MUREC-A
reconstruction program for HERA-B muon detector operating in stand-alone mode.

HERA-B Muon Detector Group

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1 Introduction.

The purpose of this note is to present the description and performance of the reconstruction code for HERA-B muon detector operating in stand-alone mode. There are two main ideas for muon track reconstruction:

1. Do not use the information from other HERA-B subdetectors. Sure advantage of this idea is that the reconstruction does not depend on configuration or operation of other subdetectors. It is very important for running in the year 1998 when the configuration of HERA-B tracker will be reduced or at the run begin when the data taking is unstable. The main problem of this method is the calculation of the multiple scattering errors. This kind of errors dominates but precise calculation of the errors is impossible because of unknown momentum. It results in increasing of the number of fake tracks or in the low reconstruction efficiency for slow particles.

2. Use the main tracker tracks as seeds for the muon detector reconstruction. The tracks are extrapolated to the muon detector and the hits are linked to these seeds. This method is more flexible in comparison with the first method, the knowledge of the momenta and track impact points allows to calculate the multiple scattering errors precisely. The matching between the muon detector track segments and the tracker segments is not needed. In the case of high target rate the second method provides less number of fake tracks. The problem is that the muon detector reconstruction is a slave of the tracker geometry and operation in this case, the tracker problems becomes the problems of muon detector reconstruction.

The strategy is to use a package of three routines for the reconstruction of muon detector tracks.

MUREC-A This reconstruction program uses the first method, MUREC-A is described in this paper. This routine may be used in RUN-98 data taking, during the start period of running with complete geometry of HERA-B detector or for online monitoring of muon detector operation.

MUREC-B This reconstruction program uses the second method, it will be released later.

MUIDEAL This program works only with Monte Carlo events, it uses Monte Carlo knowledge for pattern recognition. The efficiency of MUIDEAL is therefor 100% and it produces no fakes. MUIDEAL is described in this paper, it was used for MUREC-A performance study.

From programmer's point of view these three routines are strongly overlaped, they use the common input and output routines, have the same inner data structure, call many common routines inside but use the different methods of pattern recognition. It is convenient to combine these routines in one package.

2 Short Description.

All routines are working in ARTE frame [4] starting the version ARTE-01-06. The source code is in the subdirectory *murec* of ARTE CVS repository. Compile, link and running are provided by standard ARTE tools.

INPUT - the standard set of ARTE geometry tables (ARTE geo-file), muon detector hits are taken from ARTE table HITB.

CALL - no initialization is needed, to reconstruct one event
CALL MUIDEAL(MU2,PIX) in the case of ideal reconstruction or
CALL MURECA(MU2,PIX) in the case of autonomous reconstruction of muon detector.

OUTPUT - the muon track segments in ARTE table RSEG (CMP=8), the track parameters and covariance matrix of a track segment are transported to Z=1300 cm,
the reconstructed hits in ARTE table RHIT,
the track extrapolation of each muon track segment to the middle of the calorimeter (point on track in ARTE table RPNT),
the relations between ARTE tables.

Here INTEGER MU2,PIX are the steering parameters introduced to study the different scenarios of the muon detector geometry in run-98. Monte Carlo data are generated in the complete geometry but it is possible to process the data as generated in reduced geometry. If MU2=0 the hits from the muon superlayer MU2 are not used for the muon track reconstruction. If PIX=0 the pixel chamber hits are not used. If both MU2 and PIX are equal to any non-zero integer all hits are used for reconstruction.

3 Sorting and Preparation Step.

This step is a common step for all three routines of the package. Muon detector hits collected in the table HITB are used as input for the track reconstruction. There are three types of chambers in the muon detector: tube, pad and pixel chambers. The design of the chambers is described in HERA-B Proposal [1] and in HERA-B Technical Design Report [2]. Implementation of the chamber geometry in HBGEAN is described in software note [3]. The reconstruction program operates with the hits of three types:

1. Wires of tube and pad chambers in muon superlayers from 1 to 4.

2. Pads of pad chambers in muon superlayers 3 and 4.

3. Pixels of pixel chambers in muon superlayers from 1 to 4.

To simplify the reconstruction procedure the muon detector was divided into 38 layers. Each layer contains the hits of one type only and all hits of the layer have the same z-coordinate. The advantage of such separation is that the high momentum muon passing through a reconstruction layer produces only one hit or two neighbouring hits inside the layer. Scheme of reconstruction layers is shown in fig.1. The vertical cut of the muon detector is schematically drawn and the z-positions of the reconstruction layers are marked in this figure.

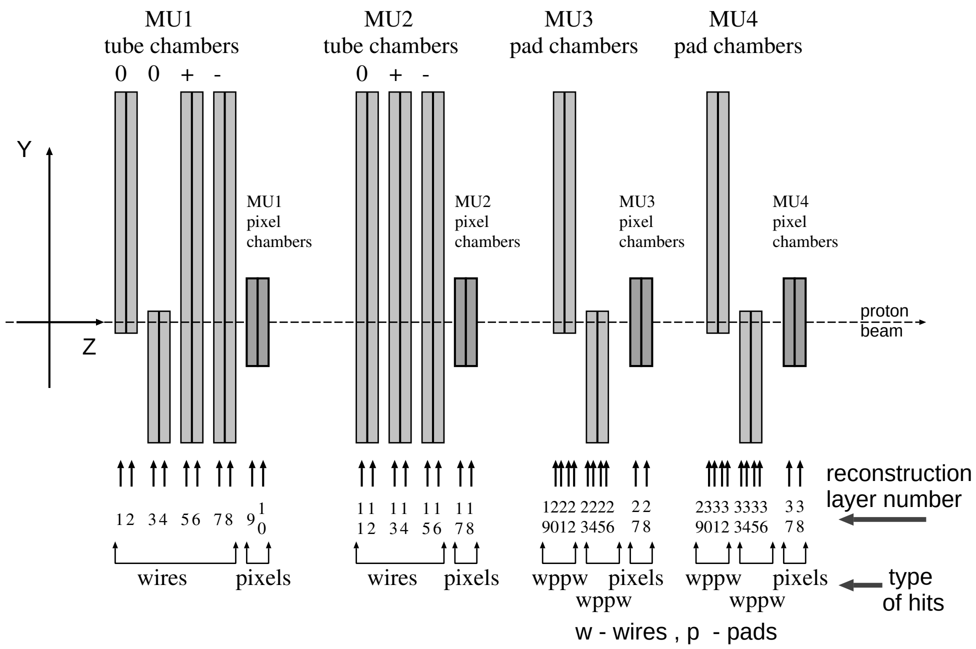

Figure 1: Reconstruction layers in HERA-B muon detector.

Muon superlayer 1 (MU1) is divided into 10 reconstruction layers. They are 4 layers of vertical tube chamber wires, 2 layers of tube chamber wires rotated by +19.67 degree, 2 layers of tube chamber wires rotated by -19.67 degree and 2 pixel layers. Each double layer of tube chambers is divided into 2 reconstruction layers. Up and down vertical tube chambers are in different reconstruction layers because of overlap.
Muon superlayer 2 (MU2) is divided into 8 reconstruction layers. They are 2 layers of vertical tube chamber wires, 2 wire layers with positive slope, 2 wire layers with negative slope and 2 pixel layers.
Each of muon superlayers 3 and 4 (MU3 and MU4) is divided into 10 layers. Each pad chamber has 4 reconstruction layers inside: one vertical wire layer, two pad layers and one wire layer again. Up and down pad chambers are shifted in z-direction and are overlaped. Therefore a superlayer has the structure wire-pad-pad-wire-wire-pad-pad-wire-pixel-pixel.
At the beginning the subroutine MURZDIN reads the geometry ARTE tables GESL and GEDE. It fixes the boundaries of the reconstruction layers and saves them in the common-block MUCZDT.
Routine MURHTIN extracts the muon hits from the table HITB, orders the hits according to the reconstruction layer scheme and writes the hits to the temporary ARTE table TMP9. The collection of hits from superlayer MU2 and the collection of pixels are under control of the steering parameters MU2 and PIX (see section 2).
Routine MURCLIN makes the clusters from the neighbouring hits belonging to the same reconstruction layer. The reconstruction procedure does not provide enough accuracy for a separation between the neighbouring hits. Moreover the separate use of neighbouring hits does not improve the accuracy of reconstruction but results in more fakes. In the case of a shower inside the

muon detector many hits can be in a small hot region, making this part of the detector useless. MURCLIN analyses the cluster size and excludes the large clusters, it saves the clusters in the temporary ARTE table TMP8.

4 Methods of the Program Tuning and Performance Analysis.

Monte Carlo events generated by HBGEAN were used for debugging and studying of the reconstruction program. The final design of muon detector described in [3] was used for the event production. Two kinds of events were generated - the events with directly produced J/Ψ and the minimum bias events, J/Ψ decayed only to $\mu^+\mu^-$. Then one event with directly produced J/Ψ was merged with the minimum bias events according to the Poisson distribution. The sample for the reconstruction program tuning contained 2000 merged events.
A start point of analysis is a selection of the Monte Carlo tracks producing hits in the muon detector and have to be reconstructed (the so called "reference tracks"). The selection criteria for the hit configuration of such tracks follows.

MU1: Track has to hit at least one pixel channel in the muon superlayer 1 or two tube chamber wires from the different stereolayers (to have a cross of wires).

MU2: No hits from the muon superlayer 2 are required.

MU3 and MU4: Track has to hit at least one pixel or pad in the muon superlayers 3 and 4, hitted pad has to be accompanied by at least one related wire.

Momentum distribution of the Monte Carlo "reference tracks" from the events with directly produced J/Ψ is shown in fig.2-a. All "reference tracks" are muons with momenta more 4 GeV/c. It is in good agreement with the preliminary calculations in [1]: a punch-through probability is negligible for the hadrons, a high energy muon loss nearly 4 GeV by ionization during the passing through both calorimeter and the muon detector shields.

The reconstructed tracks are matched to the Monte Carlo "reference tracks". The criterion of matching is a coincidence between the hits collected in reconstructed track and the hits of MC track. The definition is that the track is correctly reconstructed if more than 70% of collected hits are produced by one MC "reference track". Otherwise the reconstructed track is considered as a fake (or "ghost"). Used statistics is not enough for the punch-through calculation because there are no punched-through MC hadrons amongst the "reference tracks".

Another method of the performance analysis is a comparison of the distributions obtained with MUREC-A with the distributions obtained with MUIDEAL on the same statistics.
MUIDEAL uses the mentioned above criteria for the selection of MC "reference tracks" and it fits the hits produced by MC track exactly by the same way as MUREC-A does it. In other words MUIDEAL and MUREC-A have the same input (HITB) and both routines use the same fit and output routines but MUIDEAL uses Monte Carlo knowledge for pattern recognition. Therefore MUIDEAL always has 100% reconstruction efficiency and produces no fakes. This method is useful for the study of reconstruction efficiency as a function of sophisticated variables.

5 Calculation of the Multiple Scattering Errors.

The multiple scattering is a main source of errors in the muon detector. These errors are inversely proportional to the particle momentum and the problem is that the particle momentum is unknown in the stand-alone mode of reconstruction.

Fig.2-b shows a two-dimensional plot of the "reference track" momentum versus the variable $tan\Theta = \frac{R}{Z}$, where R is a distance between track and proton beam in the X-Y plane at

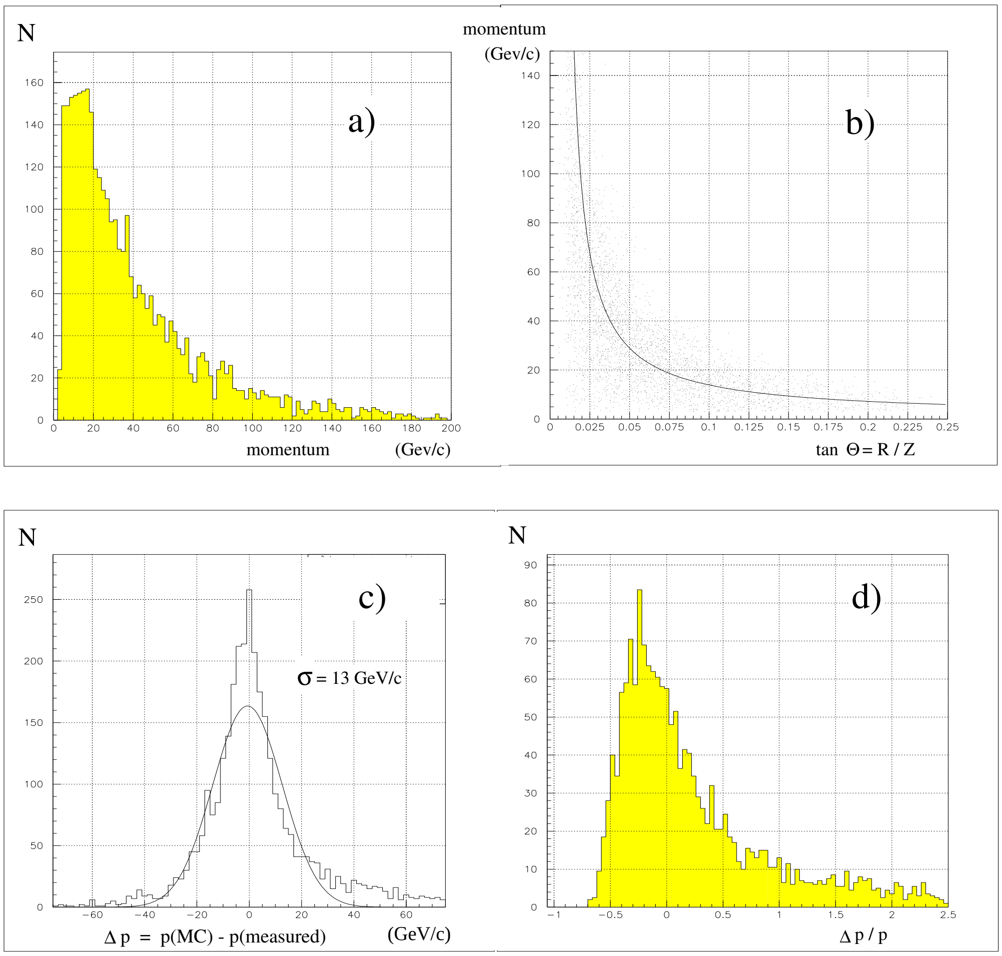

Figure 2: a) Momentum distribution of the Monte Carlo "reference tracks" from 2000 events with directly produced J/Ψ. b) Two-dimensional plot of the "reference track" momentum versus $tan\Theta = \frac{R}{Z}$, where R is a distance between track and proton beam in the XY plane at z-coordinate Z=1300 cm. c) Distribution of the "reference tracks" on the difference between Monte Carlo momentum and the momentum obtained with the procedure described in section 5. d) Distribution of the "reference tracks" on the ratio of momentum difference over the Monte Carlo momentum.

z-coordinate Z=1300 cm. The strong correlation between the two variables is seen, solid line presents the used dependence. The distribution on the difference between Monte Carlo momentum and the momentum obtained with the described dependence on $\frac{R}{Z}$ is shown in figure 2-c for selected MC tracks from 2000 events with directly produced J/Ψ. The distribution is fitted with a gaussian, $\sigma = 13$ GeV/c. Figure 2-d shows the relative accuracy of the momentum evaluation, it is a ratio of the momentum difference over the Monte Carlo momentum. It is seen that accuracy is not good but it is better than nothing.
Multiple scattering errors for the Kalman Filter procedure are calculated by routine MURMSC. The dependence drawn by solid line in fig.2-b is used for momentum calculation. Because of bad momentum knowledge it has no sense to use the detailed inner structure of muon shields for the error calculations. The rough structures of the calorimeter and muon detector shields is implemented in MURMSC to make the calculation fast.

In the case of MUREC-B (reconstruction program based on a second method) the momentum is known and MUREC-B uses more complicated procedure of the multiple scattering errors calculation. The fine structures of the calorimeter from ARTE table GCAL and the inner structure of muon detector shields from ARTE table GEDE are used in this case.

6 MUREC-A: Pattern Recognition Algorithm.

The scheme of the MUREC-A pattern recognition part is shown in figure 3. This algorithm is similar to the algorithm used in First Level Triggering. MUREC-A starts with the pad or pixel positions in the superlayer MU3. Then it fixes the zone of interest in MU4 (see fig.3-a) and selects the pairs of related MU3, MU4 pads or pixels. Routine MURPAD operates with pads, MURPIX operates with pixels. In the case of pad chamber routine MURWIR selects the pad chamber wires related with the selected pads.

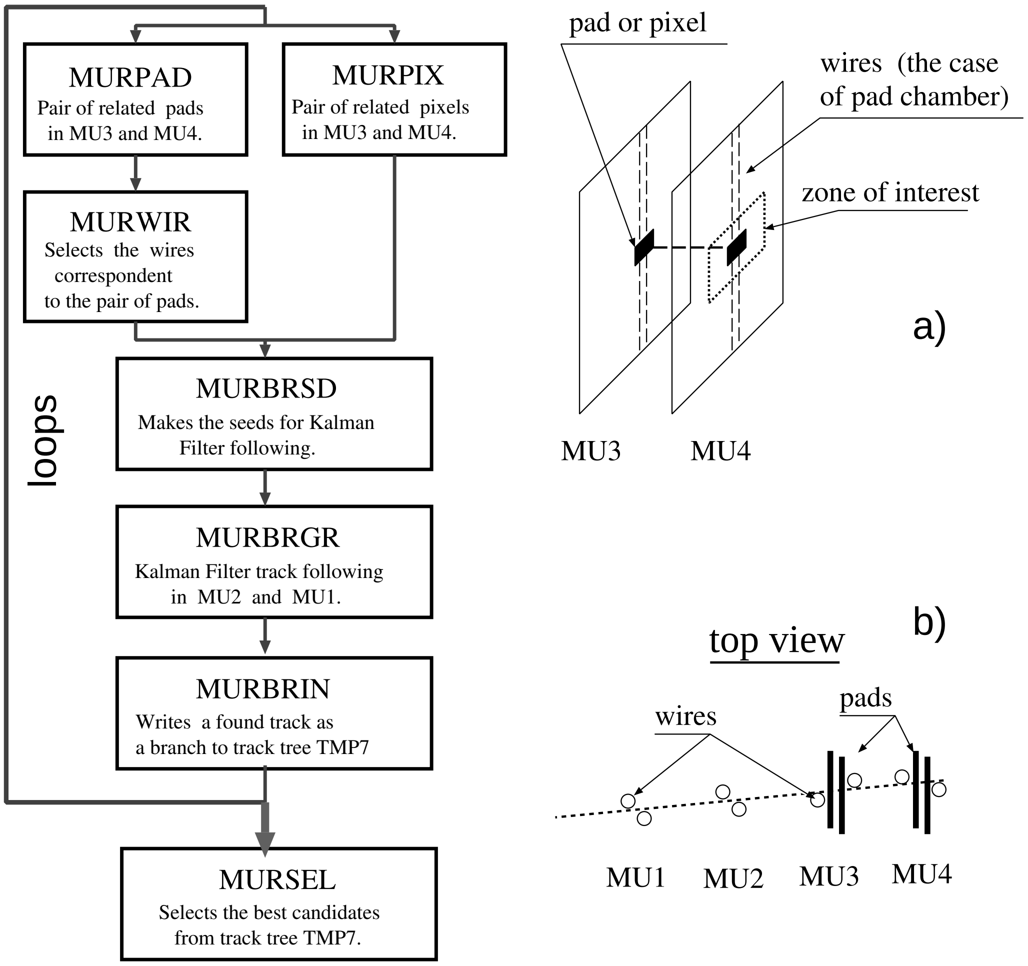

Figure 3: Algorithm of the muon detector reconstruction program MUREC-A.

Routine MURBRSD fits the selected hits and makes a seed for the Kalman filter track following. Any seed can creat a cluster of branches in a track tree, the temporary ARTE table TMP7 is used for writing of the branches.

Routine MURBRGR is used for Kalman filter upstream following. A seed obtained in the muon superlayers MU3 and MU4 is extrapolated to MU2 and MU1 (see fig.3-b), one reconstruction layer after another. Multiple scattering is considered as process noise [5]. If two or more clusters can be linked to the track in one reconstruction layer, MURBRGR creates the parallel branches. Only one cluster can be linked to a branch in one reconstruction layer. All branches created from the seed grow simultaneously when MURBRGR goes from one reconstruction layer to the next. New branches are created in the temporary ARTE table TMP7 by routine MURBRIN.

The track tree contains frequently the branches with a strong overlap. Routine MURSEL selects the best branches of the track tree. To find the best branch an estimator is calculated for all branches. The estimator includes several contributions like χ^2 of branch, number of collected hits and so on. Only candidates fulfiling the criteria described in section 4 as the "reference track" selection criteria can be selected. MURSEL finds a branch having the best estimator and excludes all branches strongly overlaped with the selected branch. Then it selects the best branch again and so on until all good tracks are found.

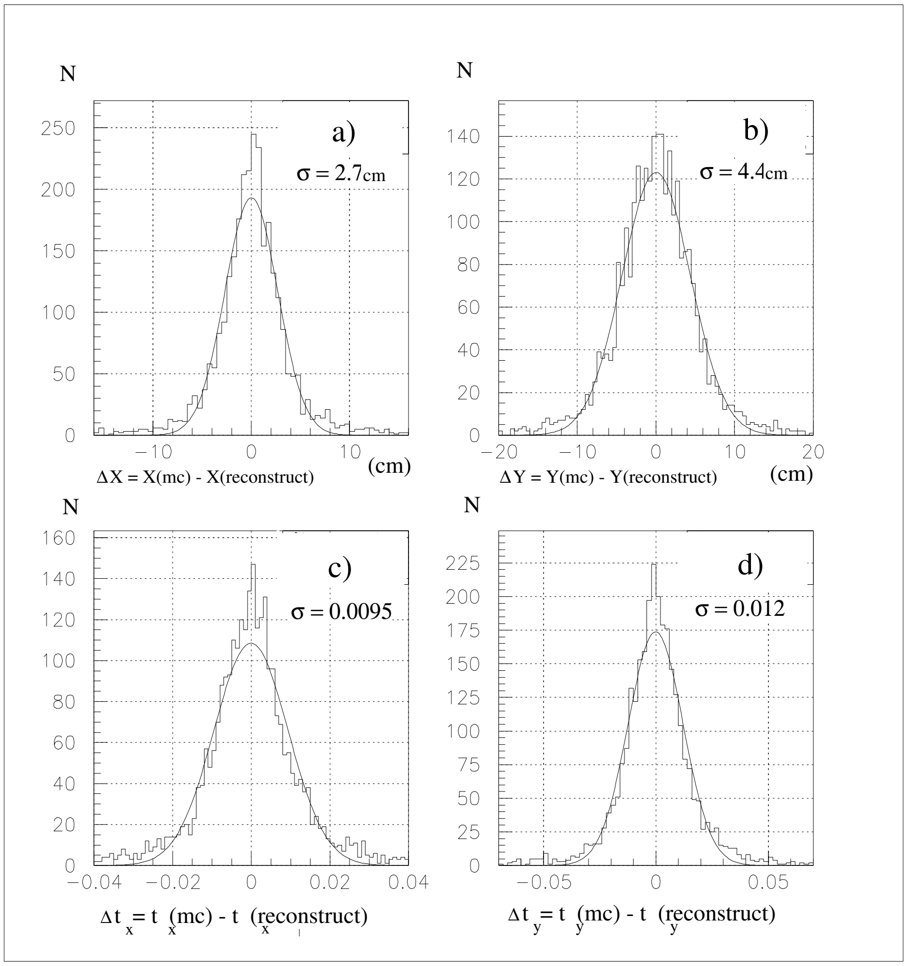

Figure 4: Differences between MC and reconstructed tracks parameters at z-coordinate of last main tracker hit of the track. a) Difference between x-coordinates of MC and reconstructed tracks. b) Difference between y-coordinates of MC and reconstructed tracks. c) Differences between slopes t_x of MC and reconstructed tracks (see parametrization in text). d) Differences between slopes t_y of MC and reconstructed tracks (see parametrization in text).

7 Track Refit and Output.

This part is a common part for all three routines of the muon detector reconstruction package. The Kalman refit method is used like it is made in SUSI [6]. The track parameters and covariance matrix obtained in the pattern recognition part are used for initialization of the Kalman filter downstream propagation. Multiple scattering is considered as a process noise. After processing of all hits the procedure is repeated in backward direction. On this step the track parameters obtained in each step of Kalman filtering are written to ARTE table RHIT as fitted hits.

The fitted track parameters and covariance matrix are propagated to z-coordinate z=1300 cm taking into account the multiple scattering in muon detector shield and in the calorimeter. Routine MURTAB saves the refit results in ARTE table RSEG (reconstructed track segments). Detector component (CMP) is set to be equal 8. Also MURTAB creates the relations between ARTE tables:

- hits (HITB) - reconstructed segments (RSEG),
- reconstructed hits (RHIT) - reconstructed segments (RSEG),
- hits (HITB) - reconstructed hits (RHIT).

The track parameters and covariance matrix of the muon track segments are propagated to the calorimeter middle z-position taking into account the multiple scattering. Results of extrapolation are written to ARTE table RPNT (point on a track). The relations between the tables RSEG and RPNT are created also.

The performance of track refit was studied on Monte Carlo events. Only reconstructed tracks matched to the Monte Carlo "reference tracks" were used for comparison. Figure 4 shows the distributions on differences between MC and reconstructed tracks parameters at the z-coordinate of last main tracker hit of the track. Last hit means the hit with maximal z-coordinate. Figure 4-a shows the distribution on the difference between track x-coordinates, fig. 4-b shows the distribution on the difference between track y-coordinates. Figures 4-c and 4-d show the distributions on the differences between track slopes t_x and t_y in track parametrization

$$x = c_x + t_x\,(z - z_0) \qquad y = c_y + t_y\,(z - z_0)$$

The distributions are fitted by a gaussian, the σ of gaussians are plotted in figure 4.

8 Performance.

The MUREC-A performance was investigated on MC events as a function of a mean number of minimum bias events merged with one event of inclusive J/Ψ production.

Figure 5-a shows MUREC-A reconstruction efficiency for all muons and for muons from J/Ψ decays. Efficiency drops with the increasing target rate (the mean number of merged minimum bias events is proportional to the target rate). Figure 5-c shows a ratio of the fake tracks over the number of reconstructed tracks. It is not surprising that the ratio of fakes goes up with the target rate. Relation between efficiency and the number of fakes is a matter of compromise. As usual, increasing the reconstruction efficiency by tuning the program parameters gives also an increase of the number of fakes. In presented version MUREC-A was tuned for the case of one inelastic interaction (in mean). In this point the reconstruction efficiency of muons is 0.95, the reconstruction efficiency of muons from J/Ψ decays is nearly 0.97 and the ratio of fakes is less 0.05.

To demonstrate the reasons of inefficiency, the distributions in figure 6 were plotted. Fig. 6-a shows the momentum distribution of Monte Carlo tracks and fig. 6-c shows the MUREC-A reconstruction efficiency as a function of momentum. The drop of efficiency is seen for momenta less than 15 GeV/c, this drop is due to the large multiple scattering of slow particles. Fig. 6-b shows the distribution on a distance between MC track and proton beam at Z=1300 cm, fig. 6-d shows MUREC-A reconstruction efficiency as a function of the same parameter. Efficiency is smaller in the region of pixel chambers. It is due to the high occupancy of pixel chambers and

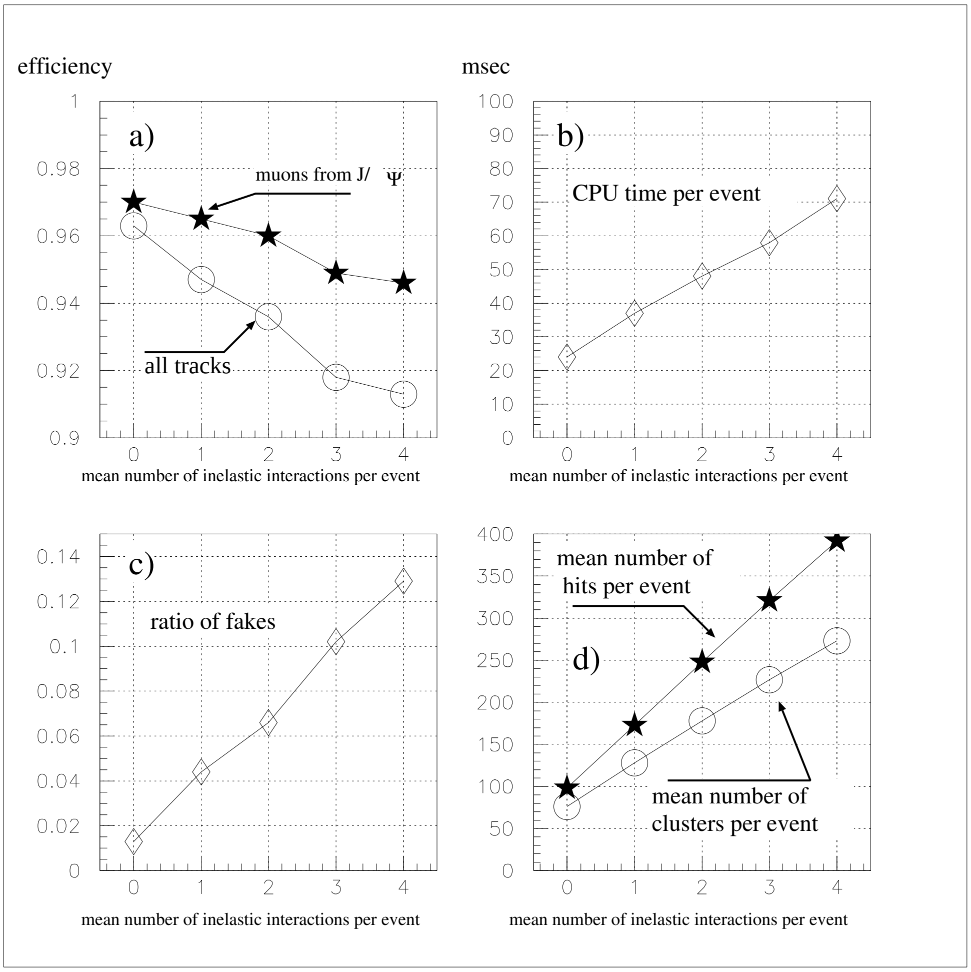

Figure 5: a) MUREC-A reconstruction efficiency for all muons and for muons from J/Ψ decays as a function of a mean number of minimum bias events merged with one event of inclusive J/Ψ production. b) Mean CPU time per event as a function of a mean number of minimum bias events. c) Ratio of fake tracks over the number of reconstructed tracks as a function of a mean number of minimum bias events. d) Mean number of hits per event and mean number of clusters per event as a function of a mean number of minimum bias events.

due to the small number of hits related with the track (only 4 pixels per track). The reflection of the relatively low reconstruction efficiency of pixel chambers is a decrease of reconstruction efficiency in the region of high momenta.

Tuning of parameters and debugging can improve the reconstruction efficiency of MUREC-A in the future but it is difficult to expect a perfect performance of MUREC-A at target rate 40 - 50 MHz. The improvement can be achieved in MUREC-B due to the use of main tracker tracks as seeds. The work is in a progress.

The mean time necessary for a reconstruction of one merged event was measured on hydra.ifh.de (SGI computer at IfH-Zeuthen). Figure 5-b shows mean CPU time per event as a function of a mean number of added inelastic interactions per event. For reference figure 5-d shows the mean number of muon detector hits per event and the mean number of clusters per event as a function of the same variable. It is seen that the processing of one event takes nearly 40 msec in the case of one minimum bias event.

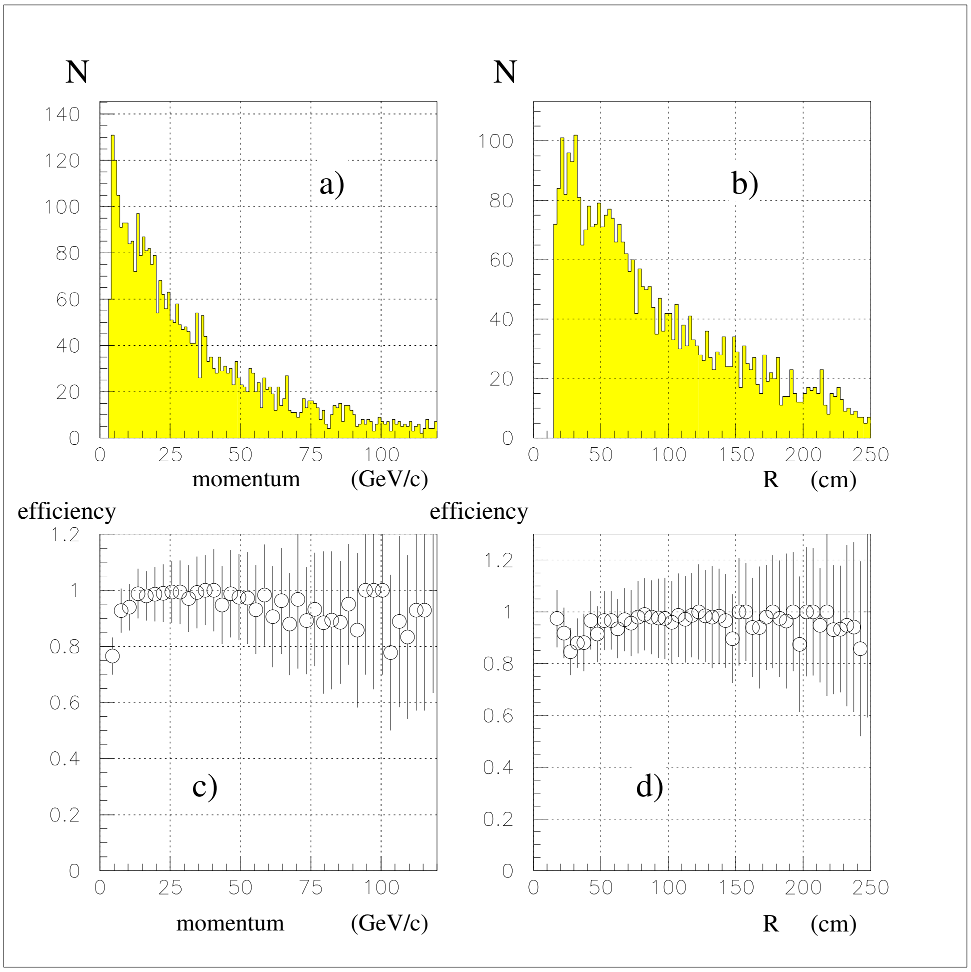

Figure 6: Distributions for the Monte Carlo merged events containing one interaction with inclusive J/Ψ production and the inelastic interactions merged according to Poisson distribution with mean value 1. a) Momentum distribution of Monte Carlo "reference tracks". b) Distribution of Monte Carlo "reference tracks" on the distance between proton beam and the track at Z=1300 cm. c) MUREC-A reconstruction efficiency as a function of momentum. d) MUREC-A reconstruction efficiency as a function of the distance between proton beam and track at Z=1300 cm.

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