Report of the Review Board for HARP (RBH)

March 1st 2007

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1. Mandate

The HARP Collaboration has recently submitted for Journal publication the article "The HARP detector at the CERN PS" which contains a technical description of the detector and its performance.

The detector calibrations and performances presented in this paper for the Time Projection Chamber (TPC) and the Resistive Plate Chambers (RPC) have been disputed by another part of the collaboration (CERN-Dubna-Protvino group, V. Ammosov et al). The comments are based on an alternative analysis ("Comments on The HARP detector at the CERN PS" and "The HARP White Book"). A Rebuttal has been made by the HARP Collaboration (Rebuttal to comments on "The HARP detector at the CERN PS").

Since the disagreement could not be resolved internally by the HARP Collaboration, the primary HARP Funding Agencies, INFN and CERN, have decided – in consultation with the SPSC Chair – to establish an external review. The scope of this review is the scientific evaluation of the detector performance presented in the HARP technical paper, focusing mainly on the disputed aspects.

The review board for HARP (RBH) comprises Lorenzo Foa'[1] (chair), Tancredi Carli[2], Juan Fuster[2], Jasper Kirkby[3] and Gigi Rolandi[3].

The review process has been based on the following documents:

1. The HARP detector at the CERN PS[4] by the HARP Coll.
2. Comments to the HARP detector at the CERN PS[4] by V. Ammosov et al.
3. Rebuttal to the Comments on the HARP detector at CERN PS[4] by the HARP Coll.
4. The HARP White Book by V. Ammosov et al.

In addition we received many reports and documents from the two parties. Two have been especially useful:

1. Track reconstruction and characterization by the HARP Collaboration
2. On static and dynamic distortions in the HARP TPC by V.Ammosov et al.

The RBH met several times with the two groups (at least 5) or in closed sessions (4 times) for about half a day and a few times via telephone conference between November and February. All members of RBH unanimously agree on the conclusions reached in this intensive work that are reported in the following pages.

[1]Appointed by INFN
[2]SPSC Referee
[3]Appointed by CERN PH
[4]Meawhile published on NIM A Volume 571 pages 527, 562 and 564

2. Executive summary

Firstly, the RBH would like to thank the official HARP Collaboration and the CERN-Dubna-Protvino group (hereinafter referred to as OH and CDP, respectively) for clarifying our questions with additional data provided in written reports, transparencies and discussions. After careful consideration of all this information, the RBH has arrived at a unanimous conclusion, which is presented in this report.

After initial examination of the documents at the start of its work, the RBH decided that the central question to address is whether or not the residual TPC distortions in the present OH analysis are causing a significant distortion of the momentum spectra for the first 100 events in each spill, beyond the stated systematic errors. The present OH wide-angle physics analysis is restricted to around the first 100 events in each spill (corresponding to about one third of the total events) in order to reduce the effect of uncorrected dynamic TPC distortions due to positive ion buildup in the TPC. The claim of OH is that the momentum bias is small for these events (<3% at 0.5 GeV/c). This is disputed by CDP, who claim the presence of a large momentum bias in the present OH analysis due to uncorrected TPC distortions.

The RBH finds clear evidence for a significant momentum bias in the OH analysis, pointing in the direction of a systematic momentum shift to lower values for positive tracks in a positive B field (and, by implication, to higher values for a reversal of either the charge or the B field). The bias is shown by the disagreement between the observed and expected particle energy loss (dE/dx) measured in the TPC for protons above about 0.4 GeV/c. Moreover, this bias can explain quantitatively the observed negative shift between RPC-measured and TPC-predicted time-of-flight for protons, for which OH has provided no convincing explanation.

The RBH finds no evidence of any significant momentum bias in the CDP analysis, extending through all events in the spill. Comparing the 1/pt spectra of OH and CDP shows that the momentum bias observed in OH data results in a significant distortion of the momentum spectra – substantially larger than the stated systematic errors – in the restricted low energy region below 0.5 GeV/c that is used in the OH wide angle physics analysis.

3. Analysis

3.1 Background information

The HARP TPC suffered a number of severe problems during data taking, including a wrong setting of the voltage of the inner field cage, signal cross-talk in the readout electronics, and an incorrect matching of the voltages of the wire grids near the pad plane which resulted in a substantial fraction of positive ions flowing back into the drift volume. As result of these effects the trajectories of the drift electrons are systematically displaced in r-phi as a function of numerous parameters: radial and z positions, event time with respect to the start of the spill, B field polarity, and the particular run conditions such as beam intensity and target.

The "static distortions" which are present at the start of the spill (due to the field cage voltage error and possible mis-match of the voltage of the gating grid) are calibrated using cosmic rays runs and fitting a model of the distortions based on the *a priori* knowledge of the electric and magnetic fields. The techniques used by OH and by CDP are different. Both groups fit full cosmic ray tracks that traverse the TPC and pass near to the beam axis; however, in addition, CDP also requires a match of the track with the RPC overlap region in order to constrain the reconstructed track to an external frame. The "dynamic distortions" which grow with time from the start of the spill (caused by the positive ions drifting back into the drift volume) are also treated in a different way. OH decided at this stage to restrict the analysis to the initial part of the spill (approximately corresponding to the first 100 events) and to assess a systematic error large enough to include the momentum bias caused by leaving the dynamic distortions uncorrected. OH is working on the correction of the dynamic distortions for a second phase of the analysis. CDP has finalized a model that uses the measured TPC charge distribution with time in the spill, and then propagates a fraction of this charge back through the TPC volume, numerically calculating the resultant electric field distortion and therefore the drift error.

The TPC static distortions (due to the field cage voltage error) are large: up to 10 mm in the r-phi (azimuthal) direction, which is relevant for momentum measurement. The dynamic distortions are comparable: up to 10 mm in r-phi over the full spill. These distortions may be compared with the sagitta of 4 mm for 1 GeV/c transverse momentum (pt). The E-field-induced distortions in the radial direction are smaller by about a factor of 3, and affect the polar angle measurement negligibly. The dE/dx measurement (based on TPC pulse height measurements) is not affected by the distortions. Including the vertex constraint in the fit improves the resolution by about a factor 2. The sign and the size of the sagitta bias are also affected by the inclusion or not of the vertex point in the fit (referred to as "constrained" and "unconstrained" fits, respectively). Both OH and CDP use the vertex constraint in their baseline momentum measurements. For protons with large dE/dx, the energy loss in the material between the vertex and the gas must be taken into account in the fit.

A very efficient tool for studying TPC distortions is the possibility to reverse the magnetic field since this reverses the sign of the (**E**x**B**) r-phi distortions. CDP has proven to us the stability of their correction when reversing the magnetic field. We have only seen a few plots from OH with negative magnet polarity: the main reason is that OH has not yet calibrated the bulk of these runs. We have seen elastic scattering (H target) data from OH with negative magnet polarity. These fits were without the beam constraint and the statistics were insufficient to exclude a possible momentum bias at the level discussed below. Unfortunately, we have not received plots from OH of TPC residuals comparing the two different polarities; these would be a direct way to assess the residual distortions.

For the above reasons our investigations have mainly addressed a single question: how well OH has under control the TPC momentum scale in their analysis – a quantity that directly concerns the wide angle physics to be measured by HARP, namely differential cross sections as a function of momentum and angle. We have also investigated the RPC calibration – but only addressing the influence of a momentum bias of the TPC in this calibration. The RPCs are only marginally used in the present OH analysis.

3.2 RPC time-of-flight

In the IEEE paper published by OH, the time response of the RPC to protons and pions is different. Further progress has been made since then, including the application of corrections due to the energy loss when traversing the detector, which are larger for protons than for pions. However, the time response of pions and protons is still different, as shown in Fig.1.

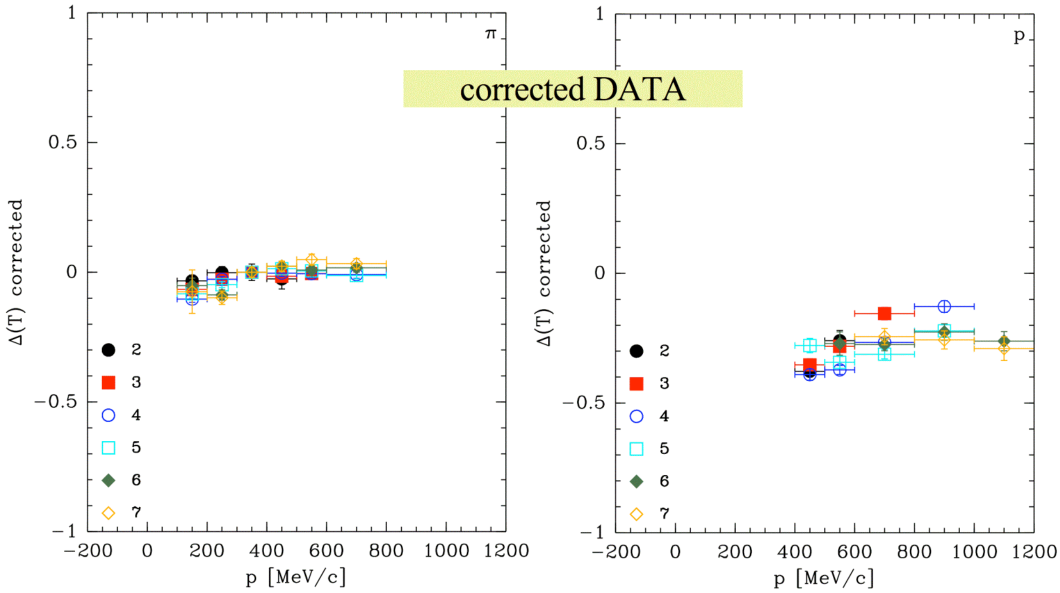

Fig.1: The OH analysis of ΔT = (measured – predicted) time-of-flight for pions (left panel) and protons (right panel), after all corrections have been applied. The measured time is provided by the RPC signal time and the predicted time is based on the track momentum measured in the TPC. The numbers refer to RPC pad ring (equivalent to z position; with 2 in the most backward direction). Whereas the pion data are centered near zero, the proton data are seen to be systematically shifted to negative times by around 300 ps.

The origin of this discrepancy has not been convincingly explained to us. OH states that this is possibly due to the response of the RPC to different ionization density of pions and protons. We suggest another possibility: that it could indicate a systematic bias of the sagitta error by ~ 1 mm (equivalent to a bias on the measured momentum by about -0.2 GeV/c for positive tracks around 0.8 GeV/c). This would cause the predicted flight time to be longer than the true time, hence producing a negative shift for the proton tracks (whose predicted velocity is sensitive to momentum errors up to around 1 GeV/c, whereas pions are not). We note that the CDP analysis does not show any time discrepancy between protons and pions.

3.3 Momentum bias

Fig 2 shows the momentum bias in OH data for the fit using the TPC only (unconstrained tracks) in elastic events as function of the event number in the spill. The event number is approximately equivalent to time in the spill (there are typically around 350 events during the 0.4 s spill).

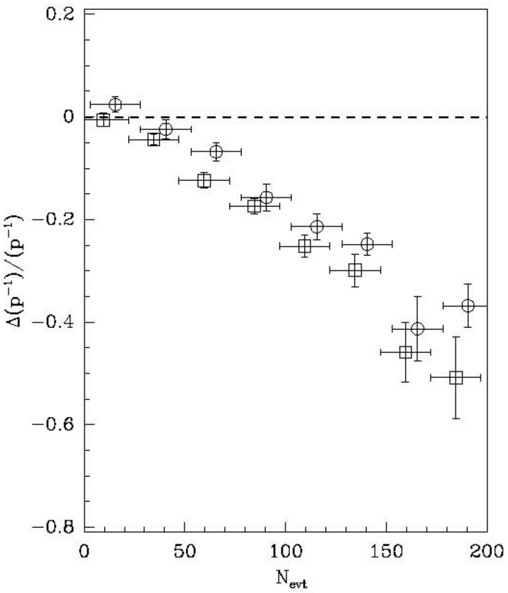

Fig. 2: OH analysis of the momentum bias for unconstrained fits (1/p_measured – 1/p_predicted)/(1/p_predicted) for elastic scattered protons as a function of event number in the spill. The squares are 3 GeV/c data and the circles are 5 GeV/c data. A momentum bias is seen for these unconstrained data due to TPC dynamic distortions that reaches -25% after 100 events (the mean momentum is around 350 MeV/c for these data).

The effect of the dynamic distortions is clearly visible and the effect is large. The dynamic distortions increase linearly with the number of events and reach 25% bias at 100 events. The bias is different in the two runs reflecting different conditions of the beam. The bias is such that the measured momentum for positive tracks is larger than the predicted momentum. The reconstructed tracks miss the interaction vertex and the average impact parameter (d0') is used as estimator of the amount of distortion. The analysis uses events with d0'<5 mm, corresponding typically to 100 events in the spill. OH calibrates the momentum scale using elastic events and the unconstrained fit to the first 50 events in the spill.

OH uses the vertex constrained fit for their analysis, i.e. the tracks are now fitted using the biased points in the TPC and the un-biased vertex point. OH states that, owing the properly chosen weight of the vertex point and owing to a feature of the dynamic distortions (a zero crossing point near to the center of gravity of the weights of the points), the bias on the constrained fit is less than 3% for pt up to about 0.5 GeV/c. Due to the difficulties explained above (energy loss of protons in the cryogenic target and inner field cage) this statement has not been proven to us directly with elastic scattering data. Using data with other targets, OH provides a stability check over the first 100 events by selecting protons with dE/dx (Fig. 3) and a study of the relative difference between inverse momenta reconstructed on generic tracks with constrained and unconstrained fit that apparently shows no bias and also good agreement with Monte Carlo prediction.

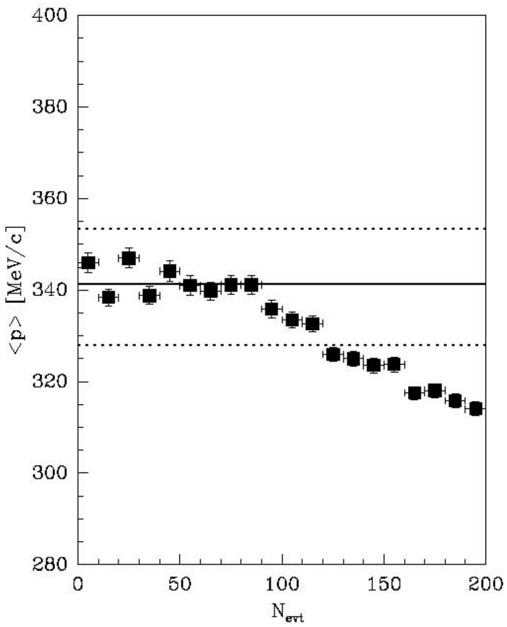

Fig. 3: OH analysis of the average momentum of the protons, selected by dE/dx, versus the number of the event in the spill. The data are constrained fits and are integrated over several targets. The dotted lines correspond to a ±3% band.

Figure 3 is obtained by combining data from a quite large number of data sets and shows indeed a stability better than 3%. However it also has some features that are difficult to understand. The size of dynamic distortions must change linearly in time (as seen in Fig. 2). Here we see that Fig. 3 has a discontinuity around event 100 and then decreases with a slope of about 6% per 100 events.

The bias for constrained fits has the opposite sign compared to the case for unconstrained fits; the average momentum of positive tracks decreases as the distortion increases. We conclude from Fig. 2 that the dynamic distortions act to decrease the curvature of positive tracks in the TPC. However, when the vertex constraint is included in these distorted tracks (which have a large impact parameter of up to 5 mm with respect to the vertex), the sign reverses and the effect of the dynamic distortions is to progressively increase the curvature (i.e. reduce the momentum of positive tracks), as seen in Fig. 3. This qualitatively agrees with what we would expect and implies the presence of large fit residuals (poor fit quality) in the TPC for the constrained tracks.

3.4 Momentum calibration with the TPC dE/dx measurement

The measurement of dE/dx vs. momentum for constrained tracks by OH is shown in Fig. 4.

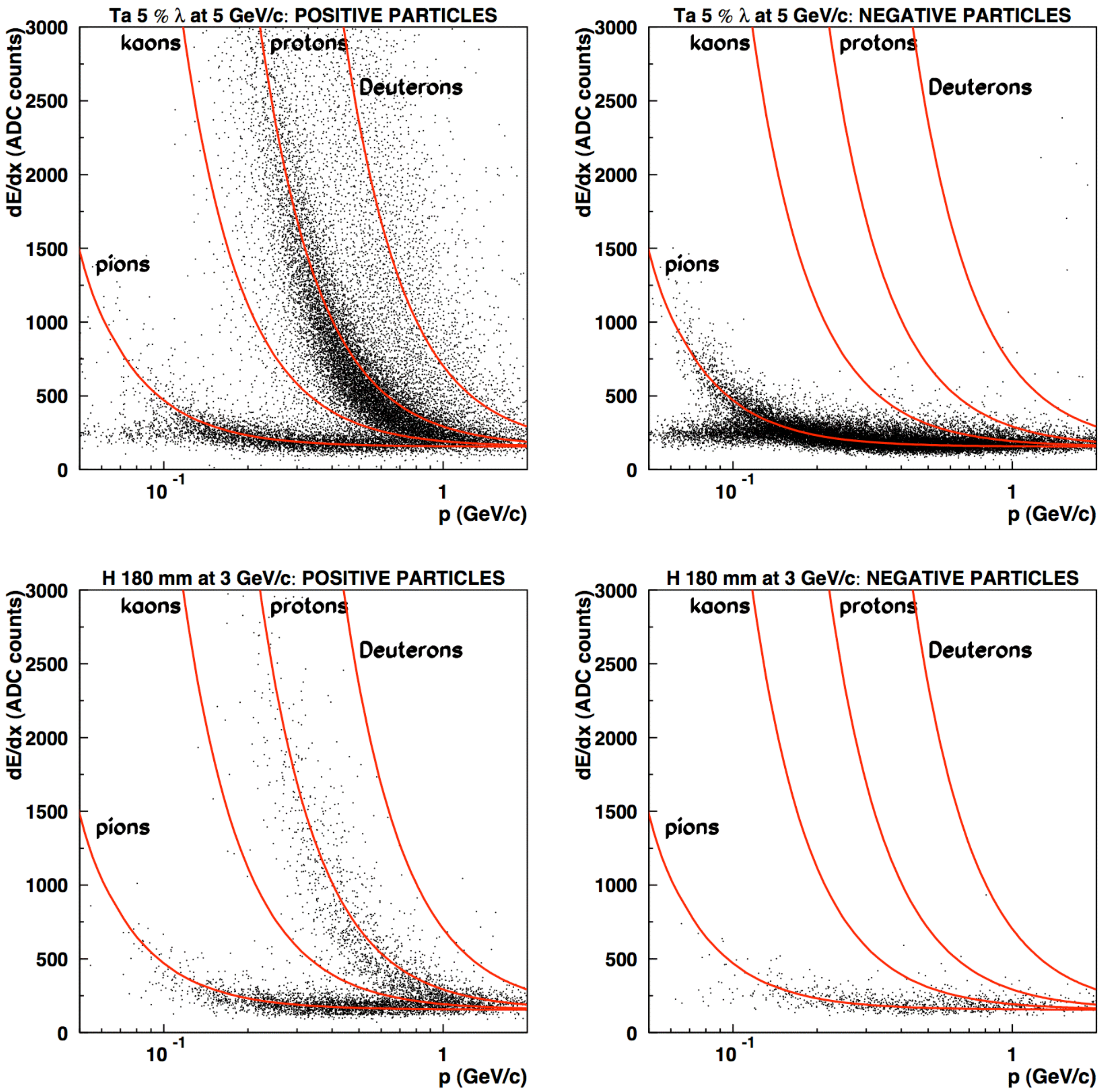

Fig. 4: OH analysis of TPC dE/dx vs. constrained momentum, shown separately for positive (left) and negative (right) particles, and for 5 GeV/c Ta (upper) and 3 GeV/c H (lower) targets. The data are restricted to the first 100 events in the spill.

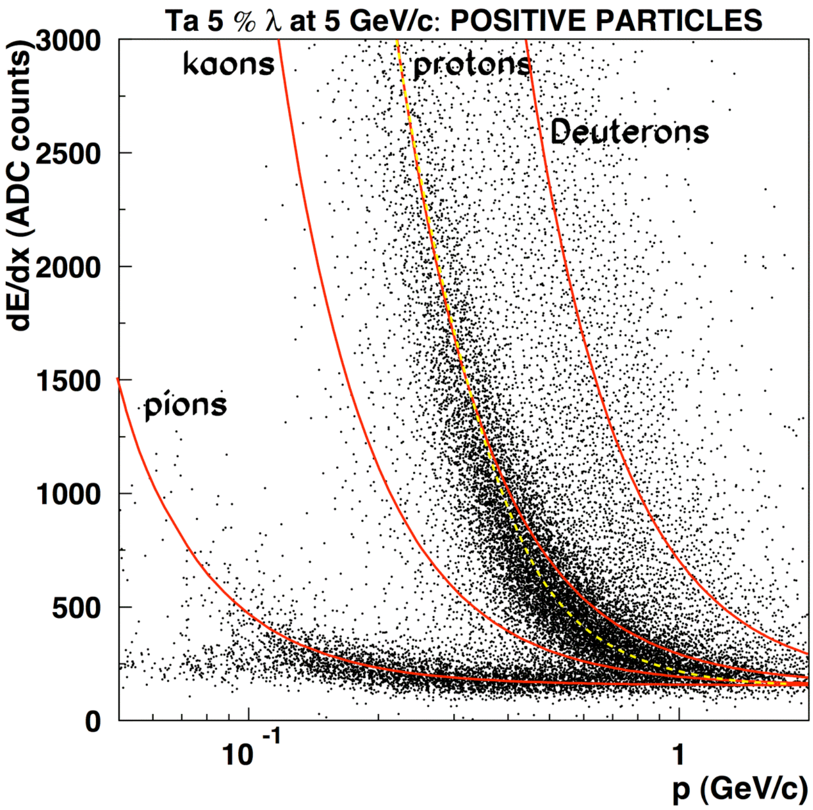

Fig 5: OH analysis of TPC dE/dx vs. constrained momentum for positive particles and 5 GeV/c Ta target, for the first 100 events in the spill (same data as top left panel in Fig.4). The solid red curves are the OH curves for the expected dE/dx (1/beta^2) and the dashed yellow curve is a smooth curve drawn by eye through the centre of the proton distribution. Above about 0.4 GeV/c the proton momenta are seen to fall systematically below the values expected from the dE/dx measurement – by around 0.2 GeV/c in the region near 0.8-1 GeV/c.

A close look at the plots shows that the measured protons do not match the prediction in the region above about 400 MeV/c, while the pions fit the expected curve well in the mip region (Fig. 5). The bias is in the direction of decreasing the momentum, consistent with what we expect from the constrained fit in the presence of distortions. It corresponds to a bias of roughly 15% at 600 MeV (evaluated from a slice of the plot). OH says that the curves are only approximate (1/beta^2) and that no careful calibration has been performed to fit the expected curves to the data. However, our understanding is that once the pions define the minimum ionizing pulse height, there is little room left for further adjustment. We have also confirmed independently that the expected curves in Figs. 4 and 5 are reasonably correct. We asked OH to provide calibrated and corrected curves and very recently we received a set of plots. We studied them in detail and we decided not to change our conclusions. The motivations for this decision are presented in the Appendix A to this report.

We have asked CDP to provide the same dE/dx plot on the same dataset. The data are shown in Figs. 6 and 7. We have checked that the expected curves in Fig. 4 and Fig. 6 are almost identical (as they should be). The CDP data fit the expected curves much better. Moreover the CDP data include all events in the spill. We have seen separate data for the first 100 and last 100 events; they are practically identical. A selection with a cut $2.55<dE/dx<3.45$ mips selects protons in the region of 0.6 GeV/c. This selection from CDP is shown in Fig. 8, comparing the first 100 and last 100 events in the spill. There is no bias.

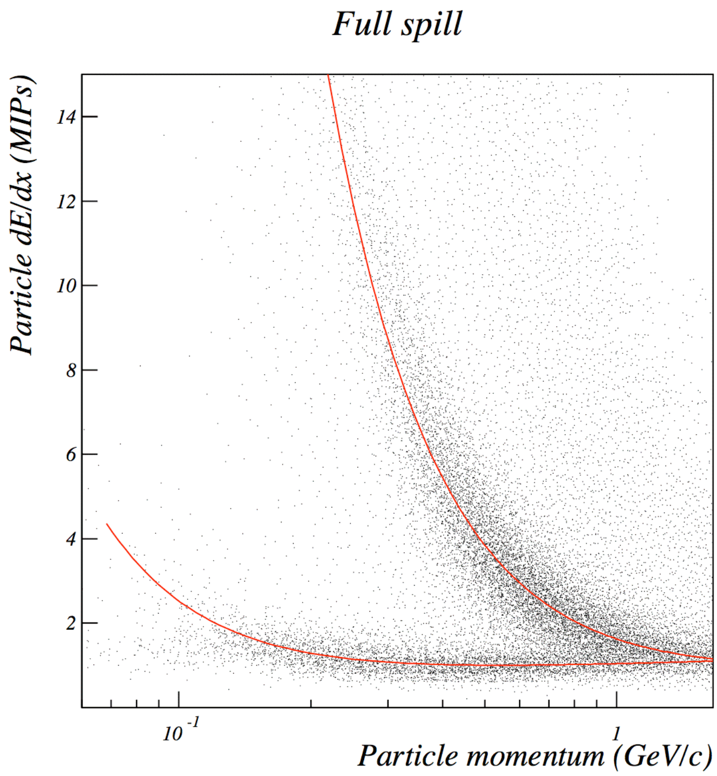

Fig. 6: CDP analysis of TPC dE/dx vs. constrained momentum for positive particles and 5 GeV/c Ta target. The solid red curves show the expected dE/dx for pions (lower) and protons (upper). All events in the spill are included. These data may be directly compared with the OH data in Fig. 5.

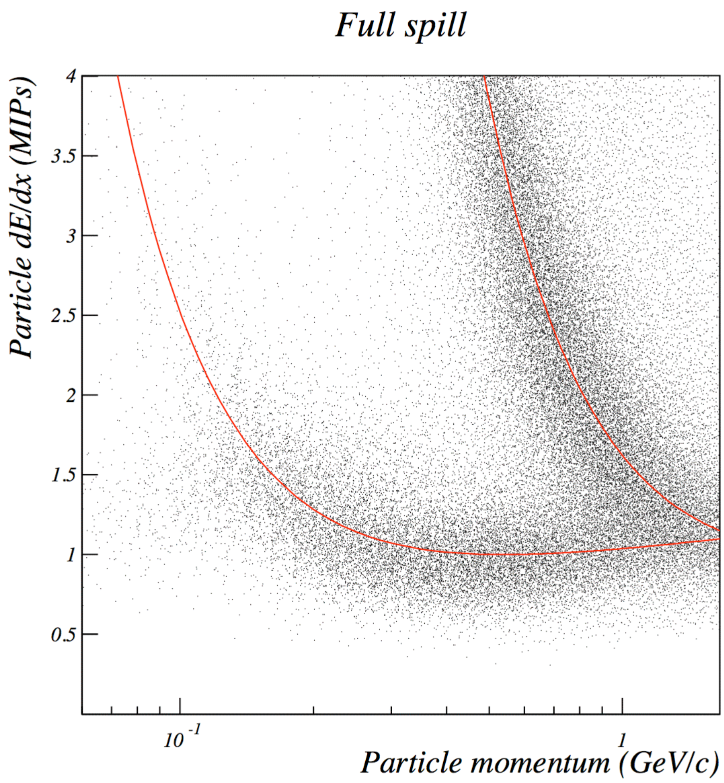

Fig. 7: CDP data: blow-up of the low pulse height region in Fig. 6 to show the high momentum region in more detail.

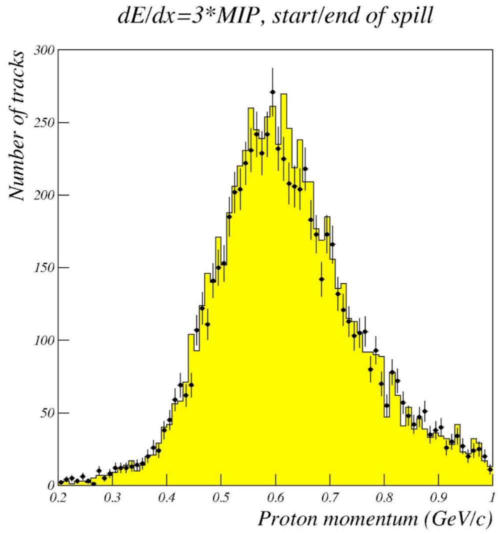

Fig. 8: CDP analysis of the proton momentum distribution (constrained fit) for tracks selected with a TPC pulse height 2.55 < dE/dx<3.45 mip, for 5 GeV/c Ta data. The momentum distribution is shown at the start of the spill (line) and at the end of the spill (points). No bias is seen.

3.5 Comparison of OH and CDP momentum spectra

We asked both OH and CDP for a plot of signed 1/pt for unselected tracks in the TPC from the same dataset – 3 GeV/c Ta. The plots are shown overlaid in Fig. 10. The dashed lines have been drawn through the OH data points by eye; the relative normalization has also been drawn by eye. Two plots are shown per group showing the spectra at the beginning and the end of the data they use in the spill.

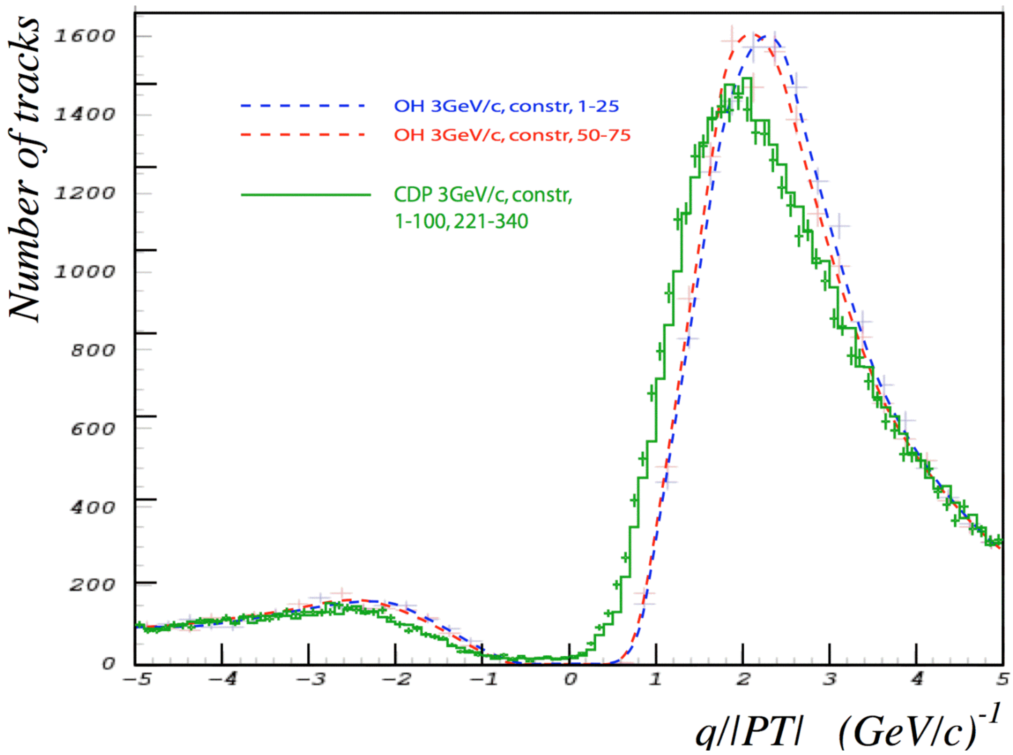

Fig. 10: Comparison OH and CDP signed 1/pt distributions for constrained fits of unselected tracks in the TPC (3 GeV/c Ta data). The OH data correspond to events 1-25 (blue dashed line) and 50-75 (red dashed line) in the spill. The CDP data correspond to the first 100 events (green line) and last 100 events (green crosses) in the spill.

While there is approximate consistency between the beginning and "end of fill" data (though the end is different for the two groups), the curves of the two groups are not consistent. There is a clear discrepancy between the two sets of about Delta(1/pt) = 0.3 (GeV/c)-1, consistent on both the positive and the negative sides. The central part of the plot shows the typical behavior of a sagitta bias i.e. a rigid translation between the spectra of the two groups. Assuming a constant sagitta bias for all tracks, one should also see the same shift on the trailing edge of the protons (the region above 3 GeV/c-1). This is not seen.

3.6 Conclusions on the OH momentum bias

Assuming that CDP data are not biased – based on the previous discussion – then the observed shift in the OH data in Fig. 10 is consistent in sign and magnitude with the effects seen in:

- Fig. 5: the dE/dx plot, where a 15% shift at 600 MeV/c toward lower momenta is equivalent to a bias of 0.25 (GeV/c)-1 and
- Fig. 1: the RPC timing difference for pions and protons. A momentum bias of 0.25 (GeV/c)-1 would shift all proton points upwards by ~(300 ps)/γ, greatly improving the agreement of the pion and proton data (the γ range is 1.1–1.4).

Figure 10 also indicates that the vertex constraint has a significant bias on the momentum even before the onset of dynamic distortions. One possible explanation of these observations is that run-by-run static corrections are not yet properly corrected in the OH data and that the small dynamic distortions internally apparent in the OH data (red vs. blue dashed lines in Fig. 10) are in fact due to an interplay of significant dynamic distortions with finite residual static distortions.

We have not yet seen a study of the absolute calibration of the momentum scale in CDP analysis (i.e. a comparison with elastic scattering data). However the fit to the peak of Fig. 8 gives a value of momentum of 0.599 +/- 0.001 GeV/c to be compared with an expected value of the momentum for a 3 mips proton of 0.588 GeV/c : i.e. 2% agreement. This indicates no bias in the CDP momentum scale to better than a few %.

Our interpretation, therefore, of the plots shown in Fig. 10 is that the bias on the CDP data is much smaller than the bias on the OH data. Looking now in the region of 0.5 GeV/c, which is the upper momentum limit of the present physics analysis by OH, the momentum bias is at least 10%, which is much larger than the 3% bias quoted by OH. The momentum bias has a considerable impact on the particle cross sections; specifically one can see in the negative part of the distribution that at 1/pt = 2 (GeV/c)-1 the rate of negative pions measured by OH is at least 20% larger than that measured by CDP.

APPENDIX A

OH provided the calibrated dE/dx curve shown in Fig. A1. The calibration was performed in two steps: 1) dE/dx peaks are fitted in different momentum slices to obtain some representative points (indicated by red spots on the plot) ; 2) pion and proton data points are fitted simultaneously to the curves expected from theory leaving as free parameter the normalization of the vertical scale.

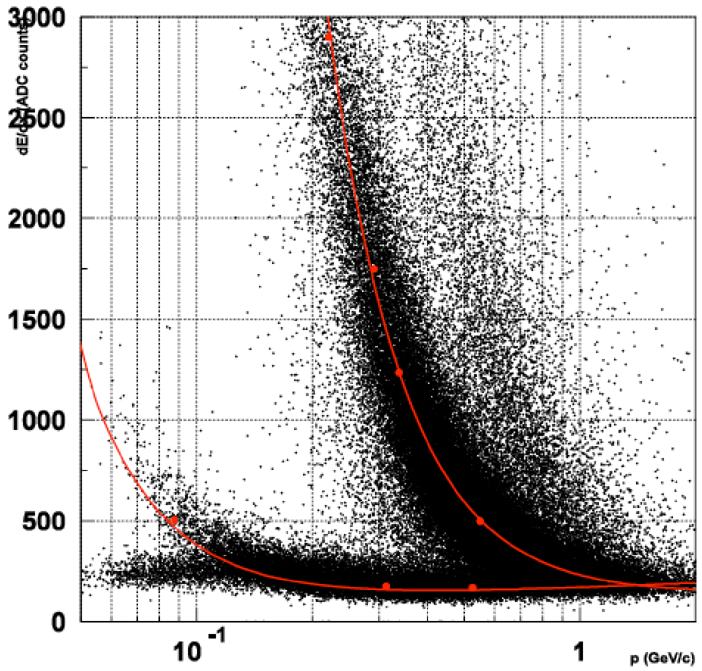

Fig A1: OH analysis of TPC dE/dx vs. constrained momentum for positive particles and 5 GeV/c Ta target. Same data as Fig. 5 now with curves calibrated by fitting the theory through dE/dx peaks evaluated in momentum slices (red spots) .

The new calibration curve fits reasonably well the proton data, much better than what shown in figure 5.

We notice that the calibration procedure used by OH differs from the standard calibration procedure. The standard procedure for dE/dx calibration uses only pions with momentum between 400 and 500 MeV/c (mips) in order to be insensitive to the momentum error. It is surprising that OH has not adopted this procedure that would have been appropriate for discussing a possible momentum bias in the proton data.

Figure A2 shows an enlargement of the plot of Fig A1, but using a box histogram that allows a better evaluation of the distribution of the data. We notice the following features:

- The fit goes above the proton data and below the pion data, trying to compensate the discrepancy seen in fig 5.

- The fit does not go through the peak of the pion distribution in the mip region and is actually significantly below.

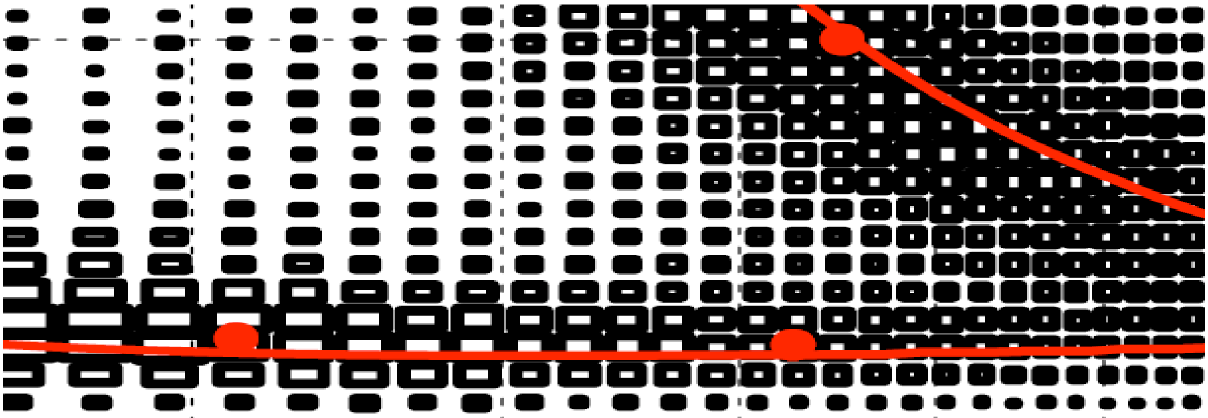

Fig A2: OH analysis of TPC dE/dx vs. Enlargement of Fig A1 in the mip region

The discrepancy of the pion calibration line with the data can be quantified using a dE/dx distribution of negative particles in the momentum slice 300 to 350 MeV/c. This is not exactly at the minimum, but the dE/dx distribution is flat enough. The slice is shown in figure A3. The value of the pion calibration curve at 325 MeV taken from figure A1 (158+/-3 ADC counts) and with the value taken from figure 5 (180 +/- 3 ADC counts) are also indicated.

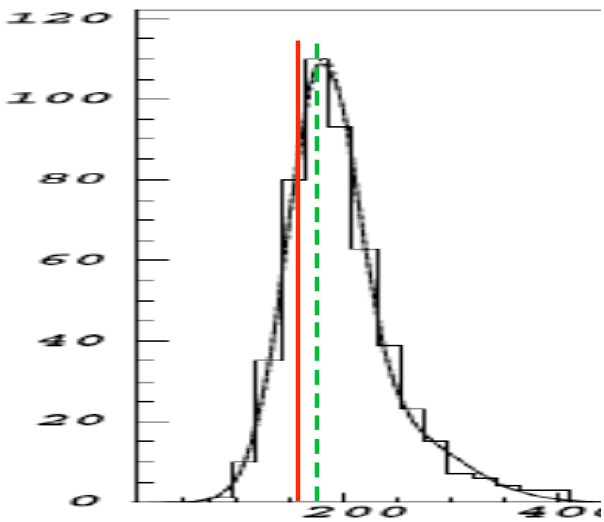

Fig A3: OH analysis. dE/dx slice for negative particles with momentum between 300 and 350 MeV/c. Also indicated are the value of the pion calibration curve shown in figure 5 (dashed green line) and the calibration curve shown in fig A1 (full red line). The horizontal scale is in ADC counts.

The calibration curve of figure 5 fits the pions close to minimum much better. The new calibration provided by OH is lower by some 14%.

The new OH calibration curve can be also compared with a dE/dx slice obtained selecting negative particles with momentum between 75 and 100 MeV/c. This slice is shown in figure A4. Here the analysis is more difficult since the dE/dx of pions changes by almost a factor of 2 between 100 MeV/c and 75 MeV/c and one has to take into account how the population of pions is distributed in the bin. Inspecting Fig. A1 one notices that the population is possibly biased toward the high side of the bin. In the following we assume in first instance that the population is flat and later we analyze the consequences of a possible bias toward the high side of the bin. The pion peak of figure A4 is at 535 ADC counts. The new calibration curve at p=87 MeV/c is at 465 ADC counts. The old calibration curve at p=87 MeV/c is at 574 ADC counts.

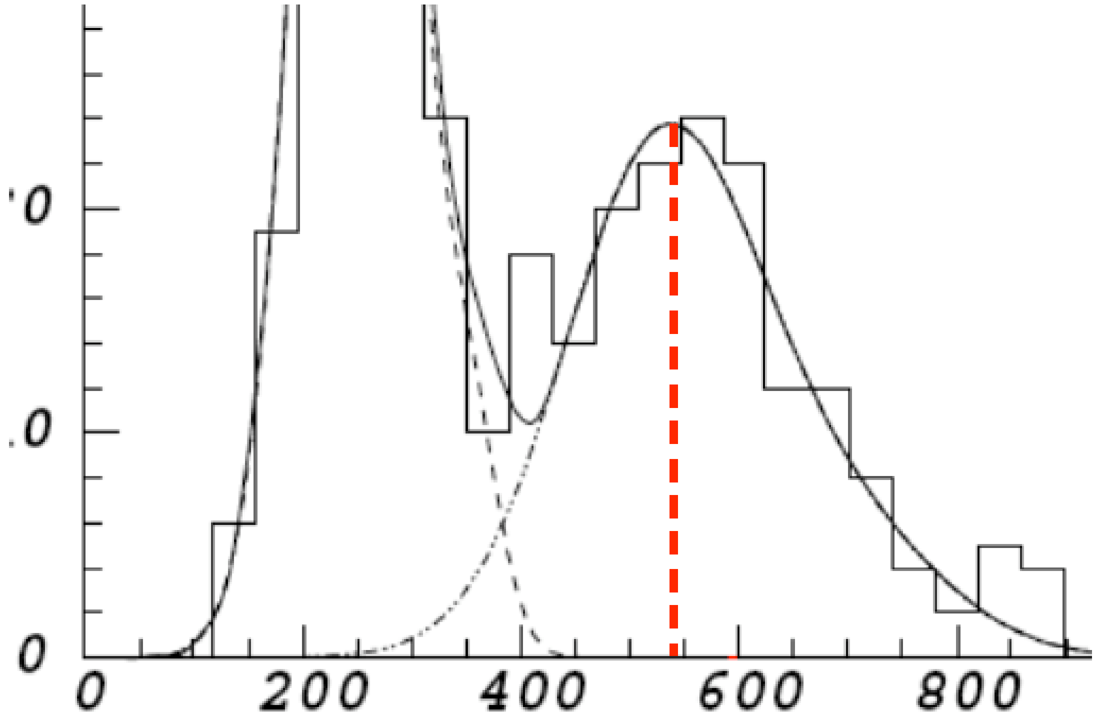

Fig A4: OH analysis. dE/dx slice for negative particles with momentum between 75 and 100 MeV/c. The peak on the left is produced by electrons, that on the right by pions. The red dashed line indicates the position of the peak. The horizontal scale is in ADC counts.

The new calibration curve is 13% lower compared to the peak and the old calibration curve is 7% higher. If the population in the bin is biased toward higher value of the momentum the position of the peak has to be corrected toward higher values (because in the histogram there are more entries at lower dE/dx) increasing the agreement with the old calibration curve and the disagreement with the new one.

In passing we notice that the red spot on the pion curve of figure A1 just below p=90 MeV/c is at 500 ADC counts. This is not compatible with the slice of figure A4.

In conclusion: The curve used by OH in figure 5 fits reasonably the dE/dx distributions of pions, while the new dE/dx calibration curve presented by OH does not fit well the dE/dx distribution of the pions. Possible momentum bias of the protons should be studied with a calibration based on pion data that is robust against momentum bias.