HARP Collaboration

HARP Memo 06-104
19 October 2006
revised and updated 18 May 2007
updated 31 December 2007
corrected 23 January 2008
http://cern.ch/dydak/dEdx.pdf

Pad equalization and dE/dx in the HARP TPC

V. Ammosov, I. Boyko, G. Chelkov, D. Dedovitch, F. Dydak, A. Elagin, M. Gostkin, A. Guskov, V. Koreshev, Z. Kroumchtein, Yu. Nefedov, K. Nikolaev, J. Wotschack, A. Zhemchugov

Abstract

In the HARP TPC, the specific ionization dE/dx depends critically on the pad equalization, which in turn depends on the crosstalk correction. We discuss the TPC pad equalization algorithm and its performance in terms of average and resolution of dE/dx of negative pions with an average active track length of 300 mm. The observed dE/dx of pions and protons agrees satisfactorily with the theoretical expectation, the resolution for a minimum-ionizing track length of 300 mm is 16%.

Contents

1 Introduction **2**

2 Dependence of dE/dx on gas pressure and temperature **2**

2.1 Theoretical expectations 2

2.2 Practical considerations 3

3 Pad equalization algorithm **4**

4 Calculation of dE/dx **5**

5 dE/dx for standard temperature and pressure **6**

6 Correction of dE/dx for polar-angle dependence **9**

7 Resolution of dE/dx **9**

8 Comparison with the 'official' analysis **18**

8.1 Pad equalization 18

8.2 Resolution of dE/dx 19

****

The results presented in this HARP Memo can be freely used by the HARP Collaboration at large, if correctly referenced.

****

1 Introduction

The HARP TPC was designed, *inter alia*, with the goal of separating pions from protons and electrons through the specific ionization $\mathrm{d}E/\mathrm{d}x$. A pre-condition is the equalization of the pad response at the level of a few percent, such that a non-perfect pad equalization has no significant effect on the $\mathrm{d}E/\mathrm{d}x$ resolution.

While the HARP TPC is in principle equipped with all tools needed for very good pad equalization, the unforeseen crosstalk between TPC pads poses *a priori* a sincere threat.

We recall that our group's crosstalk correction algorithm [1, 2] is a purely experimental approach, designed to reduce the number of unphysical 'satellite' pads (caused by crosstalk) as much as possible. Our algorithm makes no attempt to restore perfectly the pad charge that would have been measured in the absence of crosstalk. In particular, no attempt is made to recover negative signal charges which have been compensated by positive signals charges from crosstalk[1].

In this paper, we discuss first the correction of the gas gain for changes of gas pressure and temperature, then describe our pad equalization algorithm, and give results of the $\mathrm{d}E/\mathrm{d}x$ of charged pions in terms of averages and resolutions. We also comment on the algorithms used in the 'official' HARP analysis.

2 Dependence of dE/dx on gas pressure and temperature

2.1 Theoretical expectations

The relative change of the gas gain at the sense wires (the gas gain determines the recorded pad signals) is for small variations of the gas density proportional to the relative change of gas density (see, for example, Ref. [3]):

$$\frac{\Delta G}{G} = K \cdot \frac{\Delta \rho}{\rho} , \tag{1}$$

where G is the gain at the sense wires, ρ the gas density, and K a proportionality constant.

The constant K is dominantly determined by the avalanche development in the vicinity of the sense wires, and thus by the excitation and ionization cross sections of electrons that have been accelerated in the strong electric field around the sense wires. While the sign

[1]By contrast, 'official' HARP's crosstalk correction algorithm aims at reconstructing the original pulse shape on the basis of the unidirectional crosstalk model; while our algorithm covers both unidirectional and bidirectional crosstalk over any number of generations but limits itself to negative charges, the 'official' crosstalk algorithm works both with positive and negative charges but limits itself to unidirectional crosstalk over one generation; therefore, neither of the two approaches is perfect; only experimental evidence can decide which of the two gives better results in terms of the two performance parameters that are expected to depend sensitively on the proper correction of crosstalk: $\mathrm{d}E/\mathrm{d}x$ resolution and $r{\cdot}\phi$ resolution.

and the numerical value can be estimated, its precise value must be measured for every gas mixture and electric field configuration.

The constant K is in the range -3 to -8 [3] for typical TPC gas mixtures[2]. In the ALEPH TPC (that had the same gas mixture and the same atmospheric pressure) the constant was measured to be -3.7 [4].

The negative sign of the constant K means that an **increase of gas density** (caused by an increase of pressure at constant temperature, or a decrease of temperature at constant pressure) causes the **gain to decrease**. Since $|K| > 1$, the relative decrease of the gain is larger than the relative increase of the gas density.

According to the law of ideal gases, the following relation is expected to hold approximately between the relative changes of the gas density, temperature and pressure:

$$\frac{\Delta\rho}{\rho} \simeq \frac{\Delta P}{P} - \frac{\Delta T}{T} \; , \tag{2}$$

where T is the absolute temperature and P the absolute pressure.

2.2 Practical considerations

Other than for the electron drift velocity [5], it is not the temperature of the gas in the TPC volume that is relevant for the gain, but rather the temperature of the pad plane, since the sense wires are only at 5 mm distance from the pad plane.

The temperature of the pad plane was recorded by sensors, however not for each of the six sectors. We come back to this important point in Section 5.

The atmospheric pressure was recorded during data taking, as well as the TPC gas pressure at the outlet (located at the TPC's downstream face). Numerically, both pressure readings are on linear scales, with both the slopes and the averages unknown. This linear relation was established by a detailed comparison with the atmospheric pressure logged by the meteorological station of Geneva–Cointrin [6]. The readings are shown as a function of time in Fig. 1 for nearly all the data taking in 2002. It appears that the TPC gas pressure measured at the outlet shows sometime saturation of response. Therefore, we use the atmospheric pressure recorded by HARP as representing the TPC gas pressure (neglecting the ~ 5 mbar overpressure of the latter).

Finally, for the same reasons as discussed for the drift velocity [5], an effect on the gain stemming from water molecules cannot be excluded. We note that for the gain, other than for the drift velocity, not only differences in the excitation cross sections but also differences in the ionization cross sections matter.

[2]The mixture in the HARP TPC is 91% argon and 9% methane by volume.

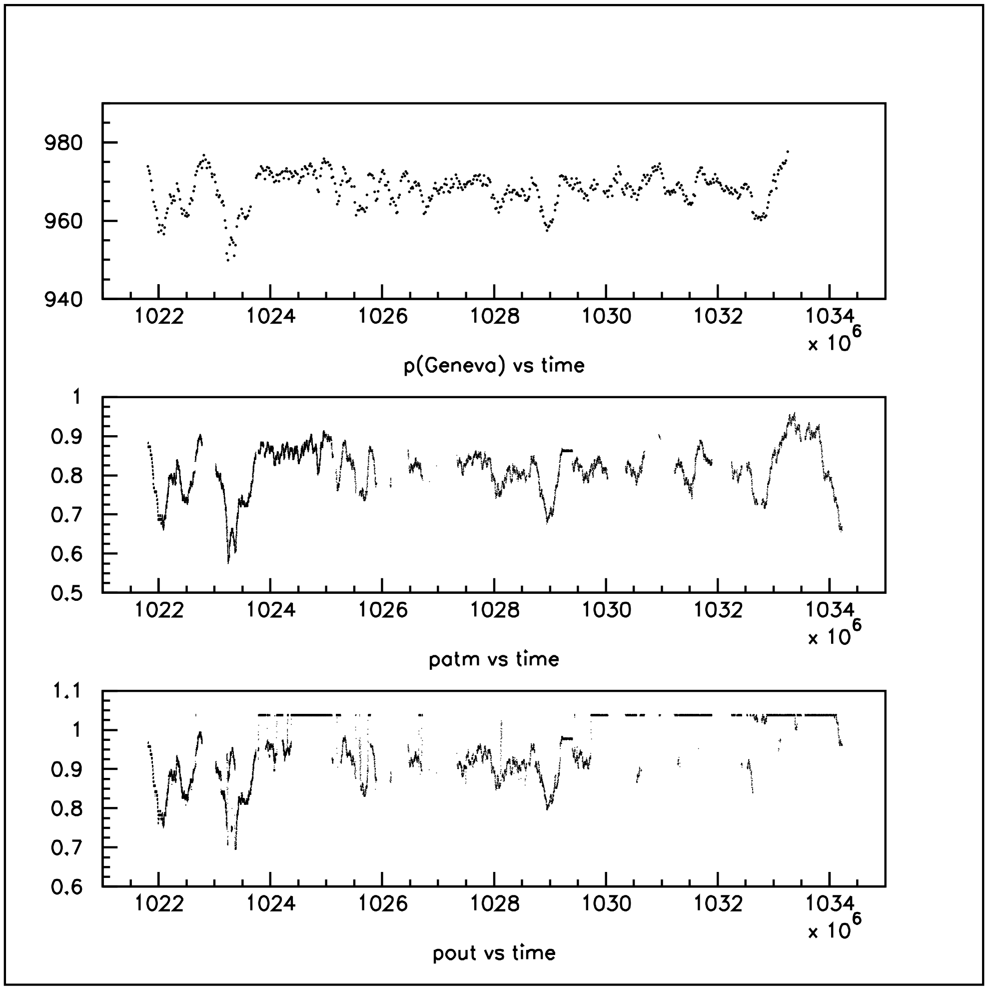

Figure 1: Atmospheric pressure (hPa) as recorded by the meteorological station of Geneva–Cointrin (top panel); atmospheric pressure (arb. units) as recorded by HARP (middle panel); gas pressure (arb. units) at the TPC outlet (bottom panel); the horizontal axis gives the time (in seconds, with an arbitrary offset) from mid May to the end of September in 2002.

3 Pad equalization algorithm

Our pad equalization algorithm rests on the normalization that is provided by the so-called 'krypton calibration' [7].

One might argue that the results obtained from the krypton calibration do not apply to all data because of a possible variation with time of the signal amplification of the readout electronics. One might also argue that the effect from 'krypton crosstalk' is different from the effect of 'track crosstalk' (for a discussion of this subtle difference, see below).

We undertook special studies to address these issues. These studies comprised the following steps:

1. we start from the pad equalization that we obtained from the deposit of charges from radioactive $^{83\mathrm{m}}$Kr decay products in special calibration runs [7]; we keep in mind that

this will not be the best possible pad equalization since localized 'krypton' crosstalk (*i.e.* crosstalk typical for clusters localized within a few cm), and not extended 'track' crosstalk (the latter mainly arises from bi-directional crosstalk between adjacent pad rings as has been established in our crosstalk studies), is at work; also, the pad normalization at the time of the krypton calibration may *a priori* not be optimal for all data taking periods;

2. we correct for the dependence of the gas gain on pressure and temperature (both parameters were continuously recorded during data taking), and for possible drifts of the pad pulseheights with time;

3. we correct for the difference between krypton crosstalk and track crosstalk; for this, we use only TPC hits from minimum-ionizing particles (more precisely, we require $\mathrm{d}E/\mathrm{d}x < 2$ m.i.p.), which excludes a dependence on the ratio of secondary pions and protons and hence on the beam and/or target setting; then, we multiply every measured pad charge by $\sin\theta$, where θ is the polar angle of the track, which eliminates a charge dependence on the **average** polar angle of secondary tracks and thus once more on the beam and/or target setting; finally, we only use signals from a TPC pad when this pad is a 'leading pad' in the TPC cluster, which minimizes effects from electronic thresholds and noise.

Normalizing the resulting average pad amplitude to unity gives the pad equalization constant. In principle, the inclusion of step (3) yields the best possible pad equalization constant for the data set under consideration. In practice, it turned out that the correction from krypton crosstalk to track crosstalk is negligibly small with respect to the intrinsic $\mathrm{d}E/\mathrm{d}x$ resolution. Step (3) is therefore not needed and is not part of our normal analysis routine.

That the amplification of the readout elelctronics is sufficiently stable with time is discussed in Section 5.

4 Calculation of $\mathrm{d}E/\mathrm{d}x$

The $\mathrm{d}E/\mathrm{d}x$ of a track is calculated as follows. The total pulseheights of the clusters along its trajectory are added up, as are the physical path lengths associated with each cluster. If there are two adjacent clusters in the same pad row, both pulseheights are added but the path length is used only once. Missing clusters along the trajectory do neither contribute to the charge nor to the path length.

With a view to achieving the best possible $\mathrm{d}E/\mathrm{d}x$ resolution, it is common to order the pulse-height samples along a track according to pulse height, and to discard fixed fractions of all samples at both the low and the high end. The relatively small number of samples in the HARP TPC (maximum of 20) did not permit this procedure; rather, the two samples with the largest pulse heights were removed in case of 10 or more contributing samples; in case of less than 10 contributing samples, the one sample with the largest pulseheight was removed. Samples from pad rows 1 and 20 (which had systematically lower pulse heights) were ignored throughout. The standard cut for a 'good' $\mathrm{d}E/\mathrm{d}x$ required a minimum of eight samples.

The specific ionization dE/dx is calculated as the ratio of the accumulated pulseheight to the accumulated path length.

5 dE/dx for standard temperature and pressure

Equations (1) and (2) suggest the following *ansatz* for the specific ionization dE/dx around a conveniently chosen value of T/P :

$$\mathrm{d}E/\mathrm{d}x = P1\,[1 + P2 \cdot (\xi - \xi_0)] \;, \tag{3}$$

where $\xi = T/P$ and $\xi_0 = 0.318$. The ratio ξ_0 is realized by the reference temperature $T = 25°\mathrm{C}$ and the reference pressure $P = 938$ hPa.

The dE/dx in Eq. (3) must refer to a well-defined physical quantity. As such, we chose the dE/dx of negative pions in the momentum range from 0.45–0.80 GeV/c, with a view to matching closely the minimum-ionizing pulseheight. Numerically, the dE/dx in Eq. (3) was determined from a Gaussian fit of the dE/dx distribution of individual tracks where the dE/dx range was truncated at the high end at 50% of the maximum.

The expectation of a linear dependence on the variable ξ is well borne out by the data, as shown in Fig. 2 separately for the six TPC sectors. The choice of the specific value $\xi_0 = 0.318$ is motivated by the wish to minimize the correlation between the parameters $P1$ and $P2$. The parameter P1 denotes a dE/dx that refers to $\xi = 0.318$.

Table 1 lists the parameters $P1$ and $P2$ of Eq. (3) for eight different data sets, separately for the six TPC sectors.

The parameters $P1$ are also shown in Fig. 3 for the six TPC sectors (the same eight data sets are referred to that appear with the numbering from 1 to 8 in Table 1).

Since the parameters $P1$ and $P2$ are derived from negative pion tracks, their errors are large in data sets with few negative pions (this is particularly the case in the water data which were taken with the low beam momentum of 1.5 GeV/c).

While there is no doubt about the gas pressure to be used for the calculation of ξ in Eq. (3), there are uncertainties about the temperature to be used.

The relevant pad plane temperature is driven by the power released by the preamplifiers. The six sectors are in first approximation thermally independent of each other. Therefore, we may expect sudden temperature jumps whenever groups of preamplifiers connected to the same power supply switched off and on, as it happened at occasions during data taking. The TPC sectors 2 and 5 were affected more than others. Therefore, we must *a priori* be prepared for differences between sectors, and – in one or the other sector – seemingly random temperature jumps as a function of time.

From Eq. (3) one can easily show that the normalized value $P1$ would be different if instead the correct temperature a biased temperature would be used. By contrast, the slope $P2$ is virtually invariant against a permanently biased temperature[3].

[3]An unstable bias in temperature readings would lead to apparent changes of the slope, too.

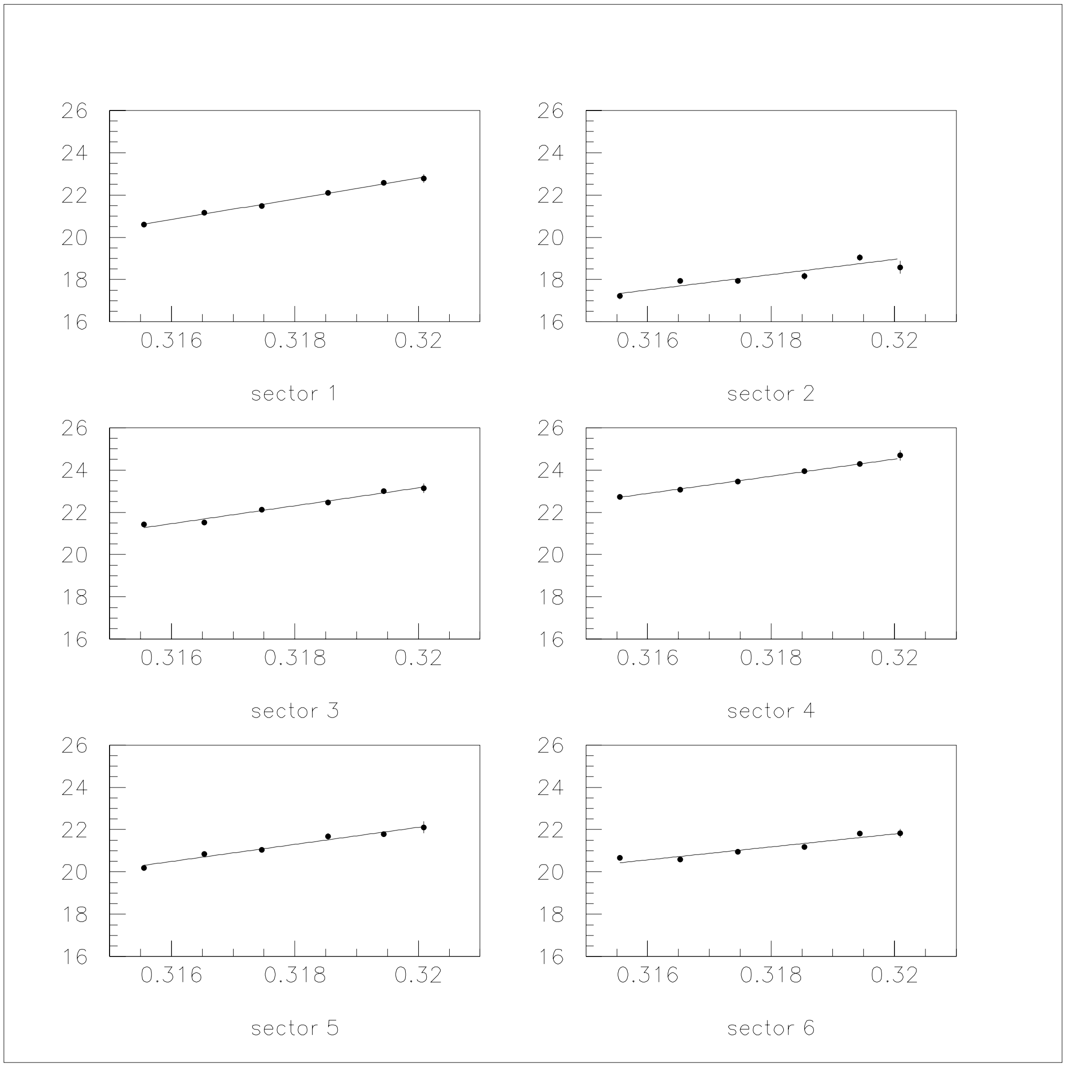

Figure 2: Dependence of the specific ionization dE/dx (arb. units) on the variable $\xi = T/P$ (Kelvin/hPa), separately for the six TPC sectors; thinBe+8.9 data.

Small systematic differences of the parameter $P1$ between sectors and data sets are conjectured to arise from biased temperatures, from electronic drifts, from small variations of the gas mixture, and from varying contamination of the TPC gas with water.

The parameters P1 of the eight different data sets fluctuate by maximally $\pm$ 5% with respect to their averages; these fluctuations represent the intrinsic 'amplitude instability' of the HARP TPC.

Dividing dE/dx of any specific track, after correction for gas pressure and temperature, by the value given by Eq. (3) yields a 'normalized' dE/dx that is used to characterize tracks. The minimum-ionizing dE/dx will then be close to unity. This normalization eliminates drifts of the pad pulseheights with time although this is not necessary as they turned out to be pretty stable.

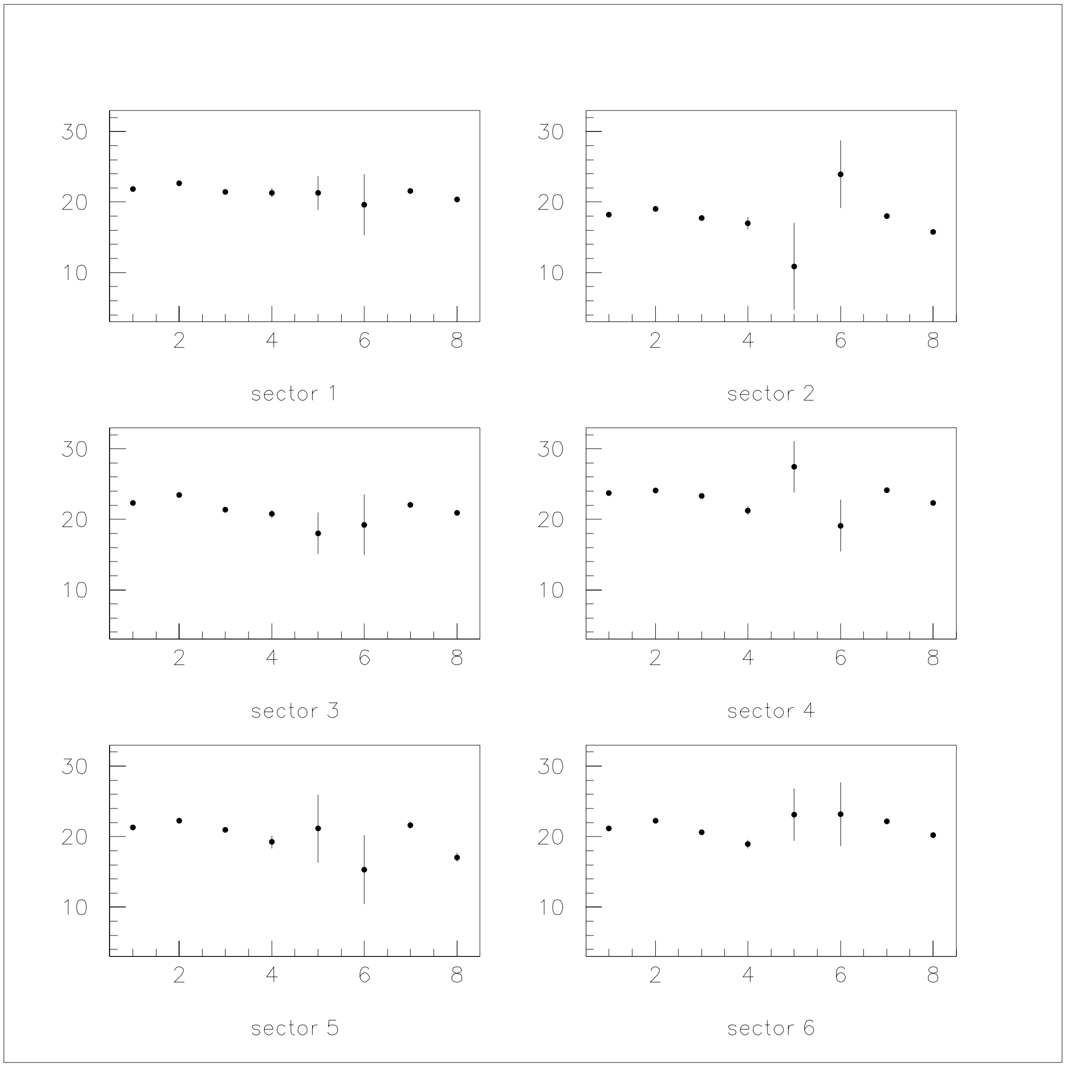

Figure 3: Parameters P1 as listed in Table 1, after correction for temperature and pressure, from eight different data sets (numbered 1 to 8), separately for the six TPC sectors.

From Eq. (3) follows

$$\frac{\Delta G}{G} = \xi_0 P2 \left(\frac{\Delta T}{T} - \frac{\Delta P}{P} \right) , \tag{4}$$

and from equating with Eq. (1)

$$K = -\xi_0 P2 .$$

With an average measured slope $P2 \simeq 16$, it follows

$$K \simeq -5.1 .$$

This result checks well with the range reported in the literature [3], $-8 \leq K \leq -3$, however we consider our result as qualitative proof of consistency rather than a precise measurement of K.

6 Correction of dE/dx for polar-angle dependence

The removal of the two largest samples and the removal of the single largest sample, respectively, is motivated by the reduction of the Landau tail. The Landau tail is stronger for short tracks (with polar angle $\theta \sim 90°$) than for longer tracks with smaller polar angle. Qualitatively, one expects from the removal of the largest samples a small increase of dE/dx with increasing track length[4].

Also crosstalk is in principle polar-angle dependent and may lead to some polar-angle dependence of dE/dx. This latter dependence will be sector-specific, since crosstalk varies considerably between TPC sectors.

Figures 4 and 5 show separately for the six TPC sectors and averaged over all TPC sectors, respectively, the polar-angle dependence of dE/dx from minimum-ionizing negative pions with an average active track length of 300 mm, after normalization to standard temperature and pressure; the expectation of a mild increase with the polar angle is in general borne out, but not in all sectors which points to some contribution from crosstalk.

Although the polar-angle dependence is small we correct for it, with a view to minimizing problems in the separation of particles[5].

The correction function maintains the average dE/dx but replaces the dE/dx of a track with polar angle θ by

$$\frac{\mathrm{d}E/\mathrm{d}x}{C0 + C1/\sin\theta + C2/\sin^2\theta} ,$$

with the (sector-dependent) coefficients C1, C2 and C3 listed in Table 2.

7 Resolution of dE/dx

The energy loss is statistically distributed around its expectation value. For thin absorbers, the energy loss is distributed according to the (strongly asymmetric) Landau distribution, for thick absorbers the distribution becomes approximately Gaussian. The TPC gas represents a thin absorber, therefore the average energy loss per unit length is much larger than the most probable one.

We recall first the usual recipe to achieve the best possible resolution of dE/dx: the ordering of samples according by pulse height and discarding fixed fractions of all samples both at the low and at the high end.

At the low pulse height end, the energy loss is biased by samples that fall below the (hardware or software) threshold of a channel. Though small, the pulseheight of this channel is unknown. Since the fraction of missing samples will depend on the track's polar angle (it will be largest at 90 degrees), the bias of the average dE/dx is minimized if at the low pulse height end a fixed fraction (typically 5–10%) of all samples is removed.

[4] This increase is not a physical increase but an artefact stemming from the way dE/dx is calculated.

[5] We consider the dependence of average dE/dx on the particle abundances in different settings of beam momentum and target, introduced by this procedure, as the smaller problem.

At the high pulse height end, also a fixed fraction (typically 20–40%) of the samples is removed.

General experience with the measurement of energy loss, and specific experience from the ALEPH TPC, has led to the following empirical expectation for the resolution [4, 8],

$$\sigma/E_{\mathrm{loss}} \simeq C \cdot N^{-0.5} \cdot (\sin\theta)^{0.4} , \tag{5}$$

where N is the number of samples and θ is the track's polar angle; C is a proportionality constant which is $C = 1.19$ for ALEPH, and $C = 0.68$ for HARP (the difference takes the different physical sample lengths into account).

As discussed already in Section 4, the small number of samples in the HARP TPC do not permit to apply this usual recipe. First, we have to remove samples from padrings 1 and 20 throughout, since these pulseheights at the inner and outer sector borders are systematically different from the pulseheights of all other padrings. Second, we do not remove a fixed fraction of samples with zero or small pulse height, but retain only non-zero pulseheights in the samples. Third, we do not remove a fixed fraction at the high pulse height end but remove two largest-pulseheight samples, or one.

With $N = 18$ and $\theta = 75°$, the expected resolution σ/E from Eq. (5) is 16%, for pions.

Figure 6 shows the distribution of the energy loss measured in the HARP TPC. The data are from the exposure of a 5% λ_{abs} beryllium target to +8.9 GeV/c protons. Pions in the momentum band from 0.45–0.8 GeV/c were selected, in all six TPC sectors. The active track length was required to be in the range 200–400 mm. The Gaussian fit of the distribution gives a resolution[6] of 16% (looking at more data sets, we find resolutions between 16 and 17%).

This good resolution permits to conclude that residual crosstalk is not detrimental for dE/dx.

In Fig. 7 we show the resolution of dE/dx for eight different data sets, separately for the six TPC sectors. In Fig. 8 we show the resolutions for the same eight data sets, this time averaged over the six TPC sectors. There are no significant differences of the resolution across the six TPC sectors and across different data sets spanning several months of time.

Finally, we show in Fig. 9 a plot of dE/dx versus momentum, obtained from the thinBe+8.9 data set; the corrections for gas pressure and temperature changes have been applied throughout, as well as the correction for the polar-angle dependence. The agreement with the theoretical expectation is satisfactory.

[6]The resolution is determined in a Gaussian fit where the dE/dx range is truncated at the high end at 50% of the maximum; note that the fit procedure is different from ALEPH's, hence the resolution expected from Eq. (5) should be considered as guidance only.

Table 1: Parameters $P1$ and $P2$ of Eq. (3), in arbitrary units, from minimum-ionizing negative pions in the momentum range from 0.45–0.80 GeV/c, for eight different data sets, for the six TPC sectors.

		thinBe+8.9 (1)	thinBe−8.0 (2)	thinTa+3.0 (3)	thinTa+5.0 (4)
1	$P1$	21.82 ± 0.04	22.65 ± 0.10	21.44 ± 0.24	21.35 ± 0.63
	$P2$	22.6 ± 1.3	22.4 ± 2.4	9.1 ± 8.2	32.2 ± 10.2
2	$P1$	18.23 ± 0.07	19.04 ± 0.12	17.75 ± 0.40	16.99 ± 0.88
	$P2$	19.8± 2.5	31.0 ± 3.2	10.0 ± 17.2	16.9 ± 19.4
3	$P1$	22.31 ± 0.05	23.49 ± 0.10	21.40 ± 0.25	20.75 ± 0.59
	$P2$	19.0 ± 1.4	22.0 ± 2.3	15.3 ± 8.8	22.3 ± 10.3
4	$P1$	23.70 ± 0.05	24.06 ± 0.11	23.32 ± 0.26	21.24 ± 0.61
	$P2$	17.1 ± 1.2	21.2 ± 2.4	9.4 ± 8.6	9.0 ± 10.8
5	$P1$	21.30 ± 0.06	22.27 ± 0.15	20.96 ± 0.33	19.26 ± 0.91
	$P2$	20.0 ± 1.9	21.1 ± 3.6	46.5 ± 12.0	9.9 ± 17.8
6	$P1$	21.18 ± 0.04	22.24 ± 0.10	20.65 ± 0.24	18.91 ± 0.61
	$P2$	14.5 ± 1.4	22.6 ± 2.4	14.3 ± 9.0	-0.7 ± 12.5
		thickH2O+1.5 (5)	thinH2O+1.5 (6)	H2+3.0 (7)	H2−3.0 (8)
1	$P1$	21.3 ± 2.4	19.6 ± 4.3	21.57 ± 0.27	20.34 ± 0.35
	$P2$	21.2 ± 15.1	4 ± 53	28.2 ± 13.6	-3.4 ± 56.9
2	$P1$	10.9 ± 6.2	23.9 ± 4.8	18.01 ± 0.38	15.78 ± 0.38
	$P2$	-74 ± 134	78 ± 31	33.7 ± 24.7	318 ± 96
3	$P1$	18.0 ± 2.9	19.2 ± 4.3	22.03 ± 0.28	20.90 ± 0.36
	$P2$	-5.6 ± 26.7	10 ± 51	28.0 ± 14.0	-12.9 ± 48.6
4	$P1$	27.4 ± 3.7	19.1 ± 3.7	24.12 ± 0.30	22.29 ± 0.35
	$P2$	43.0 ± 15.0	-21 ± 51	16.1 ± 13.3	37.7 ± 53.6
5	$P1$	21.1 ± 4.8	15.3 ± 4.9	21.63 ± 0.45	17.08 ± 0.65
	$P2$	21.8 ± 32.3	-48 ± 93	-19.2 ± 21.1	311 ± 137
6	$P1$	23.1 ± 3.7	23.2 ± 4.5	22.15 ± 0.31	20.24 ± 0.34
	$P2$	30.8 ± 20.5	45 ± 39	3.9 ± 14.7	-12.4 ± 49.4

Table 2: Coefficients C1, C2 and C3 for the correction of the polar-angle dependence of dE/dx, separately for the six TPC sectors, and averaged over all TPC sectors.

Sector	C0	C1	C2
1	0.64158	0.30725	-.05733
2	0.77655	0.18181	-.02971
3	0.68208	0.28370	-.05592
4	0.60140	0.35546	-.07023
5	0.66902	0.28515	-.05402
6	0.69582	0.27836	-.05580
All	0.66415	0.29746	-.05793

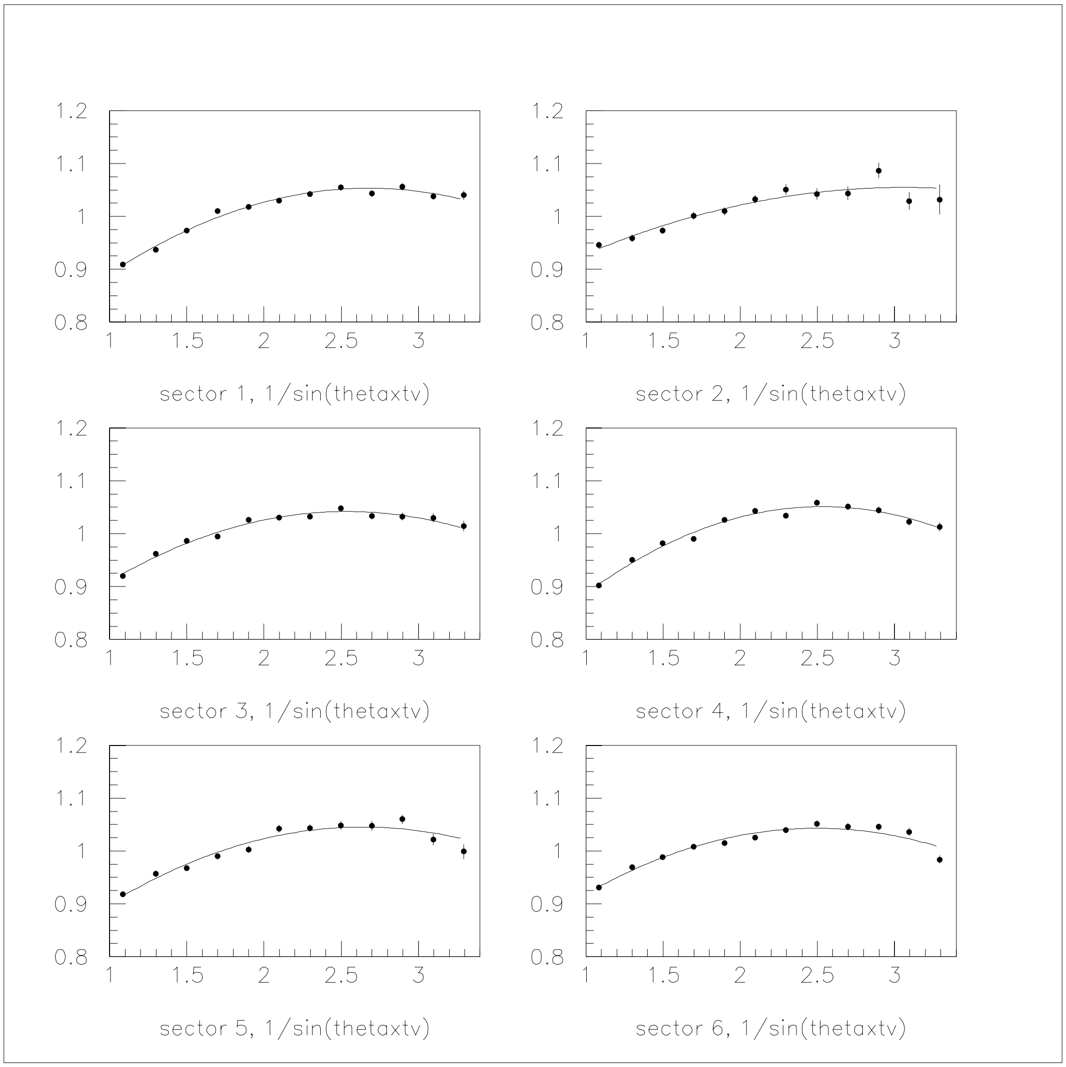

Figure 4: ThinBe+8.9 data: dependence on $1/\sin\theta$ of $\mathrm{d}E/\mathrm{d}x$ from minimum-ionizing negative pions with an average active track length of 300 mm, separately for the six TPC sectors; the smooth line represents the functional form of the correction for the polar-angle dependence.

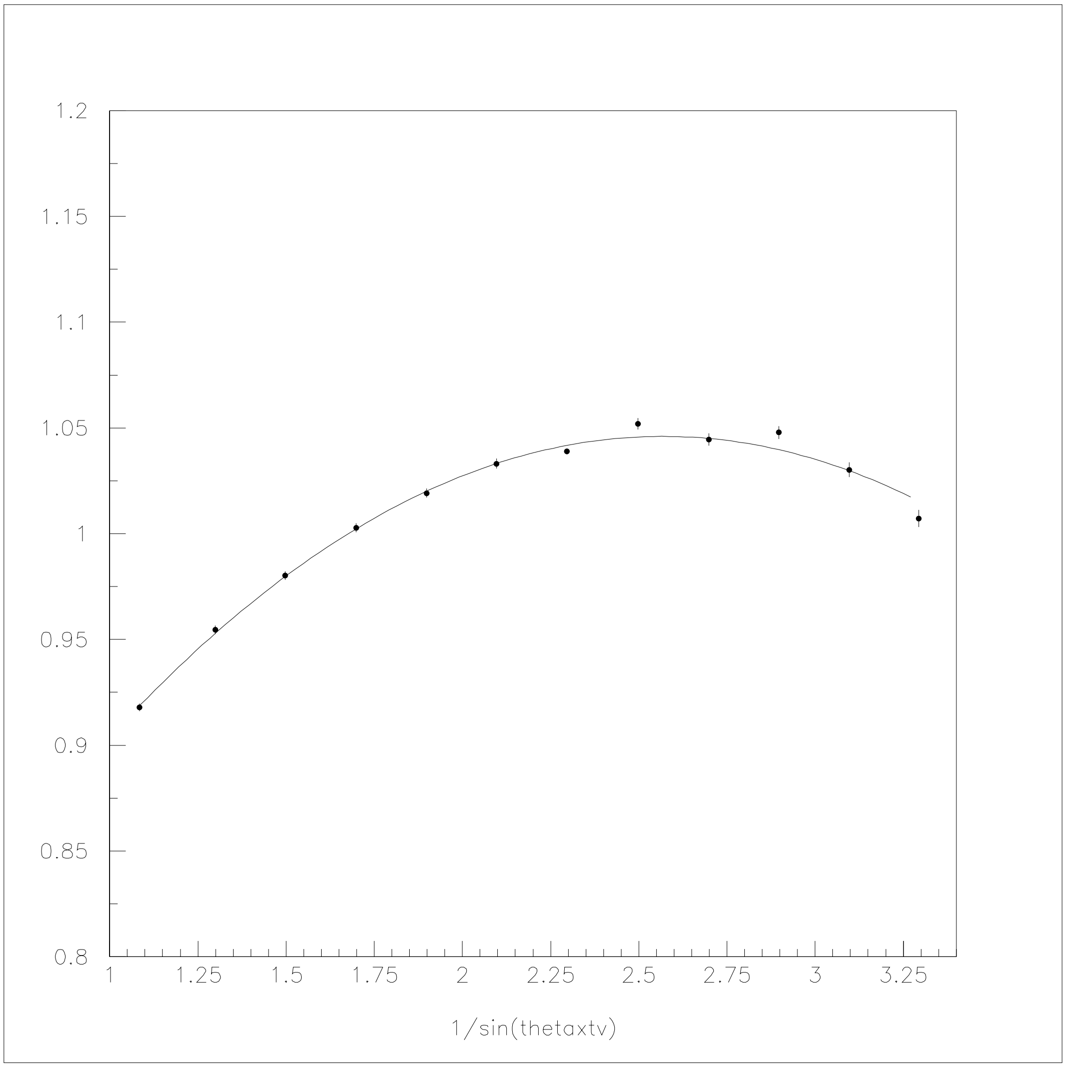

Figure 5: ThinBe+8.9 data: dependence on $1/\sin\theta$ of $\mathrm{d}E/\mathrm{d}x$ from minimum-ionizing negative pions with an average active track length of 300 mm, averaged over the six TPC sectors; the smooth line represents the functional form of the correction for the polar-angle dependence.

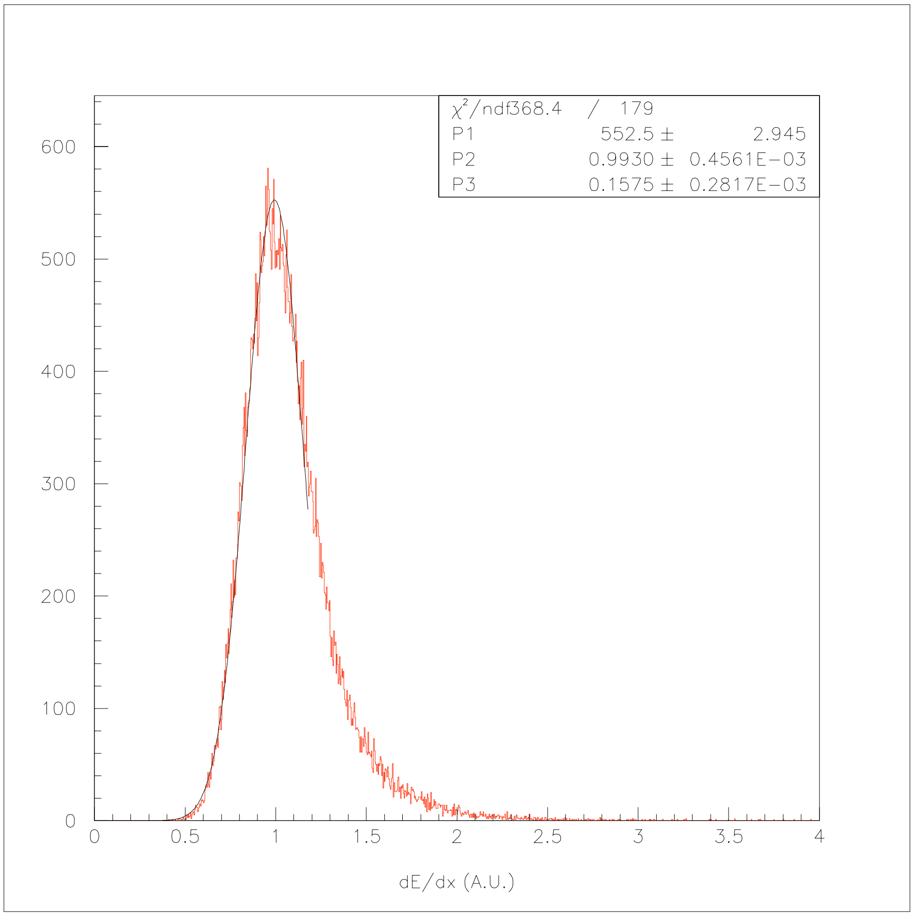

Figure 6: dE/dx distribution (arb. units), averaged over all six TPC sectors; overlayed is a Gaussian fit that is truncated at the side of large pulse heights at half maximum; thinBe+8.9 data.

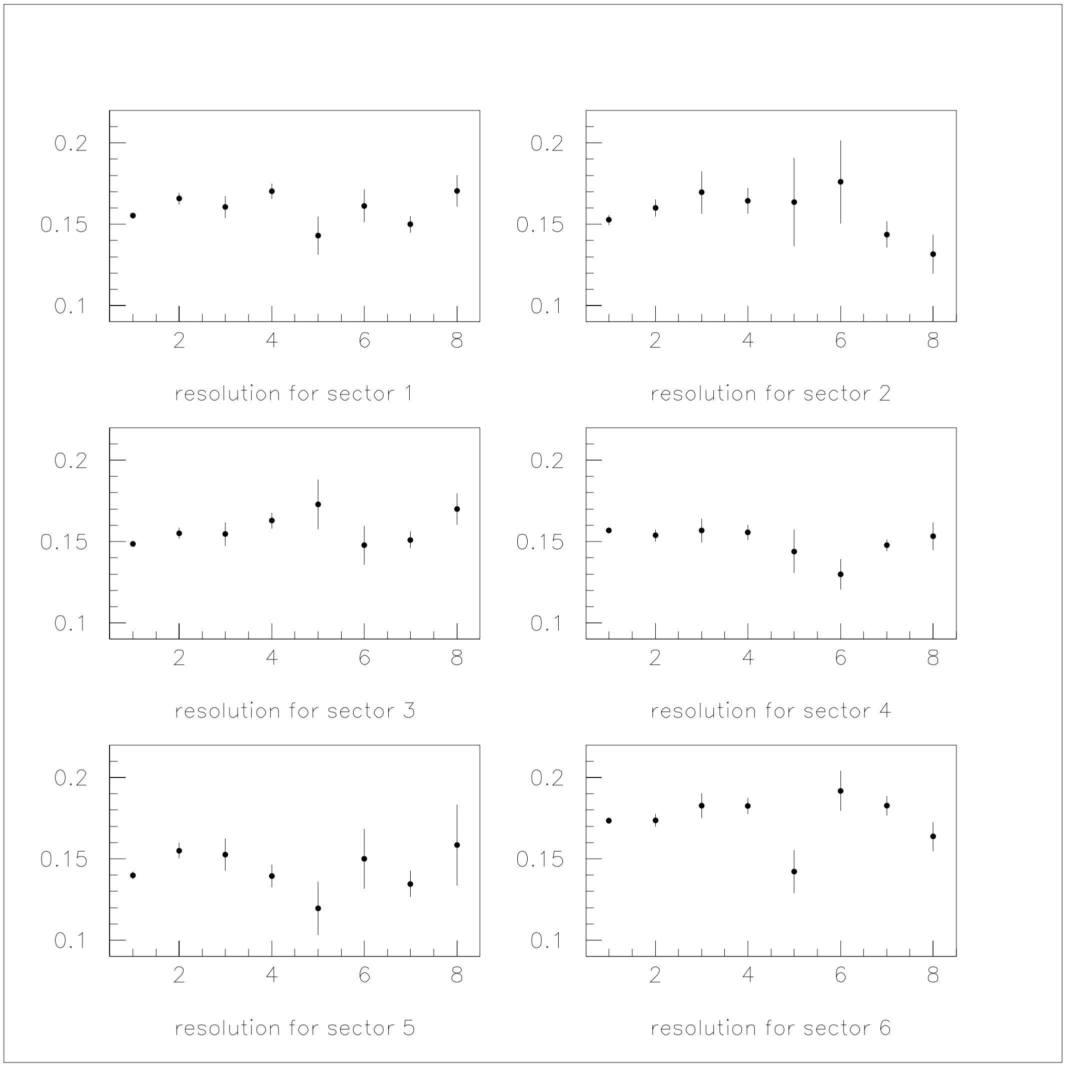

Figure 7: The resolution of $\mathrm{d}E/\mathrm{d}x$ for eight different data sets, separately for the six TPC sectors; a minimum of 8 samples after truncation is required.

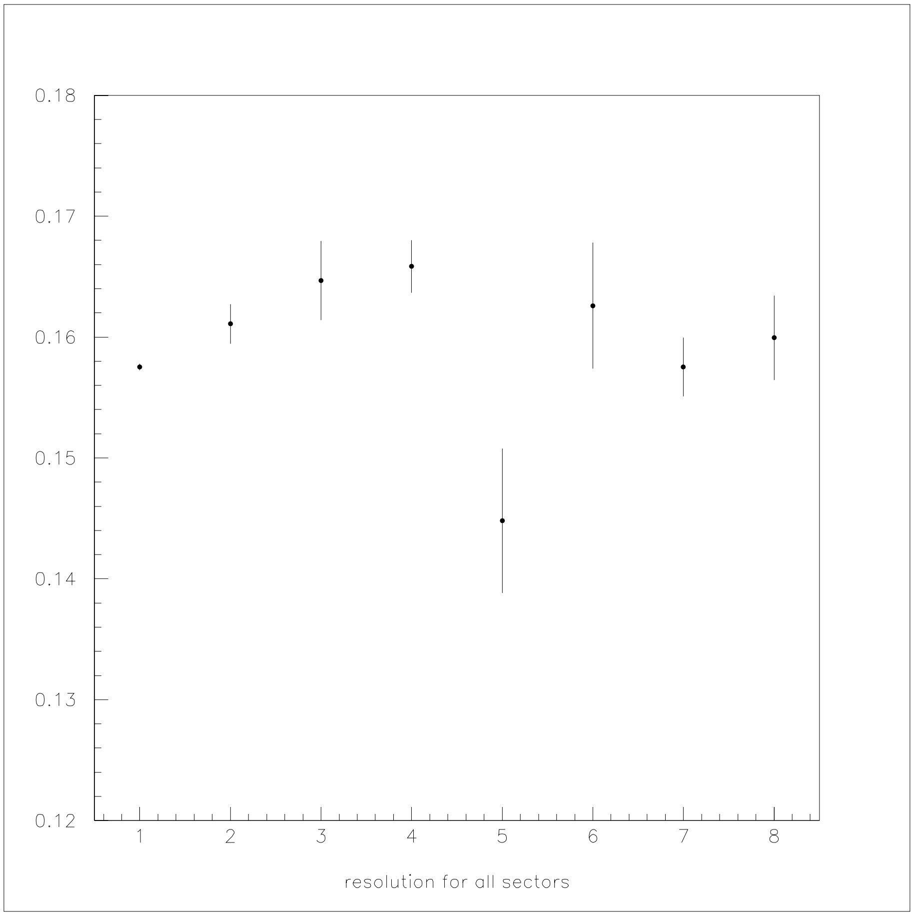

Figure 8: The resolution of dE/dx separately for the eight data sets, averaged over the six TPC sectors; a minimum of 8 samples after truncation is required.

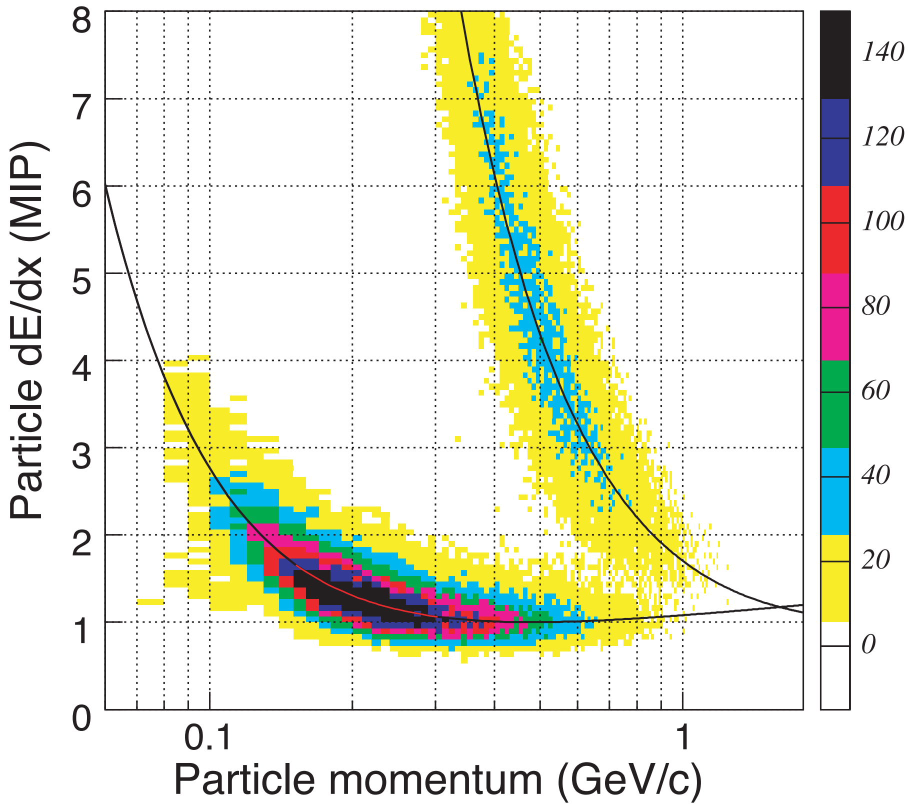

Figure 9: Specific ionization d$E/$dx [in units of minimum-ionizing pulse height] versus momentum [GeV/c] for positive secondaries, together with the theoretical expectations for pions and protons; corrections for changes of gas pressure and temperature, and for the polar-angle dependence, applied.

8 Comparison with the ‘official’ analysis

8.1 Pad equalization

The ‘official’ claim (see the left panel in Fig. 10, reproduced here from the HARP Technical Paper [9]) is that the pulseheight normalization of the TPC pads is strongly varying with time, both on the average and even more so for individually (an individual fluctuation of 18% is claimed).

By contrast, the right panel in Fig. 10 shows the comparison of the pulseheight normalizations of the TPC pads from our group, between a data set from May 2002 and another data set from August 2002; there is an individual fluctuation of $\sigma = 4.6\%$, at variance with the ‘official’ claim.

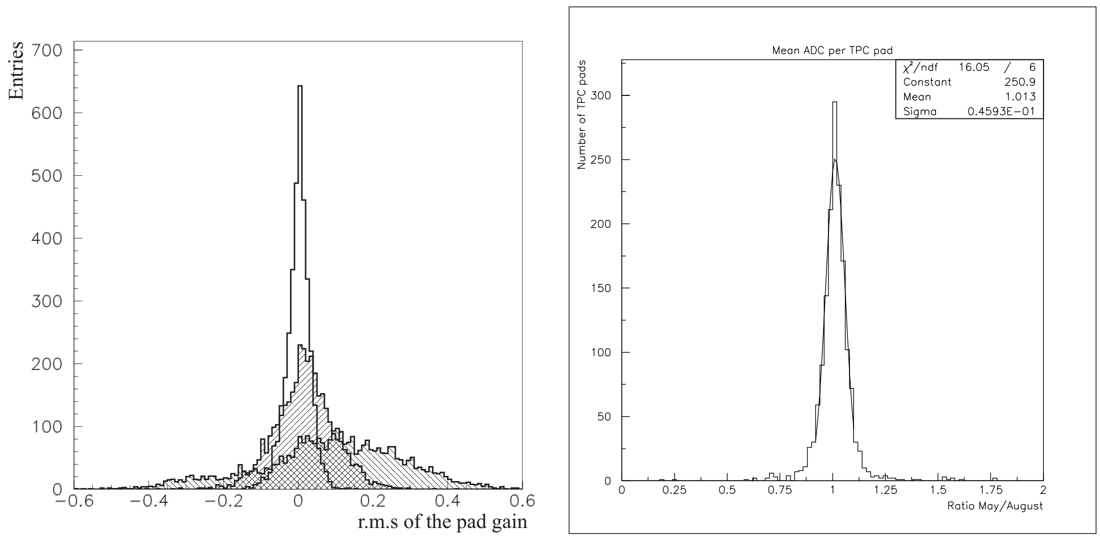

Figure 10: Pad pulseheight fluctuations between different data sets; left panel: ‘official’ result on the pulseheight fluctuation of the TPC pads, for 36 hours time difference (open histogram), one week time difference (grey-shaded histogram) and two months time difference (dark-shaded histogram); for the latter case, the individual fluctuation is 18% r.m.s.; right panel: our result on the pulseheight fluctuation of the TPC pads; for runs with a time difference of three months (in May and in August 2002), the individual fluctuation is 4.6% r.m.s.

We hold that the ‘official’ method to obtain the pad pulseheight normalization from physics ‘super-events’[7] is flawed for three reasons:

- pions and (slow) protons have a very different specific ionization; yet the proton/pion ratio depends on the beam and target setting (thus introducing, indirectly, a dependence on ‘run time’);

[7] In a ‘superevent’, the TPC charges in all pads are averaged over a large number of tracks from many events.

- without correction for the charge deposit with the track's polar angle, the pulseheight normalization becomes dependent on the polar angle distribution of tracks, thus enhancing the dependency on beam and target setting;
- the spectrum of the pad pulseheight is a steeply falling spectrum because of the sharing of pulseheights between several pads; this spectrum has no intrinsic 'physical' normalization (such as the minimum-ionizing pulseheight); as a consequence, the average pulseheight is critically dependent on the low-energy threshold and on noise, respectively.

In the right panel of Fig. 10 we only entered pads with sufficient statistics. It was required that the mean pad gain is known with relative statistical error less than 7% (for both run periods). This excludes fake 'variations of gain' due to statistical fluctuations. As a result, the r.m.s. difference between the two run periods in May and August 2002 is found to be 4.6%, a fluctuation that is consistent with statistics only.

After due correction of the pulseheight for pressure and temperature variations, a remaining dependence on run time would primarily be attributed to drifts of the analogue readout electronics. Above, in Fig. 3, we showed already this drift in terms of a well-defined physics quantity: the energy loss of pions along a track length of 300 mm. The data are shown for six data sets, spanning the time from May to September 2002. It appears that the amplitude of the readout electronics is remarkably stable (the maximum fluctuation in six different data sets is $\pm$ 5% from the average), in stark contrast to the claims of the 'official' analysis.

The pulseheight fluctuation with time as reported in the 'official' large-angle analysis is merely the result of a wrong analysis concept; on top of that, it is wrong to correct for pulseheight variations which originate from statistical fluctuations.

8.2 Resolution of dE/dx

As for the 'official' dE/dx resolution, the HARP Technical Paper [9, 10] gives no quantitative information. The 'official' Memo on TPC performance [11] quotes an 18% resolution for pions in the momentum range 300–400 MeV/c. However, this resolution cannot be directly compared with our resolution because (i) the truncation of the Gaussian fit at large pulseheights is somewhat different, and (ii) the physical length over which dE/dx is evaluated, is not specified (according to Eq. (5), the resolution improves with increasing track length and, for fixed radius, with decreasing $\sin\theta$, respectively).

We conjecture that if the same is compared with the same, the 'official' dE/dx resolution will be somewhat worse than ours. The origin of the difference can be traced back to pad equalization and crosstalk correction.

Acknowledgement

We wish to thank R. Veenhof for several useful discussions.

References

[1] A. De Min, F. Dydak, A. Guskov, A. Krasnoperov, Yu. Nefedov and A. Zhemchugov, TPC cross-talk correction: CERN–Dubna–Milano algorithm and results, HARP Memo 03-003 (6 July 2003), *http://cern.ch/dydak/crosstalk3.ps*

[2] F. Dydak, A. Guskov, A. Krasnoperov, Yu. Nefedov, J. Wotschack and A. Zhemchugov, Performance of TPC crosstalk correction, HARP Memo 04-101 (7 May 2004), *http://cern.ch/dydak/crosstalk4.ps*

[3] W. Blum and L. Rolandi, Particle Detection with Drift Chambers, Springer Verlag (Berlin, Heidelberg, New York), 1993

[4] D. Buskulic *et al.*, Nucl. Instr. and Methods **A360** (1995) 481

[5] V. Ammosov *et al.*, The electron drift velocity in the HARP TPC, HARP memo (in preparation).

[6] *http://meteo.infospace.ru/wcarch/html*

[7] A. De Min and F. Dydak, Analysis of HARP TPC krypton data, HARP Memo 04-103 (23 April 2004), *http://cern.ch/dydak/kryptonCalib.ps*

[8] Particle Data Group, Phys. Lett. **B592** (2004) 1, p.262

[9] M.G. Catanesi *et al.*, The HARP detector at the CERN PS, Nucl. Instrum. Methods Phys. Res. **A571** (2007) 527

[10] HARP Collaboration, Rebuttal of "Comments to 'The HARP detector at the CERN PS' ", Nucl. Instrum. Methods Phys. Res. **A571** (2007) 564

[11] S. Borghi *et al.*, 'HARP TPC performances', HARP memo 06-001 (4 October 2005), also available at *http://cern.ch/dydak/HARP-Memo-01-2006.pdf*