Simulation and Reconstruction of Data from the STAR FTPC

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Abstract

The main challenge facing the reconstruction software for the STAR FTPCs is to handle the high track density in the forward region while keeping the consumption of computing time moderate. Making use of fast algorithms initially developed for online reconstruction, the FTPC software follows a conventional approach of cluster finding and track reconstruction from the found points. The cluster finder includes calibration and distortion corrections, while the track reconstruction code includes a fast vertex estimation and momentum fitting. Simulations can be done at the space point level and at the level of electronics response. Simulations indicate that the acceptance and position resolution predicted in the FTPC proposal can be achieved. The average momentum resolution is expected to be 12.5%, and the reconstruction efficiency reaches 80% in parts of the phase space.

This STAR note contains parts of Holm Hümmler's Ph.D. thesis. The full text of the thesis is available from http://wwwstar.mppmu.mpg.de/Doc/hh_thesis.ps.gz

Chapter 1

Introduction

The STAR Forward TPCs allow to determine the momentum of charged particles passing through their volume by measuring the curvature of their trajectories in a known magnetic field. To reconstruct a particle's trajectory, the position of its ionization track is measured in two dimensions (pad position and drift time) at each of the padrows it passes, with the position of the padrow providing the third dimension. The number of the padrows in which the track passes through the sensitive volume depends on the track's angle to the beam axis.

The first step in the reconstruction (cluster finding) is to calculate these track points from the charge distribution measured by the readout electronics. In a second step (track finding), these hit points are grouped to tracks. Using the magnet field map, the up to ten position measurements per track are then used to fit the momentum.

To determine the efficiency of the detector and the reconstruction chain, the response of the detector to passing particles at given momenta is simulated. This can be done by either simulating the detector response to entire events or by embedding single simulated tracks in the raw data measured in a real nuclear collision event.

Usually, the results of the simulation are analyzed in a number of intervals (bins) in kinematic variables describing longitudinal and transverse momentum. The comparison of the tracks reconstructed to the tracks put into the simulation yields information about the following three properties of the detector and the reconstruction chain:

- **Acceptance:** The acceptance of the detector is defined to comprise all the bins in longitudinal and transverse momentum in which the number and quality of reconstructed tracks is sufficient to do an analysis. This definition of the acceptance from reconstructed tracks is different from the geometrical acceptance, which includes all the particles that traverse enough of the sensitive volume of the detector to produce a potential track. Especially, it is dependent on the quality criteria a properly reconstructed track has to meet and on the magnitude of the correction factors that is considered acceptable in the analysis.

- **Efficiency:** The efficiency is defined as the percentage of the tracks within the acceptance that is actually reconstructed properly. It is defined for each bin within the acceptance and is dependent on the quality criteria imposed on the reconstructed

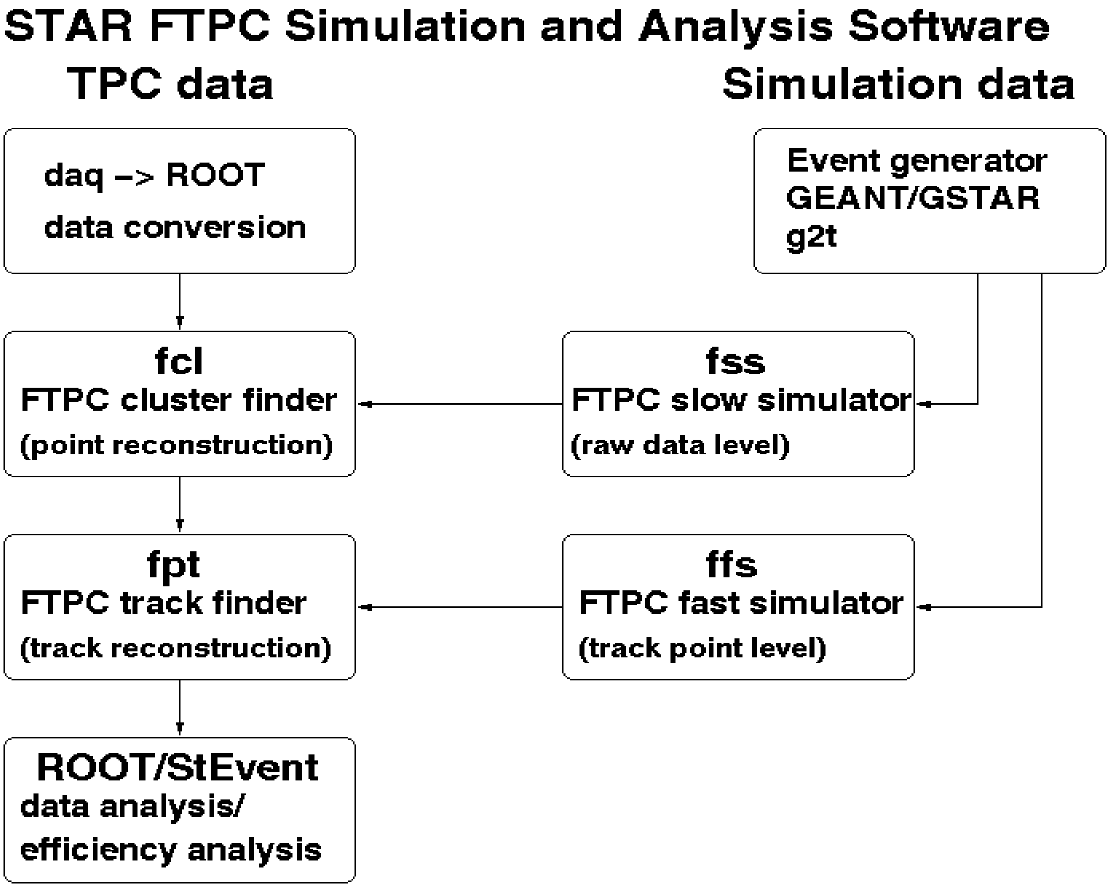

Figure 1.1: *Overview of the STAR FTPC simulation and analysis chain.*

tracks. The efficiency can be determined by analyzing the reconstruction of simulated tracks embedded in real data.

- **Contamination:** A reconstructed track sample can include a certain number of tracks that are not adequate reconstructions of any real particle track from the original event. Possible sources of unwanted tracks are:
  - The reconstructed track contains points that should not be on this track.
  - One original track has been fragmented into several reconstructed tracks.
  - A track is attributed to a track sample to which it should not belong (for example an electron track from gamma conversion is counted as a primary hadron).

In accordance with Konrad [Kon97], the contamination is here used in the sense of the percentage of all found tracks that are not correctly reconstructed original tracks. It can only be determined from completely simulated events. Therefore, the precision is worse than for measuring the efficiency, because not only the track but also the background, which has a strong influence on the contamination, has to be simulated. Contamination can only be corrected for if there is sufficient confidence that the simulated background adds the same contamination as the real one and if the calibration is done in intervals of every variable the analysis is done for.

> Consequently, it is useful to limit the accepted track quality and the acceptance in such a way that the error introduced by contamination is small.

If the contamination can be neglected, the reconstruction efficiency can be accounted for by scaling measured particle abundancies in each bin with the inverse efficiency for that bin.

Figure 1.1 gives an overview of the reconstruction chain for measured data from the data aquisition system as well as simulation on the track point level (fast simulation) and on the level of electronics signals (slow simulation).

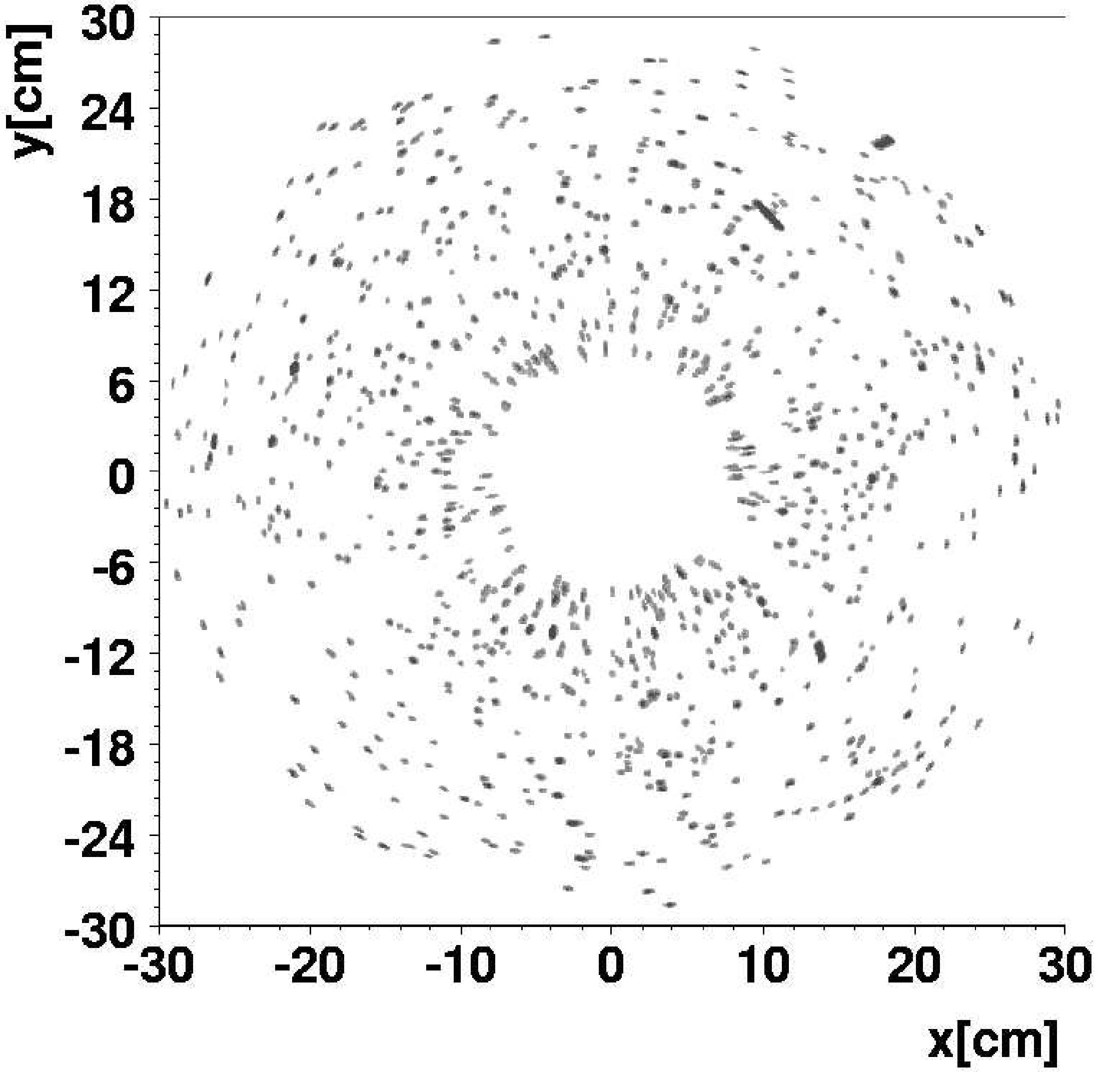

Figure 1.2: *Distribution of the raw data in one FTPC padrow plotted in cartesian coordinates. The beampipe is in the center of the plot, around the origin of the coordinate system, parallel to the z-axis, which points out of the plot. The plot shows simulated data from the Venus event generator, which is generally seen as an upper limit for the particle densities to be expected in the experiment. The track density and thus the number of clusters including charge from more than one track is visibly higher at low radii.*

Chapter 2

Reconstruction of Track Points

The reconstruction of track points is done by the Forward-TPC Cluster Finding module (StFtpcClusterMaker/fcl). It is optimized to deal with high track densities while minimizing the use of computing time. The module reads in the electronics signal data from the data acquisition or from the simulation, looks for coherent areas of nonzero charge (clusters), deconvolutes merged clusters and fits the point coordinates. Calibration constants for electronics effects can be taken into account in the fitting process. The transformation from pad and time to cartesian coordinates includes the correction of distortions introduced by the magnetic field.

2.1 The Charge Distribution in the Raw Data Format

For one trigger taken in both Forward-TPCs, the charge deposited on each of the 19200 pads is sampled 256 times over a time of 51.2 microseconds, generating a total of almost five million digitized amplitude values to be stored. The analog to digital converters in the front end electronics digitize each value in ten bits, but to save storage space and transfer bandwidth, the data is compressed to eight bits (one byte) in the data aquisition system. For TPC data, where energy loss measurements of low-momentum particles depend on a large dynamic range, this compression is done logarithmically. As in the acceptance of the FTPCs almost all hadrons have a small energy loss, a linear compression by truncation of two bits is sufficient. Therefore, 8 bit data from the FTPC can directly be used for fitting without prior decompression.

Figure 1.2 shows the charge distribution measured in one padrow of the FTPC in a central collision. As the charge after diffusion and smearing in the gas amplification fills only about 3% of the sensitive volume in the outer parts and up to 30% in the inner parts of the chamber, a significant reduction of the data volume can be achieved by zero-suppression. Only values exceeding a certain threshold in more than one consecutive time sample are stored. Choosing the threshold is a problem of optimization: It should be well above the average level of the electronics noise (to keep the noise from being stored), but for good position resolution it should be low enough to allow a signal on at least three adjacent pads for every track over every padrow. The laboratory measurements by

Marstaller [Mar98] were done with a threshold corresponding to a digitized value of five channels after 8 bit compression and showed satisfactory position resolution.

The zero-suppressed data is stored in two simple vectors: The ADC vector contains only the non-zero digitized values, while the sequence vector contains, for each time sequence of consecutive non-zero values on a pad, the position of the pad in the chamber, the position in time and the number of values in the sequence, packed into 16 bits.

Addtional index tables can be set up to point to the beginning of individual pads or sectors or of the second FTPC in the raw data, but they are not used in the point reconstruction process, which always runs over all the available data, accessing through a specialized interface class.

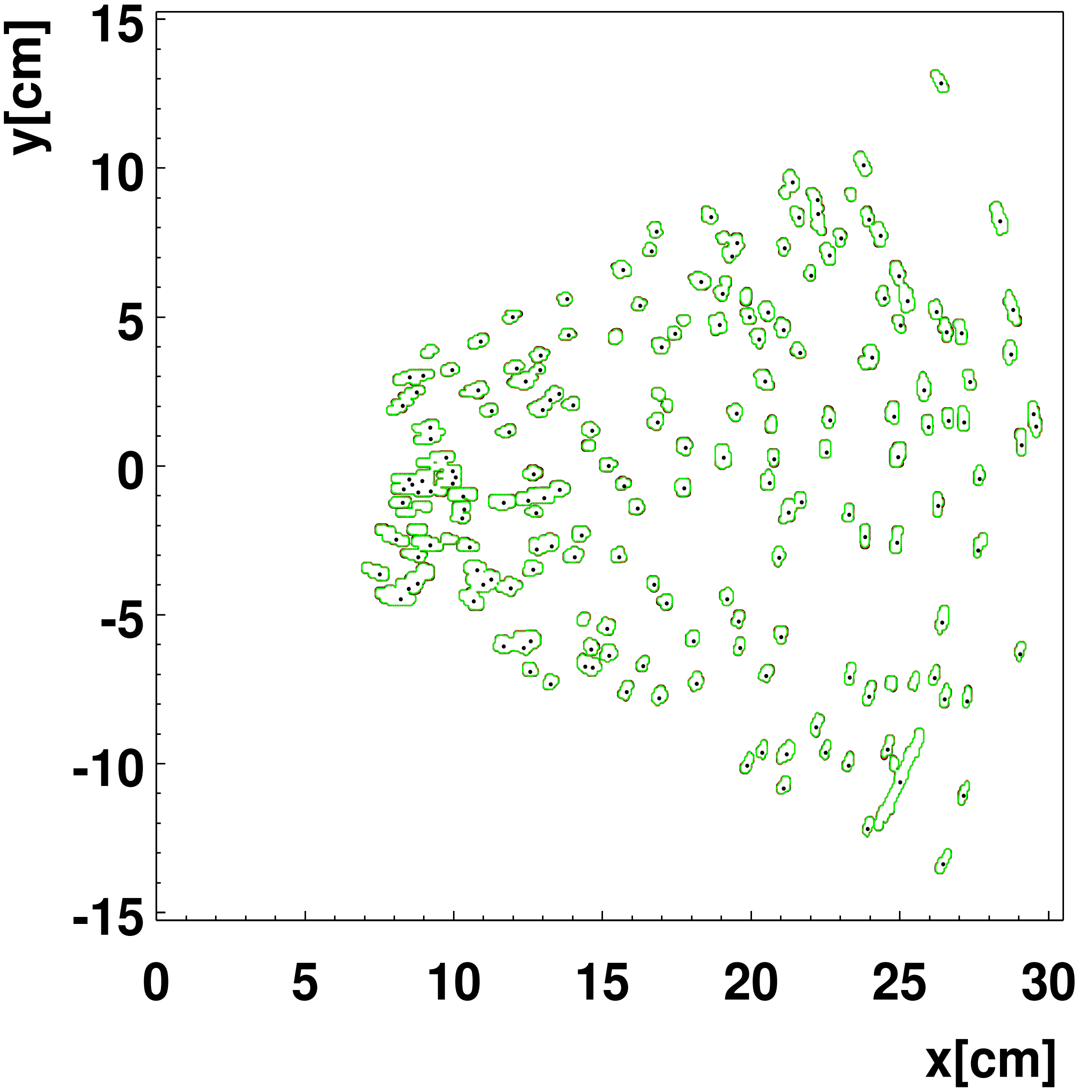

Figure 2.1: *Distribution of the raw data in one FTPC sector and reconstructed hit positions plotted in cartesian coordinates. The contours show the outlines of the deposited charge; the black dots signify reconstructed cluster positions. The beampipe is to the left of the plot, around the origin of the coordinate system, parallel to the z-axis, which points out of the plot. The plot shows simulated data from the Venus event generator.*

2.2 Finding Clusters in the Charge Distribution

Each track crossing a padrow creates a signal in several consecutive time samples on several adjacent pads. In a pad-time plane, corresponding to a cut perpendicular to the beam line (figure 2.1), these signals form a coherent area of charge, called a cluster. As can be seen in the figure, the radial drift stretches the clusters in the radial direction and focuses them in azimuthal direction for small radii, corresponding to long drift lengths. A cluster can include charge from more than one track if their signals overlap, which is common in the area of high track densities at low radii in the FTPC.

The first step in the point reconstruction is to identify these clusters of charge in the raw data distribution and to prepare them for further processing. This is done with an algorithm developed by Dirk Schmischke to reconstruct events online while the data is being taken, with a minimum use of computing time.

The basic idea is to limit the number of accesses to the large sequence and ADC vectors, which reside in the computer's relatively slow main memory or may even be swapped out to disk. Therefore, the sequence vector is read and unpacked only once, sequentially, by the cluster finding routine, and the ADC vector is only accessed in the process of cluster fitting. The data which is currently being processed is kept in a small, self-managed piece of memory for fast and efficient access.

As the clusterfinder iterates over all the pads in one sector, only the sequences on the current pad and on the last pad are kept in memory and checked for adjacent sequences. Adjacent sequences are stored as a cluster under construction (CUC) in a special memory block reserved for quick access. If the sequence on the last pad already belongs to a CUC, the sequence on the current pad is added, otherwise a new CUC is created. Each CUC that has not had any additions on the current pad or includes the last pad in the sector is considered a finished cluster and is passed on to the fit routine. CUCs can also be fused or contain more than one sequence per pad, which makes the code somewhat slower but guarantees proper handling of more complicated clusters from overlapping signals. Figure 2.2 illustrates the principles of CUC generation and buildup.

2.3 Cluster Deconvolution and Fitting of Track Points

Ideally, each track produces exactly one cluster of charge in each padrow it crosses. However, especially in the case of high track densities, a cluster can contain charge deposited by more than one track (merged clusters). The aim of the cluster finding software is to identify these merged clusters and to reconstruct the single track points contributing to them.

Merged clusters can be identified by either using information from already partially reconstructed tracks or by studying the charge distribution within the clusters. Although sophisticated measures of the cluster shapes are imaginable [Car98], the STAR FTPC cluster finder uses a simpler approach: Clusters are only treated as merged if their charge distribution has more than one local maximum. In this case, the single maxima also provide starting points for the deconvolution of the single charge distributions in the cluster.

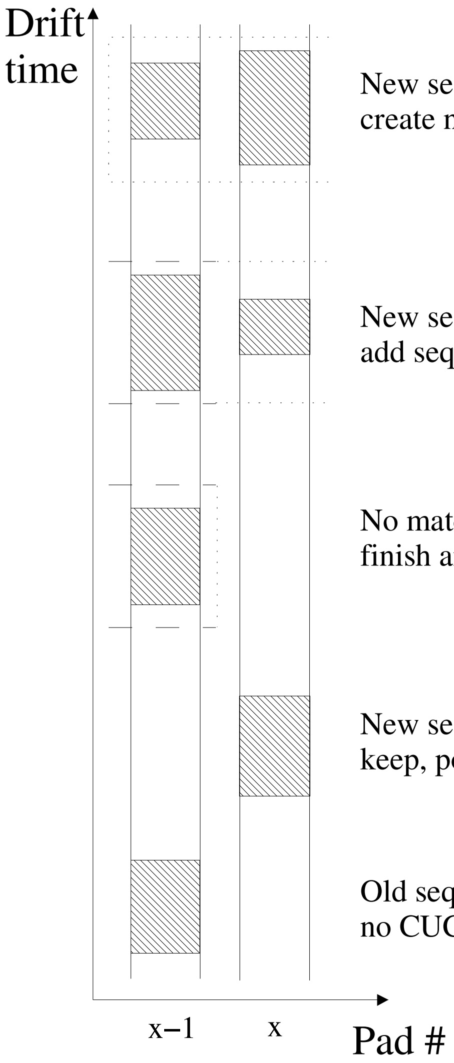

Figure 2.2: *Possible steps in the generation and buildup of clusters under construction (CUCs) in the cluster finding process. The shaded areas signify time samples in which charge has been recorded; the dashed boxes signify existing clusters under construction, and the dotted boxes visualize changes or new clusters under construction.*

Therefore, the cluster fit routine starts by finding local maxima in all the sequences the cluster is made up of. The sequence maxima are then matched and tested if they are 2-dimensional maxima in the charge distribution.

If a cluster has only one maximum, it is processed to one track point. The charge in the cluster is summed up, and the centroid and width of the charge distribution are calculated, independently in padrow and time direction by either calculating the weighted mean and the mean squared deviation of the charge distribution or by assuming a Gaussian shape and fitting it to the maximum and its two neighboring values.

If a cluster has more than one local maximum, each of the maxima is processed to one track point. In this deconvolution process, a distribution function for the charge measured around one track point has to be assumed. The most precise method of cluster deconvolution is to describe the whole charge distribution in the cluster by a sum of two-dimensional Gaussians and minimize the errors using a Levenberg-Marquardt algorithm [Pre92]. If a large number of track hits contribute to one charge cluster, this can be extremely time consuming, the computing time rising with the square of the number of fit parameters times the number of charge values times the number of iterations needed. The fastest method, on the other hand, is to do simple Gaussian fits in the immediate vicinity of the local maxima, neglecting the influence the different track points have on each other, as it is done in the STAR TPC cluster finder [Lis96]. The STAR FTPC cluster finder uses an intermediate method, taking the noniterative local Gaussian fits only as a first guess and then iteratively subtracting the influence of one track point on the other before recalculating the fits. The calcutation time is proportional to the square of the number of local maxima times the number of iterations, the latter usually being smaller than five for reasonably shaped clusters.

2.4 Calibration of Electronics Effects

The readout electronics records a charge amplitude sampled for a series of timebins. Consequently, calibrations for electronics effects can in general be transformations of the recorded amplitude and of the timing of the sample for each single electronics channel. As all analog components are tested and selected for good linearity, a linear transformation is sufficient for the amplitude calibration. The time is defined by a common clock for all channels, so only a constant, additive calibration term for each channel is needed for the timing, to compensate for potentially different signal run times in the connections to the single channels.

The amplitude calibration can in principle be done at any step in the raw data chain without losing precision, but the time offsets can not be applied to the raw data before processing, because the shifts introduced by the calibration are smaller than one timebin.

The STAR FTPC cluster finder incorporates both calibrations in the cluster fitting process. All charge values are calibrated during the peak finding process, the first point in the analysis when every single amplitude value is accessed. Time values are calibrated at the moment when they are used in the position fit.

2.5 Distortion Correction and Transformation of Pad / Time Information to Cartesian Coordinates

In the STAR Forward TPCs, the coordinate transformation from pad position and drift time to points in cartesian space is much more complicated than in the TPCs used in other experiments, where the drift is linear and the drift time is proportional to the drift distance. In the FTPCs, the drift velocity is not only a non-linear function of the radial electric field; the drift is also influenced by the magnetic field, which is almost perpendicular to the electric field lines and not constant over the volume of the chamber, as shown

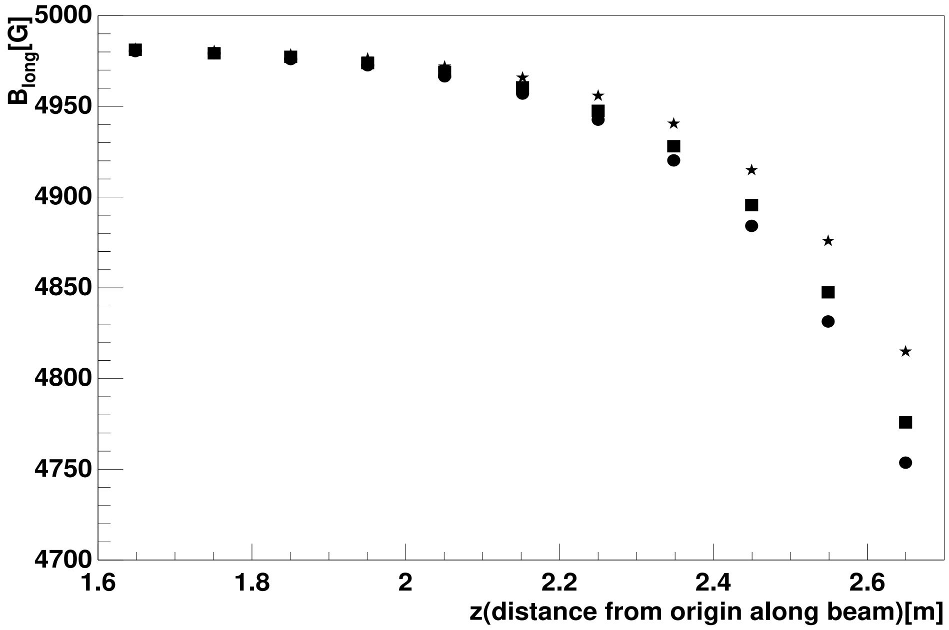

Figure 2.3: *The longitudinal component of the magnetic field in one Forward-TPC plotted against the position in z-direction. Circles show the field at a radius of 8 cm, the inner boundary of the FTPC sensitive volume, squares at 18 cm, and stars signify the field at r = 28 cm, in the outer part of the FTPC.*

in figures 2.3 and 2.4. Neither of these influences is small enough to be treated as a correction to a linear base calculation, as it was done in the NA49 experiment [Hum97][Kro95]. Therefore, the coordinate transformation can not be separated from the distortion correction.

The drift parameters at every given point in the chamber have to be calculated from the local electric and magnetic field using the gas parameters. An advantage which can be used is that both the electric and magnetic field in the volume of the FTPCs are with a good precision azimuthally symmetric around the same axis. Therefore, only a two-dimensional map of drift parameters has to be calculated.

To determine these drift properties, the FTPC software makes use of the MAGBOLTZ code, developed at CERN and implemented as part of the Garfield gas detector simulation package [Vee98]. MAGBOLTZ can statistically calculate drift parameters from microscopic properties for a wide selection of gases under a variety of conditions. Comparisons with other calculation methods and measurements done by Bittl et al. ([Bea97], more detailed in [Bit97]) show that for the gas and field configuration of the FTPCs, MAGBOLTZ is in good agreement with experimental data.

The main parts of the MAGBOLTZ code have been translated from the original FORTRAN version to C/C++ and implemented in the STAR software environment, so they can be used to automatically recalculate the drift parameter map if the gas composition or field configurations in the FTPCs are changed. Since the resulting parameters show in a good approximation linear dependence on the density of the surrounding gas, linear approximation is used to account for changes in the air pressure or the temperature

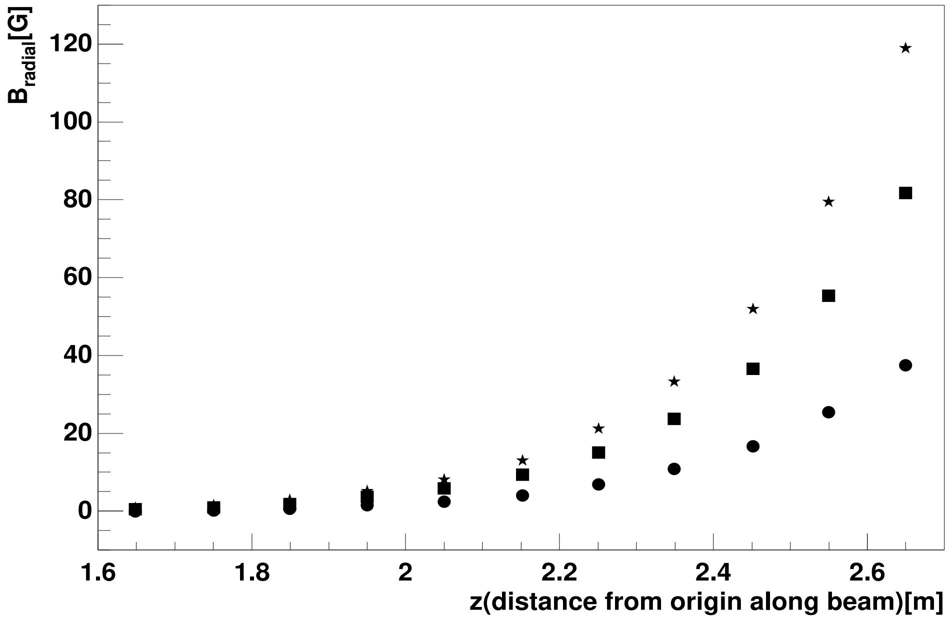

Figure 2.4: *The radial component of the magnetic field in one Forward-TPC plotted against the position in z-direction. Circles show the field at a radius of 8 cm, the inner boundary of the FTPC sensitive volume, squares at 18 cm, and stars signify the field at r = 28 cm, in the outer part of the FTPC.*

around the detector. A normalized drift velocity as a measure for the gas density can be obtained from the drift monitors implemented in the FTPC gas system.

The cluster finder uses the drift parameter map and pressure measurements from the database to generate, by numerical integration, a look-up table to convert drift time information to a point radius and angular displacement during the electron drift, for each padrow. A schematic drawing explaining the angular displacement can be seen in figure 2.5. Radius, angular displacement and the arrival point of the cluster on the pads can easily be transformed into 2-dimensional cartesian coordinates. The third coordinate is simply the position of the padrow in beam direction.

2.6 Performance of the Point Reconstruction

Figure 2.1 gives a visual impression of the performance of the point reconstruction. The reconstruction code can deconvolute even the very complex clusters in the high density region close to the beampipe, in the left part of the figure. Cluster finding, fitting and unfolding of a full event in both FTPCs for this event needed about five seconds on a 400 MHz Intel Pentium II processor.

Elongated clusters, which are caused by low-energy electrons spiraling in the magnetic field, are properly recognized and fitted as single hits if their charge distribution is sufficiently homogeneous. Otherwise, the code can mistake charge fluctuations in the cluster as individual hits and try to unfold the hit positions. Appropriate rejection cuts will have

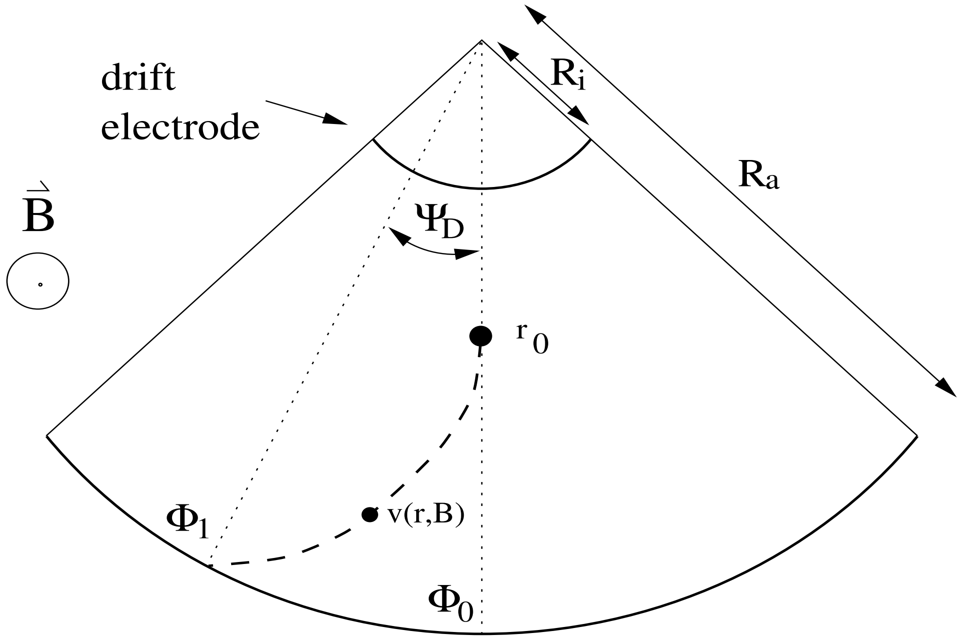

Figure 2.5: *Schematic drawing of the electron drift in the FTPC. The ionization electrons produced at the radial position r_0 and the azimuthal position Φ_0 arrive at the readout plane (with radius R_a) at the azimuthal position Φ_1, displaced by the displacement angle Ψ_D.*

to be developed when raw data from real collisions is available for verification and when the density of electron spirals in the chamber is known. An example of a properly reconstructed electron spiral cluster can be seen in the lower right hand corner of figure 2.1.

A small number of clusters in the figure have no points associated to them. In these cases, the point was deleted because the peak height associated to it was too small. This cut is necessary to reject artifacts from the unfolding but also removes single hits in which energy deposition from the GEANT simulation code was too small for a realistic minimum ionizing particle. In the real detector, similar effects could appear as a result of electronics noise.

Chapter 3

Reconstruction of Tracks and Particle Momenta

The second step in the analysis of FTPC data is the reconstruction of particle tracks and their momenta. The reconstruction of tracks (tracking) in this case means only to identify the points belonging to one track and to group them together in a data structure. The reconstruction of momenta (fitting) then uses the positions of these points and the magnetic field to determine the momentum a particle must have had to pass these points. Tracking routines often use momentum calculations to distinguish particle tracks from random combinations of close-by points, but in general a separate fitting pass after the track reconstruction is necessary to achieve the best possible momentum resolution.

3.1 Finding the Main Interaction Point

The main interaction point of the collision from which all initially produced particles originate (primary vertex) is used as input for the track and momentum reconstruction. For the track reconstruction, it helps to form track hypotheses from groups of hits and to distinguish real particle trajectories from background. For the momentum reconstruction, it provides an additional point on the trajectory with a long lever arm to the points reconstructed in the chamber.

In a collider, the beams in the interaction zone are highly focused and almost parallel while they intersect to achieve the highest possible number of collisions per time interval. Therefore, the radial position of the interaction vertex is defined by the beam position, which is relatively stable during one run of datataking. Along the beamline (z direction), the vertex can fluctuate over the whole area where the two beam bunches can overlap, which extends over several ten centimeters in RHIC. Therefore, the important coordinate of the vertex position is the z coordinate, whereas the radial position can safely be assumed to agree with the beam position for the current run to less than 200μm.

Because of their higher track multiplicities, shorter lever arms and larger angles to the beam axis, the silicon vertex tracker and the central TPC are in a better position to measure the primary vertex position than the FTPC. However, to be able to run without data

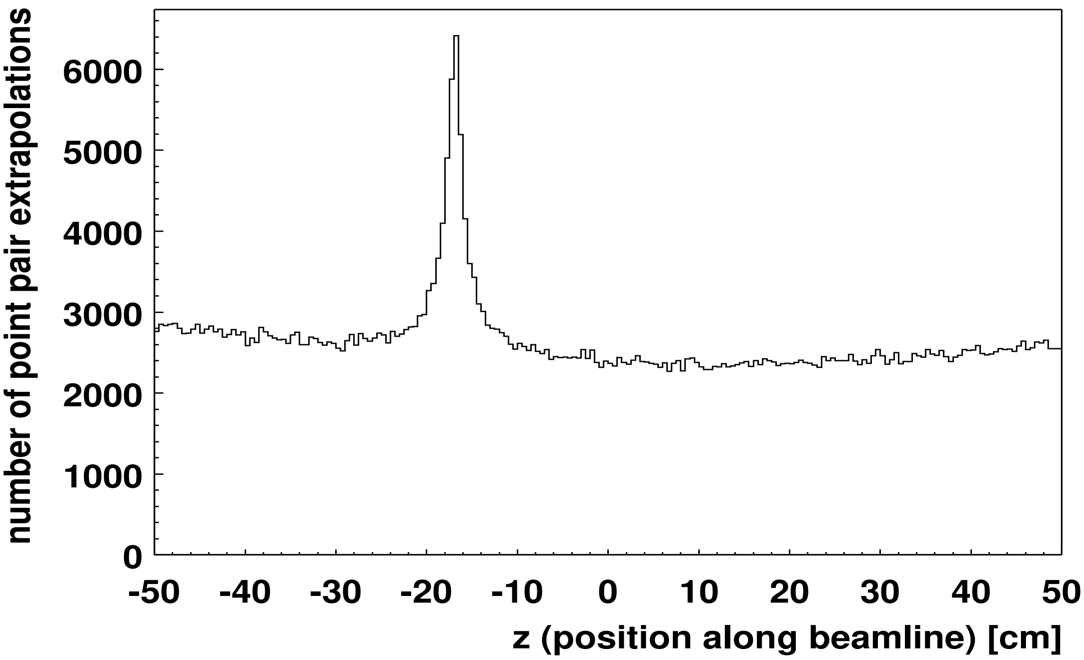

Figure 3.1: *Histogram used by the vertex finder to determine the z position of the main interaction point. Straight lines through all pairs of hit points in a radius-z plane are extrapolated to zero radius. The main interaction point put into the simulation of -16.37 cm was reconstructed as -16.35 cm.*

from the other detectors present, the FTPC analysis software has to be able to derive at least the z position of the primary vertex from its own data.

Since the vertex finding is done before the track reconstruction, random point combinations have to be used to find the vertex. To limit the number of computer operations, all points are first projected onto a radius-z plane. Then, all possible pairs of points in the same z-hemisphere and the same azimuthal sector are used to define straight lines. If the intersect point of a line with the z-axis is within a realistic range for the vertex position, an entry is made in the bin of an array (histogram) corresponding to its z position. Pairs of points on the same track will extrapolate back to the primary vertex, forming a pileup of entries above the combinatorial background, as can be seen in figure 3.1. Entries from strongly curved tracks, scattered or decaying particles widen the peak. The bin with the highest number of entries and its two neighbours are then used to fit the vertex position.

3.2 Track Reconstruction

The STAR FTPC track reconstruction code was designed by Markus Oldenburg and Andreas Schüttauf [Old01], based on an algorithm developed by Pablo Yepes for fast online reconstruction [Yep96]. It is a conventional track-following algorithm optimized for minimum use of computing power in the high track densities expected in the FTPCs (see figure 3.2).

To speed up the process of finding points belonging to the same tracks, all available points are first sorted into bins by padrows as well as azimuthal and polar angles from the main interaction point. Then, track seeds are generated by grouping together three close points in adjacent padrows. These track seeds are then extrapolated to other padrows by a momentum hypothesis, and the appropriate bins are searched for potential further track points. All position caculations are done in a transformed coordinate system in which points appear on a straight line if they form a helix in cartesian coordinates. This processing step, known as conformal mapping, saves calculation time in the fitting of track hypotheses, because all fits can be done by linear regression. If certain quality criteria are met, the group of points is stored as a track.

In a first pass this is done under the assumption that the tracks originate from the main interaction point. In a second pass, the remaining points are used to reconstruct tracks from other origins, which may result from scattering processes or particle decays.

3.3 Momentum Reconstruction

When a charged particle traverses a magnetic field, it is exposed to a Lorentz force, which influences its equations of motion. In the case of a homogeneous magnetic field and negligible other influences (like multiple scattering off the atoms in the traversed medium), this will lead to a trajectory in the shape of a helix. In this case, the momentum can easily be determined by a least squares minimization of the helix parameters with respect to the points on the reconstructed track.

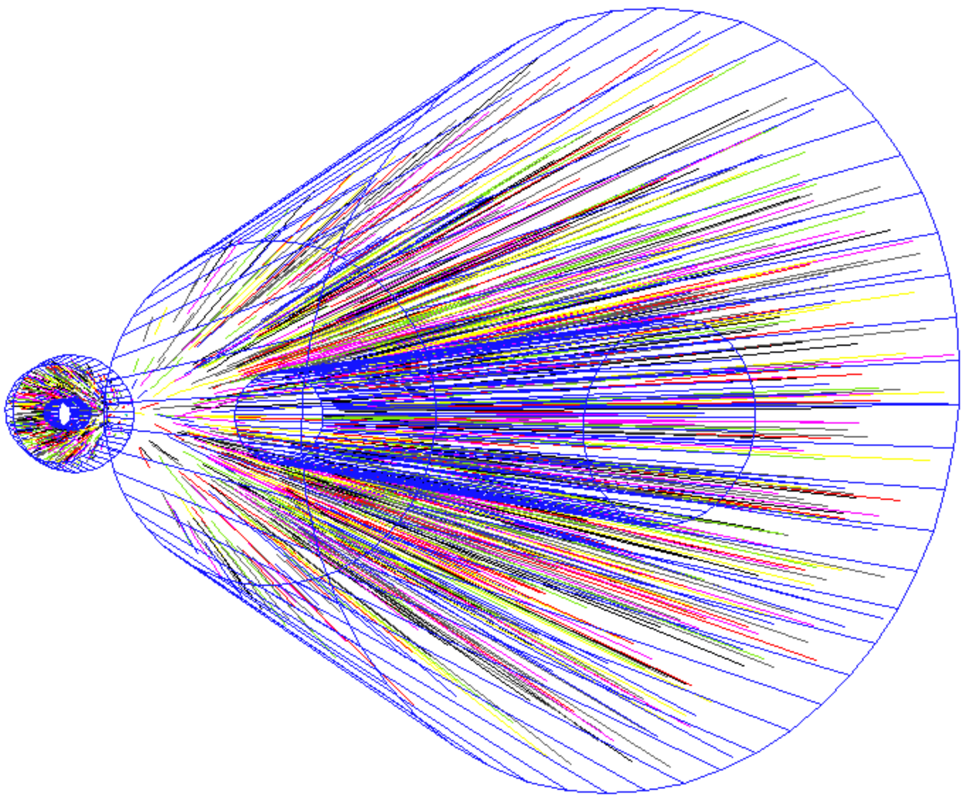

Figure 3.2: *3d-visualization of tracks reconstructed in the FTPCs in one event simulated with the event generator HIJING.*

If the magnetic field is not homogeneous, however, the momentum reconstruction becomes much more complicated (see [Boc90]). As in this case the acceleration of the particle depends on both its velocity and its position in the field,

$$u'' = f(u', B(u)) \tag{3.1}$$

all three parameters (position, velocity and acceleration) can only be calculated recursively for each single point along the path. In the commonly used Runge-Kutta method [Abr70][Myr79], such a recursive formula is used to calculate the errors to be minimized in a Levenberg-Marquardt fit (as in section 2.3).

The momentum fit routines for the STAR FTPC avoid these time-consuming calculations by making use of the near-homogeneity of the magnetic field within the FTPC acceptance.

As can be seen in figures 2.3 and 2.4, a particle originating from the main interaction point will be moving in a field that is in good agreement with homogeneity until it reaches the center of the FTPC. In the outer half of the FTPC, beyond 2.1 m in z from the main interaction point, field inhomogeneities of up to five percent occur: as a radial field component appears, the main component of the field is slightly reduced.

To obtain a first momentum hypothesis, full homogeneity of the field is assumed. Helix parameters are calculated by a fast circle fit in the x-y-plane and a linear regression to the r-z-projections of the track points. In general, the momentum hypothesis resulting from this helix will be too high, because the diverging magnetic field in the outer part of the chamber tends to make tracks straighter. Starting at the first reconstructed fit point, this first guess is then extrapolated through the measured field by iterating over a series of short helix segments. That procedure is efficient in this case because the spatial derivatives of the field are very small compared to its total magnitude. The momentum reconstruction routine then shifts all points on the track by the distance between the initial helix fit and the extrapolated momentum hypothesis. These point shifts are smaller than 200 μm for the outermost points in the FTPC and much smaller for all others. Another helix fit to the shifted pseudo-points yields the final particle momentum vector for any point along the track.

As a cross-check, this procedure has been iterated to convergence, and all changes after the first iteration were negligible.

For particles originating from the main interaction point, including this point in the fit significantly improves the momentum resolution. The tracking code already returns some information about the origin of the track, but for the later analysis of the reconstructed data it is useful to have a quantitative criterion. Therefore, all tracks are first fit without the main interaction point. The reconstructed momentum is then extrapolated back and the radial distance of the track extrapolation (impact parameter) to the main interaction point is calculated. If the impact parameter is smaller than a defined limit, the fit is redone using the main interaction point as the first track point.

3.4 Performance of the Track and Momentum Reconstruction Software

Depending on the particle multiplicity, the track and momentum reconstruction software uses around ten seconds of computing time on a 400 MHz Intel Pentium II processor. This time consumption is about evenly distributed between the vertex finding, point sorting, actual tracking and momentum fitting.

Aspects of reconstructed track reliability and momentum reconstruction quality will be discussed in chapter 5.

Chapter 4

Determining Reconstruction Efficiency and Momentum Resolution Using Simulated Data

To determine the acceptance of the detector and to estimate the efficiency and contamination of the data, reconstructed tracks can be compared to simulated data from known trajectories. To generate simulated data as input for the reconstruction chain, the simulation has to go through three stages:

- **Event generation.** In the first stage the input for the simulation chain is defined by setting a particle type, start point and start momentum for each particle in the event. The input can range from individually defined single particles through standardized particle ensembles to full-scale microscopic simulations of heavy-ion collisions using approaches like string theory or parton cascades. Microscopic event generators used in STAR include HIJING and VENUS for standardized testing as well as RQMD and VNI to test the search for special physics signals.

- **Particle evolvement simulation.** The path of a particle to and through the detector is simulated using the GEANT package [Saa95]. Based on geometry files that include a three-dimensional description of relevant material, fields and sensitive areas, GEANT reads the start points and momenta of the input particles and iterates over their time evolution. Whenever a charged particle passes through a volume that has been declared a sensitive layer of the detector, the energy loss in this volume is stored as a particle hit.

- **Detector response simulation.** The last step of the simulation is to calculate the detector response from the energy deposited in a certain sensitive volume. This can be done either by converting the particle hits directly to space points or by calculating the full detector response and creating simulated raw data.

4.0.1 Simulation at the Raw Data Level

Simulation at the raw data level is done in the slow simulation chain. Here, the focus is on the best possible, detailed simulation of the detector's single components. The energy deposited in a sensitive volume is converted to an electron cloud. The drift of this electron cloud through the chamber gas is then simulated including diffusion, magnetic field effects and electron loss in the gas. Finally, the gas amplification is simulated and the generated charge is distributed on the appropriate electronics channels. Calibrations and other electronics effects can be included in the code but were not used in the simulations presented in this note. The data stored by the slow simulator is equivalent to raw data from the experiment and can be read by the clusterfinder.

The basis of the FTPC slow simulator (fss) is code developed by Wen Gong for the detailed simulation of single charge clusters. The current version has been expanded to handle whole simulated collisions, but the calculation of electron drift and electronics response needs a significantly longer computing time than simulations at the space point level. Also, the connection of reconstructed space points and the particles they originate from is lost in this process.

4.0.2 Simulation at the Space Point Level

Simulation at the space point level, done with the fast simulation chain, is used for high statistics analysis in the search for certain physics signals. The focus is not on the precise simulation of every single track point but on the physics results that can be extracted from a large number of events given the known performance of the detector and the data reconstruction. Therefore, simple parametrizations are used instead of detailed calculations to limit the use of computing time.

Each particle hit stored by GEANT is converted to one track point as it would be reconstructed by the cluster finder. According to the given parameters, the hit positions are dithered to account for the limited position resolution of the detector, and the energy loss is converted into a reconstructed cluster charge. The fast simulator also removes all points that would not be reconstructed due to the blind areas at the boundaries between two FTPC sectors. Finally, all pairs of points that are too close to be separated by the cluster unfolding algorithm are merged. Distortions by magnetic field effects are not calculated explicitly, but the errors in their compensation are included in the error parameters. The output data can be fed directly into the track reconstruction software. The cluster finder is not needed in the fast simulation chain.

As in this case a direct connection between GEANT hits and track points is maintained, the fast simulator can also store information about the generating particle with each point. This can be used as a simple way of matching reconstructed tracks to the simulation.

The FTPC fast simulator (ffs) was developed from code written by Michael Konrad for his thesis [Kon97].

4.0.3 Analysis of Simulated Data

To determine the quality of the reconstruction including the reconstruction efficiency, contamination and momentum resolution, the reconstructed tracks have to be compared to the particle momenta entered into the simulation. In principle this could be done by matching tracks according to their momenta. However, that would not allow to disentangle the errors in track reconstruction and momentum measurement.

Therefore, in the FTPC analysis, track matching was done by first matching the constituent points and then asking for a minimum number or minimum ratio of correct points on a track to consider the track correctly reconstructed. This can be done by either using the information stored by the fast simulator as mentioned in 4.0.2 or with the help of the StAssociator program developed by Manuel Calderon [Cal01]. StAssociator matches reconstructed points to hits stored by GEANT based on local proximity.

Chapter 5

Expected Performance of the STAR FTPC

5.1 Expected Position Resolution

In any detector using the principle of a magnetic spectrometer, the precision of the position measurements along the path of the particles has an impact on the precision of the momentum measurement.

Measuring the position resolution of a detector in the absolute reference frame of the main coordinate system of an experiment is usually difficult. Reconstructed point coordinates would have to be compared to the real trajectory of a passing particle, which in most cases is unknown. Sometimes, independent calibration systems, like a second detector or a laser, can provide well-measured trajectories for calibration, but even then, the questions of alignment between the detector, the calibration system and the main coordinate system remain to be solved.

As a simple way of obtaining information about the position resolution, single measured points can be compared to their position as predicted from trajectories reconstructed in the detector itself. The resulting deviations, called residuals, yield informations about the internal position errors of the detector. Ideally, each point for which the residual is calculated should be excluded from the reconstruction of the trajectory it is compared to, but for a sufficiently high number of used points, the bias introduced is small and is usually neglected.

Applying a residual analysis to simulated data can serve for two purposes. First, it helps to estimate the errors introduced by all effects that are included in the simulation, usually a lower limit for the errors in the actual measurement. This gives an impression of the magnitude of the position errors to be expected in the detector. Systematically excluding effects from the simulation can then serve to disentangle the errors introduced by different sources. Second, residuals from a simpler type of simulation can be compared to those from measurement or from a more detailed simulation to calibrate the error parametrization.

To find the best possible error parameters for the fast simulator to be used in the large scale production of simulated events, fast simulator residuals were compared to those found when using the slow simulator. To isolate the effect of the errors introduced in the

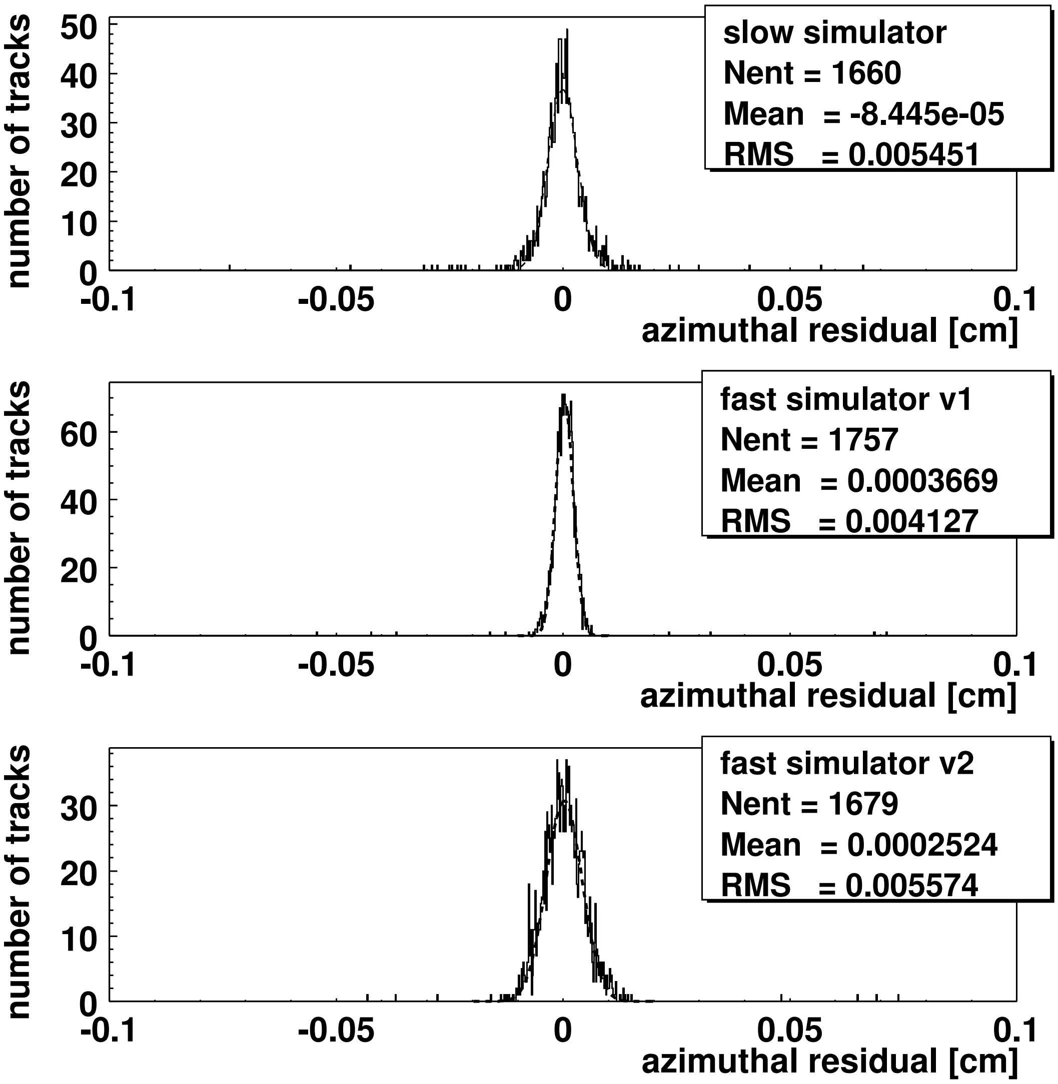

Figure 5.1: *Azimuthal residuals in the padrow closest to the interaction point from simulation. The top plot shows the residuals from the slow simulator. The central plot was done with fast simulator version 1 using the error parametrization by Konrad, the bottom plot using version 2 with new error handling. Nent is the number of reconstructed tracks used. Mean is the mean value and RMS the standard deviation of the distribution.*

simulation of the detector resolution as much as possible from particle scattering or track density effects, all particle interactions except energy loss were neglected in the simulation, and only 100 tracks per event were used.

Figure 5.1 shows the residual distribution in azimuthal direction for the same data processed with different simulators. The residuals resulting from slow simulation, shown at the top, were used as a reference to calibrate the error parameters in the fast simulator. The fast simulator version 1 with errors following a box shaped probability distribution and with error parameters used for earlier simulations (as in [Kon97], [Bie98]) is shown in the center of the figure.

On all padrows and in both azimuthal and radial direction, the residuals from the old fast simulator were significantly narrower than the more realistic ones from the slow simulator. Therefore, the box shaped error distribution in the fast simulator was replaced with a Gaussian error parametrization in the revised fast simulator, called version 2. The width of the error probability distributions was adjusted to yield similar mean square errors of the overall distributions for both simulators. Thus, the χ^2-values from the momentum fits will be comparable. The residuals for the fast simulator with adjusted error parametrization can be seen at the bottom of figure 5.1. The agreement with the slow simulator distribution is still not perfect, since the errors from the slow simulator have some non-Gaussian components. These higher moments of the distribution result for example from unfolding imperfections, boundary and threshold effects and are hard to implement in the fast simulation, so they have been neglected.

In all cases, there were no significant systematic shifts of the mean value of residuals between simulators.

The data from fast simulator version 1 consistently had about 6% more reconstructed tracks than slow simulator data. This has been traced back to an error in the handling of sector boundaries in the fast simulator. Some track points that in reality would have been in the blind area between sectors had been accepted in the simulation. The fast simulator version 2, which has a corrected sector boundary handling, shows a satisfactory agreement with the slow simulator.

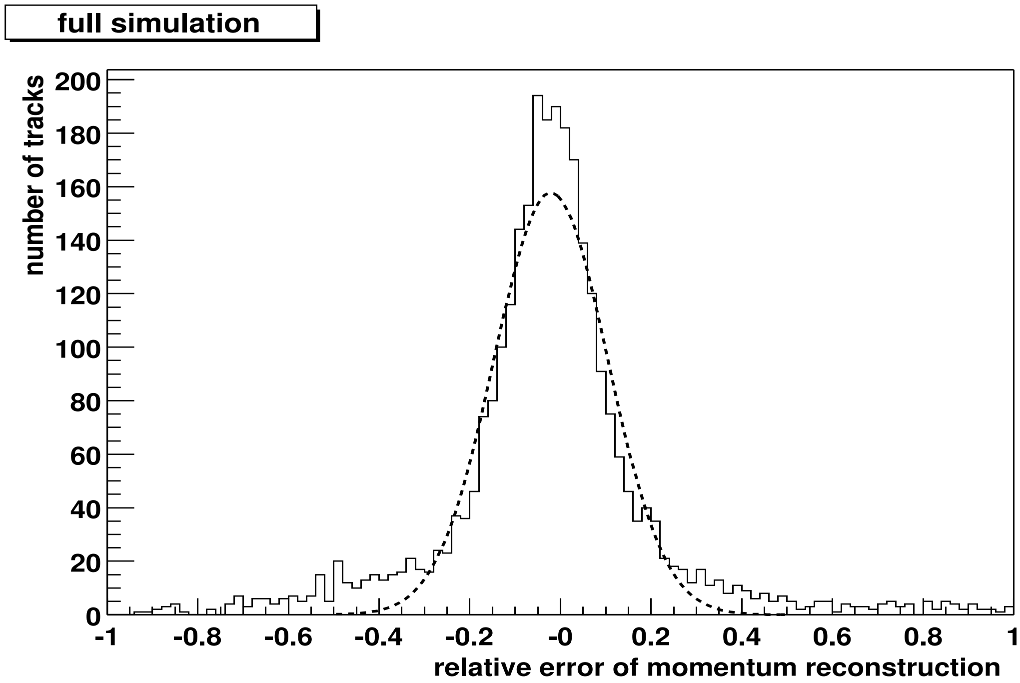

Figure 5.2: *Relative error of the total momentum reconstructed in the FTPCs, after full simulation of scattering effects and detector response. The dashed line is a Gaussian best approximation, which has a sigma of 12.5%.*

5.2 Limiting Factors of the Momentum Resolution

The position resolution of every tracking detector is affected by a number of factors ranging from mechanical deformation to electronics noise. Besides statistical fluctuations of

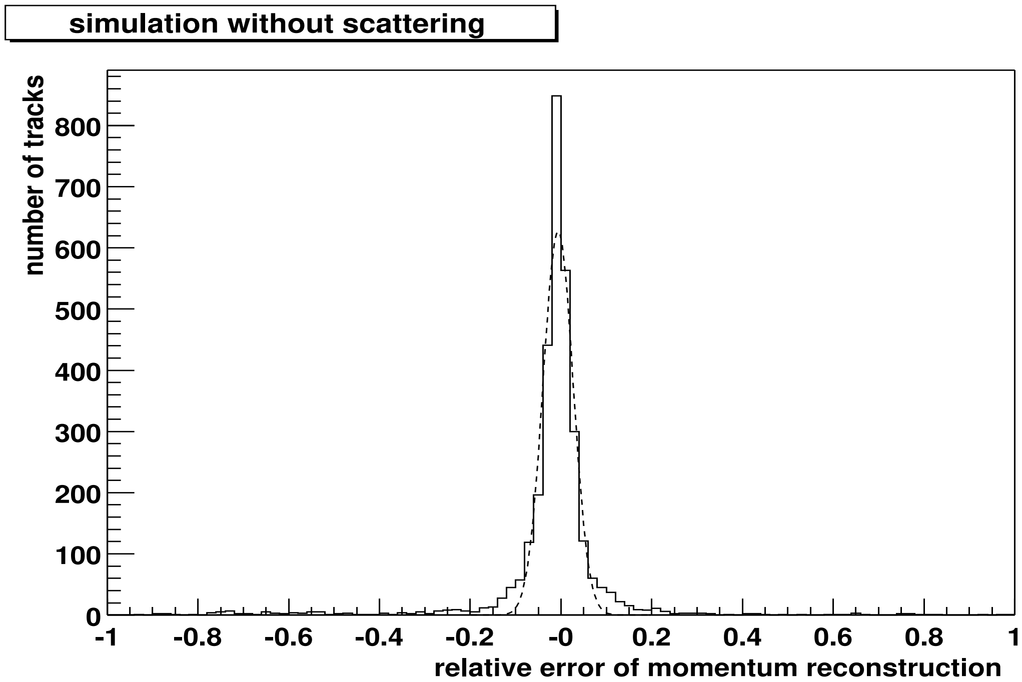

Figure 5.3: *Relative error of the total momentum reconstructed in the FTPCs, after full simulation of the detector response, but neglecting all effects of particle scattering. The dashed line is a Gaussian best approximation, which has a sigma of 3.3%.*

the measured hit around the real particle track point, systematic distortions of the position reconstruction can have a significant impact on the quality of the data. Most of these problems are hard to quantify in the planning and construction stage of the detector. Even careful studies after installation (using for example survey data, particle tracks without magnetic field or laser calibration as in [Hum97] or in [App93]) sometimes do not allow their detailed simulation. In many cases, they are at best treated in the form of effective corrections in the data analysis, never fully eliminating their consequences from the physics results.

In the case of the FTPC, the greatest known potential sources of position measurement distortions are imperfections of the magnetic field corrections and mechanical deformations of the detector caused by its own weight.

To estimate the impact these uncertainties have on the quality of the results, it is useful to understand the limiting factors of the momentum reconstruction. If the position error is the dominant cause of errors in the reconstructed momenta, great care must be taken to reduce or at least understand and correct all significant systematic distortions. On the other hand, the major source of momentum error may also be interactions of the particles in or on the way to the detector. In this case, the analysis should aim at the best possible simulation of the effect and include the results in the efficiency calculation and the interpretation of the data. For example, large random errors on the momentum reconstruction make particle interferometry studies almost impossible while only imposing a minor bias on inclusive particle spectra.

To study the impact of different factors on the momentum resolution, reconstructed particle momenta from simulation were compared to the input momenta of the simulated

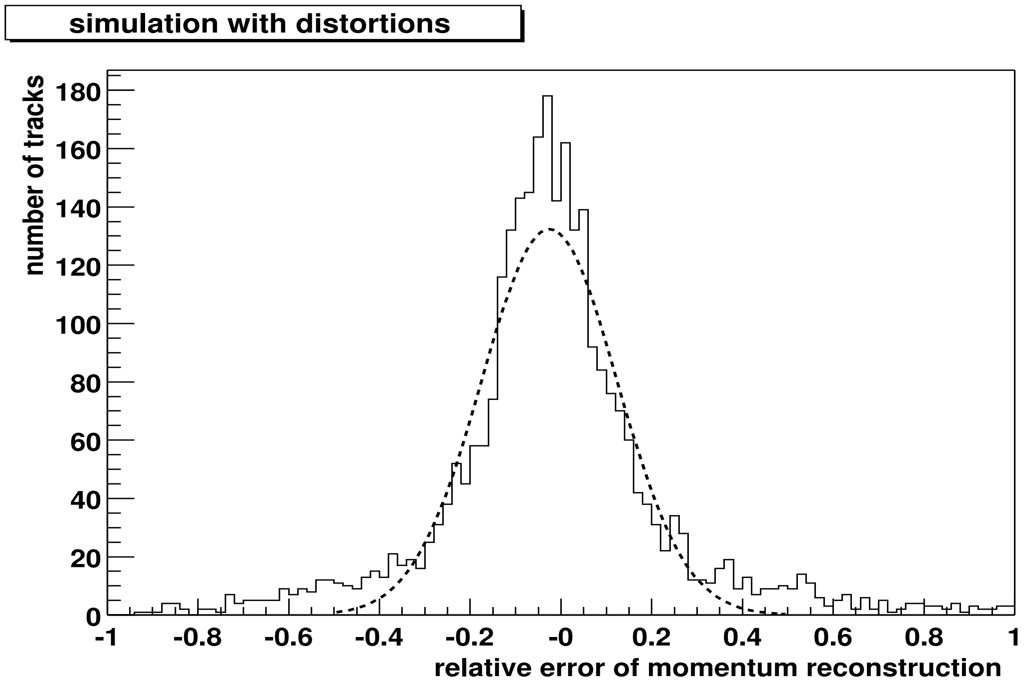

Figure 5.4: *Relative error of the total momentum reconstructed in the FTPCs, after full simulation of scattering effects and detector response, with additional distortions as expected from gravitational deformation of the detector. The dashed line is a Gaussian best approximation, which has a sigma of 14.9%.*

particles. Fast simulation was used for easy matching of input and reconstructed tracks. To limit the influence of hit merging and of tracking code inefficiencies, not more than 100 particles were simulated in each event. The simulated particles were pions, randomly distributed over the acceptance of the FTPC, with rapidities of $2.5 < |y| < 4$ and transverse momenta between 0.1 GeV/c and 1 GeV/c. Only reconstructed tracks with at least eight hits all originating from the same input particle were included in the analysis. For each track, the relative error of the momentum reconstruction was calculated:

$$\frac{\Delta p}{p} = \frac{p_{reconstructed} - p_{input}}{p_{input}} \tag{5.1}$$

Figure 5.2 shows the relative error of the reconstruction of total momenta with the full simulation of all interactions and the detector response. Figure 5.3 represents the same data with all particle interactions (except energy loss) suppressed in the GEANT stage of the simulation. In both cases, the error distributions are not exactly Gaussian. However, tracks with a reconstructed momentum that deviates strongly from the real particle momentum are of no use to the analysis and have to be treated as background. Therefore, the width of a Gaussian approximation to the error distribution is a good measure for the momentum deviation of the usable part of the data.

The standard deviation of the fit is 12.5% for the full simulation and only 3.3% for the simulation without scattering. Also, in the simulation with scattering about an order of magnitude more tracks has been reconstructed with totally wrong momenta, probably due to nuclear interactions with high momentum transfer. Consequently, averaged over the FTPC acceptance, particle interactions must be the limiting factor for the momentum resolution. Obviously, their relative influence decreases with increasing particle momenta, but is, for example, still dominant for pions at $y = 3.5$ and a transverse momentum of 500 MeV/c.

The simulation presented above includes only the statistical position errors introduced in the fast simulator as derived from the slow simulator data presented in section 5.1. To predict if possible systematic uncertainties would have a more severe impact on the position resolution, their magnitude first has to be estimated.

Distortions caused by errors in the calculation of the electron drift of the detector are difficult to predict. Although the program used for the calculation, MAGBOLTZ, shows good agreement with experimental data, it is not certain that the prediction will be precise to the 100 μm level. However, the quality of this correction can be studied by comparing reconstructed laser tracks with and without magnetic field. Since the laser system was designed not to move when the magnet is turned on, the results should be useful in testing and possibly improving the drift calculation.

For the analysis of mechanical deformations, the laser system will be less helpful because there are no measurements on the detector before deformations occur and because laser system mirrors may move with the structure they are attached to. Precision measurements with external optical instruments will also be difficult once the FTPCs are installed in the STAR detector.

Therefore, it is improbable that detailed correction routines will be available soon. However, finite element model analyses and test measurements on the aluminum frame with weights applied can give a first impression of the magnitude of deformations that are to be expected [Ack00]:

- Gravitation deforms the aluminum support structure of the chamber from a cylinder to an elliptical cylinder. Model calculations and measurements are not in agreement, but the most pessimistic prediction is a deformation of about 150 μm.
- As the FTPC is not suspended in the center of the support structure, the end of the chamber facing the interaction point hangs down by 50 to 70 μm.
- The tensions of the wires running along the chamber to form the Frisch grid and the gating grid apply a total force of about 3000 N to the chamber. Calculations predict a longitudinal contraction of the chamber by about 150 μm.

Changes corresponding to upper limits of the distortions caused by these deformations have been artificially applied to simulated data processed with the full simulation including particle interactions. The distribution of the resulting momentum reconstruction errors can be seen in figure 5.4. The changes compared to the reconstruction of undistorted data in figure 5.2 include a worsening of the momentum error from 12.5% to 14.9%.

Since these results represent a worst-case scenario, it can be said that the detector deformation is expected to have a non-negligible but limited impact on the analysis. A careful study of the distortions and possible correction methods should be done once calibration data from the installed detector is available.

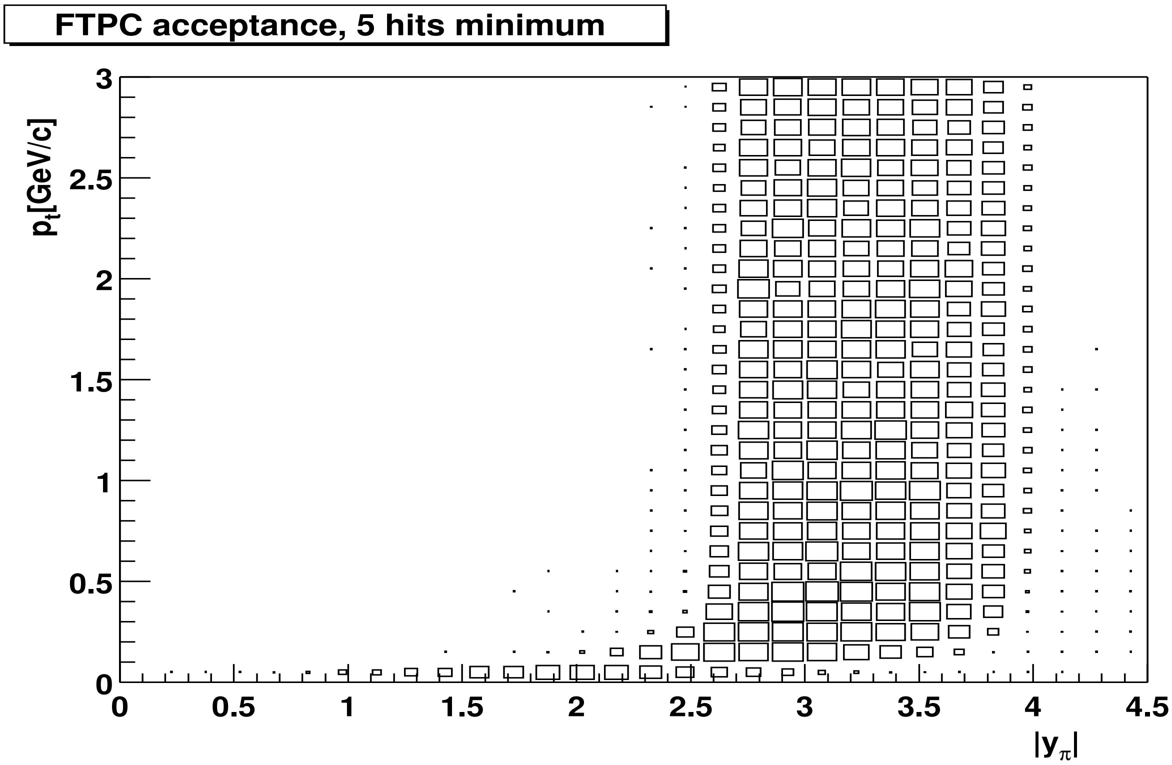

Figure 5.5: *FTPC acceptance in rapidity and transverse momentum for pion tracks with at least five hits in the FTPC. The size of the boxes corresponds to the probability of reconstructing a pion of the given momentum. The acceptance is symmetric for positive and negative rapidities.*

5.3 Expected Detector Acceptance

The acceptance of the FTPC depends on the quality criteria applied to the tracks included in the analysis. The design acceptance of the FTPC, covering pseudorapidities (corresponding to rapidities at high transverse momenta) from 2.5 to 4, is achieved if all tracks with at least five hits are used. This can be seen in figure 5.5, which shows the acceptance in rapidity and transverse momentum for pions. Accepting tracks with less than five hits would not be useful, because of their deteriorating momentum resolution and increasing contamination.

If in actual events the contamination increases or if the position resolution turns out to be worse than expected, it may be necessary to limit the analysis to longer tracks. In this case, particles entering the FTPC through the high voltage electrode or leaving it through the readout plane would increasingly be eliminated from the analysis, reducing the FTPC acceptance for high and low rapidities, respectively. If only tracks leaving charge in all ten padrows are accepted, the acceptance drops to the area in figure 5.6.

An extension of the FTPCs' acceptance results from the fluctuation of the collision point in the interaction region. A collision point that is strongly off-center shifts the acceptance of one FTPC to smaller, of the other FTPC to larger absolute values in rapidity. This effect can cover about 0.5 units in rapidity and can be useful to extend the analysis if sufficient statistics is available.

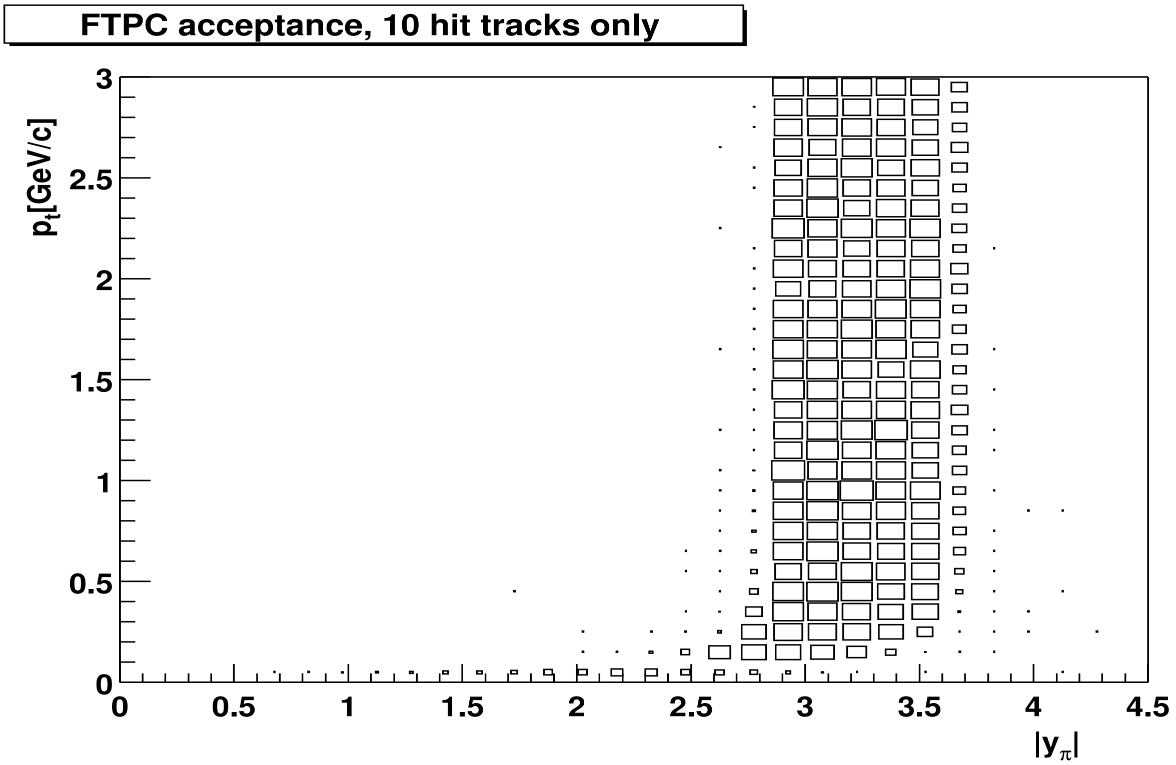

Figure 5.6: *FTPC acceptance in rapidity and transverse momentum for pion tracks with the maximum number of ten hits in the FTPC. The size of the boxes corresponds to the probability of reconstructing a pion of the given momentum. The acceptance is symmetric for positive and negative rapidities.*

5.4 Efficiency, Contamination and Correction Factors

To calculate the reconstruction efficiency and the contamination (as defined in chapter 1) of the track reconstruction on the basis of completely simulated events, the fast simulation chain was used. Thus, each point on a reconstructed track could be traced back to the simulated track it was generated from.

To get meaningful values for efficiency and contamination, it is necessary to define which simulated tracks should be reconstructed and under which circumstances a reconstructed track is considered correct.

For the following analysis, a simulated track that should be reconstructed ("good simulated track") was defined as follows:

- The track can geometrically leave at least five hits in the FTPCs. This corresponds to a fixed range in pseudorapidity for each possible position of the main interaction point. As the pseudorapidity of a primary particle is defined at the interaction point, single particles may be scattered into or out of this geometrical acceptance, leading to a smearing of the accepted pseudorapidity range.

- The track originates from the main interaction point.

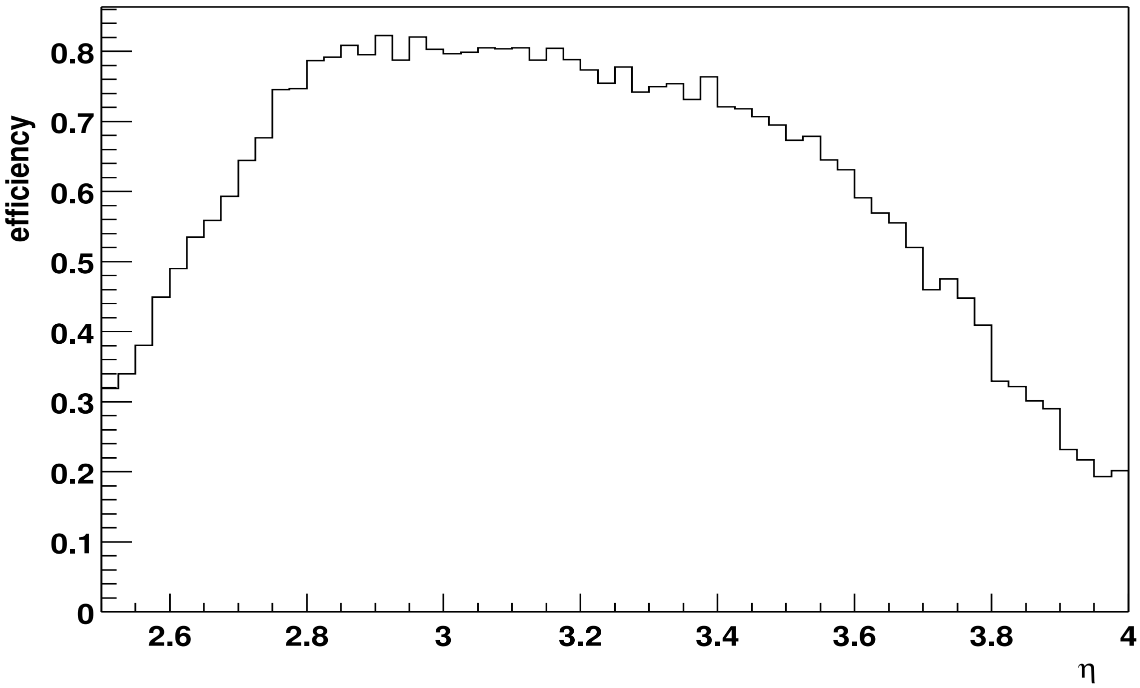

Figure 5.7: *Tracking efficiency versus pseudorapidity determined from 70 events simulated with HIJING.*

- The particle producing the track is not an electron or a positron.

In principle, a reconstructed track can be considered correct if its reconstructed momentum agrees with sufficient accuracy with the momentum of the simulated track that is assigned to it. However, this procedure would not allow to separate weaknesses in the track reconstruction from those in the momentum reconstruction. Therefore, the criteria for a correctly reconstructed track were defined based on the points the track consists of:

- All points on the track were traced back to the same simulated (parent) track.
- The parent track belonged to the sample that should be reconstructed.
- If two reconstructed tracks have the same parent (track splitting), only one is considered correct.

Only reconstructed tracks with at least five points were included in the analysis. Also, tracks that could not successfully be extrapolated to the main interaction point in the momentum fit were excluded. A separate analysis will have to be done for tracks not originating from the main interaction point when strange particle decays are to be studied. Based on these definitions, efficiency (eff) and contamination ($cont$) can be calculated as follows:

$$eff = \frac{\#correctly\ reconstructed\ tracks}{\#good\ simulated\ tracks} \tag{5.2}$$

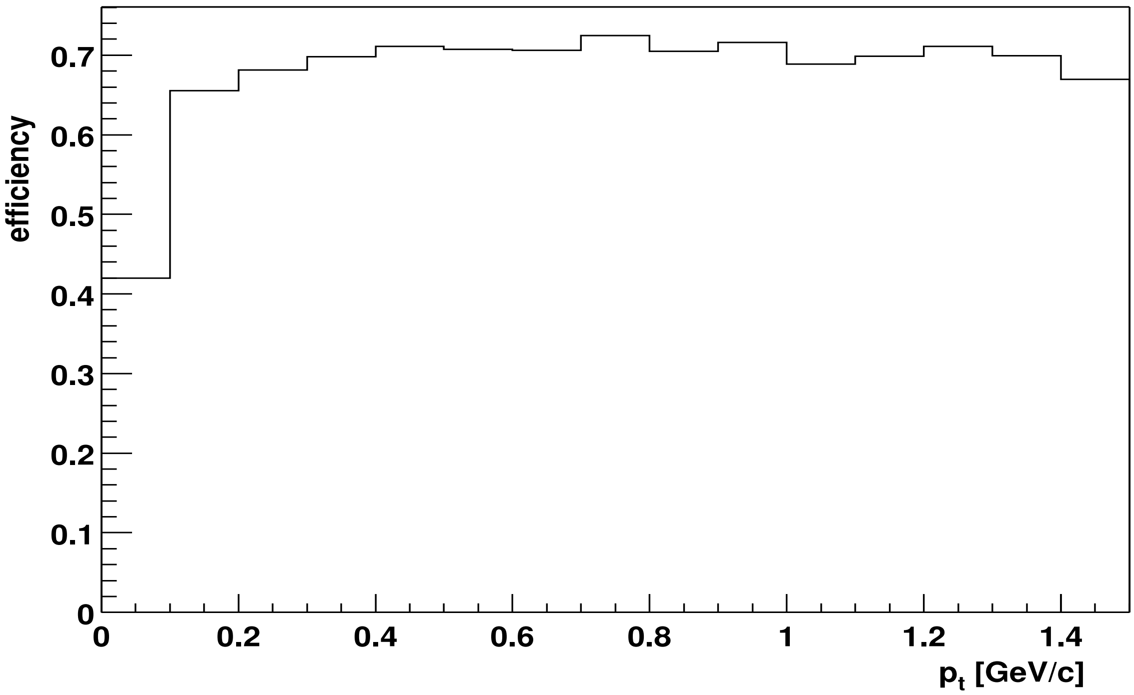

Figure 5.8: *Tracking efficiency versus transverse momentum determined from 70 events simulated with HIJING.*

$$cont = \frac{\#incorrectly\ reconstructed\ tracks}{\#reconstructed\ tracks} \tag{5.3}$$

These numbers can be calculated for the whole detector or for intervals in different kinematic variables. To evaluate the tracker, the kinematic variables chosen were transverse momentum and pseudorapidity. Whereas the rapidity is generally used in the analysis of particle spectra, the pseudorapidity was preferred here because it corresponds directly to a parameter measured in the detector, the angle between a track and the beam axis. The analysis was done in two dimensions, but as both variables show no strong correlations between the two dimensions, only the one-dimensional dependencies of efficiency and contamination are shown here. The efficiency and contamination analysis was done with 70 events, corresponding to about 42000 good simulated tracks, simulated with the HIJING event generator and processed through the fast simulation chain. Using other event generators, the results vary by less than 5%.

The reconstruction efficiency as a function of the pseudorapidity η in figure 5.7 shows efficiencies around 80% at the center of the acceptance. Significantly lower values appear in the areas where tracks get shorter and single missing points can already lead to a loss of the whole track. This dropoff is different for high and low values of η because of the different geometrical limitations and because of the high track density in the forward (high η) region.

Figure 5.8 shows that the tracking efficiency does not depend on transverse momentum except for a significant dropoff at small transverse momenta, corresponding to strongly curved tracks. For these tracks, the contamination (figure 5.9) shows a strong increase.

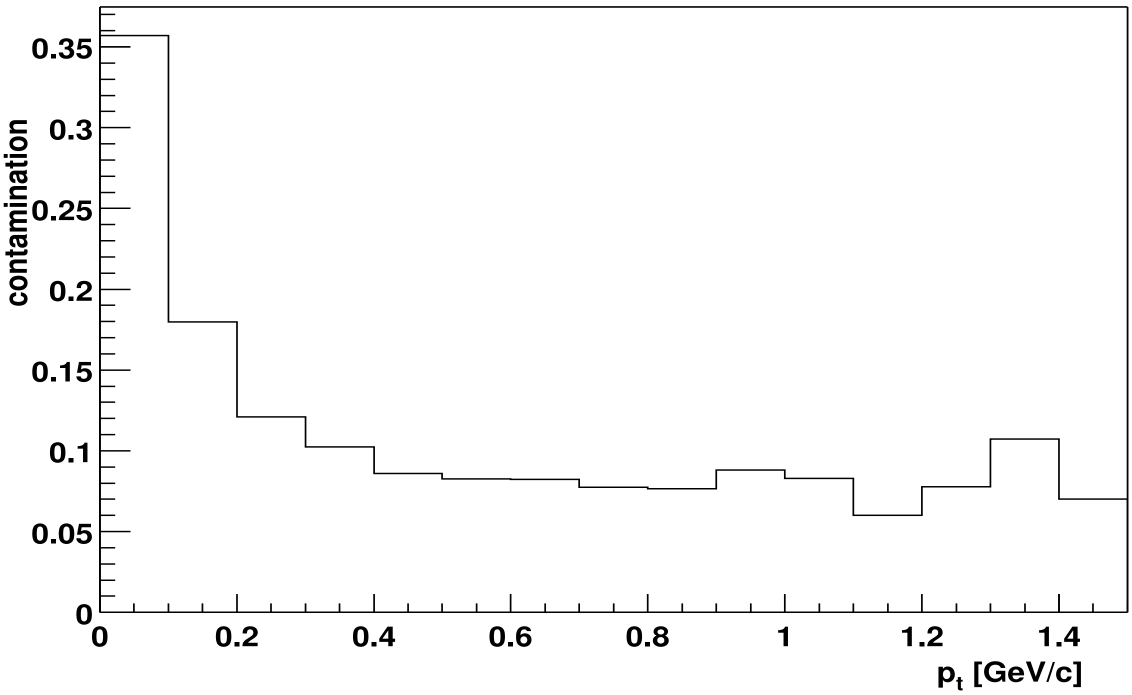

Figure 5.9: *Contamination versus transverse momentum determined from 70 events simulated with HIJING.*

Therefore, any studies of particles at transverse momenta of less than 100 MeV/c in the FTPC appear problematic.

The contamination shows a weak dependence on the pseudorapidity (figure 5.10), slowly increasing from 10% in the low η region to 20% at high pseudorapidities. This is in contradiction with the results by Konrad [Kon97], but the differences may be explained by the different track reconstruction algorithms used, different selection criteria for correct tracks and additional matter, like the beampipe supports, included in the present simulation.

To analyze the sources of the contamination, table 5.1 shows the average numbers per event of reconstructed tracks, contamination tracks and the different sources of the contamination. The numbers of the sources do not add up to the number of contamination tracks, as for example most electrons also do not originate from the main interaction point. As can be seen, the dominant part of the contamination are tracks not originating from the main interaction point. Besides electrons and positrons from gamma conversion, this also includes particles created in weak decays. As most of these decays happen close to the main interaction point, they are extremely difficult to exclude from the analysis.

To clarify where contamination tracks are produced, figure 5.11 shows the z-position of the production point (vertex) of particles leaving tracks in the FTPC. The data was produced from the already mentioned 70 events simulated with HIJING. The top plot shows all particles leaving more than five hits in the FTPC. The central plot includes only particles which are reconstructed as contamination tracks, and the bottom plot is limited to those contamination tracks caused by electrons.

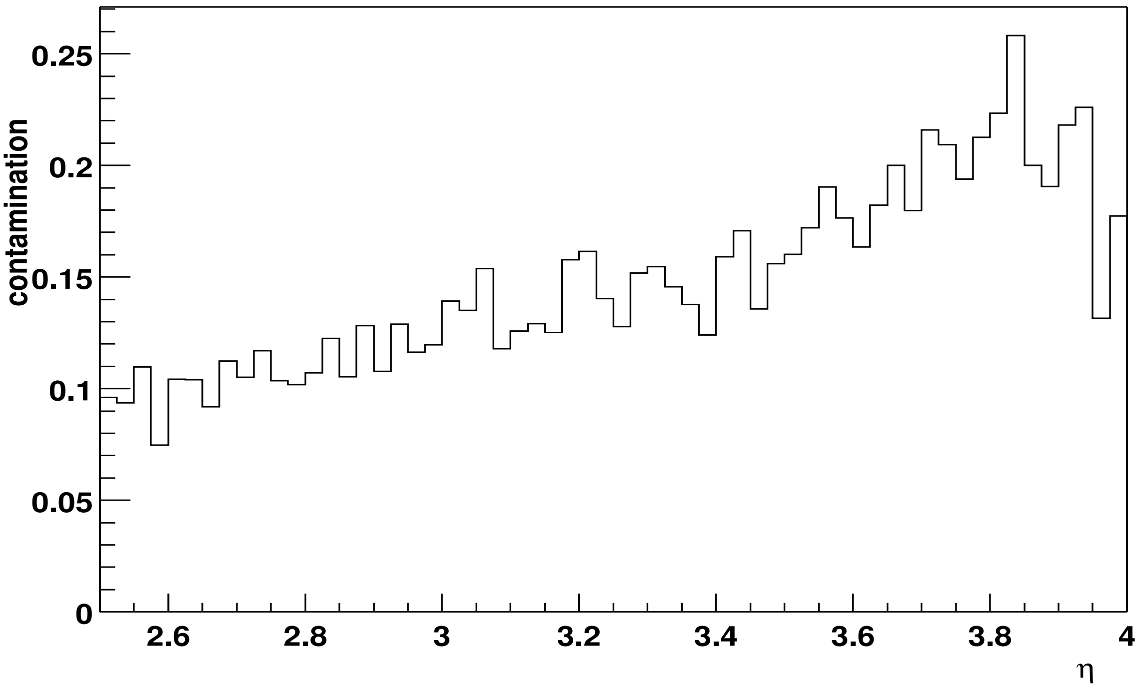

Figure 5.10: *Contamination versus pseudorapidity determined from 70 events simulated with HIJING.*

The plots reflect the geometry of the experiment. The primary interactions all take place at $\mid z \mid < 40\,\mathrm{cm}$. The silicon tracker ends at $\mid z \mid = 50\,\mathrm{cm}$; a support structure for the beampipe is located at $\mid z \mid = 55\,\mathrm{cm}$; the transition of the beampipe material from beryllium to aluminum is at $\mid z \mid = 75\,\mathrm{cm}$, and the FTPC begins at $\mid z \mid = 150\,\mathrm{cm}$. Most of the particles created close to the FTPC are suppressed by the reconstruction algorithm or the track extrapolation to the main interaction point. The hadron contamination is mostly produced in the vicinity of the main interaction point and will be very difficult to suppress further. A large part of the electron contamination is produced by gamma ray conversion in the beampipe support.

The reconstruction efficiencies quoted above are calculated assuming that the acceptance does not depend on the azimuth. The "good simulated tracks" include tracks that pass through the blind areas at the sector boundaries of the FTPC. As their points are not found, these tracks can never be reconstructed, which imposes an upper limit of about 92% on the reconstruction efficiency. This problem could in principle be avoided by limiting the acceptance to certain areas in azimuth, avoiding the sector boundaries.

reconstructed tracks	639
correctly reconstructed tracks	551
total contamination tracks	88
split tracks	8
tracks with points from different parent tracks	16
tracks with parent not from main interaction point	74
tracks with parent electron or positron track	42

Table 5.1: *Average composition of the contamination per event.*

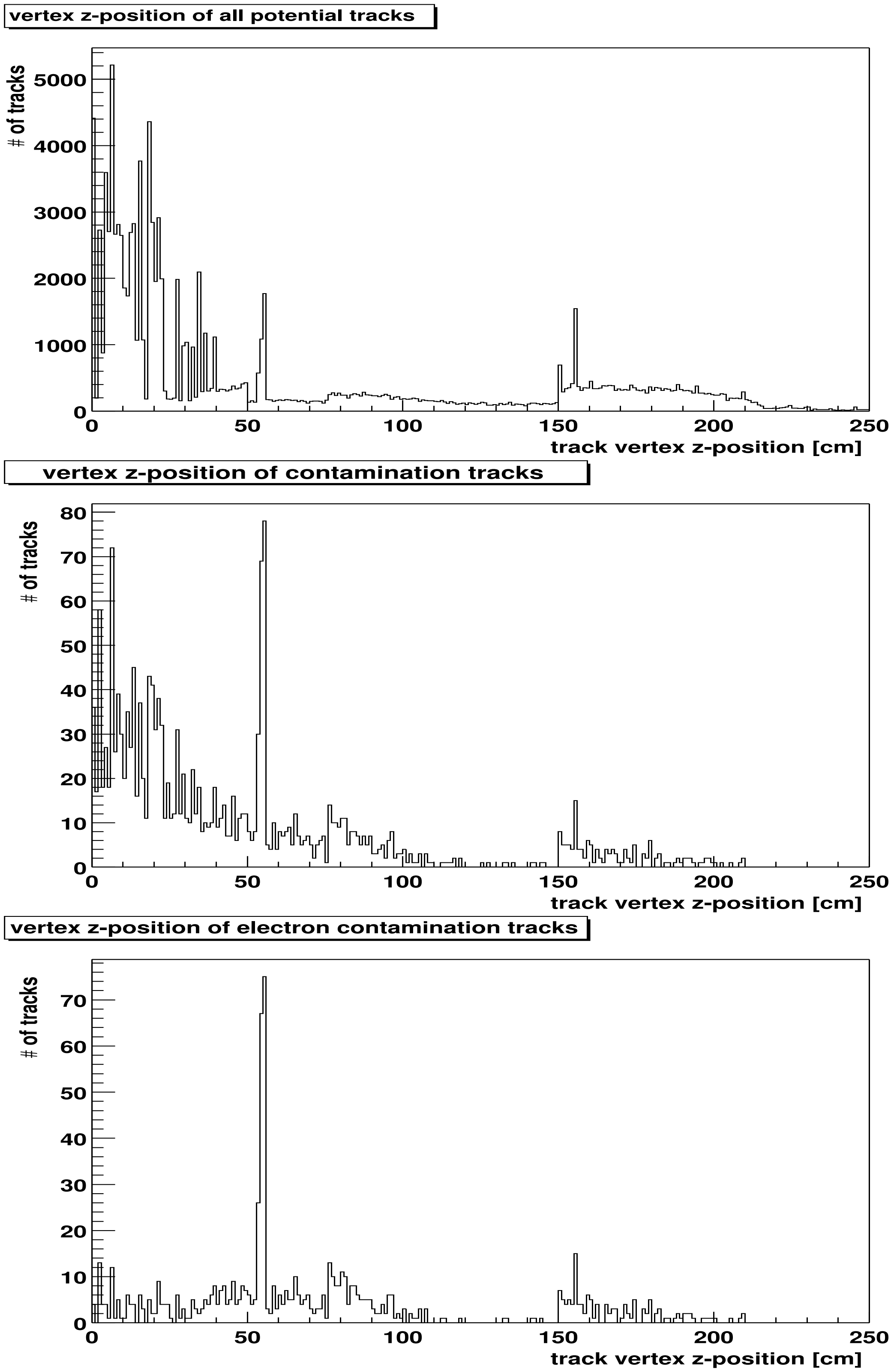

Figure 5.11: *Distribution of the z-coordinate (along the beamline) of the production vertices of particles leaving at least five hits in the Forward TPCs from 70 events simulated using HIJING. The systematics of the distribution are symmetric around z = 0. The top plot shows all tracks, the central plot only those that are falsely reconstructed as coming from the main interaction point. The bottom plot shows only those falsely reconstructed tracks produced by electrons or positrons.*

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