THE CPLEAR PARTICLE IDENTIFICATION DETECTOR

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Abstract

The CPLEAR experiment will measure CP violation parameters in the neutral kaon system, using a low-energy antiproton beam from the Low-Energy Antiproton Ring (LEAR) at CERN. One of its subdetectors, the Particle Identification Detector (PID), makes a fast separation of pions and kaons, which is essential for the experiment. This paper describes the design of the PID and its performance during beam tests and during initial runs at LEAR. A pion rejection efficiency of 99.7% for the first-level trigger (after 60 ns) is found in the relevant momentum region.

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1. INTRODUCTION

The physics motivation of the CPLEAR experiment is to study CP-violation phenomena using the improved source of antiprotons at the CERN Low-Energy Antiproton Ring (LEAR) [1]. An intense ($2 \times 10^6 \text{ s}^{-1}$) beam of low-energy (200 MeV/c) antiprotons is stopped in a pressurized hydrogen gas target to obtain a high flux of tagged K^0 and $\bar{K}^0$ mesons through the annihilation channels (referred to as golden events)

$$\bar{p}p \text{ (at rest)} \rightarrow \pi^\pm K^\mp K^0(\bar{K}^0),$$

each with a branching ratio of 0.2%. The relevant kaon momentum in these channels ranges from 350 to 760 MeV/c. In order to select the golden events, the large background of pions from the ordinary annihilation channels has to be efficiently rejected by the trigger.

The Particle Identification Detector (PID) has been designed to provide information on the nature of particles sufficiently fast to be used in the trigger of the CPLEAR experiment without introducing dead-time. It consists of a pair of scintillators with a Cherenkov detector in between. It provides kaon-pion separation via a threshold Cherenkov at the first-level trigger, and dE/dx and time-of-flight (TOF) information at a later trigger level. This information, is available as discriminator signals and as analog-to digital converter (ADC) and time-to-digital converter (TDC) data, respectively.

A detailed description of the PID is given in section 2 and the results from beam tests of a prototype are presented in section 3. The performance of the final PID module, working in the CPLEAR detector at LEAR, is described in section 4. The conclusion is given in section 5.

2. THE DETECTOR

The CPLEAR detector [2] (fig. 1) has been designed to tag neutral kaons arising from $\bar{p}p$ annihilations and to identify their decay products. It is cylindrically symmetric and placed inside a solenoidal magnet of 3 m length and 2 m diameter, with a field of 0.44 T. In the centre is a hydrogen-gas target. The detector components are two proportional chambers, six drift chambers, two layers of 32×6 streamer tubes, 32 sectors of scintillator-Cherenkov-scintillator sandwiches, and outermost an electromagnetic calorimeter. More details are given elsewhere [2-4].

Within the CPLEAR detector the main task of the PID is to define rapidly candidate charged-particle and kaon tracks. As mentioned above, this identification is essential in order to trigger on the annihilation channels of interest. Furthermore, the PID information is important for the electron-pion separation required in the analysis of the semileptonic K^0 decay channels.

The PID consists of 32 identical sectors of an inner scintillator (S1) 3 cm thick, a Cherenkov counter (C) 8 cm thick, and an outer scintillator (S2) 1.4 cm thick. These sectors form a cylinder with radii R_{in} of 62 cm to R_{out} of 76 cm (fig. 1) and an active length of 3.1 m. Some of the physical properties and parameters of the PID elements are given in table 1. The PID was designed to give a high efficiency for the kaon-pion separation in the momentum range 300 to 750 MeV/c.

The CPLEAR experiment has a multilevel trigger based on several on-line trigger processors [5]. An early trigger decision is made within 60 ns after the trigger receives the beam-counter signal, provided a kaon candidate and at least one more charged-particle candidate are present. This means that for at least one of the 32 sectors, there is a kaon

candidate, consisting of coincident hits in the scintillators and no hit in the corresponding Cherenkov ($S1 \cdot \bar{C} \cdot S2$), plus one or more hits in another inner scintillator ($S1$). At a later trigger stage, after about $2 \mu\text{s}$, a refined particle-identification analysis is used, based on on-line pulse-height and TOF information.

Each element of the PID is equipped with light guides and photomultipliers (PMs). The light guides, made of polymethyl methacrylate (PMMA), are straight and pass through 32 holes in each of the magnet end-caps. This construction enables the latter to be removed (after dismounting the PM tubes) without removing the PID. Each scintillator is equipped with one PM at each end, whilst the Cherenkov has two PMs at each end to improve the light collection. Owing to the limited space, it was necessary to mount the PMs of the $S2$ scintillators and of the Cherenkovs perpendicular to the detector axis (fig. 2). Therefore, the ends of the $S2$ scintillator light guides are cut to 45° . The light guides of the Cherenkovs are of similar design, having two prisms to divide the light between the two PMs at each end of the sector. The $S1$ PM tubes are mounted along the axis of the scintillator to maximize light transmission and to minimize the time dispersion.

The $S1$ scintillators were optimized within the geometrical constraints for good time and energy resolution. For the best possible timing, one needs to maximize the number of photoelectrons in the PM as well as the speed of the PM and the response of the scintillator material. Bicron BC408 scintillator was chosen for its combination of high light output, fast pulse response, and long attenuation length (about 360 cm with the chosen $S1$ scintillator cross-section). Each trapezoidal scintillator ($3 \text{ cm} \times 11\text{--}12 \text{ cm} \times 310 \text{ cm}$) was glued at each end to 1 m long light guides, which lead to 5 cm diameter Philips XP4222B PMs. The XP4222B is very similar to the XP2020 but has a higher average quantum efficiency and a less stringent noise limit. The size of the holes in the end-caps of the magnet limits the cross-section of the light guides to $6.5 \text{ cm} \times 3.0 \text{ cm}$, which somewhat reduces the amount of light delivered to the PMs. The signal from a PM is fed to a constant-fraction timing discriminator and then to a TDC, as well as to an ADC for pulse-height analysis. The TDCs provide 10-bit accuracy, 70 ns full scale, whilst the ADCs provide 7-bit accuracy. The same types of ADCs are used for pulse-height analysis of all Cherenkov and $S2$ signals.

The $S2$ counters are 1.4 cm thick pieces of NE102A scintillator from Nuclear Enterprises, with XP2232B PMs at each end. The main task of the $S2$ is to make sure that a particle passing through $S1$ also passes through the Cherenkov counter. In addition, pulse-height information from the $S2$ counters is also used for dE/dx , as in the case of $S1$.

The Cherenkov counter walls, which are in the form of long extruded tubes, and the light guides are made of UV-transparent PMMA (transmitting light of wavelengths above 210 nm). The tubes are filled with Fluorinert (C_6F_{14}) FC72*) as liquid radiator. Ideally, for an optimal kaon-pion separation, a Cherenkov radiator with a refractive index $n = 1.19$, corresponding to a threshold at $\beta = 0.84$ (matching the maximum kaon velocity), should be used. The FC72 is however the only liquid available in suitable quantities with a sufficiently low refractive index ($n = 1.26$ corresponding to $\beta = 0.79$). The use of water with $n = 1.33$ certainly has practical advantages. However, a water radiator has been extensively studied and has been found to be unsuitable because of its high refractive index and because of achromatic effects on the threshold [6]. Owing to the energy loss in

*) Trademark of 3M.

S1 and in the FC72, the effective threshold kaon velocity is $\beta = 0.81$, sufficiently close to the kinematical limit of 0.84. In the relevant range of the overall quantum efficiency, the FC72 has a very low achromaticity, thus allowing a well-defined threshold, corresponding to a velocity uncertainty of $\Delta\beta \approx 0.01$ (fig. 3a).

In order to match the Cherenkov light output to the response of the PM, a wavelength shifter has been used, which has to have several properties: appropriate wavelength shift, low self-absorption, and sufficient solubility in FC72. With the help of the Ciba Geigy AG laboratory, the most suitable substance was found to be diphenyl-oxazole (PPO)**). By adding 20 mg/l of PPO a good match to the Cherenkov PM spectral response has been achieved. The PPO absorbs most of the light in the wavelength interval 270–320 nm and re-emits it in the region of 300–450 nm (there being a peak at 350 nm) with a quantum efficiency of about 70% (fig. 3b) [7]. The shifted Cherenkov light is emitted isotropically, which tends to make the light-collection efficiency more uniform along the length of the Cherenkov counter. The uniformity of the efficiency is further improved by painting the outside of the innermost 80 cm of the Cherenkov box with white reflecting paint, NE561 ***). In the regions near the ends of the counter, the light is directed towards the box walls at large angles and is totally reflected, leading to a very good light collection. In the central region, however, where owing to a large number of reflections the light would be trapped, the white paint applied on the PMMA box will diffuse it along the box axis. This has been shown to considerably improve the light collection in the centre of the counter [6, 8].

The PMs on the Cherenkov counters are Philips XP3462. The quantum efficiency of such a PM as a function of wavelength is shown in fig. 3a. This PM tube has a good single photoelectron resolution, which makes a well-defined discriminator threshold setting possible. A detailed description of the considerations in the general design of the Cherenkov detector is given in ref. [6].

The PM signals are split into a fast trigger branch and an ADC branch (fig. 4): immediately in the case of the scintillator pulses and after amplification for the Cherenkov pulses. The S1 signals are split further to provide the inputs of the TDCs. The signals of the trigger branch are fed to discriminators, which provide hit pattern information to the early decision trigger processor. Flash ADCs and flash TDCs have been specially designed to handle the high rate and to produce the digital information in about 1 μ s [9]. A bus connects them to a hard-wired processor, which performs cuts on dE/dx and TOF for the scintillators and pulse-height information for the Cherenkovs.

The PID is equipped with several systems for monitoring and calibration. To check and calibrate the ADCs and the discriminators, a set of DAC-controlled pulsers injecting pulses of well-defined charge into the front-end electronics are used. Light-emitting diodes have been glued onto all light guides and can be pulsed when a fast check or PM calibration is required. Ultraviolet (UV) light pulses from a nitrogen laser can be provided with good time definition, at the centre of each counter, through a set of quartz fibres. This system is mainly used for the TOF calibration and stability monitoring of the S1 counters. All these systems are remotely controlled from a dedicated central processor unit (CPU) in a VME environment [10].

**) Manufactured by Merck.

***) Trademark of Nuclear Enterprises, Inc.

3. BEAM TEST

A prototype of the Cherenkov was tested at the Paul-Scherrer Institute [8]. A fully equipped PID with light guides and PMs was tested at the CERN Proton Synchrotron (PS). The layout of the PS test is shown in fig. 5. Measurements were made in such a way as to simulate the real detector conditions, with the incident angle α varying between -45° and $+60^\circ$. The momentum of an unseparated beam, consisting of protons, pions, and electrons, could be varied in the range of 0.8–2.0 GeV/c. The electrons were eliminated from the trigger by a threshold gas Cherenkov counter. Data from ADC, TDC, and pattern units were recorded on magnetic tape. Protons and pions were identified off-line by the TOF difference between two beam scintillation counters.

3.1 Results

For a given beam velocity and angle α (fig. 5) the average number of photoelectrons $\langle n \rangle$ was calculated separately for protons and pions from the mean of the pulse-height distribution. The values of $\langle N \rangle = \sum_{i=1}^4 \langle n_i \rangle$, i.e. the sum of the photoelectrons given by the four PMs of the Cherenkov, are given as a function of α and β in figs. 6 and 7; they decrease linearly with β^{-2} , as expected for Cherenkov light. The error bars in these figures show systematic errors rather than statistical errors, estimated by using different methods in analysing the pulse-height spectra to get the average number of photoelectrons. A small background can be seen below the threshold velocity. From the pulse-height spectra for these events it is concluded that this background is due to a small contamination (1–2%) of pions in the proton spectra. These background events originate from strong interactions and knock-on electrons produced in the S1 scintillator and the Cherenkov counter.

4. RESULTS FROM INITIAL LEAR RUNS

During 1989, most parts of the CPLEAR detector became operational and several millions $\bar{p}p$ annihilation events were recorded. For the results presented here two different triggers were used: the minimum-bias trigger, requiring a coincidence between the beam counter and one S1 element (mainly charged pions), and the kaon trigger described in section 2 (mainly an $S1 \cdot \bar{C} \cdot S2$). In the off-line analysis the momentum vector of each particle was determined by the standard CPLEAR magnetic analysis using proportional chambers, drift chambers, and streamer tubes. For all tracks in the present study we have required that they give signals in both S1 and S2 in the same sector to ensure that they traverse the Cherenkov.

4.1 Results

Typical Cherenkov, S1, and S2 ADC spectra are shown in fig. 8. In the Cherenkov spectrum the pedestal, and the first and second resolved photoelectron peaks can be seen, whereas the scintillator spectra show the pedestals and the minimum-ionization peaks. The threshold for the Cherenkov discriminators is set between the pedestal and the first photoelectron peak, and for the scintillators it is set well below the minimum-ionization peak. The hatched areas indicate signals that pass the discriminator requirements of the trigger.

Owing to the high photoelectron statistics available from the S1 counters, the dE/dx information is good, as shown by the scatter plots of dE/dx against momentum in figs. 9a and b. One can clearly see the pion (lower) and the kaon (upper) bands which are well resolved up to 650 MeV/c. Further, by comparing Fig. 9a (all tracks) with 9b (where

only tracks with the $S1 \cdot \bar{C} \cdot S2$ signature are plotted) the effect of the Cherenkov veto in suppressing pions above 300 MeV/c incident momentum is clearly visible. Kaons with momentum less than 350 MeV/c are absent in fig. 9 because they do not reach S2: they stop in the material on their way.

For S2 the separation between the pion and kaon band is increased by the energy loss suffered by charged particles when they traverse S1 and the Cherenkov counter. However, this advantage is largely offset by a smaller amount of produced light compared to S1. Particle identification in S2 by dE/dx is not as efficient as in S1, but gives a valuable independent complement (figs. 9c and d).

In the following analysis, cuts in dE/dx are applied. A cut variable, s , approximating a one standard deviation, is used. This variable has been determined from dE/dx distributions in narrow momentum bands such that the content between plus and minus 1s around the expected value is about 70% of the total distribution.

The TOF measurement in CPLEAR is normally done by examining the difference of TOF between two tracks. This is because the time between the passage of the incoming antiprotons through the beam counter (which provides the TDC start via the trigger) and the annihilation has an event-to-event fluctuation of the same order as the TOF of the pions or the kaons themselves. The time resolution between two pions entering two different S1 detectors is 0.26 ns r.m.s, averaged over all 32 sectors, which corresponds to 0.18 ns for a single track. Figure 10 shows a scatter plot (kaon-trigger data) of the difference (Dt) between the measured time difference of two tracks and the expected time difference if both particles were pions. One particle is required to be a pion (using Cherenkov and dE/dx information) with momentum 350 ± 25 MeV/c and Dt is plotted as a function of the momentum of the other particle. Both particles are required to be in the central 30 cm of S1. The two-pion band is centred around zero as expected and the band of kaon-pion combination falls off with decreasing momentum around its calculated mean (central curved line). In fig. 10 are also shown lines corresponding to +1 and -1 standard deviation. The inset shows the band between 350 and 450 MeV/c (dashed lines) projected on the Dt axis, with a fit to a double Gaussian. The width of the kaon peak is larger than that of the pion peak in this histogram since the mean position of the kaon peak varies with the momentum. The dE/dx and timing information form together an effective means of separating pions from kaons, which is to first order independent of the Cherenkov signals.

By using minimum-bias trigger data (where about 99% of the primary charged tracks are pions) and requiring that the tracks have a dE/dx value in both S1 and S2 within 1s of the expected pion value, a very clean pion sample can be obtained. For this sample, the average number of photoelectrons per PM ($\langle n_{phe} \rangle$), as a function of the distance between the points where the tracks cross the Cherenkov and where the light guide starts, is shown in fig. 11 for the momentum intervals 300 ± 10 MeV/c and 600 ± 10 MeV/c. As expected, $\langle n_{phe} \rangle$ falls roughly exponentially with the distance, but flattens out at 200 cm at a level of about half a photoelectron, independent of momentum. This could be due to Cherenkov or scintillator light produced in the plastic walls, or to knock-on electrons. The shoulders at 110 cm are due to the painting of the centre of the Cherenkov box (see section 2) and clearly show how this increases the light yield at large distances [8]. The solid lines indicate the behaviour of $\langle n_{phe} \rangle$ as simulated by a semi-empiric Monte Carlo program, partly tuned to these beam data, where Cherenkov, optical, and geometrical effects are considered [6].

In fig. 12 the average number of photoelectrons per PM is shown as a function of the momentum for tracks crossing the middle of the detector (± 20 cm) and 50 ± 10 cm from the light guide. The rise of the data for momenta smaller than 250 MeV/c is due to a relatively large fraction of electrons contaminating the pion sample there. These electrons often give large light yield, causing a high average value of $\langle n_{\text{phe}} \rangle$. This can be seen in fig. 13a, which is a scatter plot of the same data as in the lower curve in fig. 12. From figs. 13a and b one clearly sees how the pions start to give Cherenkov light above about 190 MeV/c, in good agreement with the theoretically expected value. Electrons are not seen below 160 MeV/c, because particles are selected in the pion band, which has a rapidly increasing dE/dx below 200 MeV/c (see fig. 8), whilst dE/dx for electrons is constant down to much lower values.

It is of great importance for the CPLEAR experiment that the fast kaon-pion separation works with high efficiency at the trigger level. A 'kaon' is flagged by the trigger if at most one of the four PMs connected to the same Cherenkov sector gives an output above the discriminator level, in coincidence with at least one S1 and one S2 discriminator signal in the same sector (i.e. a $S1 \cdot \bar{C} \cdot S2$). If the opposite is true, a pion is assumed. The aim is to optimize the $S1 \cdot \bar{C} \cdot S2$ signature so that real kaons are found with high efficiency, whilst as few pions as possible are mistaken for kaons.

We describe how the pion-veto efficiency of the Cherenkov is determined. Using minimum-bias trigger data, pions are selected by requiring the dE/dx to be less than 1s from the pion expected value in both S1 and S2, but more than 2s away from the expected kaon value in S1 and more than 1s away from that in S2. Any pair of tracks is required to be in disagreement with a kaon-pion hypothesis on the TOF, but in agreement with a pion-pion hypothesis. Figure 14 shows the Cherenkov efficiency (as seen by the trigger) for these tracks as a function of momentum. The efficiency rises sharply above 200 MeV/c, reaches 98% at 300 MeV/c, flattens out around 350 MeV/c, and reaches $99.8 \pm 0.1\%$ above 500 MeV/c.

These numbers are obtained when a pion is demanded as strictly as possible. However, from the point of view of the CPLEAR trigger the most important question is, What is the probability that an $S1 \cdot \bar{C} \cdot S2$ signature does not come from a kaon? To answer this question the whole region in dE/dx where kaons are not expected should be considered without any TOF requirements. Thus the only requirements made are that dE/dx be at least 2s below the expected kaon value in S1 and at least 1s below that in S2. (The probability of having a kaon is then still less than 10^{-4} .) The efficiency in this case rises somewhat slower, and an inefficiency of 0.26% with $\pm 0.04\%$ statistical error is obtained in the region of 500 to 700 MeV/c.

It should be noted that the numbers given here could be improved, by further optimization and tuning. On the other hand, a special class of pions which interact strongly somewhere in the PID, thereby giving a large energy deposition in S1 or S2, are not identified as pions by the dE/dx cut above. Moreover, this class of pions may, on the average, be less efficiently detected by the Cherenkov counter, thus deteriorating the overall efficiency. To estimate this effect, the results from different cuts in dE/dx in the momentum region between 250 and 350 MeV/c, where the pion and kaon lines are well separated, were compared. It is estimated that the overall inefficiency, including this effect, does not change by more than 50%.

The determination of the efficiency of identifying charged kaons at the first-level trigger, i.e. the probability that a charged kaon gives a $S1 \cdot \bar{C} \cdot S2$ signature, is based on

measurements in the $K^+K^-\pi^+\pi^-$ channel, where the second kaon can be identified without biases. A clean sample of $KK\pi\pi$ events is obtained by kinematical cuts [4] from kaon-trigger data. The second, unbiased, kaon is selected to have opposite charge to the first, TOF consistent with a kaon hypothesis, and a dE/dx value in S1 lying in the kaon band. The efficiency for this kaon to give a $S1*\bar{C}*S2$ signature is found to be about 75% for momenta above 400 MeV/c, decreasing with decreasing momentum. This number agrees with a study where no kinematical cuts were used. It is also supported by Monte Carlo results, where the effects of decay, knock-on electrons, and scintillator and Cherenkov light in the plastic walls are considered as well as, to some extent, strong interactions (GHEISHA [11]).

5. CONCLUSION

The PID for the CPLEAR experiment has been successfully tested under data-taking conditions, achieving its design performances. It consists of 32 sectors of scintillator-Cherenkov-scintillator sandwiches (S1-C-S2), providing discriminator signals for a fast trigger and signals for ADCs and (for S1) TDCs. For pions positively identified by dE/dx in S1 and S2, the rejection efficiency of the threshold Cherenkov at the first trigger level is $98.0 \pm 0.2\%$ at 350 MeV/c, rising to $99.8 \pm 0.1\%$ above 500 MeV/c. The overall rejection efficiency when integrating over the relevant pion momentum spectra is 99.7%. The efficiency of detecting a charged kaon in the first trigger level is 75%. The TOF resolution is 0.18 ns per track, averaged over all of the S1 scintillators. Together, dE/dx information and TOF provide a powerful kaon-pion separation, independent of the Cherenkov, which will be used in a later trigger level; this will improve the pion rejection at the on-line level by about a factor of 4.

For a given pion-rejection level, one can calculate the overall efficiency for identifying kaons using the four methods of particle identification (Cherenkov, dE/dx in S1 and S2, and TOF) in an independent way. As an example from the offline analysis we find that the probability of a pion being misidentified as a kaon is less than 4×10^{-6} , giving an efficiency of 60% for kaons at 350 MeV/c momentum. The risk of misidentification increases as the momentum increases, but even at 650 MeV/c the probability of mistaking a pion for a kaon is only 2×10^{-4} , with a 40% efficiency for kaons. The probability that a kaon will be misidentified as a pion is less than 10^{-6} with an efficiency of 90% for pions at 350 MeV/c, whereas at 650 MeV/c the probability is 10^{-3} with 40% efficiency. The difference in these values for pions and kaons can be explained by the Landau tail at low momentum and by the momentum dependences in the four methods used. Using a more elaborate algorithm, which considers all available information and, in particular, the ADC information of the Cherenkov, the numbers quoted above should be improved.

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Table 1
Physical properties and parameters of the PID elements

Element	S1	Cherenkov	S2
<i>Detector</i>			
Material	BC 108 ^{a)}	Extruded PMMA ^{b)} tube Radiator: liquid FC72	NE 102 ^{c)}
Length (cm)	310	310	310
Thickness (cm)	3.0	8.0	1.4
Thickness of FC72 (cm)		7.5	
<i>Light guide</i>			
Material	PMMA	PMMA	PMMA
Length (cm)	110	100	75
<i>Photomultiplier</i>			
Type	XP4222B	XP3462	NP2232B

a) Bicron Corporation

b) PMMA = polymethyl methacrylate

c) Nuclear Enterprises

Figure captions

Fig. 1 Cross-section of the CPLEAR detector showing one of the first golden events.

Fig. 2 View of the light guides and PMs of one end of a PID.

Fig. 3 a) Dispersion curve of FC72 (left); quantum efficiency of the XP3462 PM (right).
b) Absorption and emission of PPO.

Fig. 4 Electronic layout of the PID.

Fig. 5 The PID layout in the beam test at the PS.

Fig. 6 Number of photoelectrons as a function of α measured at the PS. The lines are hand-drawn through the data points to guide the eye.

Fig. 7 Number of photoelectrons as a function of β^{-2} measured at the PS. The straight lines are hand-drawn through the data points to guide the eye.

Fig. 8 Typical ADC spectra for a) the Cherenkov PM, b) the S1 PM, and c) the S2 PM. The hatched areas are signals that pass the discriminator cut for the trigger. Note that the tops of the pedestals have been cut.

Fig. 9 Scatter plot of dE/dx in S1 [(a) and (b)] and S2 [(c) and (d)] against momentum; a) and c) all tracks from the kaon trigger, b) and d) tracks with the $S1 \cdot \bar{C} \cdot S2$ signature. The momentum in S2 has been corrected for the energy loss when passing the PID.

Fig. 10 Scatter plot of the difference between the measured time difference of two tracks and the expected time difference assuming both tracks were pions, as a function of the momentum of the second track. The first track is a pion with a momentum of 350 ± 25 MeV/c. The lines show the expected mean values for pions (at $Dt=0$) and kaons (middle curved line), with $\pm 1\sigma$ bands. The inset is the 350–450 MeV/c band (as shown by the dashed vertical lines in the main figure) projected onto the Dt -axis, with a fit to a double Gaussian.

Fig. 11 Average number of photoelectrons per PM as a function of distance from the light guide for pions with $p = 300 \pm 10$ MeV/c (open circles) and $p = 600 \pm 10$ MeV/c (filled triangles). The curves show values from Monte Carlo simulations.

Fig. 12 Average number of photoelectrons per PM as a function of momentum for pions in the middle 20 cm of the counter (open circles) and 50 ± 10 cm from the light guide (filled triangles). The curves show values from Monte Carlo simulations.

Fig. 13 Scatter plot of $N = \sum_{i=1}^4 n_i$ (sum over the 4 PMs in one sector) against momentum for the middle 20 cm (a) and 50 cm from the light guide (b). Note the difference in scale in a) and b).

Fig. 14 Efficiency as a function of momentum for the $S1 \cdot \bar{C} \cdot S2$ pion-veto trigger; a) and b) show the same data but with different scales.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14