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Track Reconstruction in Heavy Ion Events using the CMS Tracker

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Abstract

The Large Hadron Collider (LHC) at CERN will collide protons at $\sqrt{s} = 14$ TeV and lead ions at $\sqrt{s_{NN}} = 5.5$ 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 1500 to 4000 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. In this note the algorithms used for pattern recognition in the very high track density environment of heavy ion collisions will be described. Detailed studies using the full detector simulation and reconstruction are presented and achieved reconstruction efficiencies, fake rates and resolutions are discussed.

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. Track reconstruction in the CMS Silicon tracker in a very high track density environment thus is a key element to the success of the CMS heavy ion program. In heavy ion collisions the expected high charged particle density, dN/dy of 1500 to 4000 particles per unit rapidity in central Pb+Pb collisions, gives 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 ($R < 14$ cm, $|z| < 50$ cm) and silicon strip detectors for the outer layers (20 cm$< R < 110$ cm, 70 cm $< |z| < 275$ cm). The pixel detectors provide 2 or 3 three-dimensional hits with a precision of about 10 μm in $R\phi$ and 15 μm in z. The strip detectors measure up to 14 hits with a precision ranging from 10 μm to 60 μm in $R\phi$. Up to five hits are recorded on double-sided detectors which are formed by gluing two detectors back-to-back with a stereo angle of 100 mrad to provide a three-dimensional information [1].

2.1 The Environment

The studies presented in this note are based on Pb+Pb events simulated with the HYDJET generator [2]. Events simulated with this generator consist of contributions of soft particle production by a hydrodynamic module of the generator and multiple hard collisions simulated by PYTHIA. The high p_T region of the particle spectrum is dominated by jets originating from hard collisions.

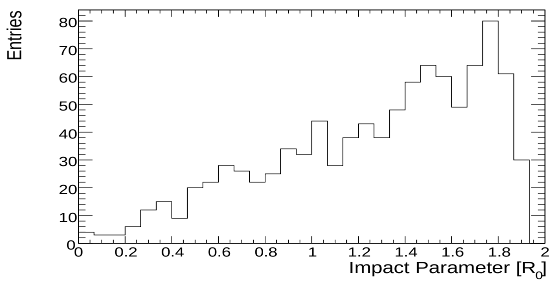

Figure 1: Impact parameter distribution, in units of the nuclear radius R_0, for minimum bias Pb+Pb collisions simulated with the HYDJET event generator.

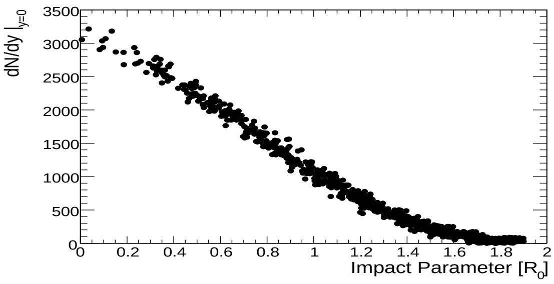

Figure 2: Charged particle density as a function of the impact parameter of Pb+Pb collisions in units of the nuclear radius R_0.

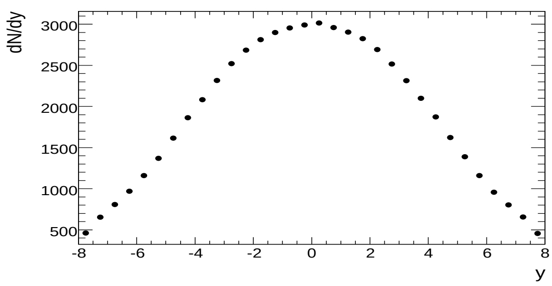

Figure 3: Charged particle density in central Pb+Pb collisions as a function of rapidity.

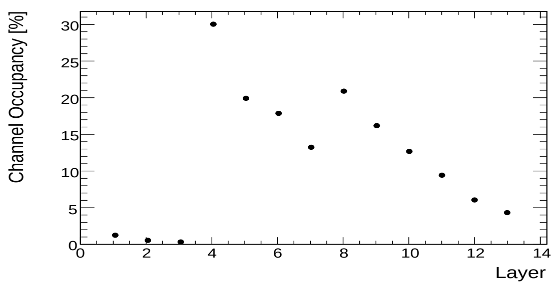

Figure 4: Channel occupancy in the barrel region as a function of detector layer. Layer 1-3 correspond to the pixel detector, 4-7 to the inner and 8-13 to the outer Si-strip tracker.

At the design luminosity of the LHC of $10^{27} cm^{-2} s^{-1}$ for Pb beams collisions will occur at a rate of 8kHz. Heavy ion collisions occur at a varying impact parameter that determines the overlap of the colliding nuclei and thus the overall multiplicity of the events. Figure 1 shows the distribution of impact parameters in a sample of minimum bias events. Figure 2 shows the dependence of the charged particle density on the impact parameter.

The maximum charged particle density of central Pb+Pb collisions cannot be easily extrapolated from RHIC [3, 4, 5, 6] energies to the LHC, because of the large increase in beam energy. Extrapolations are subject to a substantial uncertainty. A simple extrapolation assuming a logarithmic increase of the charged particle density with the nucleon-nucleon center-of-mass energy [4] would predict 1500 to 2000 charged particles per unit rapidity for central heavy ion collisions. For this study the parameters of the HYDJET event generator are set to produce a charged particle density of 3000 to 3500 per unit rapidity, as shown in Fig. 3. The studies presented in this note are performed close to the upper limit of expected charged particle densities to get a conservative estimate of the detector performance. Figure 4 shows the channel occupancy, defined as the fraction of channels above threshold, in the barrel region of the detector corresponding to this charged particle density.

The following parameter settings are used to generate the events for this study:

```
(AHYD) 207.       ! atomic weight
(NETA) 35000      ! mean soft particle multiplicity in central Pb+Pb events
(XSEL) 1          ! xsel=1 - hydro + pythia jets
(XLFL) 3.75       ! maximum longitudinal flow rapidity, 0.01<XLFL<7.
(XTFL) 1.         ! maximum transverse flow rapidity, 0.01<XTFL<3.
(XART) 1.         ! fraction of soft multiplicity prop.to # of N-participants
```

3 The Pattern Recognition Algorithms

The track reconstruction package for heavy ion events is based on the standard reconstruction algorithms developed for p+p collisions [7]. The default algorithm is based on 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.

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. 4, the default track reconstruction procedure is modified in a few key places:

Track Seeding. The p+p 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. Clusters from 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 proportional to the cluster width is assigned to merged hits. The large error assigned these hits and the possibility to associate hits to multiple tracks ensures that all trajectories contributing to a merged cluster can be reconstructed without biasing the momentum assignment by the loss of position information due to the hit merging.

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

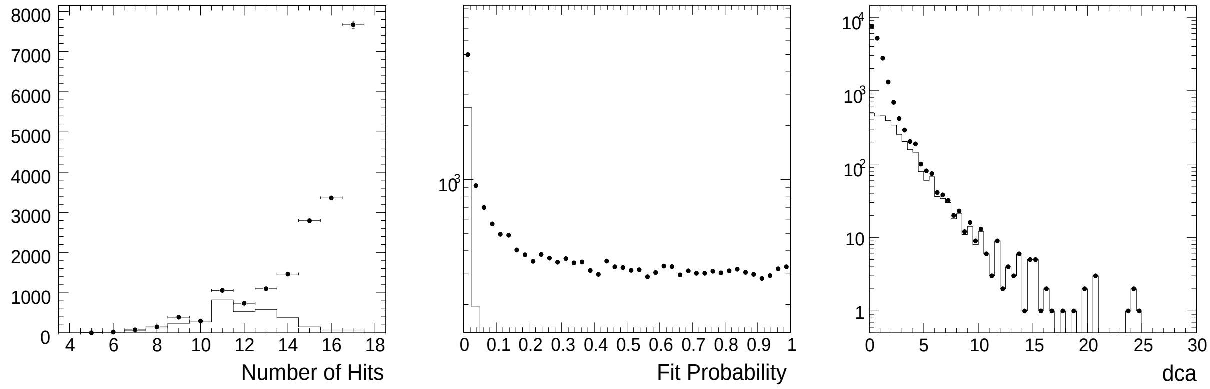

Figure 5: Track quality measures for all reconstructed tracks (symbols) and for fake tracks contained in the sample (histogram). Left: Number of hits per reconstructed track. Hits on stereo layers are counted as two separate hits. Center: χ^2 probability distribution for reconstructed tracks. Right: Distance of closest approach (dca) to the primary vertex in the transverse plane normalized by the error.

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. 5.

4 Reconstruction Performance

The algorithmic reconstruction efficiencies are evaluated for reconstructible tracks, by matching reconstructed tracks to simulated tracks on a hit-by-hit basis. To be matched a reconstructed track needs to include more than 50% of the hits of the simulated track. A track is considered reconstructible if it has 3 or more hits in the pixel detector and a hit on at least 8 different detector layers in total. With the pattern recognition strategy described in Section 3, a high algorithmic reconstruction efficiency can be achieved in central heavy ion collisions while retaining a very low fake rate. Figures 6 and 7 show the track reconstruction efficiency and fake rate as a function of transverse momentum for two sets of quality cuts imposed on the reconstructed tracks. For high efficiency a track is only required to have at least 12 hits. Hits on double-layers are counted as two separate hits since stereo layers are split in the track fit. For a low fake rate additional cuts are imposed on a minimum fit probability of 0.01 and a 3 sigma cut on the compatibility of the measured transverse impact parameter with the beam. The momentum and impact parameter resolution achieved in heavy ion collisions (see Fig. 8) are comparable to the resolution in low occupancy p+p events.

5 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.

5.1 The Pixel Detector

The occupancy of the pixel detectors in heavy ion events is rather low due to the high granularity (see Fig. 4). However, because of their finite size, the readout buffers can still be filled by data from heavy ion events. A detailed description of the pixel detector layout and readout scheme can be found in [1].

The critical items in the pixel readout chain are the readout chip (ROC) and the input buffer to the front-end driver FED. Those elements are prone to data losses due to static and dynamical effects. Static effects refer to properties of the data within one event independent of the collision history or future. The large number of hits in a single central event saturating a readout buffer is an example of a static effect.

Dynamic effects are due to the filling of buffers by a succession of small events at a high data rate. Dynamic effects play an important role when reading out data from p+p interactions at very high luminosity. At the rather modest collision rate of 8kHz for Pb ions dynamic effects will be negligible, since the average time between collisions

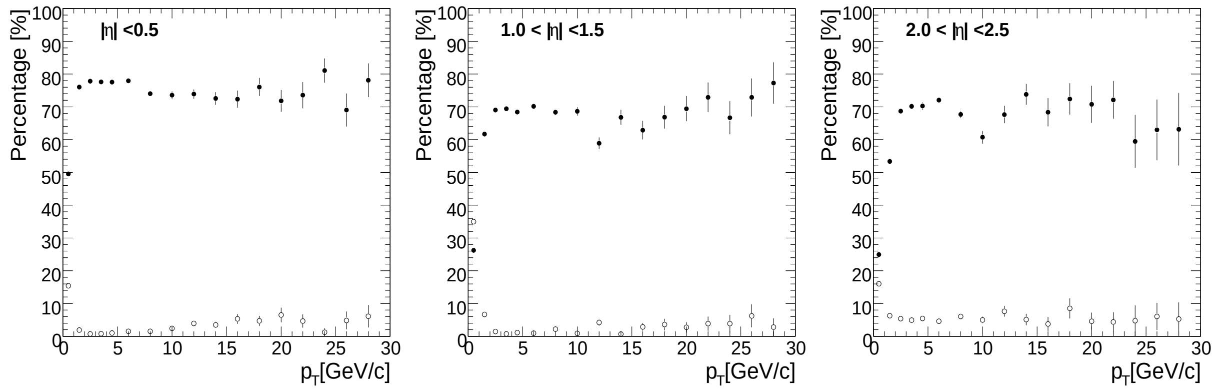

Figure 6: Reconstruction efficiency (full symbols) and fake rate (open symbols) as a function of transverse momentum in three pseudorapidity regions of the tracker for central Pb+Pb collisions with $dN/dy \approx 3000$. The track quality cuts are optimized for low fake rate (Number of hits > 12, Fit probability > 0.01 and dca < 3).

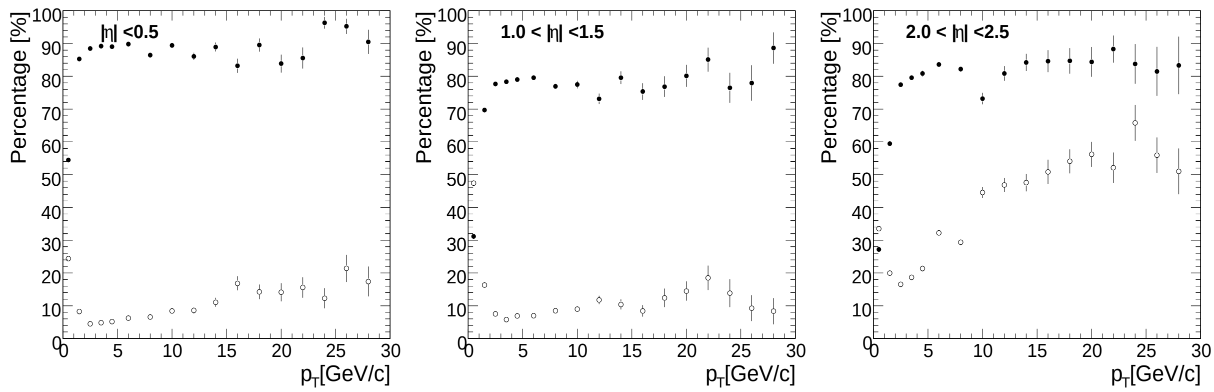

Figure 7: Reconstruction efficiency (full symbols) and fake rate (open symbols) as a function of transverse momentum in three pseudorapidity regions of the tracker for central Pb+Pb collisions with $dN/dy \approx 3000$. The track quality cuts are optimized for high efficiency (Number of hits > 12).

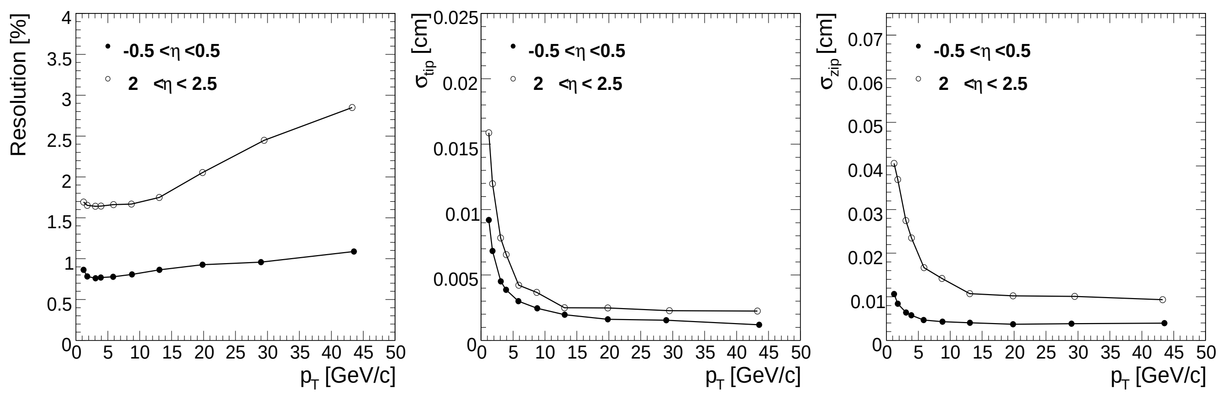

Figure 8: The p_T dependence of the track parameter resolution achieved in heavy ion events in the barrel region (full symbols) and in the forward region (open symbols). Left: Transverse momentum resolution. Center: Transverse impact parameter resolution. Right: Longitudinal impact parameter resolution.

($\approx 125\mu s$) is much larger than the duration of a readout/reset cycle ($\approx 3\mu s$) of the readout chain. Static effects are studied by propagating central Pb+Pb collisions through a full detector simulation and counting the number of hits in the various readout buffers.

5.1.1 The Readout Chip

Each ROC reads out an array of 52×80 pixels and is organized in double-columns (DCOLs). Each DCOL consists of a group of 160 pixels. For each DCOL up to 31 hits can be buffered before it is reset. Figure 9 shows a distribution of the number of hits found per DCOL in the first layer of the pixel detectors. Within one heavy ion event only 8×10^{-5} of all DCOLs in the innermost detector layer contain more than 31 hits.

This number does not scale directly with the number of charged particles per event due to correlations within the event in form of the large number of mini-jets produced in each collision. The loss of information due to this buffer overflow is small. Since the heavy ion track reconstruction relies on one hit in each of the three pixel layers to generate track seeds, one can estimate a loss of reconstruction efficiency of $\approx 0.02\%$ due to this effect.

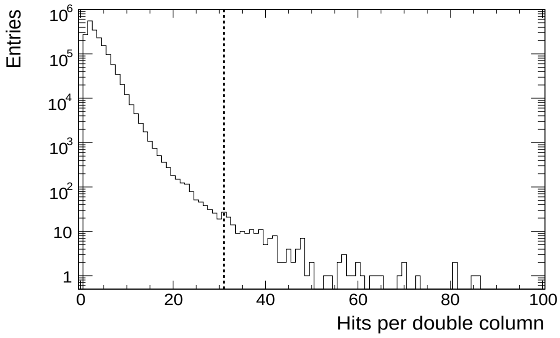

Figure 9: Number of hits per DCOL in the first layer of the pixel detector.

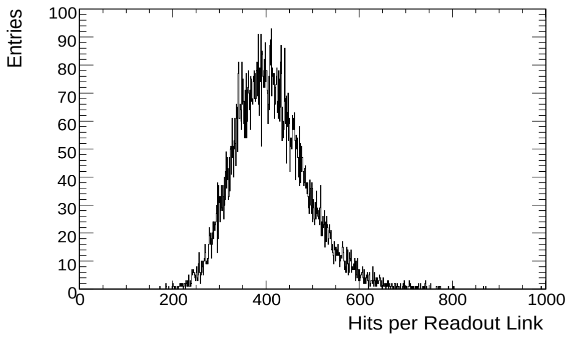

Figure 10: Number of pixels per link to the FED for the first layer of the pixel detector.

5.1.2 The FED input buffer

The FED has input buffers to store intermediate data for each of the 32 links connecting a ROC to the FED. These buffers have a finite size of 1000 pixel per input link. Figure 10 shows the distribution of the number of hits per readout link for central heavy ion collisions. Even for central heavy ion collisions number of hits stays well below the limit of 1000 hits per link.

5.2 The Silicon Tracker

The Si-strip tracker has to cope with a high detector occupancy in central heavy ion collisions. In such an environment two effects can be identified that lead to a potential loss of reconstruction efficiency: The Common Mode Noise (CMN) subtraction and highly ionizing particles.

5.2.1 Common Mode Noise Subtraction

The Si-strip tracker data is likely to be subject to common mode variations of unknown magnitude. The strips of each detector element are read out in groups of 128 channels by front end chips, the so called APVs, which include pre-amplifier and shaper stages for each channel. The analog data from the APVs is transfered by optical fibers to the FED. 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 [7]. 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. Figure 11 shows the difference between the reconstructed CMN offset and the true baseline as a function of detector occupancy. This artificial offset leads to an inefficiency in the hit finding. The probability to lose a hit is estimated by matching the reconstructed clusters on a given detector unit to the true simulated clusters.

Figure 12 shows the probability to lose a hit due to the miscalculation of the CMN offset in heavy ion events as function of the detector layer. The additional hit loss probability introduced by the incorrect CMN subtraction is most pronounced in the first two layers of Si-strip detectors.

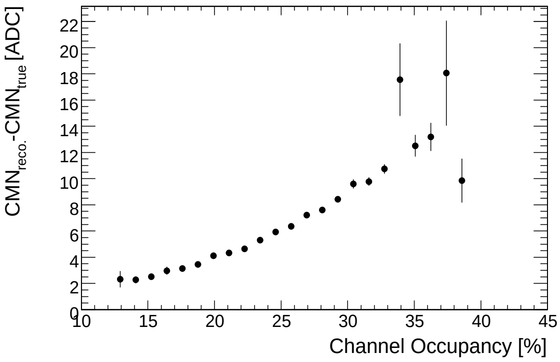

Figure 11: Difference between reconstructed CMN and true CMN as a function of channel occupancy using the median based CMN estimation.

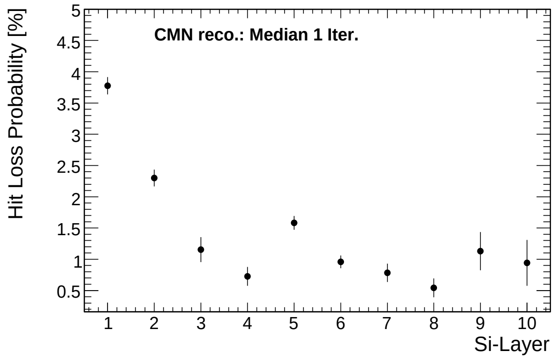

Figure 12: Average hit loss probability due to the median based CMN offset subtraction as a function of detector layer in the barrel region of the Si-strip tracker.

To estimate the loss of track reconstruction efficiency due to this loss of hits the same event sample is reconstructed twice: once using the true baseline level, and once simulating CMN and using the default CMN estimation/subtraction algorithm. Figure 13 shows the track reconstruction efficiency and fake rate for the sample using the median based CMN subtraction. In Fig. 14 the difference in reconstruction efficiency between the two samples is shown. A reduction of reconstruction efficiency of about 5% is observed.

To investigate the possibility of regaining the efficiency lost due to the default CMN subtraction algorithm, the parameters of the algorithm are changed, so it performs three iterations when calculating the median of the ADC values. In each iteration strips with signals above 3 times the sigma of the noise are excluded from the offset calculation.

Figure 15 shows the misplacement of the reconstructed CMN offset obtained with these settings as a function of detector occupancy. The strong dependence observed using the default settings is significantly reduced. Consequently also the hit loss probability in this case is only slightly increased compared to the hit loss probability seen when using the true CMN offset as shown in Fig. 16. The track reconstruction efficiency, shown in Fig 17, is almost fully restored compared to the sample using the true CMN offset (see fig. 18).

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 performed in the high level trigger farm where more CPU power would be available.

5.2.2 Highly Ionizing Particles

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 p+p interactions [8]. The HIP effect in the Si-tracker can be simulated in the ORCA reconstruction package based on a parametrization of test beam results. The hit loss probability for each layer in the Si-strip detector is shown in Fig. 19. The resulting loss of reconstruction efficiency is estimated by comparing the same data sample reconstructed with and without the effect. Figure 20 shows the estimated loss of reconstruction efficiency due to the HIP effect as a function of

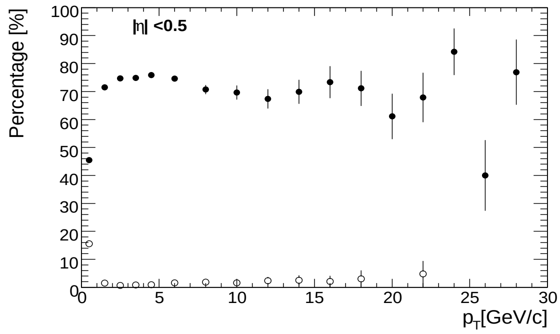

Figure 13: Reconstruction efficiency and fake rate as function of transverse momentum in the barrel region of the Si-strip tracker using the median based CMN offset subtraction.

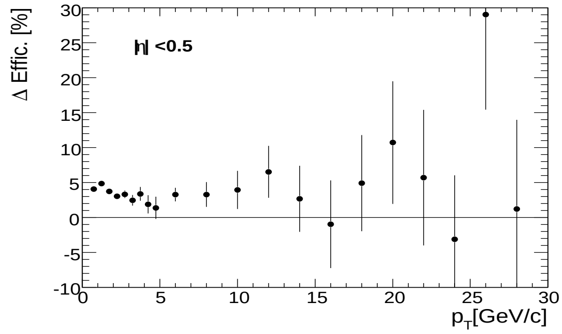

Figure 14: Absolute loss of reconstruction efficiency due to the median based CMN reconstruction for tracks with $|\eta| < 0.5$.

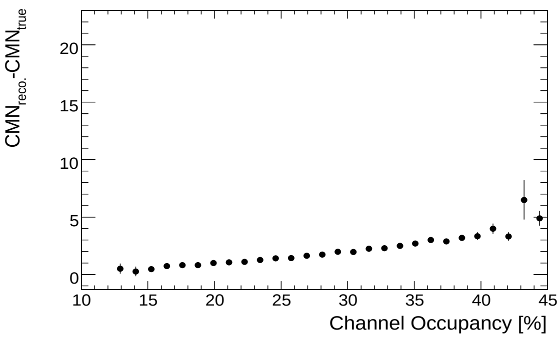

Figure 15: Difference between reconstructed CMN and true CMN as a function of channel occupancy using the median based CMN estimation with 3 iterations.

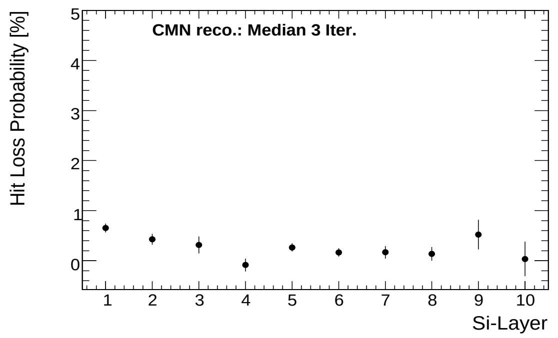

Figure 16: Average hit loss probability due to the median based CMN offset subtraction after 3 iterations as a function of detector layer in the barrel region of the Si-strip tracker.

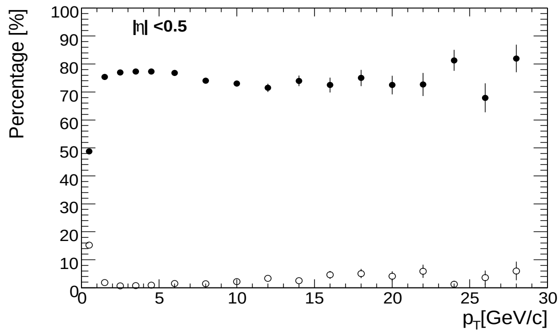

Figure 17: Reconstruction efficiency and fake rate as function of transverse momentum in the barrel region of the Si-strip tracker using the median based CMN offset subtraction with 3 iterations.

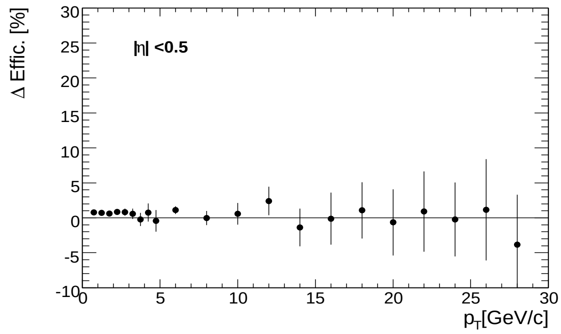

Figure 18: Absolute loss of reconstruction efficiency due to the median based CMN reconstruction with 3 iterations for tracks with $|\eta| < 0.5$.

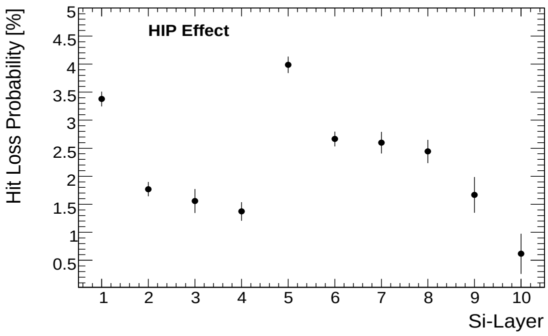

Figure 19: Average hit loss probability due to the HIP effect as a function of detector layer in the barrel region of the Si-strip tracker.

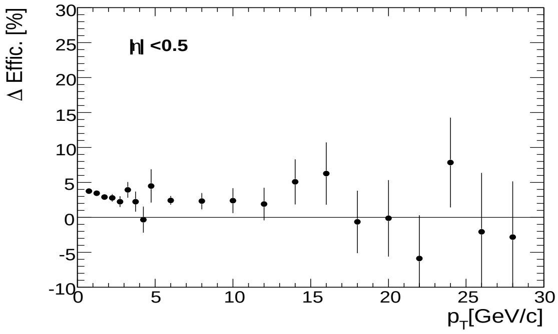

Figure 20: Absolute loss of reconstruction efficiency due to the HIP effect for tracks with $|\eta| < 0.5$.

transverse momentum for the central region of the tracker. An overall loss of 3-5% reconstruction efficiency is observed for central Pb+Pb collisions.

6 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 p+p 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 algorithms in preparation of the arrival of heavy ion beams in LHC in 2008.

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