provide high efficiency reconstruction of high-$\mathrm{p_T}$ charged hadrons in jets. The tracker is also required to resolve nearby tracks in a large multiplicity environment and to identify b quarks and τ leptons via secondary vertices.

The requirements on the reconstruction software are stringent; pattern recognition algorithms need to be efficient and robust in order to ensure high performance in track and vertex reconstruction, in the presence of multiple scattering, large particle multiplicity and large background due to hits from low momentum tracks, δ rays and secondary activities. Some of the algorithms developed so far have been implemented in the CMS reconstruction program, ORCA [1].

The CMS tracker [2] is made of an inner silicon pixel detector and a silicon microstrip tracker. The pixel detector consists of three cylindrical layers in the barrel at radii 4.4, 7.5 and 10.2 cm, and two pairs of end-cap disks at $|z| = 34.5$ cm and 46.5 cm down to $|\eta| = 2.2$. The hit position resolution is ~ 10 μm in the (r, ϕ) plane and 17 μm in (r, z) plane. The silicon microstrip detector covers radii between 20 and 110 cm. The barrel region is divided into an Inner Barrel (TIB), made of four layers of sensors, and an Outer Barrel (TOB) made of six layers. The TIB is completed on each side by three inner disks (TID). The forward region is equipped with nine Endcap disks (TEC) [3]. The hit position resolution achieved is $\sigma_{r,\phi}$ = 40-60 μm in (r, ϕ) plane and $\sigma_z = 500$ μm along z.

2 Track reconstruction and performance

The basic ingredients for track reconstruction are the track model, which describes the trajectory of a particle in a magnetic field and the description of material effects, which affects the measurements and their uncertainties at a detector surface.
In order to speed up the reconstruction, all material is assumed to be concentrated on thin surfaces and two numbers are used to describe the material properties of each detector layer: the thickness, expressed in units of radiation length, and the thickness multiplied by the mean ratio of the atomic number to the atomic mass. The energy loss of particles in the tracker material (for electrons due to Bremsstrahlung, for all other particles due to ionization according to Bethe-Block formula [4]) and the multiple scattering (Highland Gaussian approximation [5]) are taken into account.

The track reconstruction in ORCA proceeds through the following steps:

- the seed generation, which provides initial trajectory candidates, either internally to the tracking detector (inner tracker or muon system) or externally by using input from other detectors (calorimeters);
- the trajectory building, which, starting from the seeds, proceeds with the propagation of the trajectory state to the subsequent reachable layers. The predicted trajectory state is updated by combining compatible measurements on each layer;
- the trajectory cleaning, which resolves ambiguities among multiple reconstructed trajectories;
- the trajectory smoothing, which combines the forward and backward fits.

In the trajectory building process, the tasks of track finding and fitting can be performed with hard assignment of hits to tracks, for which a hit either does or does not contribute to a track, or accordingly to an assignment probability distribution (soft assignment), for which a hit can contribute to several tracks. Both approaches use the Kalman filter formalism [6]. The Kalman filter is a method of estimating the states of dynamic systems. Its application to track fitting is straightforward if the track (described by five parameters) is interpreted as a discrete time-evolving system.

The tracking performance is expressed in terms of efficiency and momentum resolution. The global efficiency, which includes the efficiency of the trajectory builder step, the acceptance and the hit reconstruction efficiency, is shown in Fig. 1 as a function of $|\eta|$, for three samples of single muon events with $\mathrm{p_T} = 1, 10, 100\,\mathrm{GeV}/c$. The tracking is fully efficient over the $|\eta|$ range covered by the detector; the degradation at $\eta \sim 0$ is due to the gaps between the two halves of the pixel barrel while that at $|\eta| \geq 2.25$ is caused by the reduced coverage of the end-cap disks.

The transverse momentum resolution for the same single muon samples is shown in Fig. 2. It is better than 3% for $p_T \leq 100\,\mathrm{GeV}/c$ up to $|\eta|$=1.75; at large η, the resolution is affected by the reduced lever arm of the track. The gap between the barrel and the end-cap disks causes a slight degradation at $|\eta| \sim 1$. At momenta smaller than $100\,\mathrm{GeV}/c$ the multiple scattering becomes significant and the p_T resolution reflects the amount of material traversed by the particles.

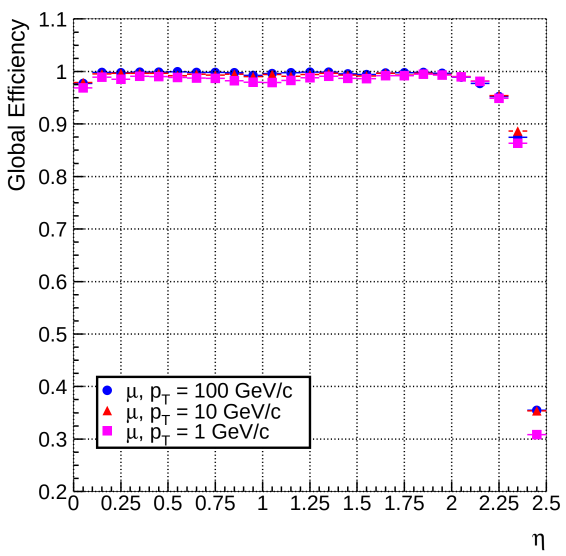

Figure 1: Global efficiency of the tracking algorithm for single muon events with $p_T = 1, 10, 100\,\mathrm{GeV}/c$ as a function of $|\eta|$.

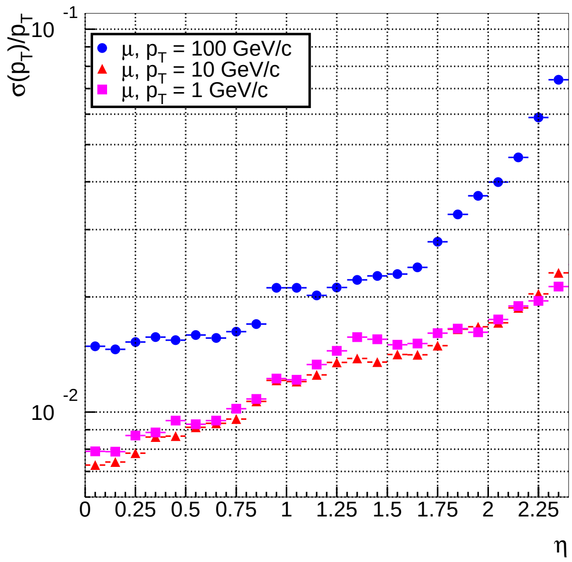

Figure 2: Transverse momentum resolution for single muon events with $p_T = 1, 10, 100\,\mathrm{GeV}/c$ as a function of $|\eta|$.

The Kalman filter is optimal if the track parametrization can be approximated by a linear function of the track parameters in the neighbourhood of the track, and if the distributions of the measurement uncertainties and of the material effects (mainly multiple scattering) are close to Gaussian. If the last hypothesis is not satisfied, the linear Kalman filter can be generalized to deal with non-Gaussian noise, provided that all distributions involved are mixtures of Gaussians. The resulting algorithm, in which several Kalman filters run in parallel, is called Gaussian Sum Filter (GSF).

A GSF algorithm was implemented in ORCA [7] for electron-track reconstruction (where the Bremsstrahlung energy loss distribution is highly non Gaussian), leading to 30 % improvement of the momentum resolution for $10\,\mathrm{GeV}/c$ electrons with respect to the standard Kalman filter.

A track fitting method, implemeting the soft hit assignment, was also developed (Deterministic Annealing Filter) [8]. Hits are assigned to tracks according to an assignment probability distribution computed from the hit residuals. The deterministic approach copes better with the large track multiplicity expected at high luminosity.

3 Vertex reconstruction and performance

Vertex reconstruction algorithms are needed to reconstruct the primary interaction point as well as for the detection and reconstruction of displaced secondary vertices (e.g., inside b jets).

The primary vertex finding starts from hit triplets in the pixel detector; hits are matched in (r, ϕ) and (r, z) to define track candidates. Primary vertices made out of at least three tracks crossing the z axis are used to build a list. Tracks incompatible with any of the vertex candidates are excluded from further processing. The tracking efficiency is above 90% with a ghost rate between 1% and 10%. In a second step, only the primary vertex candidates with at least three valid tracks with $p_T > 1\,\mathrm{GeV}/c$ are kept. The z position of each vertex is given by the mean value of the z impact parameters of all pertaining tracks.

The main primary vertex, i.e., that originating from the signal interaction, is found with 95% efficiency [9]. The primary vertex reconstruction in the pixel detector leads to a position resolution ranging from 20 to 70 μm as shown in Fig. 3. The use of the pixel detector alone makes the reconstruction very fast and useable in the High-Level Trigger. The vertex position resolution can be brought down to 15 μm by using the whole tracker; the computing time consumption, however, is too large and this procedure is appropriate only for accurate offline reconstruction.

4 Tracking for the High-Level Trigger

Track reconstruction in the High-Level Trigger (HLT) is guided by the presence in the event of a Level-1 trigger object or an HLT candidate, with the aim of determining lepton isolation, tagging b jets and improving the p_T resolution of muons [10].

Computing time constraints in the HLT are stringent and tracking algorithms are required to be robust and fast. Track reconstruction can be speeded up by looking for tracks only in the regions of interest defined by Level-1 objects (regional tracking), reducing the number of track seeds in the event. Tracking can also be partial/conditional and it can be stopped when tracks satisfy certain basic requirements (e.g., a minimum number of hits, a minimum p_T, etc.) while keeping the performance at an acceptable level. The p_T resolution as a function of the number of hits reconstructed per track is shown in Fig. 4. The asymptotic value of the resolution is reached with five or six reconstructed hits.

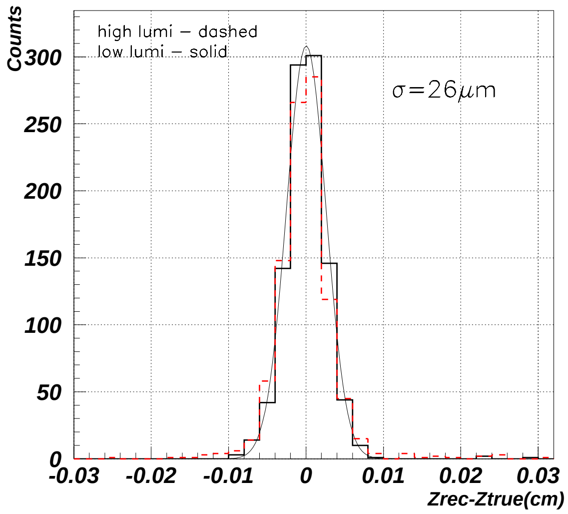

Figure 3: Difference in the z position between the reconstructed and the simulated vertex at low and high luminosity. The standard deviation of the Gaussian fit is quoted as the resolution on the primary vertex position.

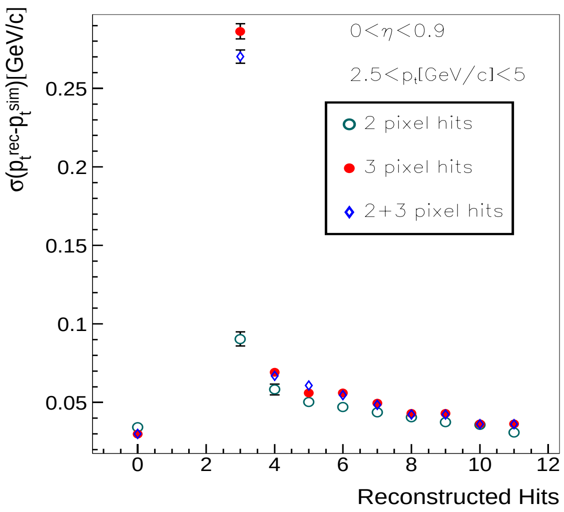

Figure 4: P_T resolution as a function a number of reconstructed hits in the barrel compared to the full tracker performance (the leftmost point at "0").

5 Conclusions

The CMS pixel and microstrip silicon tracker performance at LHC is expected to meet the prior requirements. Track reconstruction algorithms based on the Kalman Filter are robust and fully efficient. The pixel detector allows fast and efficient seed generation and vertex reconstruction. A good precision in the track reconstruction is already achievable with the pixel hits and four silicon strip hits. The possibility to perform fast track reconstruction at High-Level Trigger was studied and proven feasible.

References

[1] *"ORCA User Guide"*, http://cmsdoc.cern.ch/orca

[2] *"The Tracker Project TDR"*, **CERN/LHCC 98-6**.

[3] *"Addendum to the CMS Tracker by the CMS Collaboration"*, **CERN/LHCC 2000-016**.

[4] K. Hagiwara ed al., *"Review of Particle Physics"* Phys. Rev. **D66** (2002) 010001

[5] V. Highland, *"Some practical remarks on mutiple scattering"*, Nucl. Instrum. and Methods **129** (1975) 479.

[6] R. Frühwirth, *"Application of Kalman filtering to track and vertex fitting"*, Nucl. Instrum. and Methods. **A 262** (1987) 444.

[7] W. Adam, R. Frühwirth, A. Strandlie, and T. Todorov, *"Reconstruction of electrons with the Gaussian-sum filter in the CMS tracker at LHC"*, CMS Collaboration, **CMS CR-2003/012**

[8] R. Frühwirth and A. Strandlie, *"Track fitting with ambiguities and noise: a study of elastic tracking and non-linear filters"* Comput. Phys. Commun. **120** (1999) 197.

[9] *"CMS Data Acquisition and Higher Level Trigger TDR: section 14"*, **CERN/LHCC 02-26**.

[10] *"CMS Data Acquisition and Higher Level Trigger TDR: section 15"*, **CERN/LHCC 02-26**.