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Track reconstruction in heavy ion collisions with the CMS silicon tracker

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Abstract

The Large Hadron Collider at CERN will collide protons at $\sqrt{S} = 14\,\mathrm{TeV}$ and lead ions at $\sqrt{S_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$. The study of heavy ion collisions is an integral part of the physics program of the Compact Muon Solenoid (CMS). Central heavy ion events at LHC energies are expected to produce a multiplicity of up to 3500 charged particles per unit of rapidity. The CMS detector features a large acceptance and high resolution silicon tracker consisting of pixel and strip detector layers. We describe the algorithms used for pattern recognition in the very high track density environment of heavy ion collisions. Detailed studies using the full detector simulation and reconstruction are presented and achieved reconstruction efficiencies, fake rates and resolutions are discussed.

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Keywords: CMS; Silicon tracker; Track reconstruction; Heavy ion; High density environment

1. Introduction

The ability to reconstruct individual charged particles in heavy ion collisions allows a vast field of physics topics to be addressed when studying strongly interacting matter at the LHC. Thus, track reconstruction in the CMS silicon tracker in a very high track density environment is a key element to the success of the CMS heavy ion program. In heavy ion collisions the expected high charged particle density, $\mathrm{d}N/\mathrm{d}y$ of up to 3500 particles per unit rapidity in central Pb + Pb collisions [1], leads to a very high detector occupancy. The combinatorial challenge resulting from the high hit density requires robust reconstruction algorithms to achieve efficient pattern recognition while maintaining a low fake rate.

2. The CMS tracker

The CMS tracker is a 5.5 m long, 1.1 m radius cylindrical detector. It is equipped with silicon pixel detectors in the innermost part ($R < 14\,\mathrm{cm}$, $|z| < 50\,\mathrm{cm}$) and silicon strip detectors for the outer layers ($R < 110\,\mathrm{cm}$, $|z| < 275\,\mathrm{cm}$). The pixel detectors provide 2–3 3D hits with a precision of about $10\,\mu\mathrm{m}$ in $R\phi$ and $15\,\mu\mathrm{m}$ in z. The strip detectors measure 8–14 hits with a precision ranging from 10 to $60\,\mu\mathrm{m}$ in $R\phi$. Out of those hits five are recorded on double-sided detectors which add a small-angle stereo measurement to provide 3D information [2].

3. Pattern recognition

The track reconstruction package for heavy ion events is based on the standard reconstruction algorithms developed for pp collisions [3]. The default algorithm is based on a seeded pattern recognition using a Kalman Filter formalism. This strategy is composed of four phases:

(1) trajectory seed generation in the pixel detector;
(2) trajectory building—inside-out propagation;
(3) trajectory cleaning—resolution of ambiguities;
(4) trajectory smoothing—final fit.

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4. Modifications to the algorithm

The track reconstruction algorithm for heavy ion events needs to be robust against the combinatorial problem resulting from the high particle density. To cope with the high occupancy in the Si-strip detectors, shown in Fig. 1, the default track reconstruction procedure is modified in a few key places:

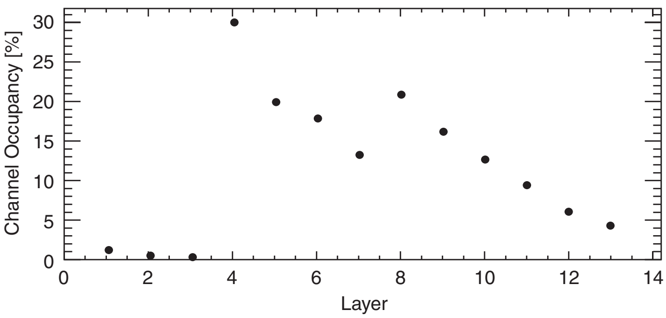

Fig. 1. Channel occupancy in the barrel region as a function of detector layer. Layers 1–3 correspond to the pixel detector, 4–13 to the Si-strip tracker.

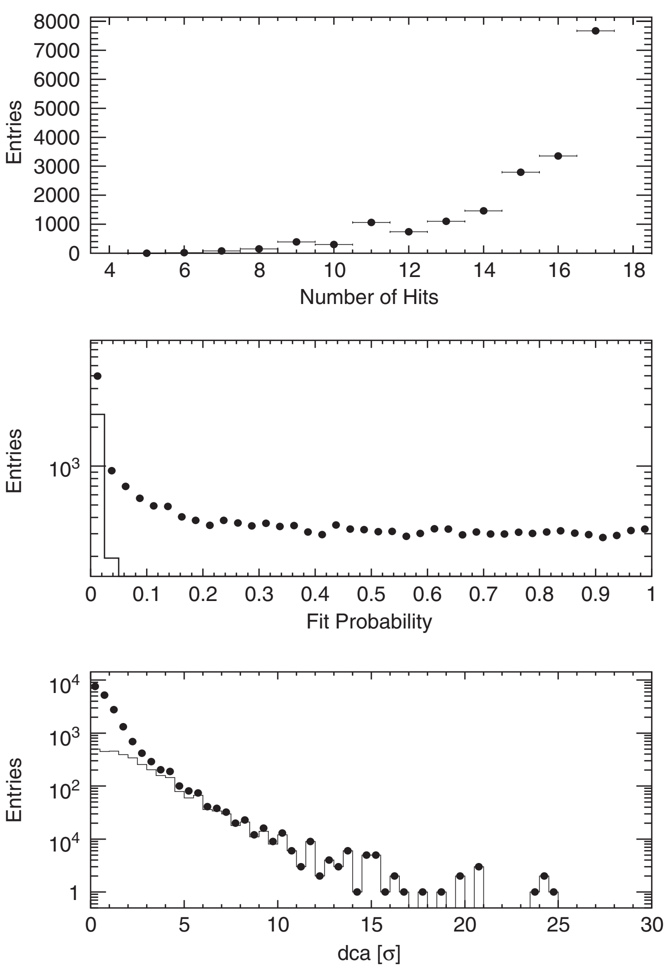

Fig. 2. Track quality measures for all reconstructed tracks (symbols) and for fake tracks contained in the sample (histogram). Upper: number of hits per reconstructed track. Hits on stereo layers are counted as two separate hits. Center: χ^2 probability distribution for reconstructed tracks. Lower: distance of closest approach, dca, to the primary vertex normalized by the error.

Track seeding: The pp track reconstruction package is optimized for maximum overall reconstruction efficiency. Track seeds are generated from two-hit combinations in the three layers of pixel detectors to compensate the lack of hermeticity of a single detector layer. In heavy ion events, the seeding relies on three-hit combinations in the pixel detectors to achieve more precise initial estimates of the track parameters. Requiring three hits in three detector layers results in a 10% loss of overall reconstruction efficiency due to the geometric acceptance of the detector.

Merged hits: In heavy ion events, a significant fraction of clusters in the Si-strip detectors originate from overlapping hits. Merged hits are recognized by comparing the found cluster width with the width expected from the angle of the trajectory to the detector surface. An error corresponding to the full cluster width is assigned to merged hits.

Split stereo layers: In the final smoothing step, hits in the double-sided silicon strip layers are split and treated as separate hits. The stereo information of these detector layers cannot be used due to the high track density and overlapping hits.

Track quality: The number of fake tracks in the final data sample is controlled by imposing constraints on the quality of the reconstructed tracks. The reconstruction quality is addressed by the number of reconstructed hits on the track, the χ^2-probability of the track fit and the compatibility of the track with the event vertex. The corresponding distributions are shown in Fig. 2.

5. Performance plots

The performance of the track reconstruction algorithms in heavy ion collisions is evaluated using a data sample generated by the HYDJET event generator [4] with parameters tuned to yield a charged particle density $\mathrm{d}N/\mathrm{d}y \approx 3000$ at $y = 0$. Events simulated by HYDJET include both soft particle production simulated by a hydrodynamic module and multiple hard collisions simulated by PYTHIA. The high p_{T} part of the particle spectrum is dominated by jets originating from hard collisions.

With the modifications of Section 4, a high algorithmic reconstruction efficiency can be achieved in central heavy ion collisions while retaining a very low fake rate. Fig. 3 shows the track reconstruction efficiency and fake rate as a function of transverse momentum in the barrel region of the tracker for two sets of quality cuts imposed on the reconstructed tracks. The momentum and impact parameter resolution achieved in heavy ion collisions (see Fig. 4) is comparable to the resolution in low occupancy pp events.

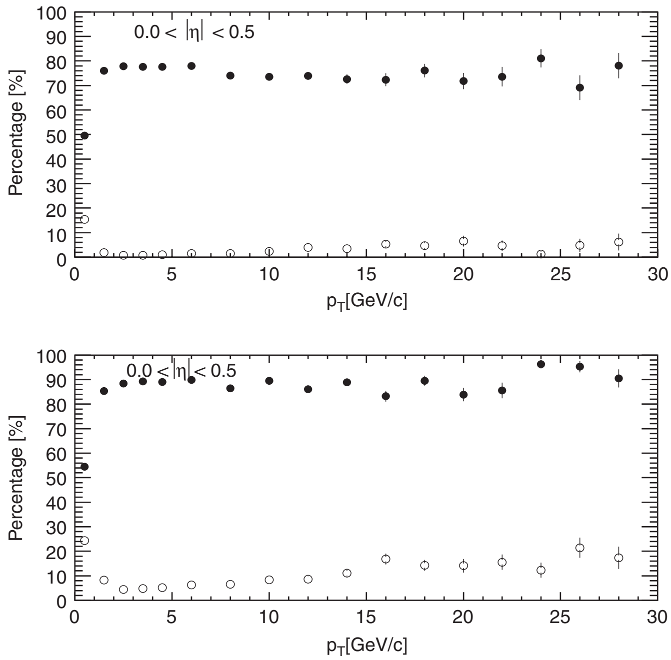

Fig. 3. Reconstruction efficiency (full symbols) and fake rate (open symbols) as a function of transverse momentum in the barrel region of the tracker for central Pb + Pb collisions with $dN/dy \approx 3000$. Upper: track quality cuts optimized for low fake rate (number of hits >12, fit probability >0.01 and dca <3). Lower: track quality cuts optimized for high efficiency (number of hits >12).

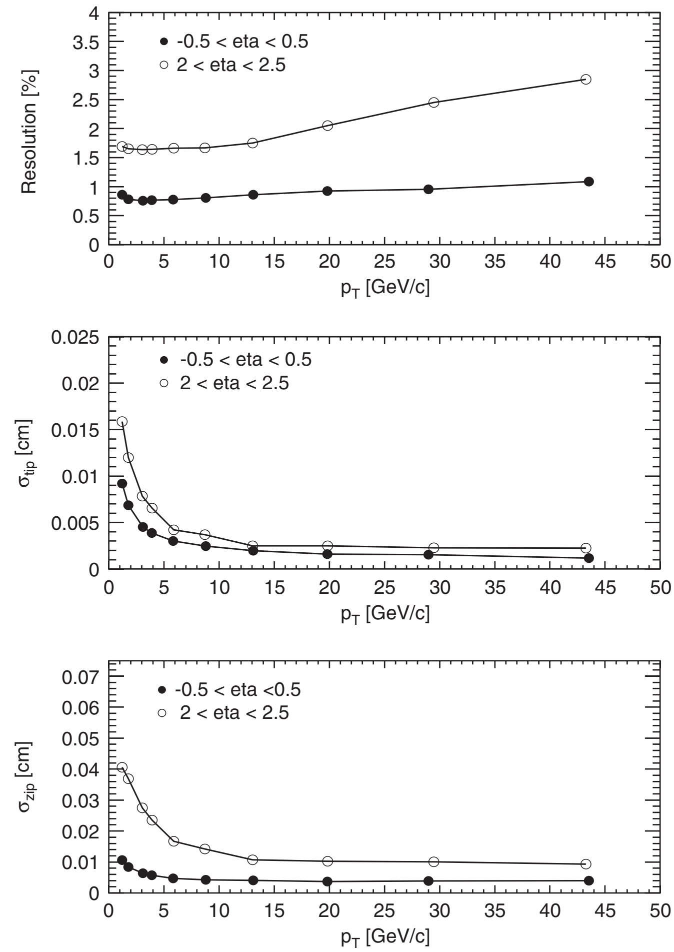

Fig. 4. The p_T dependence of the track parameter resolution achieved in heavy ion events in the barrel region (full symbols) and in the forward region (open symbols). Upper: transverse momentum resolution. Center: transverse impact parameter resolution. Lower: longitudinal impact parameter resolution.

6. High occupancy effects in detector hardware and readout

To demonstrate the feasibility of reconstructing charged particles in the high occupancy environment of heavy ion collisions, a detailed study using full detector simulation and reconstruction was made. At each stage of the readout chain, the ability of the readout electronics and buffers of the detector components to cope with the high hit density was checked. All detector components were found to be fully functional. However, two effects can be identified that lead to a potential loss of reconstruction efficiency.

The first effect is due to the Common Mode Noise (CMN) subtraction in the silicon strip tracker. The Si-strip tracker data are likely to be subject to common mode variations of unknown magnitude. The strips of each detector element are readout in groups of 128 channels by the front end chips, the so called APV (for Analog Pipeline Voltage mode), which includes pre-amplifier and shaper stages for each channel. The analog data from the APV are transferred by optical fibers to Front End Driver (FED) digitizing boards. The FED performs pedestal subtraction, CMN correction and zero-suppression using firmware algorithms implemented within FPGA devices so that only useful signal information is transmitted to the data acquisition system [3]. The common mode offset is estimated by calculating the median ADC value of the data on the 128 strips read by each APV.

At high occupancy, this simple algorithm introduces a false common mode offset that is dependent on the detector occupancy which, in turn, leads to an inefficiency in the hit finding. A hit loss probability of up to 4% is observed for the innermost detector layer. This inefficiency can be fully recovered with a more sophisticated common mode offset estimate. Currently, more sophisticated and robust algorithms for the CMN subtraction are under evaluation that could be implemented in the FED firmware. If a CPU-intensive algorithm that cannot be implemented in the FED firmware is required to achieve sufficiently robust performance, the detector can be read without zero-suppression due to the low 8 kHz Pb + Pb interaction rate. The CMN subtraction could then be done in the high level trigger farm where more CPU power would be available.

The second effect influencing the reconstruction efficiency is that of highly ionizing particles HIP. The high particle density in heavy ion collisions leads to a high probability of hadronic interactions with the detector material, resulting in a large charge deposit in the active detector volume. High amounts of charge will saturate the dynamic range of the readout electronics and, reconstructed hits will be lost. This is commonly referred to as the HIP effect and has been extensively studied for pp interactions [5,6]. The HIP effect in the Si-tracker can be simulated in the ORCA reconstruction package based on a parametrization of test beam results. The inefficiency due to this effect is estimated by comparing the same data sample reconstructed with and without the effect. An overall loss of 3–5% reconstruction efficiency is observed for central Pb + Pb collisions.

7. Conclusion

Using the CMS tracking system in heavy ion collisions, very good reconstruction performance for charged particles can be achieved, even with the current reconstruction software that still contains many components optimized for low occupancy pp collisions. The detector readout will be able to cope with the high particle multiplicities achieved in such collisions. Based on this positive assessment, the heavy ion group will continue to improve the tracking algorithm in preparation of the arrival of heavy ion beams in LHC in 2008.

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