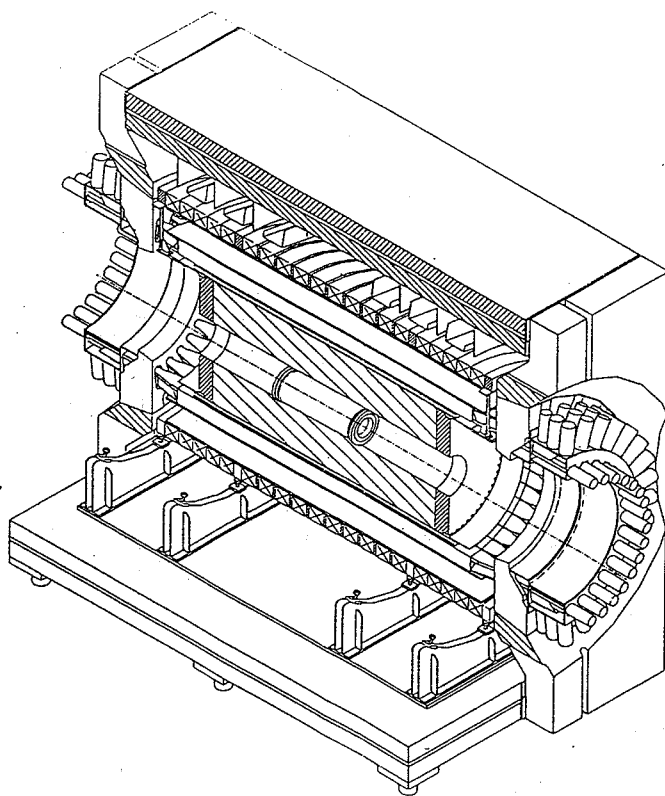




KTH

Study of Asymmetries in Semileptonic Decays of Neutral Kaons from $p\bar{p}$ Annihilation at Rest

Kåre Jansson



Thesis-1993-Jansson

Manne Siegbahn Institute of Physics
and
Royal Institute of Technology
Stockholm 1993

*your help was really
valuable!*

Kåre J



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ABSTRACT

The CPLEAR experiment at CERN is described. The detector is now fully operational and taking data.

Several studies of the Particle Identification Detector system are reported. Particle identification is primarily done by means of a Scintillator Cherenkov Scintillator sandwich, with the Cherenkov module operating as a threshold counter in order to separate pions from kaons. The particle identification also includes the use of time-of-flight as well as Cherenkov and Scintillator pulse heights. Methods using these signals in order to identify electrons coming from the semileptonic decays of neutral kaons have been developed.

Calibration data has been used to determine relative branching ratios of several final states from $p\bar{p}$ annihilation involving ρ and f_2 mesons. These results have also been used to determine the fraction of P-wave annihilation in the CPLEAR target.

A detailed study of the systematic effects in the selection of semileptonic events is reported. These events are used in order to determine values of several parameters: Δm , $\Re(x)$, $\Im(x)$, $\Re(\varepsilon_S)$ and $\Re(\varepsilon_T)$. The mass difference between K_L and K_S , Δm , is determined to $\Delta m = (5,43 \pm 0,19)10^9 \hbar/s$. The parameter x that determines the violation of the $\Delta S = \Delta Q$ rule has been studied, obtaining values of $\Re(x) = (-26_{-65}^{+53})10^{-3}$ and $\Im(x) = (-36 \pm 34)10^{-3}$. The value of $\Im(x)$ is currently the most accurate measurement. An attempt to measure the CP -violation parameter in K_S decays, ε_S , for the first time gives a value of $\Re(\varepsilon_S) = (-0,1 \pm 3,5)10^{-3}$. For the T -violating parameter ε_T a value of $\Re(\varepsilon_T) = (-1,8_{-3,3}^{+3,1})10^{-3}$ is obtained.

Descriptors: $p\bar{p}$ annihilation at rest, CPLEAR, CPT , CP -violation, T -violation, $\Delta S = \Delta Q$ rule, K^0 , $\bar{K}^0$, K_S , K_L , semileptonic decay.

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Till Maria och Lova

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Chapter 1

Introduction

1.1 What is CP -violation?

Many processes in the Universe are governed by symmetry principles. It is, however, in the breaking of these fundamental principles that new physics is discovered. In the beginning of the 1950s, *Parity* (the operation of spatial inversion of coordinates) was believed to be conserved in all processes. In 1956, with an experiment proposed by T.D. Lee (Fig 1.1) and C.N. Yang (Fig. 1.2), E.S. Wu et al. discovered that this was not true for β -decays of atomic nuclei [3]. Having a sample of spin-oriented ^{60}Co decaying to ^{60}Ni , an asymmetry in the emitted electrons was observed when reversing the direction of the polarizing field. The result was revolutionary, parity was maximally violated in weak interactions and Lee and Yang were promptly awarded the 1957 Nobel prize for physics. For a few years it was believed that taking the combined charge and parity operator, CP , this would result in an invariant state. An example is shown in Fig. 1.3 where a left-handed neutrino (which is known to exist in nature) finds itself being a right-handed anti-neutrino after operating with CP . The two other combinations have not been found in nature.

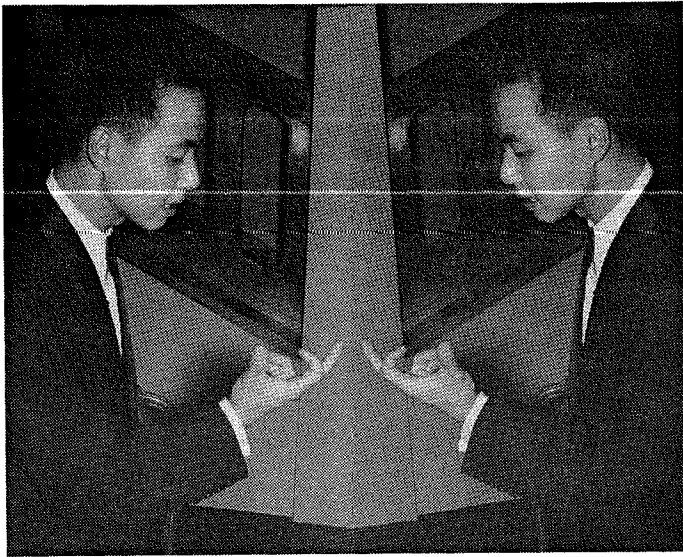


Figure 1.1: *T. D. Lee testing Parity violation after a dinner in the Manne Siegbahn villa December 11, 1957. Photo taken by Ingmar Bergström [1, page 615].*

1.2 CP is Violated!

Since Yang in Fig. 1.2 avoids giving the charges of the particles, the lecture could just as well have been given on neutral kaons and their CP quantum numbers. Here, the short-lived kaon, K_S decays predominantly to two pions, whereas the long-lived state K_L mainly gives three body final states. In 1964 Christenson et al. [4] discovered that K_L also could decay into two pions. If CP had been an exact symmetry, this would not have been possible, since its CP -eigenvalue of -1 only would allow it to decay into three pions, see Fig. 1.2. The branching ratio is small however, only about $2 \cdot 10^{-3}$ for the decay into $\pi^+\pi^-$. From the branching ratio of K_L into two pions one can derive a value of the mixing parameter $|\varepsilon_L|$ of $2,2 \cdot 10^{-3}$, i.e. an admixture of the CP -even state in the primarily CP -odd K_L of two parts per thousand.

Since the discovery, several experiments have sought for the origin of this CP -violation. It is clear that ε_L denotes CP -violation in the mixing, so-called *indirect* CP -violation. This is allowed by the Standard Model, the model that so successfully describes our present understanding of the

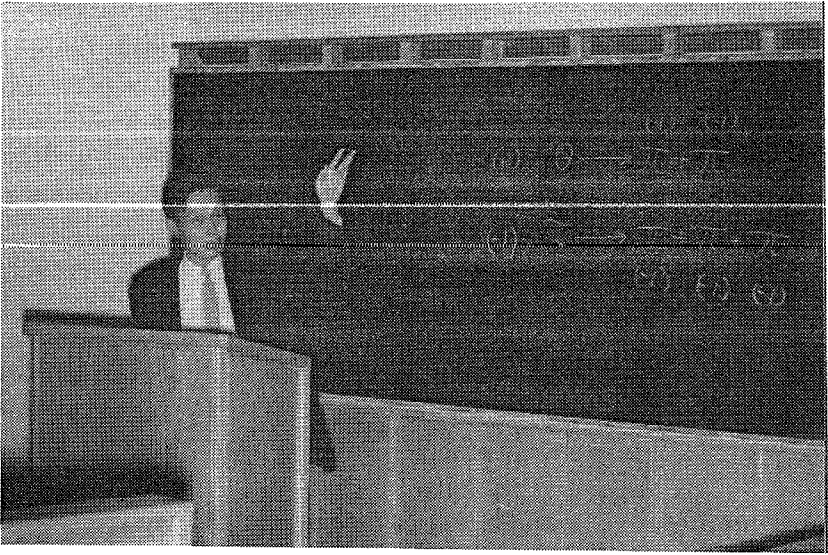


Figure 1.2: C. N. Yang giving his Nobel lecture 1957. On the blackboard is shown the parity quantum numbers for the decay of $K^\pm \rightarrow \pi^\pm \pi^0$ (at that time called θ) and the $K^\pm \rightarrow \pi^+ \pi^- \pi^\pm$ (called τ). This was known as the θ - τ puzzle at the time [2, page 343], two particles having the same mass and lifetime but different parity quantum number. Now we now know these are two different decay modes of the same particle where parity is violated in the decay. Photo taken by Ingmar Bergström [1, page 614].

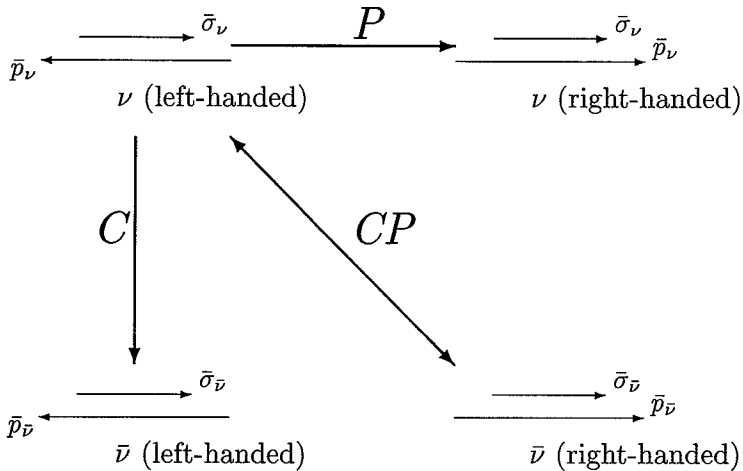


Figure 1.3: CP operating on a left-handed neutrino transforming it into a right-handed anti-neutrino. The two other combinations have not been found in nature.

Micro-cosmos. In order for the Standard Model to be correct, there is also a need for *direct* CP -violation, in the decay matrix. This is parametrized by the parameter ε' , expected to be a factor of thousand less than ε_L . It is therefore of utmost importance to determine the ratio $\varepsilon'/\varepsilon_L$ in order to test the Standard Model and discover new physics. For instance, the Super Weak Model requires $\varepsilon' \equiv 0$.

Two recent experiments have measured this ratio, with different techniques and deriving incompatible results, at least at the two standard deviation level. The NA31 experiment at CERN finds a value three standard deviations away from zero of $(2,3 \pm 0,7) \cdot 10^{-3}$ [5] whereas the E731 experiment at Fermilab finds a value of $(0,60 \pm 0,69) \cdot 10^{-3}$ [6] consistent with zero. It is imperative to solve this discrepancy with further experiments, and both experiments are in the process of preparing upgrades that will reach a sensitivity of 10^{-4} in this ratio.

1.3 Aim of the CPLEAR Experiment

The history of the CPLEAR experiment started 1985 with a proposal [7] to measure CP -violation parameters using a novel technique. The experiment is performed at CERN's Low Energy Antiproton Ring (LEAR), using the antiprotons as a source to produce kaons. Instead of having beams of K_L and K_S as the NA31 and E731 experiments, one selects in the final state events with a K^0 or $\bar{K}^0$. This is possible by looking at the reactions

$$p\bar{p} \text{ (at rest)} \rightarrow K^\pm \pi^\mp \bar{K}^0 (K^0) \quad (1.1)$$

called golden reactions in the following. By measuring the sign of the charged kaon the strangeness of the accompanying neutral kaon is known. The advantage of this method is that interference between the two final states K^0 and $\bar{K}^0$ can be directly measured, since the two states have identical decay channels. The main disadvantage is having to fight a larger background, since the annihilation branching ratio for reaction 1.1 is only $4 \cdot 10^{-3}$. In particular, a very good separation efficiency between pions and kaons is needed.

Using this new technique it will be possible to determine many quantities that never have been measured before. For instance, CP -violation in K_S decays, parametrized with ε_S will be measured for the first time. Also,

parameters related to T -violation, where T stands for time reversal can be determined. Physicists cannot run the time backwards, but one can test the reaction rate with which a $K^0 \rightarrow \bar{K}^0$ and compare it to the reversed reaction, $\bar{K}^0 \rightarrow K^0$. Any difference found would be a direct proof of T -violation. Originally, the aim was to measure ϵ'/ϵ_L with about the same accuracy as the previous experiments but with completely different systematic errors. Due to unforeseen difficulties it is now clear that the CPLEAR experiment will not be able to compete on the measurement of ϵ'/ϵ_L . Therefore ϵ'/ϵ_L will not be discussed further, see [8] for a good review of the subject.

The most powerful symmetry is the combined CPT symmetry. No one has yet been able to formulate a theory that breaks this symmetry. Assuming CPT to be a good symmetry, the measured CP -violation would directly infer an equal amount of T -violation. The CPLEAR experiment can also test CPT , but given the fact that the mass of the K^0 has been shown to equal the mass of the $\bar{K}^0$ to within one part in 10^{18} , CPT is indeed a very good symmetry.

Chapter two of this thesis describes the phenomenology of CP - and T -violation. Also, in the case of $K^0 \rightarrow 2\pi$ and 3π , results are presented together with future prospects. Chapter three describes the experimental layout, with Chapter four going more into detail about the particle identification system, the PID. Chapter five describes how the PID is used in order to separate between different particles while Chapter six gives results on meson spectroscopy, where several final states from $p\bar{p}$ annihilation involving ρ and f_2 mesons have been measured. These results have also been used to determine the fraction of P-wave annihilation in a target of 15 bar gaseous hydrogen. Chapter seven presents the main analysis of this thesis work, a study of the semileptonic decays of neutral kaons. These events are used in order to determine values of several parameters: Δm , x , $\Re(\epsilon_S)$ and $\Re(\epsilon_T)$. Δm is the mass difference between K_L and K_S , x is a parameter that measures the violation of the $\Delta S = \Delta Q$ rule, $\Re(\epsilon_S)$ is the CP -violation parameter in K_S decays and $\Re(\epsilon_T)$ is a parameter related to T -violation. Chapter eight summarizes the thesis.

Chapter 2

Phenomenology of the Neutral Kaon System

Here follows a brief description of the phenomenology of CP -violation. In the following, $\Re(x)$ stands for the real part of x , $\Im(x)$ signifies the imaginary part. This treatment follows Lee [2, pages 346-377] and Lee and Wu [9].

2.1 The $K^0 - \bar{K}^0$ System

The Hamilton operator in the neutral kaon case can be written as

$$H_K = H_0 + H_w$$

where H_0 describes the strong and electromagnetic part of the interaction and H_w the weak part. $|K^0\rangle$ and $|\bar{K}^0\rangle$ are the strangeness $S = \pm 1$ eigenstates of H_0 , respectively, which are produced in strong interaction. But the particles that propagate and decay are the eigenstates of H_K , denoted K_S and K_L for short-lived and long-lived K^0 .

In order to find these states, it is convenient to define the states that are eigenstates of the CP -operator. Choosing $CP|K^0\rangle = +|\bar{K}^0\rangle$ one can

define a CP -even state $|K_1\rangle$ and a CP -odd state $|K_2\rangle$ as

$$\begin{aligned} |K_1\rangle &= \frac{1}{\sqrt{2}} (|K^0\rangle + |\bar{K}^0\rangle) \\ |K_2\rangle &= \frac{1}{\sqrt{2}} (|K^0\rangle - |\bar{K}^0\rangle) \end{aligned}$$

These states are not eigenstates of strangeness. Table 2.1 summarizes the different kaons we have encountered so far. Looking at their decays one can see that the decay of K_2 to two pions is forbidden if CP is a good symmetry because $|2\pi\rangle$ is a CP -even state. When Christenson et al. [4] discovered that the long-lived state could in fact decay into two pions one was led to define the K_L as

$$|K_L\rangle = |K_2\rangle + \varepsilon_L |K_1\rangle = \frac{1}{\sqrt{2}} \left((1 + \varepsilon_L) |K^0\rangle - (1 - \varepsilon_L) |\bar{K}^0\rangle \right) \quad (2.1)$$

with $\varepsilon_L \ll 1$. Due to the smallness of the CP -, T - and CPT -violating parameters, higher order terms have been neglected throughout this chapter. Similarly one can define K_S as mainly K_1 with a small admixture of K_2 in it. However, no CP -violation in the K_S decays has been detected yet.

The two strangeness eigenstates K^0 and $\bar{K}^0$ can mix through virtual intermediate states, see Table 2.2, resulting in second order strangeness changing ($\Delta S = 2$) processes. This means that a particle that starts as a K^0 at a later time can find itself as a $\bar{K}^0$ with a probability given by its wave function $|\Psi(t)\rangle$ which can be written as a linear combination of the K^0 and $\bar{K}^0$:

$$|\Psi(t)\rangle = \alpha(t) |K^0\rangle + \beta(t) |\bar{K}^0\rangle$$

where the states K^0 and $\bar{K}^0$ are related by $|\bar{K}^0\rangle = CPT |K^0\rangle$. The time dependence can be obtained by solving the Schrödinger equation

$$i\hbar \frac{\partial}{\partial t} |\Psi(t)\rangle = \mathbf{H} |\Psi(t)\rangle \quad (2.2)$$

using perturbation theory. Generally, since $\mathbf{H}$ is a 2×2 matrix it can be written as a sum of two Hermitian matrices [2, page 348], i.e.

$$\mathbf{H} = \begin{pmatrix} \langle K^0 | H_K | K^0 \rangle & \langle K^0 | H_K | \bar{K}^0 \rangle \\ \langle \bar{K}^0 | H_K | K^0 \rangle & \langle \bar{K}^0 | H_K | \bar{K}^0 \rangle \end{pmatrix} = \mathbf{M} - i\mathbf{\Gamma}$$

where $\mathbf{M}$ is called the mass matrix and $\mathbf{\Gamma}$ is called the decay matrix. The time evolution of eq. 2.2 is given by the eigenvectors $|K_S\rangle$ and $|K_L\rangle$ for which

$$(\mathbf{M} - i\mathbf{\Gamma}) |K_{S,L}\rangle = (m_{S,L} - \frac{i}{2} \gamma_{S,L}) |K_{S,L}\rangle \quad (2.3)$$

Particle (quarks)	Eigenstate to	S	I_3	CP or CPT	Mass	Width
$K^+ (u\bar{s})$	H_0	+1	+1/2	K^-	$m_{K^\pm}$	$\gamma_{K^\pm}$
$K^- (\bar{u}s)$	H_0	-1	-1/2	K^+	$m_{K^\pm}$	$\gamma_{K^\pm}$
$K^0 (d\bar{s})$	H_0	+1	-1/2	$\bar{K}^0$	m_K	
$\bar{K}^0 (\bar{d}s)$	H_0	-1	+1/2	K^0	m_K	
K_1	H_0			K_1	m_K	
K_2	H_0			$-K_2$	m_K	
K_S	H_K				m_S	γ_S
K_L	H_K				m_L	γ_L

Table 2.1: *Summary of kaons with eigen-operator, eigenvalues S and I_3 and their masses and widths, if applicable.*

Particle	Decay mode	Branching Ratio
K_S	$\pi^+\pi^-$	$(68,61 \pm 0,28)\%$
	$\pi^0\pi^0$	$(31,39 \pm 0,28)\%$
	$\pi^+\pi^-\gamma$	$(1,85 \pm 0,10)10^{-3}$
	$\gamma\gamma$	$(2,4 \pm 1,2)10^{-6}$
	$\pi^+\pi^-\pi^0$	$< 4,9 \cdot 10^{-5} \text{ 90\% C.L.}$
	$\pi^0\pi^0\pi^0$	$< 3,7 \cdot 10^{-5} \text{ 90\% C.L.}$
K_L	$\pi^\pm e^\mp \bar{\nu}_e(\nu_e)$	$(38,7 \pm 0,5)\%$
	$\pi^\pm \mu^\mp \bar{\nu}_\mu(\nu_\mu u)$	$(27,0 \pm 0,4)\%$
	$\pi^+\pi^-\pi^0$	$(12,38 \pm 0,21)\%$
	$\pi^0\pi^0\pi^0$	$(21,6 \pm 0,8)\%$
	$\pi^\pm e^\mp \bar{\nu}_e(\nu_e)\gamma$	$(1,3 \pm 0,8)\%$
	$\pi^+\pi^-$	$(2,03 \pm 0,04)10^{-3}$
	$\pi^0\pi^0$	$(9,09 \pm 0,35)10^{-4}$
	$\gamma\gamma$	$(5,70 \pm 0,27)10^{-4}$

Table 2.2: *Examples of decay modes of neutral kaons. The K_S lifetime is $\tau_S = (0,8922 \pm 0,0020)10^{-10}s$, K_L has a life time of $\tau_L = (5,17 \pm 0,04)10^{-8}s$.*

where

$$\begin{aligned} m_{S,L} &= m_K \mp \frac{\Delta m}{2} = \frac{1}{2}(M_{11} + M_{22}) \mp \Re(M_{12}) \\ \frac{1}{2}\gamma_{S,L} &= \Gamma_K \mp \frac{\Delta\Gamma}{2} = \frac{1}{2}(\Gamma_{11} + \Gamma_{22}) \mp \Re(\Gamma_{12}). \end{aligned}$$

Here, it is interesting to note the smallness of $\Delta m = m_L - m_S$, $\Delta m/m_K = 10^{-14}$. The eigenvectors of eq. 2.3 can be written

$$|K_S(t)\rangle = e^{-(im_S + \gamma_S/2)t} |K_S(0)\rangle \quad (2.4)$$

$$|K_L(t)\rangle = e^{-(im_L + \gamma_L/2)t} |K_L(0)\rangle \quad (2.5)$$

Allowing for possible T - and CPT -violation, the solutions $|K_S(0)\rangle$ and $|K_L(0)\rangle$ can be written as

$$|K_S(0)\rangle = \frac{1}{\sqrt{2}} \left((1 + \varepsilon_T + \delta_{CPT}) |K^0\rangle + (1 - \varepsilon_T - \delta_{CPT}) |\bar{K}^0\rangle \right) \quad (2.6)$$

$$|K_L(0)\rangle = \frac{1}{\sqrt{2}} \left((1 + \varepsilon_T - \delta_{CPT}) |K^0\rangle - (1 - \varepsilon_T + \delta_{CPT}) |\bar{K}^0\rangle \right) \quad (2.7)$$

where ε_T and δ_{CPT} are small compared to 1. ε_T and δ_{CPT} can be written as

$$\varepsilon_T = \frac{\langle \bar{K}^0 | H_w | K^0 \rangle - \langle K^0 | H_w | \bar{K}^0 \rangle}{\Delta m + \frac{i}{2} \Delta \Gamma} \quad (2.8)$$

$$\delta_{CPT} = \frac{\langle \bar{K}^0 | H_w | \bar{K}^0 \rangle - \langle K^0 | H_w | K^0 \rangle}{\Delta m + \frac{i}{2} \Delta \Gamma} \quad (2.9)$$

If T -invariance is assumed eq. 2.8 implies that $\varepsilon_T = 0$ since the transition probability that a $K^0 \rightarrow \bar{K}^0$ would be equal to that of $\bar{K}^0 \rightarrow K^0$. If CPT -invariance is assumed, eq. 2.9 shows that $\delta_{CPT} = 0$, since the numerator would vanish. If both T - and CPT -invariance is assumed, CP -invariance would also follow.

Comparing equations 2.7 and 2.1 the previously defined ε_L has to be equal to $\varepsilon_T - \delta_{CPT}$. In the same manner, ε_S can be shown to be equal to $\varepsilon_T + \delta_{CPT}$. If CPT is not violated, $\varepsilon_S = \varepsilon_L = \varepsilon_T$.

Defining $\xi \equiv \langle K_S | K_L \rangle$ Theorem 2(iii) of [2, page 355] states that if CPT is not violated, ξ is real and if T is not violated then ξ is imaginary. Using eq. 2.6 and 2.7, $\xi \simeq 2\Re(\varepsilon_T) - 2i\Im(\delta_{CPT})$. Looking at the phase φ_{+-} of the measurable quantity

$$\eta_{+-} = \frac{\langle \pi^+ \pi^- | H_w | K_L \rangle}{\langle \pi^+ \pi^- | H_w | K_S \rangle} = |\eta_{+-}| e^{i\varphi_{+-}} \quad (2.10)$$

and applying unitarity one can show that

$$\eta_{+-} = \xi \frac{2i\Delta m + \gamma_S}{2\gamma_S} \quad (2.11)$$

If CPT -invariance holds, ξ is real and φ_{+-} is expected to be $(43,7 \pm 0,1)^\circ$, using eq. 2.11 and measured quantities [10]. If one instead assumes T -invariance, ξ is imaginary and $\varphi_{+-} = 43,7^\circ + 90^\circ$. Since φ_{+-} is measured to $(46,5 \pm 1,2)^\circ$ [10], the observed CP -violation originates mainly from T -violation and not violation of CPT . Thus finding ξ real is a strong support for CPT -invariance, at least for $|\Im(\delta_{CPT})| \ll |\Re(\varepsilon_T)|$.

2.2 $K^0 - \bar{K}^0$ Interference

This section describes how the interference between K^0 and $\bar{K}^0$ is used to determine CP , T and CPT related quantities in the CPLEAR experiment. In the following, since $\gamma_L \ll \gamma_S$, γ_L has been neglected compared to γ_S , i.e. $\gamma_S \pm \gamma_L \simeq \gamma_S$. Solving eq. 2.6 and 2.7 for K^0 and $\bar{K}^0$ one obtains

$$\left. \begin{array}{l} |K^0(t)\rangle \\ |\bar{K}^0(t)\rangle \end{array} \right\} = \frac{1}{\sqrt{2}} [(1 \mp \varepsilon_L)|K_S(t)\rangle \pm (1 \mp \varepsilon_S)|K_L(t)\rangle] \quad (2.12)$$

where the upper sign is for K^0 . The time dependence of eq. 2.12 is given by eq. 2.4 and 2.5. This expression can be used in order to calculate interference effects for different final states of $K^0/\bar{K}^0$ decay. The following subsections describes the decays to 2π , 3π and $\pi l\nu$.

2.2.1 Decays to Two Pions

In the $K^0 \rightarrow 2\pi$ case, the two complex numbers η_{+-} (eq. 2.10) and η_{00} (defined similarly, using the $K_L \rightarrow \pi^0\pi^0$ over $K_S \rightarrow \pi^0\pi^0$ ratio instead) can be measured, by solving for the rates (neglecting $\Im(\delta_{CPT})$)

$$\begin{aligned} & \left. \begin{array}{l} R(K^0 \rightarrow f) = |\langle f|H_w|K^0\rangle|^2 \\ R(\bar{K}^0 \rightarrow f) = |\langle f|H_w|\bar{K}^0\rangle|^2 \end{array} \right\} = \\ & = \frac{|\langle f|H_w|K_S\rangle|^2}{2} \left[(1 \mp 2\Re(\varepsilon_L))e^{-\gamma_S t} + (1 \mp 2\Re(\varepsilon_S))|\eta_f|^2 e^{-\gamma_L t} \pm \right. \\ & \quad \left. \pm 2(1 \mp 2\Re(\varepsilon_T))|\eta_f|e^{-\gamma_S t/2} \cos(\Delta m t - \varphi_f) \right] \quad (2.13) \end{aligned}$$

with $|f\rangle$ being either $|\pi^+\pi^-\rangle$ or $|\pi^0\pi^0\rangle$. These rates are shown in Fig. 2.1 for K^0 and $\bar{K}^0$ separately in the case $|f\rangle = |\pi^+\pi^-\rangle$, using data taken with the CPLEAR detector during 1990 and 1991 and correcting for acceptance [12, 13]. Note that the sum of the two rates is independent of δ_{CPT} . Taking the difference of rates, the acceptance correction is not necessary since it cancels in the asymmetry

$$\begin{aligned}
 A_f(t) &= \frac{R(\bar{K}^0 \rightarrow f) - R(K^0 \rightarrow f)}{R(\bar{K}^0 \rightarrow f) + R(K^0 \rightarrow f)} \simeq \\
 &\simeq 2\Re(\varepsilon_T) - 2\Re(\delta_{CPT}) \frac{1 - |\eta_f|^2 e^{\gamma_{st}}}{1 + |\eta_f|^2 e^{\gamma_{st}}} - \frac{2|\eta_f| e^{\gamma_{st}/2} \cos(\Delta mt - \varphi_f)}{1 + |\eta_f|^2 e^{\gamma_{st}}} = \\
 &= \left\{ \begin{array}{c} \text{Assuming } CPT \\ \delta_{CPT} = 0 \end{array} \right\} = 2\Re(\varepsilon_T) - \frac{2|\eta_f| e^{\gamma_{st}/2} \cos(\Delta mt - \varphi_f)}{1 + |\eta_f|^2 e^{\gamma_{st}}}.
 \end{aligned} \tag{2.14}$$

However, the decay rates need to be normalized due to the different interactions of K^+ and K^- in the detector. The normalization factor $\alpha = N_{K^+}/N_{K^-}$ is determined to $1,14 \pm 0,01$. The asymmetry A_{+-} is shown in Fig. 2.2. From this, $|\eta_{+-}|$ and φ_{+-} have been fitted, giving $|\eta_{+-}| = (2,30 \pm 0,10_{stat} \pm 0,04_{syst})10^{-3}$ and $\varphi_{+-} = (44,9 \pm 2,5_{stat} \pm 0,5_{syst})^\circ$ [13]. The main systematic errors come from regeneration effects and the three body background at long life-times. Including data yet to be taken during 1993 the statistical errors are expected to go down to $0,045 \cdot 10^{-3}$ on $|\eta_{+-}|$ and $0,9^\circ$ on φ_{+-} .

The analysis for the final state $|\pi^0\pi^0\rangle$ using data taken during 1992 has not yet been completed. Identification of $K^\pm\pi^\mp$ together with 4γ has been done and preliminary studies show that using 1992–1993 data the statistical error on φ_{00} will be about 3° . This final state is treated in more detail in [14].

2.2.2 Decays to Three Pions

The state $|\pi^+\pi^-\pi^0\rangle$ is not a pure CP -eigenstate, there is both a CP -odd and a CP -even part. The K_L decay to $\pi^+\pi^-\pi^0$ is almost exclusively CP -conserving. In the K_S case, neither the conserving nor the violating part has been observed. The reason for the two parts is that $CP|\pi^+\pi^-\pi^0\rangle = (-1)^{l+1}|\pi^+\pi^-\pi^0\rangle$ where l is the angular momentum between the $\pi^+\pi^-$ pair and the π^0 . Depending on the value of l the CP quantum number is even or odd. This would infer a Dalitz plot analysis, but if $K_S \rightarrow$

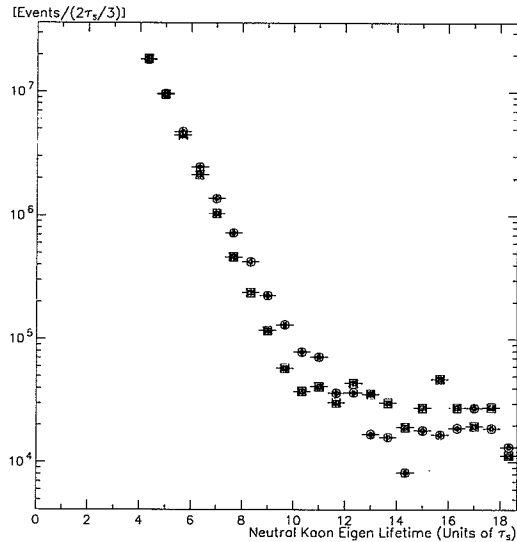


Figure 2.1: Decay rates of K^0 (squares) and $\bar{K}^0$ (circles) to $\pi^+\pi^-$, corrected for the detector acceptance, from [11]. The rates are defined in eq. 2.13.

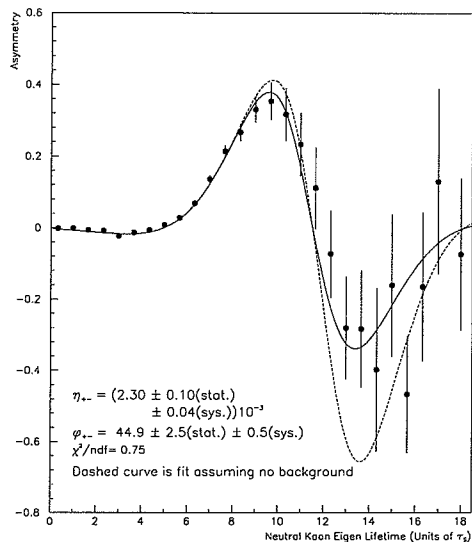


Figure 2.2: The asymmetry A_{+-} , defined in eq. 2.14.

$\pi^+\pi^-\pi^0$ is detected all over phase space one can extract the CP -violating parameter

$$\eta_{+-0} = \frac{\langle \pi^+\pi^-\pi^0 | H_w | K_S \rangle}{\langle \pi^+\pi^-\pi^0 | H_w | K_L \rangle}$$

where the pions are in a CP -odd state.

One experimental problem is that the acceptance in the low lifetime region is small. The region where the asymmetry varies rapidly is for $\Re(\eta_{+-0})$ below $2\tau_S$ and for $\Im(\eta_{+-0})$ $2-6\tau_S$. See [15] for a complete description of the phenomenology of this decay channel.

Already using 1992 data an upper limit on $|\eta_{+-0}|$ at 90% C.L. of 0,06 is found [16], including only statistical uncertainties. This is to be compared with the published upper limit of 0,35 [10]. However, it is necessary to do a careful study of the systematics involved, since the CP -violating part depends on the normalization. For the CP -conserving part it is also necessary to do an acceptance study over the full Dalitz plot. Including data taken during 1993 it is estimated that a determination of both the CP -violating and the CP -conserving decay of $K_S \rightarrow \pi^+\pi^-\pi^0$ will be possible.

The $3\pi^0$ state is a pure CP -eigenstate. Any observation of $K_S \rightarrow 3\pi^0$ would directly imply CP -violation. However, because of the difficult event topology (detecting 6γ) a determination of CP -violation in this channel will probably not be possible.

2.2.3 Semileptonic Asymmetries

The semileptonic decays of neutral kaons can be written as $K^0(\bar{K}^0) \rightarrow \pi^\pm l^\mp \bar{\nu}_l(\nu_l)$ where $l^\pm$ denotes either $e^\pm$ or $\mu^\pm$. In these decays one can define for the hadrons $\Delta S = S_f - S_i$ and $\Delta Q = Q_f - Q_i$ where the subscripts f and i stand for final and initial, respectively. The $\Delta S = \Delta Q$ rule allows the decays

$$\begin{aligned} K^0 &\rightarrow \pi^- l^+ \nu_l \\ \bar{K}^0 &\rightarrow \pi^+ l^- \bar{\nu}_l \end{aligned}$$

whereas the other two with $\Delta S = -\Delta Q$

$$K^0 \rightarrow \pi^+ l^- \bar{\nu}_l$$

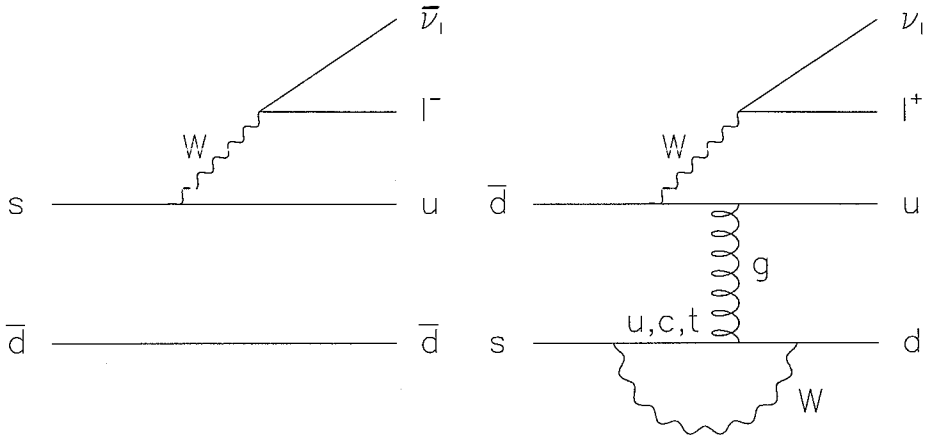


Figure 2.3: Examples of Feynman diagrams for the semileptonic decays of neutral kaons. The left diagram corresponds to a $\Delta S = \Delta Q$ transition and the right one gives $\Delta S = -\Delta Q$ [17].

$$\bar{K}^0 \rightarrow \pi^- l^+ \nu_l$$

are forbidden. This can be understood in the Standard Model by looking at the Feynman diagrams involved, Fig. 2.3, where the $\Delta S = -\Delta Q$ diagram will be very much suppressed. Defining the allowed amplitude:

$$f_{\pm s} = \langle \pi^- l_{\pm s}^+ \nu_l | H_w | K^0 \rangle$$

where the subscript $\pm s$ stands for the two possible spin-orientations of the lepton and using $CPT|\pi^\pm\rangle = |\pi^\mp\rangle$, $CPT|l_s^\pm\rangle = |l_{-s}^\mp\rangle$ and $CPT|\nu_l(\bar{\nu}_l)\rangle = |\bar{\nu}_l(\nu_l)\rangle$ the other allowed decay can be written

$$\bar{f}_{\mp s} = \langle \pi^+ l_{\mp s}^- \bar{\nu}_l | H_w | \bar{K}^0 \rangle$$

Similarly, one can define the two forbidden amplitudes as

$$\begin{aligned} g_{\mp s} &= \langle \pi^+ l_{\mp s}^- \bar{\nu}_l | H_w | K^0 \rangle \\ \bar{g}_{\pm s} &= \langle \pi^- l_{\pm s}^+ \nu_l | H_w | \bar{K}^0 \rangle \end{aligned}$$

The different $f_{\pm s}$, $\bar{f}_{\pm s}$, $g_{\pm s}$ and $\bar{g}_{\pm s}$ are the so-called form factors.

If $l = e$ four of the eight form factors have vanishing contributions to the decay rates because of the smallness of the electron mass. For simplicity, the following treatment deals only with this case. In the general

case, an extra complex quantity enters but since in the CPLEAR experiment, we can only identify the electron channel of the semileptonic case, there is no possibility to determine it. Some of our detected semileptonic events will indeed have a $\mu^\pm$ instead of an $e^\pm$, see Section 5.1.2 and 7.2. Since this only happens in about 5% of the events it is assumed that any difference in the form factors for decays into muons and electrons is negligible.

Under this assumption and assuming that CPT is not violated in the decay we have $\bar{f}_{-s} = f_{+s}^*$ and $\bar{g}_{+s} = g_{-s}^*$, making life much more simple. Dropping the subscript, one can define a quantity x as a measure of the violation of the $\Delta S = \Delta Q$ rule as

$$x = \frac{g^*}{f}.$$

If the $\Delta S = \Delta Q$ rule holds ($x = 0$), in order for the K^0 to decay to a negative lepton it has to oscillate to a $\bar{K}^0$, thereby making it possible to measure T -violation. The semileptonic decay rates of neutral kaons can be calculated using the rates defined in eq. 2.12. R_+ denotes the decay rate of K^0 to a positron, $\bar{R}_-$ the $\bar{K}^0$ decay to an electron, etc.

$$\begin{aligned} R_+(\bar{R}_-) &\propto [1 + 2\Re(x) \pm 2\Re(\varepsilon_S) \mp 2\Re(\varepsilon_L)]e^{-\gamma_S t} + \\ &+ [1 - 2\Re(x) \mp 2\Re(\varepsilon_S) \pm 2\Re(\varepsilon_L)]e^{-\gamma_L t} + \\ &+ 2e^{-\gamma_S t/2} \cos(\Delta m t) + \\ &+ 4[\mp \Im(x) \mp \Im(\varepsilon_S) \pm \Im(\varepsilon_L)]e^{-\gamma_S t/2} \sin(\Delta m t) \quad (2.15) \end{aligned}$$

$$\begin{aligned} R_-(\bar{R}_+) &\propto [1 + 2\Re(x) \mp 2\Re(\varepsilon_S) \mp 2\Re(\varepsilon_L)]e^{-\gamma_S t} + \\ &+ [1 - 2\Re(x) \mp 2\Re(\varepsilon_S) \mp 2\Re(\varepsilon_L)]e^{-\gamma_L t} + \\ &+ 2[-1 \pm 2\Re(\varepsilon_S) \pm 2\Re(\varepsilon_L)]e^{-\gamma_S t/2} \cos(\Delta m t) + \\ &+ 4[\mp \Im(x)]e^{-\gamma_S t/2} \sin(\Delta m t) \quad (2.16) \end{aligned}$$

where the lower sign corresponds to the rate in parenthesis. These decay rates can be used to build various asymmetries that can be used to extract $\Delta m, \Re(x), \Im(x), \Re(\varepsilon_S)$ and $\Re(\varepsilon_T)$.

The asymmetry A_1

$$A_1(t) = \frac{R_+ + \bar{R}_- - (\bar{R}_+ + R_-)}{R_+ + \bar{R}_- + \bar{R}_+ + R_-} \simeq$$

$$\simeq \frac{2 \cos(\Delta m t) e^{-\gamma_S t/2}}{(1 + 2\Re(x))e^{-\gamma_S t} + (1 - 2\Re(x))e^{-\gamma_L t}} \quad (2.17)$$

is sensitive to the mass difference Δm and $\Re(x)$. The A_2 asymmetry

$$A_2(t) = \frac{\bar{R}_+ + \bar{R}_- - (R_+ + R_-)}{\bar{R}_+ + \bar{R}_- + R_+ + R_-} = \frac{N_2}{D_2} \quad (2.18)$$

where

$$\begin{aligned} N_2 &\simeq 2\Re(\varepsilon_L)e^{-\gamma_S t} + 2\Re(\varepsilon_S)e^{-\gamma_L t} + \\ &- 2[(\Re(\varepsilon_S) + \Re(\varepsilon_L))e^{-\gamma_S t/2} \cos(\Delta m t) + \\ &+ 2[\Im(\varepsilon_S) - \Im(\varepsilon_L) + 2\Im(x)]e^{-\gamma_S t/2} \sin(\Delta m t) \end{aligned}$$

and

$$D_2 \simeq (1 + 2\Re(x))e^{-\gamma_S t} + (1 - 2\Re(x))e^{-\gamma_L t}$$

can be used to measure $\Im(x)$ and $\Re(\varepsilon_S)$.

Setting $x = 0$ and forming the asymmetry $A_T(t)$

$$A_T(t) = \frac{\bar{R}_+ - R_-}{\bar{R}_+ + R_-} = 2\Re(\varepsilon_S) + 2\Re(\varepsilon_L) = 4\Re(\varepsilon_T) \quad (2.19)$$

$\Re(\varepsilon_T)$ can be directly determined. If a value different from zero is found, this would be a direct proof of T -violation.

In order to be able to measure these asymmetries, the relative acceptances for different particles need to be determined. The ratio $\alpha = N_{K^+}/N_{K^-}$ must be determined from data, and is greater than one due to different strong interactions of K^+ and K^- . Also, a determination of the ratio $\eta = P(e^-\pi^+)/P(e^+\pi^-)$, where $P(e^-\pi^+)$ is the probability to detect a $e^-\pi^+$ pair, is necessary and can be done by the use of the semileptonic decays themselves. One can show that

$$\eta = \frac{(\bar{N}_- + \alpha N_-)(1 + \delta)}{(\bar{N}_+ + \alpha N_+)(1 - \delta)}. \quad (2.20)$$

Here $\delta = (3,27 \pm 0,12)10^{-3}$ [10] is the measured K_L charge asymmetry, $R(K_L \rightarrow \pi^+ e^+ \nu) - R(K_L \rightarrow \pi^- e^- \bar{\nu})$ over the sum. This asymmetry, measured at K_L life-times greater than $14\tau_S$ is equal to $2\Re(\varepsilon_L)$ if $x = 0$. The $\bar{N}_+$ etc. are the number of semileptonic events in the different channels and are related to the semileptonic rates defined previously through the

relations $\bar{R}_+ \propto \bar{N}_+/\alpha$, $\bar{R}_- \propto \bar{N}_-/\alpha\eta$, $R_+ \propto N_+$ and $R_- \propto N_-/\eta$. In order to stay compatible with the δ determination, eq. 2.20 is only used to determine η with semileptonic events in the 14–30 τ_S region, see Chapter seven.

Alternatively, both α and η can be determined in a model dependent way. If $x = 0$ the asymmetries

$$A_\alpha = \sqrt{\frac{\bar{R}_+ \bar{R}_-}{R_+ R_-}} = (1 - 4\Re(\varepsilon_T)) = \frac{1}{\alpha} \sqrt{\frac{\bar{N}_+ \bar{N}_-}{N_+ N_-}} \quad (2.21)$$

and

$$A_\eta = \sqrt{\frac{R_- \bar{R}_-}{R_+ \bar{R}_+}} = (1 + 4\Re(\varepsilon_T)) = \frac{1}{\eta} \sqrt{\frac{N_- \bar{N}_-}{N_+ \bar{N}_+}}. \quad (2.22)$$

These asymmetries are used in order to check the model independent methods, see Section 7.4.1.

Results for Δm , $\Re(x)$, $\Im(x)$, $\Re(\varepsilon_S)$ and $\Re(\varepsilon_T)$ are given in Chapter seven.

Chapter 3

Overview of the CPLEAR Experiment

3.1 Physics Requirements and General Layout

As stated previously, the detector must be able to identify and tag events with a neutral kaon from the reaction $p\bar{p} \rightarrow K^\pm \pi^\mp \bar{K}^0 (K^0)$. These so-called golden events have a total branching ratio of only 0,4% making background suppression very important. Also, the various asymmetries in $K^0/\bar{K}^0$ decays should be contained in the detector. One therefore puts the following physics requirements on the detector performance:

- Good detection efficiency for golden events, combined with a high efficiency of rejecting multi-pion final states.
- Sensitivity to reconstruct the decay vertex of the kaon, both neutral and charged modes to distances corresponding to at least $15\tau_S$.
- Little material in the central part of the detector in order to avoid regeneration effects which would smear out the asymmetries.
- High data taking rate and good trigger efficiency in order to get the high statistics needed for physics analysis. This includes hard wired processors in order to reconstruct the kinematics of the events on-line.

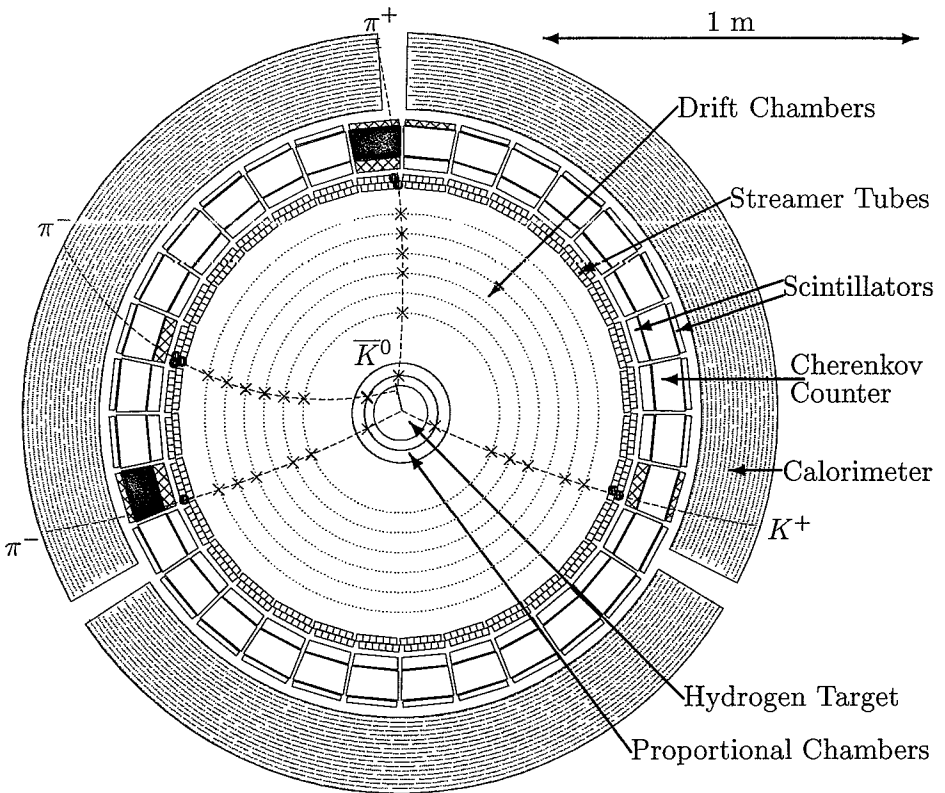


Figure 3.1: *Transverse view of the CPLEAR detector with a $\bar{K}^0 \rightarrow \pi^+\pi^-$ event.*

Furthermore, it should fit inside the existing DM2 magnet [18] used at Orsay, thus setting a limit on the radius of 1 m.

In order to accomplish this, the CPLEAR collaboration has developed and built the detector which is shown in Fig. 3.1 and Fig. 3.2. Fig. 3.3 shows a three-dimensional view defining the axes of the coordinate system. Starting at the centre, there is a gaseous hydrogen target surrounded by a set of proportional chambers and drift chambers in order to reconstruct and measure the momenta of charged tracks. Two layers of streamer tubes follow which give a fast z -measurement of the track and hence measure the momentum component parallel to the beam. A set of scintillators and Cherenkov counters, called the PID (for Particle Identification Detector), performs the $K^\pm/\pi^\pm$ -separation on-line as well as refined particle identification of $K^\pm, \pi^\pm, e^\pm$ off-line. The outermost detector is a calorimeter that measures electromagnetic showers. Energy

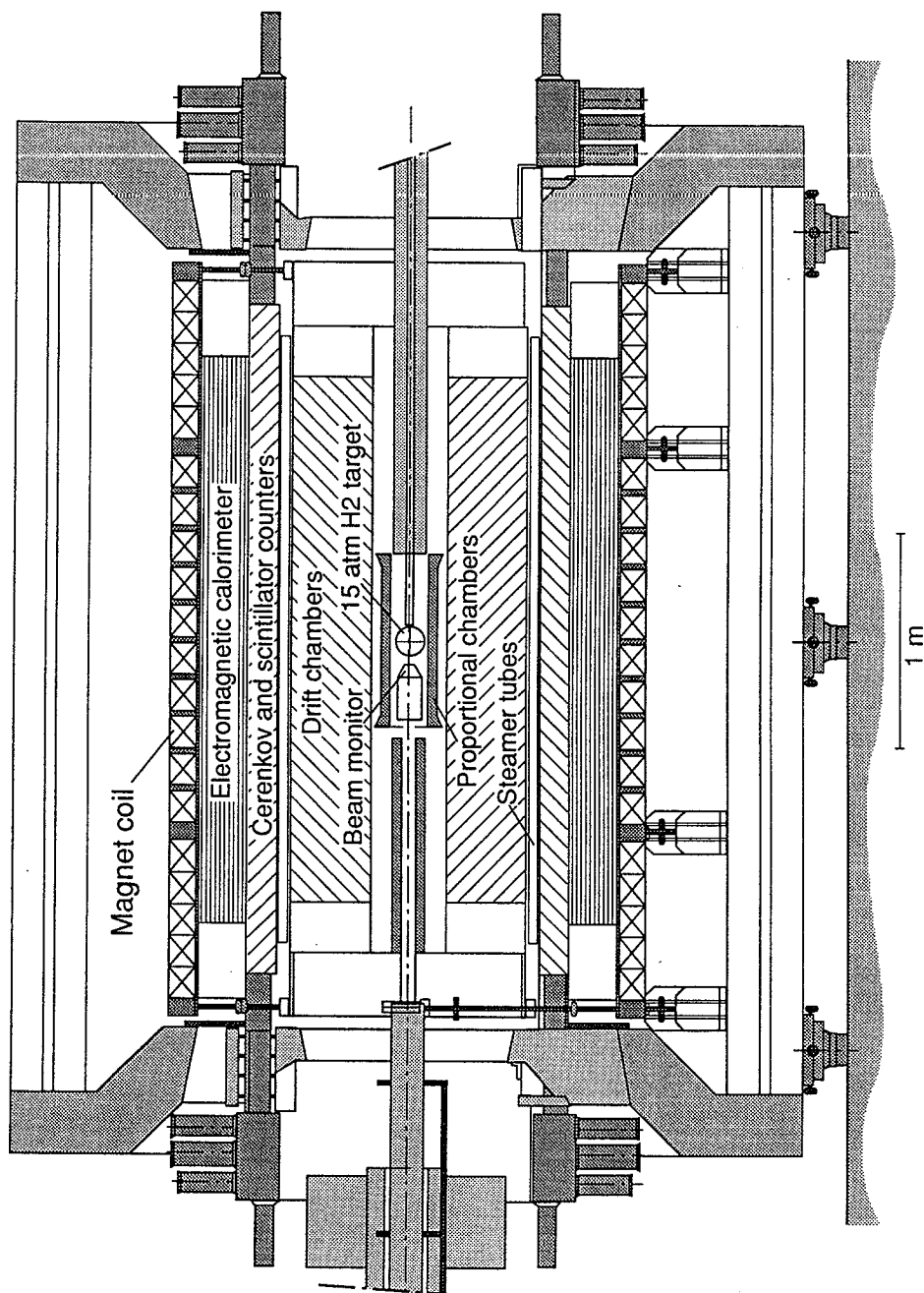


Figure 3.2: Side view of the CPLEAR detector.

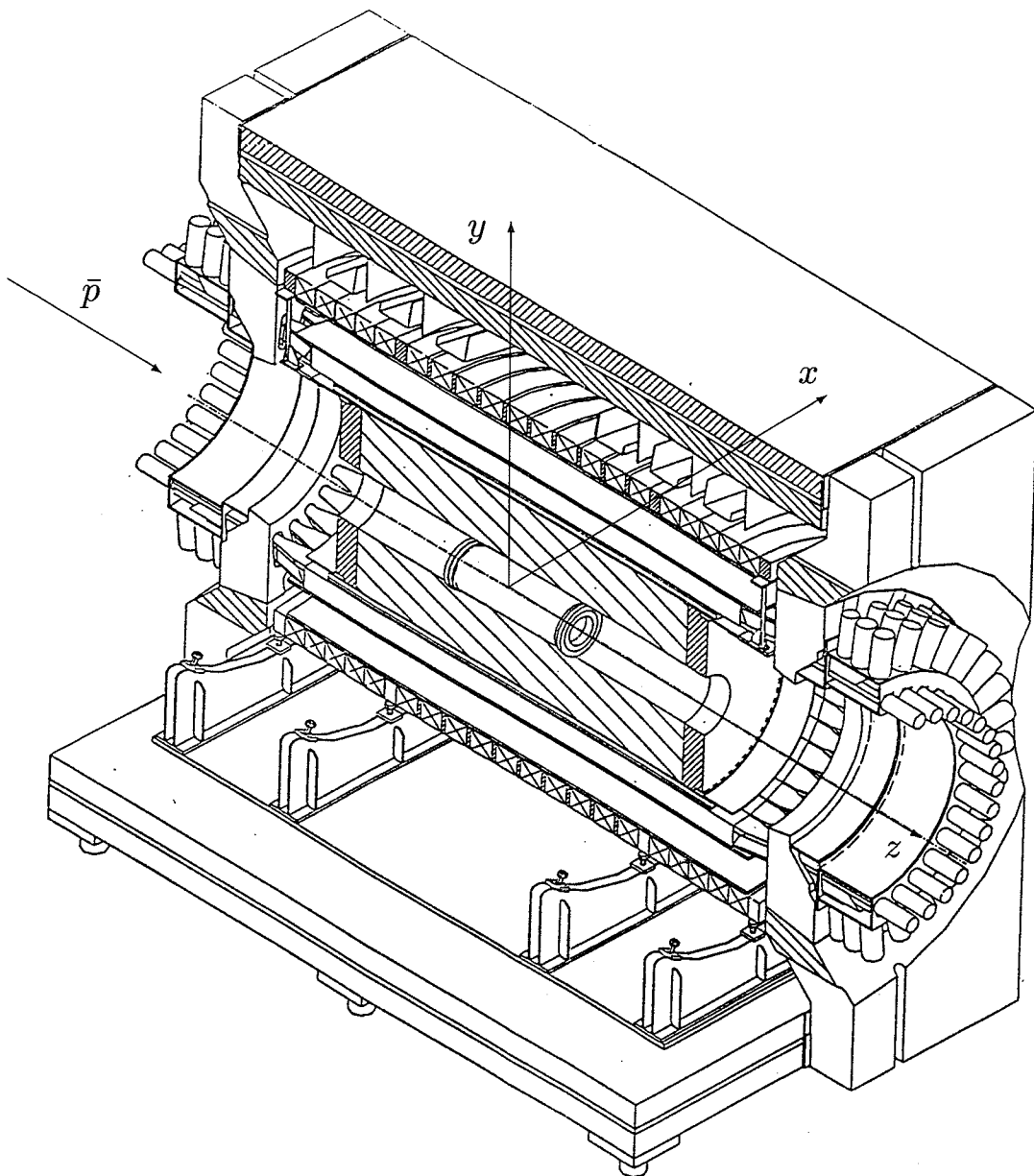


Figure 3.3: 3-D view of the CPLEAR detector defining the coordinate system.

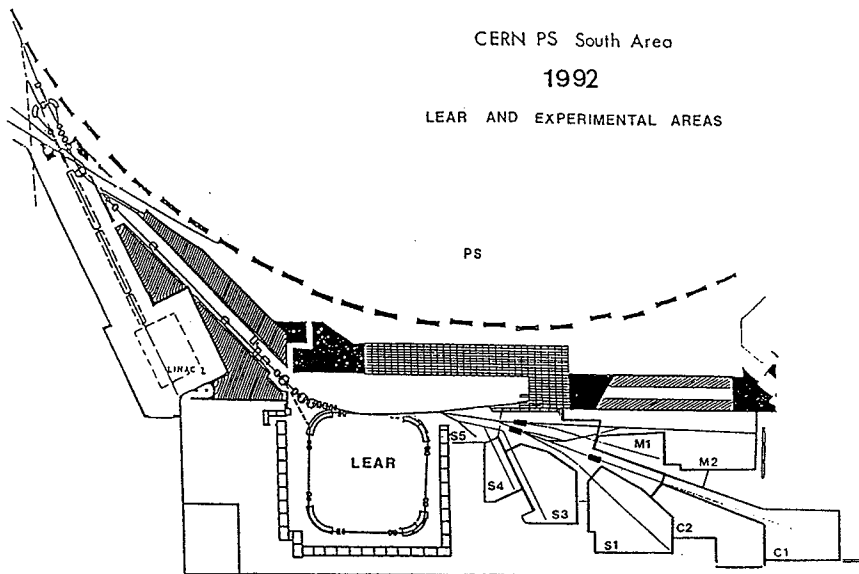


Figure 3.4: *LEAR with CPLEAR at the S1 beam-line.*

and impact position of photons from π^0 decays give a good reconstruction of the $K^0 \rightarrow \pi^0 \pi^0$ decay vertex. The calorimeter can also be used for separating $e^\pm$ from $\pi^\pm$ since the showers from these particles have quite different energy deposit patterns. The whole detector fits inside a magnet that gives a 0,44 T field parallel or antiparallel to the beam [18]. The polarity of the magnet is frequently changed (of the order of once per day) in order to minimize the detector systematic errors. The rest of this chapter describes the various sub-detectors in more detail.

3.2 The Beam Line and Target

The experiment uses the S1 beam line at LEAR, see Fig. 3.4. LEAR can deliver continuous low momentum antiproton beams with intensities up to 2 MHz and extremely narrow spread in momentum, $\Delta p/p \approx 10^{-3}$. Only the high intensities are of interest to us, since the 200 MeV/c antiprotons delivered by LEAR are slowed down with the help of degraders, so that

they stop and interact in the target. Thereby we achieve a well defined initial state of antiproton-proton annihilation at rest.

A spherical target with 7 cm radius made of 800 μm thick kevlar filled with H_2 gas at 15 atm was chosen to meet with the requirement of little material in order to avoid regeneration. Since the beam is stopped in the target there is no radiation hazard at the downstream end, which makes the detector partly accessible even during data taking. The beam enters the target via a 120 μm thick mylar window and is monitored by two Multi Wire Proportional Chambers and a small scintillator, called the Beam Monitor [19]. Each proportional chamber has only two anode wires 8 mm apart. Reading out the cathode strips measures the position of the beam to within 0,5 mm. The plastic scintillator is 7 mm in diameter and 1 mm thick and provides the start pulse for the experiment. It also gives an inhibit signal should two antiprotons arrive within 93 ns. It is read out by 192 plexiglass fibres to a photomultiplier tube. In between the two detectors there is a turnable beryllium degrader, that is used to adjust the stopping position in the target. The target and beam monitor has been developed at the Technical University of Delft, Holland [20]. A pictorial view of the target and beam monitor is given in Fig. 3.5.

The slowing down and annihilation of antiprotons is a complex process. The straggling in the target leads to the stopping distributions that are shown in Fig. 3.6. The r.m.s. spread in r is about 6 mm and the FWHM in z about 6 cm due to the relatively low pressure in the target. The spread in z corresponds to a difference in annihilation time of about 2,5 ns. This means that the global start of the experiment is not suitable for time-of-flight (TOF) measurements of particles. In order to use TOF one has to measure time differences between tracks, see Section 4.1.2.

3.3 Detecting Charged Tracks

The aim of the central part of the detector is to detect charged tracks and measure their momenta. Closest to the target there are two Multi Wire Proportional Chambers (PC1 and PC2), followed by six Drift Chambers (DC1-DC6) and two layers of Streamer Tubes (ST1 and ST2). These systems are described in more detail in the sections below.

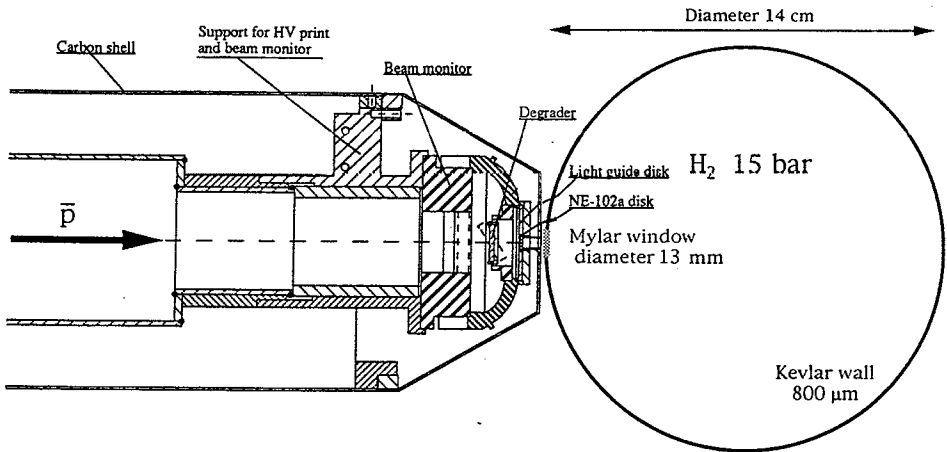


Figure 3.5: *The target and beam monitor.*

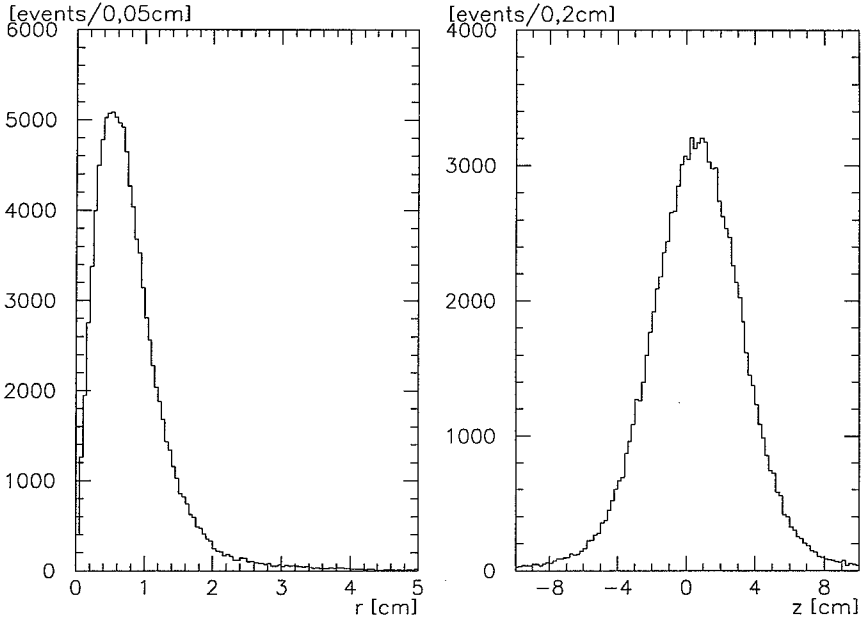


Figure 3.6: *Left is shown the transversal stopping distribution, right the stopping distribution parallel to the beam.*

Parameter	PC1	PC2
Inner radius [cm]	9,025	12,200
Outer radius [cm]	10,025	13,200
<i>Wires:</i>		
Radius [cm]	9,525	12,700
Number of wires	576	768
Covered solid angle [% of 4π]	96,5	94,0
Wire spacing [mm]	1,039	1,039
<i>Cathode strips:</i>		
Number of interior strips	246	310
Number of exterior strips	262	325
Width of strips [mm]	1,721	1,721
Angle between strips and wires	$\pm 19,47^\circ$	$\pm 27,89^\circ$

Table 3.1: *Geometrical parameters of the Multi Wire Proportional Chambers [21, page 32].*

3.3.1 The Multi Wire Proportional Chambers

For the development of the Multi Wire Proportional Chamber (MWPC), Georges Charpak was awarded the 1992 Nobel Prize for physics. The detector uses a set of wires and strips to determine points in space where charged particles have passed. It requires wires that are closely spaced, of the order of 1 mm. This makes it suitable for inner tracking detectors, where the radii are not too large which would necessitate many wires and readout channels. The MWPCs of our experiment (PC1, PC2) were constructed by PSI Villigen, and are described in detail in [21].

Apart from giving the first points on charged tracks for the momentum reconstruction, the PCs serve in the trigger, at the Intermediate Decision Logic (IDL) level. Tracks are flagged as originating from the centre of the detector if they have a hit in PC1 or PC2. By requiring two tracks without such a flag, i.e. coming from a vertex outside of PC2, one can increase the fraction of events where the K^0 has a lifetime greater than about $5\tau_S$, where the interesting region for most of the asymmetries starts. Furthermore, the strip information can be read out in order to provide the z -coordinate of the track off-line.

The geometrical properties of PC1 and PC2 are described in Table 3.1. A pictorial view is given in Fig. 3.7. The active length is 70 cm, thus covering 96,5% of solid angle for PC1 and 94% for PC2. Each PC has an

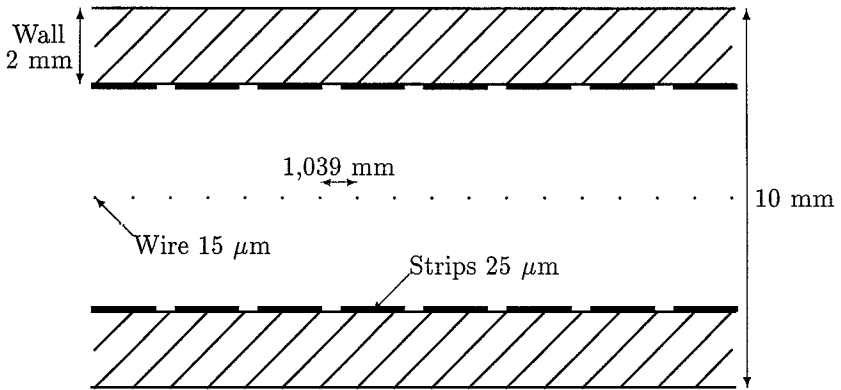


Figure 3.7: *Cross-sectional view of one of the proportional chambers. Note that even though depicted flat, the chamber geometry is actually cylindrical.*

active thickness of 6 mm with $15\ \mu\text{m}$ wires spaced 1,04 mm apart. The $25\ \mu\text{m}$ thick cathode strips are inclined an angle to the wire, in order to enable z -determination through strip readout. The gas mixture was chosen to be 79,5% argon for avalanche multiplication, 20,0% isobutane (C_4H_{10}) as a quenching gas and 0,5% freon (BrCF_3) for balancing the electron avalanches.

As it is important to avoid regeneration effects and photon conversions, care has been taken in the choice of material for the chambers. A self-supporting sandwich structure made of rohcacell and kapton is used, with each PC contributing to only $1,1 \cdot 10^{-3}$ of a radiation length.

The chambers are ideally operated at a high voltage of 2750 V. The high beam intensity, 1 MHz, makes it necessary to decrease the voltage to 2700 V in order to avoid disruptive discharges. This lowers the efficiencies of the chambers by about 1% to $(91,7 \pm 0,2)\%$ and $(92,2 \pm 0,2)\%$ for PC1 and PC2 respectively. As the IDL trigger function only asks for PC1 or PC2 combining the two independent efficiencies gives a total efficiency of 99,4% for this trigger. The spatial resolution at these operating conditions was found to be $(336 \pm 6)\ \mu\text{m}$ [21].

The wire signals are fed into a preamplifier-discriminator module developed at Saclay for the drift chamber readout [22]. Cluster processors, developed at PSI, sends the hit pattern to the trigger (IDL) within 150 ns

Drift Chamber	DC1	DC2	DC3	DC4	DC5	DC6
<i>Wires:</i>						
Radius [cm]	25,46	30,56	35,65	40,65	45,84	50,95
Number of doublets	160	192	224	256	288	320
Solid angle [% of 4π]	97,6	96,6	95,5	94,3	92,9	91,4
<i>Interior cathode:</i>						
Number of strips	275	324	378	424	465	510
Angle of strips	10,60°	13,06°	16,34°	20,06°	23,04°	25,40°
<i>Exterior cathode:</i>						
Number of strips	285	336	385	432	477	520
Angle of strips	-11,57°	-15,22°	-18,20°	-21,00°	-23,26°	-25,41°

Table 3.2: *Geometrical parameters of the Drift Chambers [22, page 75].*

and groups the information together for the Root Read Out (RRO, see Section 3.7). The strips were not completely equipped with readout electronics during 1992. Only 128 strips of PC1 were read out with ADCs and used for z reconstruction off-line. The evaluation of strip efficiency and precision is not yet completed.

3.3.2 The Drift Chambers

A Drift Chamber (DC) is a development of the MWPC where the spatial information is obtained by measuring the drift time of the electrons produced by ionization from a charged particle passing through the sensitive volume of the detector. This means that the wires can be fewer per unit length, in our case 1 cm apart instead of 1 mm. This reduces the number of channels to read out and also the material that the particles have to traverse. The CPLEAR drift chambers were developed at Saclay, Paris and are described in more detail in [22].

Using the drift chambers the momentum of a particle can be measured with a high degree of accuracy. A quick momentum test is also performed by an early level of the trigger, the p_T -cut (see Section 3.6.1), in order to improve the $K^\pm/\pi^\pm$ separation. The strip information of the chambers is read out so that the z -coordinate and thereby the z -component of the momentum can be obtained off-line.

The geometrical data of the drift chambers are given in Table 3.2. A pictorial view is given in Fig. 3.8. Each sense wire is actually a doublet,

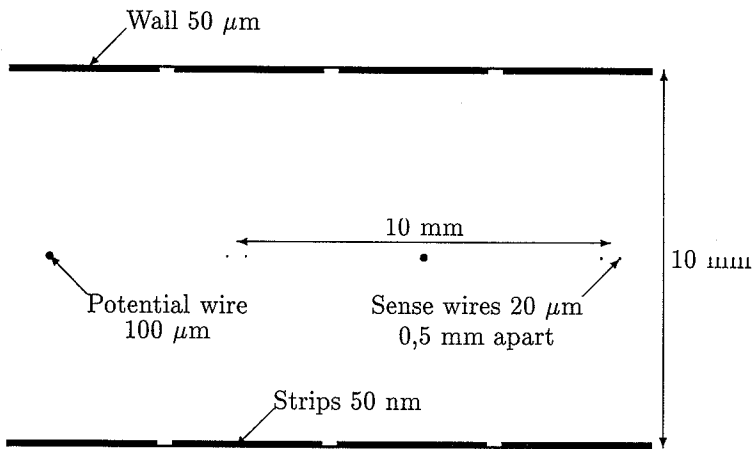


Figure 3.8: *Cross-sectional view of one of the drift chambers. Note that even though depicted flat, the chamber geometry is actually cylindrical.*

with two wires 0,5 mm apart in order to resolve left/right ambiguities during on-line reconstruction of the tracks. The doublets are separated by 1 cm, with a potential wire in between. The diameters are $20\ \mu\text{m}$ for the sense wires and $100\ \mu\text{m}$ for the potential wires. The strips are 50 nm thick gold layers deposited directly on the $50\ \mu\text{m}$ thick mylar walls. The angle of the strips to the wires is different for each chamber and varies between $\pm 25,4^\circ$ in order to make z reconstruction possible. Each drift chamber has an active thickness of 1 cm and an active length of 2,3 m. This means that the outermost chamber DC6 covers 91,4% of the solid angle.

The gas mixture chosen is an equal mixture of argon and ethane (C_2H_6). Isobutane could not be used since it would cause problems in a high-flux drift chamber, as this molecule breaks up and the purity and stability of the gas is very important for the drift times of the chamber. The drift distances are modest in this chamber, yielding a maximum drift time of 120 ns. The chambers are mainly constructed by mylar and rohacell in order to avoid regeneration effects and gamma conversions. All in all, the six drift chambers are equivalent to only $6,9 \cdot 10^{-3}$ of a radiation length.

The high voltage would ideally be 2500 V for these chambers. The voltage used is lower, about 2300 V, in order to increase the lifetime of the chambers by avoiding discharges. This setting gives a mean detection

efficiency of 97% for the wires and 90% for the strips. The spatial resolution was determined to $\sigma_{r\phi} \approx 300\mu\text{m}$ and $\sigma_z \approx 2\text{ mm}$ [22]. This means that the momentum resolution is about 5% for a 300 MeV/c track.

The signals from the wire doublets are put through preamplifiers and discriminators. The wire nearest to the avalanche will have a negative signal and pass the discriminator, the other wire will have a positive signal. The signal is delayed using 50 m cable in order to await the decision of the EDL (Section 3.6.1), after which the drift time is measured using flash-TDCs. The wire hit map for the p_T -cut is given to the trigger within 300 ns. The signals from the strips are amplified and delayed with 70 m cable. After integration 8 channels are multiplexed and converted by an ADC within 50 μs . Zero suppression is performed on-line by only reading out the signals that pass a discriminator.

3.3.3 The Streamer Tubes

A Streamer Tube (ST) is basically a proportional counter operating in limited streamer mode. This is the region where the signal is constant regardless of the wire potential. Unlike the other tracking detectors of CPLEAR, each detector volume has only one wire in it. This means that a charged particle passing through will trigger an avalanche that is collected on the sense wire. The resolution of this system is much poorer but it is possible to extract the z -coordinate on-line of a track along the detector volume whereas for the other detectors this information is only available off-line. This information is used to calculate the z -momentum component of a track, assuming that it originates from the centre of the detector. The streamer tubes of our experiment were originally developed for the Delphi experiment [23] and their design was adapted by the Liverpool group in order to suite CPLEAR conditions. A full description is found in [24].

A pictorial view is given in Fig. 3.9. The system consists of two layers of 32 streamer tube planks, each made up of 6 tubes. One layer is displaced by half a tube relative to the other in order to minimize the geometrical inefficiencies. The active length of each tube is 252 cm with an active cross section of $1,65 \times 1,65\text{ cm}^2$. The wall is made of 0,5 mm thick aluminum. Each wire is 80 μm in diameter, placed at a radius of 58,2 and 60,0 cm for the two layers, respectively. The solid angle coverage is roughly 91%.

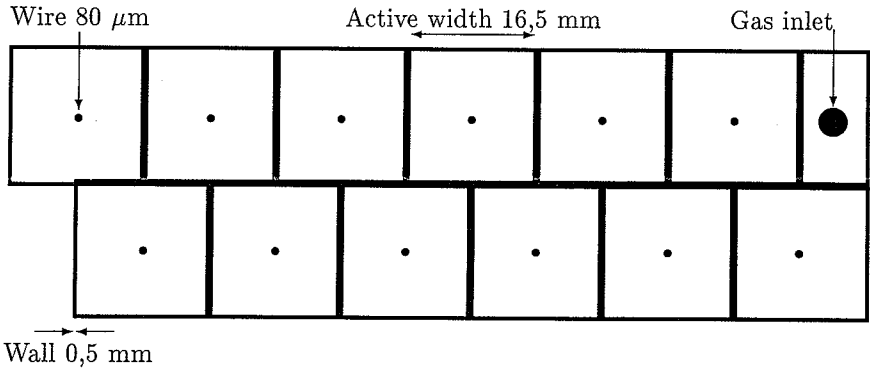


Figure 3.9: *Cross-sectional view of two streamer tube planks.*

Running conditions were optimized with a gas mixture of 50% argon, 46% isobutane and 4% methyl alcohol. A small amount of freon (0,008% $BrCF_3$) was added in order to prevent after-pulsing. With this mixture a high voltage setting of 4400 V and a discriminator threshold of 12 mV was chosen.

The z -coordinate along the wire is obtained by measuring the time difference between the arrival of the signal to the upstream and to the downstream end with a 8-bit TDC. The time resolution is equivalent to a z -resolution of about 2,2 cm per tube on-line. Three tubes are multiplexed together, so that the z information is only available for at most one of these tubes. The hit pattern of all tubes, however, is always available. This gives a resolution of 7,5 mm perpendicular to the tube. The efficiency in the central part of the tubes (around $z = 0$), where the majority of the tracks pass, is greater than 99% with an overall efficiency of about 98%.

3.4 Discriminating Between π - and K -mesons

As stated in the beginning of this chapter, the ability to tell kaons from pions is of vital importance to the experiment. Already at the first trigger level (EDL, Early Decision Logic) 110 ns after the arrival of an antiproton this has to be achieved. Cherenkov detectors provide a means of doing this. Particles that move in a medium with a velocity larger than the speed of light in that medium will produce Cherenkov radiation. Since

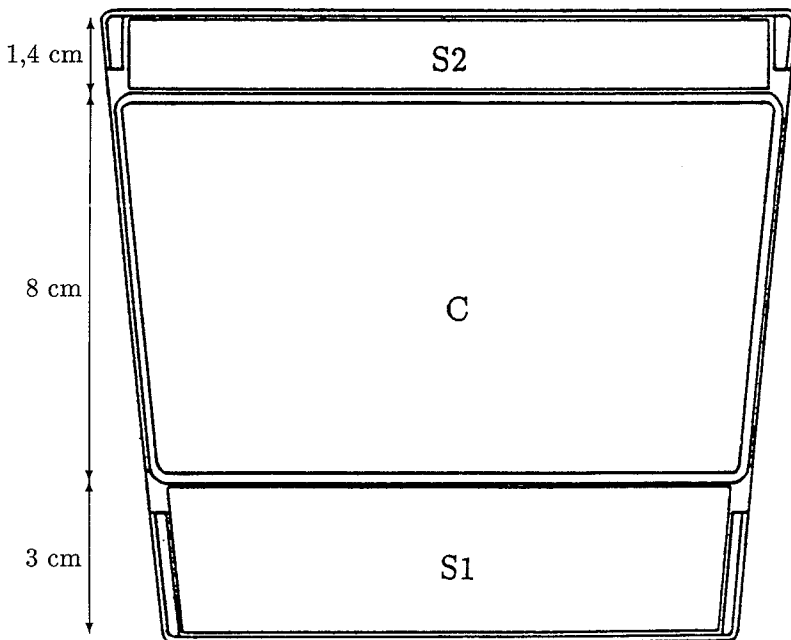


Figure 3.10: *Cross-sectional view of one PID sector.*

different particles, due to their different masses, will start to radiate at different momenta, choosing the refractive index with care will enable a threshold discrimination with this type of detector. In our case, a pion will give light whereas a kaon will not. To make sure that a particle traversed the detector a scintillator, slightly smaller, is placed on each side of the Cherenkov module. A kaon candidate is defined as having a $\overline{SCS}$ signature, that is a hit in the two scintillators but no hit in the corresponding Cherenkov counter.

Scintillators can also be used for particle identification. The energy loss of a particle can be measured and timing of the signals can be used for time-of-flight measurements. The development of the PID-system was a joint effort by the universities of Athens, Basel, Boston, Coimbra, Ioannina, Thessaloniki, and the institutes Democritos, ETH, CPPM-Marseille, MSI and CERN and is described in [25] and in greater detail in Chapter four of this thesis. Here is given a short introduction.

The candidate kaon track is subject to a cut on its transverse momentum to make sure that it is higher than the pion threshold momentum in the Cherenkov counter of about 180 MeV/c. This is called the p_T -cut, see Section 3.6.1. The PID information is also used at later stages of the

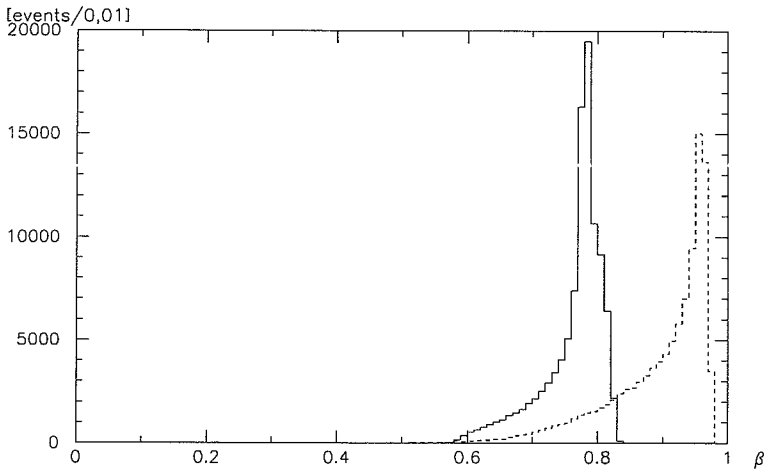


Figure 3.11: *The beta spectrum from MC golden events, kaons (solid line) and primary pions (dashed line).*

trigger. The energy loss in and the time-of-flight to the first scintillator are used as well as an improved Cherenkov pulse height analysis. The z -information from the streamer tubes (Section 3.3.3) is used to correct the measured Cherenkov pulse height which varies along the counter. Off-line, a separation between $\pi^\pm$ and $e^\pm$ is possible by combining the Cherenkov information with that of the inner scintillator.

The PID consists of 32 identical sectors, with an active length of 3,1 m. The inner radius of the PID is 62 cm and the outer is 76 cm, which means that the PID covers 90-93% of the solid angle. Each module occupies a separate slot in a 0,5 mm thick stainless steel structure, see Fig. 3.10 for a cross-sectional view of one PID module. The inner scintillator (S1) is 3 cm thick whereas the outer (S2) has a thickness of 1,4 cm. The reason that the S1 is thicker is that it is used for time-of-flight measurements that benefits from a higher light-output. The Cherenkov container is 8 cm thick with 2,5 mm thick walls. A light-guide about 1 m long is glued at each end in order to get the light pulses out of the detector to the photomultiplier tubes that are situated outside the magnet end-caps. For the scintillators, one PM is placed at each end whereas for the Cherenkov counters two are needed since the light output is much lower.

The active thickness of the Cherenkov box is 7,5 cm. Ideally, for an

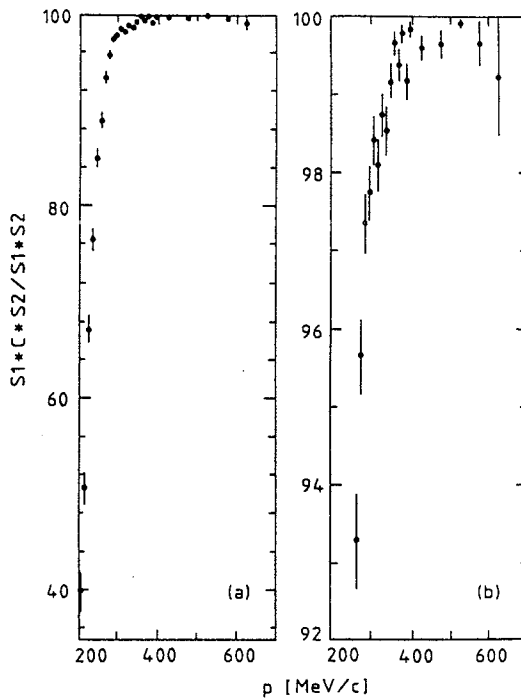


Figure 3.12: *Efficiency as a function of momentum for the $S\bar{C}S$ pion-veto trigger, from [25]. The left and right figures are the same but with a different scale.*

optimal kaon-pion separation in the 300 to 750 MeV/c range a Cherenkov radiator with a refractive index $n = 1,19$ should be used. This corresponds to a threshold for light production of $\beta = 0,84$, the maximum velocity of the charged kaon, see Fig. 3.11. No suitable materials with that low refractive index is available. A freon, FC72 (C_6F_{14}), with $n = 1,26$ was chosen instead. This corresponds to a threshold of $\beta = 0,79$, but taking the energy loss in the scintillator S1 into account an effective threshold of $\beta = 0,81$ is obtained. As can be seen from Fig. 3.11, this cuts only a few percent of the kaons from golden events.

The PID is equivalent to one half radiation length of material, which means that a photon stands a 30–40% chance to start showering there. This gives problems for the energy resolution of the calorimeter (see Section 3.5), but since the direction of the photon is conserved the position and direction determined by the calorimeter will not be much affected. There is no effect on the regeneration of K_S however, since the subsequent decay will not be detected anyway.

The signals coming from the Cherenkov photomultipliers are amplified and sent to discriminators for the trigger and flash-ADCs for refined pulse height analysis. The scintillator signals are treated in a similar way, but there is no need for an amplifier. Instead the signals are split passively, the S1 signal twice since it is sent to a flash-TDC as well as to a discriminator and flash-ADC, see Chapter four and Fig. 4.1 for more details.

The rejection efficiency of the threshold Cherenkov at the first trigger level, the $\overline{\text{SCS}}$ criteria is $(98,0 \pm 0,2)\%$ for pions with a momentum of 350 MeV/c rising to $(99,8 \pm 0,1)\%$ above 500 MeV/c, see Fig. 3.12. The efficiency of detecting a charged kaon in the first trigger level is 75%. The time-of-flight resolution is 0,18 ns per track, averaging over all scintillators.

Off-line analysis, using all possible PID information, gives the following performance of the sub-detector [25]:

At 350 MeV/c:	$\pi^\pm$	acceptance of	$4 \cdot 10^{-6}$	with a	$K^\pm$	efficiency of	60%
	$K^\pm$	"	$< 1 \cdot 10^{-6}$	"	$\pi^\pm$	"	90%
At 650 MeV/c:	$\pi^\pm$	"	$2 \cdot 10^{-4}$	"	$K^\pm$	"	40%
	$K^\pm$	"	$1 \cdot 10^{-3}$	"	$\pi^\pm$	"	40%

3.5 Detecting Neutral Particles

The neutral particles produced in the detector will normally not be seen by the tracking chambers. The neutral kaons that decay into $\pi^+\pi^-$ will be detected if the vertex lies inside the fourth drift chamber, DC4. But the ones that decay into channels containing a π^0 will have to be reconstructed with the help of the calorimeter. The π^0 immediately decays into two photons, with mean energy in the case of $K^0 \rightarrow 2\pi^0$ of only about 160 MeV. Reconstructing this decay vertex requires high spatial resolution of the photon conversion point ($\sigma \approx 5$ mm) and an energy resolution of $\sigma(E)/E \approx 20\%/\sqrt{E[\text{GeV}]}$. Also, good detection efficiency all the way down to gamma ray energies of 50 MeV is required. It was decided to build a gas-sampling calorimeter of high granularity consisting of layers of high-gain streamer tubes sandwiched between sheets of lead. The development of the calorimeter was shared between the universities of Basel, Fribourg and CERN and is described in [26, 27].

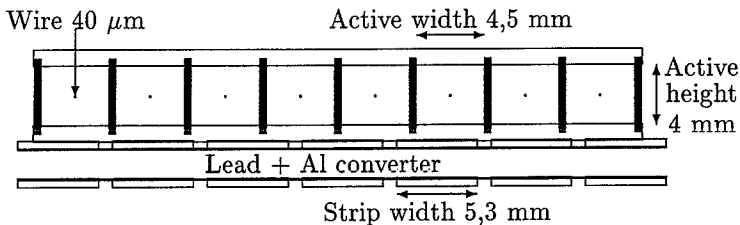


Figure 3.13: A calorimeter chamber with the converter plate in front of it.

A cross-sectional view of a building block is shown in Fig. 3.13. The space left for the calorimeter inside the magnet was only 22 cm. It was split in three identical sectors of 120° for mechanical reasons. It consists of 18 layers of altogether 6,2 radiation lengths giving a total active thickness of 21 cm. Each layer consists of a converter plate of 1,5 mm lead with 0,3 mm thick aluminum foils glued on each side, followed by cathode strips at an angle of $\pm 30^\circ$ and a width of 5,3 mm on each side of the streamer tubes. The tubes have a cross section of $4,5 \times 4,0 \text{ mm}^2$ with a $40 \mu\text{m}$ thick sense wire in the middle. Eight tubes form a chamber. The length of each chamber is 264 cm, giving a solid angle coverage of about 83%.

The gas used is a 33% pentane (C_5H_{12}) and 67% carbon dioxide mixture which, at a voltage of 3200 V, allows the wire signal to be read out without any amplification. The strip signal is amplified in order to give a similar signal to the one from the wires. All in all, the calorimeter consists of 17112 wires and 45936 strips, a total of 63048 channels which have to be read out digitally.

Looking at charged tracks with a momentum larger than 500 MeV/c that interacts in the first layer of the calorimeter, a resolution on the impact point of 3,3 mm in $r\phi$ and 7,1 mm in z is found [28]. The efficiency that a signal from a charged track is detected is better than 95% for the wires and 75-80% for the strips [14], with an average strip multiplicity of 1,3 per wire hit. Analysing data where $p\bar{p} \rightarrow \phi\pi^0$ a resolution on the opening angle of the two gammas coming from the π^0 of 7,5 mrad is found which corresponds to a spatial resolution of the impact point of 4,3 mm [28].

3.6 The Trigger System

The high data taking rate makes a sophisticated trigger system that reduces the data flow necessary. Signals from the various sub-detector systems are used in order to make decisions if an event should be kept or not. This has led to the development of dedicated Hard Wired Processors (HWP), for which Basel, CERN, Coimbra, Marseille and Orsay have been responsible. A detailed description can be found in [29] and [30].

The front end electronics (FE) of each sub-detector give signals to the hard wired processors that compute various quantities in order for the Trigger Control (TC) to make a decision. After each computation the event can be abandoned by sending a reset to the FE or the next trigger level can be launched. If all levels of the trigger are passed the TC issues a strobe to start read-out. The Spy monitors the behaviour of each trigger level and acts as an interface to the data acquisition system, see Section 3.7. The various trigger modules are summarized in Table 3.3. The object is to bring the 1 MHz beam rate down to a few hundred Hz, a rate that can be used to write data on tape without introducing a significant dead-time.

3.6.1 Hard Wired Processor 1

The HWP1 consists of the following logical steps, after which a decision can be made. The decision times and rate reduction factors for a trigger example are given in Table 3.3 and a summary of all trigger alternatives is found in Table 3.4.

EDL The Early Decision Logic takes signals from all 256 PID PM discriminators, see Section 4.1, available at the trigger 49 ns after the arrival of the beam counter signal. This information is used to count the number of $S\bar{C}S$, $N_{S\bar{C}S}$, where the two scintillators have fired in coincidence but the corresponding Cherenkov has not. A scintillator is considered to have fired if at least one of the two PMs has triggered the discriminator. For the Cherenkov at least two of the four PMs should have a signal above threshold. The charge multiplicity of the event, from the number of fired S1 modules, N_{S1} , is also counted.

Cut name	Cut description	Decision time	Reduction factor
EDL	$N_{\text{S}\bar{\text{C}}\text{S}}$ and $N_{\text{S}1}$ in the PID	115 ns	$4,06 \pm 0,05$
p_T -cut	p_T of $\text{S}\bar{\text{C}}\text{S}$ track	460 ns	$3,08 \pm 0,04$
IDL	Number of tracks	445 ns	$1,74 \pm 0,01$
C+R+K	Event topology, kinematics	$3,59 \mu\text{s}$	$2,68 \pm 0,04$
	<i>Total HWP1</i>	$4,61 \mu\text{s}$	59 ± 1
dE/dx	dE/dx in S1		$3,27 \pm 0,07$
TOF	TOF in S1		$1,54 \pm 0,03$
$N_{\text{ph.e.}}$	Cherenkov pulse height		$1,21 \pm 0,03$
	<i>Total HWP2</i>	$1,91 \mu\text{s}$	$6,1 \pm 0,2$
HWP2.5	Showers in calorimeter	$25,67 \mu\text{s}$	$2,7 \pm 0,2$
	<i>Total</i>	$32,11 \mu\text{s}$	974 ± 29

Table 3.3: *The various trigger processors, their decision times from [31], and rate reduction factors in run period 21, T607163323, from [32, 33]. All trigger steps are performed sequentially.*

- p_T -cut In order to minimize the number of slow pions with a $\text{S}\bar{\text{C}}\text{S}$ signature a cut on the transverse momentum is made. All $\text{S}\bar{\text{C}}\text{S}$ tracks are checked by looking at the wire hit in DC6 and, assuming that the track originates in the centre of the detector, looking at which wire was hit in DC1. A cut on p_T labeled 800, 400, 270 and 200 MeV/c can be made by demanding a hit in DC1 within $\pm 1, \pm 2, \pm 3$ or ± 4 wires around the wire in DC1 that corresponds to the one hit in DC6. The actual momentum cut is slightly lower and depends on the exact geometry of the chambers which has varied on a year to year basis.
- IDL The Intermediate Decision Logic makes sure that the number of hits on a track is sufficient to reconstruct it. It also counts and categorizes the tracks. It uses the OR of the hit maps from PC1 or PC2; DC1 or DC2, DC5 or DC6 together with the S1 and $\text{S}\bar{\text{C}}\text{S}$ hit maps. It defines the number of primary tracks, tracks with hits in the PCs, the total number of charged tracks and the number of kaon candidates, N_K , which are primary tracks with a $\text{S}\bar{\text{C}}\text{S}$ signature and p_T above the cut value.
- CONF Each IDL track is traced from S1 back to the detector centre, trying to find a hit in the next chamber. The search is based on hit

EDL		Kinematics	
0	Cosmics	0	Passive
1	Minimum bias; $N_{S1} \geq 1$	1	$p_K + p_\pi > 760\text{MeV}/c$
2	Passive	2	Missing mass $\approx m_{K^0}$
3	Golden; $N_{S1} \geq 2$ and $N_{\overline{S}CS} \geq 1$	3	(1) and (2)
p_T -cut		HWP2	
0	Passive	0	Passive
1	200 MeV/c	1	dE/dx
2	270 MeV/c	2	TOF
3	400 MeV/c	3	(1) and (2)
4	800 MeV/c	4	$N_{ph.e.}$
IDL		5	(1) and (4)
0	Passive	6	(2) and (4)
1	Passive	7	(1) and (6)
2	2-4 primary and $2 \oplus \geq 4$ tracks and $N_K \geq 1$	Invariant mass (not yet implemented)	
3	$(2pr \cdot 2-4tr) \oplus (3pr \cdot \geq 4tr) \oplus (4pr \cdot \geq 4tr) \cdot N_K \geq 1$		
4	2 primary and ≥ 4 tracks and $N_K \geq 1$	0	Passive
Configuration Module		1	Passive
0	Passive	2	1 Invariant mass
1	Passive	3	2 Invariant masses
2	2-4 primary and 2 or 4 tracks and $N_K \geq 1$	HWP2.5	
3	$(2pr \cdot 2-4tr) \oplus (3pr \cdot 4tr) \oplus (4pr \cdot 4tr) \cdot N_K \geq 1$	0	Passive
4	2 primary and ≥ 4 tracks and $N_K \geq 1$	n	$N_{sh} \geq n$
Register Control, kaon = ($N_K = 1$ or K^+K^-)			
0	Passive		
1	Passive		
2	2 primary and 2 tracks and kaon		
3	$(2pr \cdot 4tr) \oplus (2pr \cdot 3tr) \oplus (3pr \cdot 4tr)$ and kaon		
4	2 primary and 4tracks and kaon		
5	4 primary and 4tracks and kaon		
6	(2) or (3) or (5)		
7	(2) or (4) or (5)		
8	(3) or (5)		
9	(4) or (5)		

Table 3.4: Description of the trigger code, $\oplus$ stands for OR, $\cdot$ for AND.

maps of each detector, and if a hit is found the detailed detector data is acquired. Configuration modules translate the raw data signals to physical quantities using calibration constants and the streamer tube z measurement.

- RC** Primary tracks are parametrized making a simple fit to the data points and extracting three parameters that describe each track. The results are stored in a Register Control module and events with tracks that have not been successfully parametrized can be rejected. A check on the charge conservation of the primary tracks is also made.
- KIN** Using the results of the parametrization, kinematical quantities are calculated from the primary tracks. A cut on the missing mass of the primaries could be made, but is not implemented. Instead, a cut on the momentum sum of the primary $K^\pm\pi^\mp$ pair is made. This is the first check that a K^0 is present.

3.6.2 Hard Wired Processor 2

The Hard Wired Processor 2 (HWP2) performs a refined kaon and pion identification by using the PID information on the primary tracks. Three values are compared to the theoretically expected in order to confirm the primary $K^\pm\pi^\mp$ pair, using the z value and momentum parameters stored in the Register Control:

- $N_{ph.e.}$ The number of photo-electrons measured for the kaon candidate in the Cherenkov module.
- dE/dx The energy loss in the first scintillator for the primary kaon and pion. This introduces a momentum cut on the kaon at 350 MeV/c, see Section 4.1.1.
- TOF** The time-of-flight difference between the primary tracks.

3.6.3 Neutral Particle Triggering

Only one trigger level exists, the HWP2.5, that makes use of the calorimeter information, in order to increase the fraction of events where the K^0

has decayed to neutral final states. It only acts on events with 2 tracks, trying to veto events where the K^0 has decayed outside the fiducial volume of the detector. HWP2.5 finds the number of wire and strip clusters, and a cut on the number of neutral showers, N_{sh} , can be made. A crude calculation of the shower foot is made, based on the information of which calorimeter chamber has been hit.

After a positive HWP2.5 decision a general strobe is issued to start the read-out of the event.

3.6.4 Trigger Examples

During the years of completing the detector, the trigger has grown more and more sophisticated. Since the data analysed in this thesis comes from different years, the conditions under which they were taken were not always the same.

The most simple trigger is just asking for at least one S1 module hit and is denoted T1 and called minimum bias trigger. Naturally this saturates the data taking, and it is only used for calibration since the number of golden events is low.

The decision of each trigger module is added to the trigger code as a separate digit, with a higher number denoting stricter cuts. Much of the data presented here is taken with the T423 trigger, where the 3 stands for EDL golden decision, the 2 for a p_T -cut level of 270 MeV/c and the 4 stands for an IDL decision requiring 4 tracks, two primary and two secondary.

The number of different trigger levels is reflected in the growth of the trigger number. At the end of 1992 the trigger was often set to T605172223 or T607163323. Each digit corresponds to a cut level of a given trigger module, and the interested reader can deduce the meaning of these triggers from Table 3.4. Often, the magnet polarity is added to the trigger code, M1T1 would indicate minimum bias data taken with positive magnetic field, whereas M2T1 denotes the same trigger taken with reversed magnetic field.

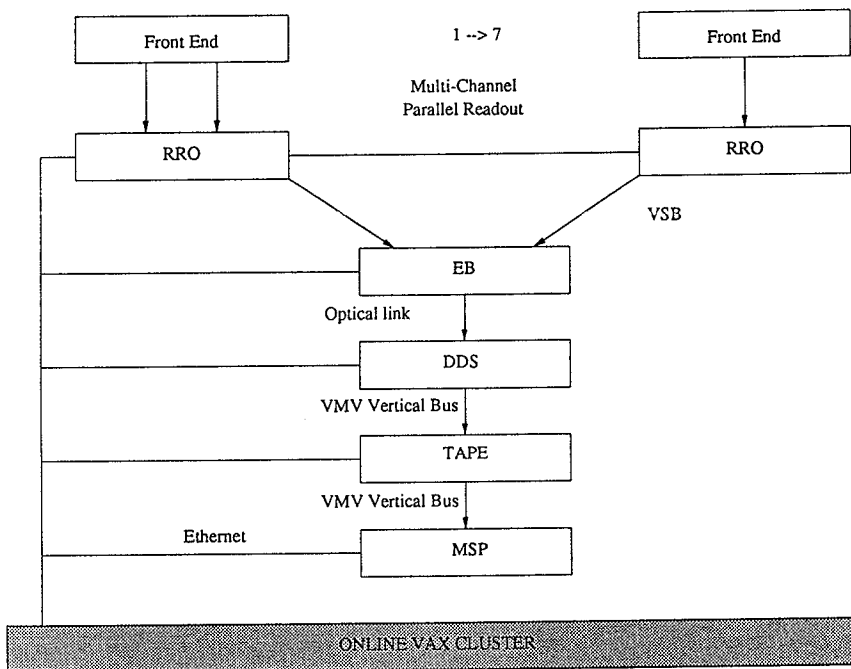


Figure 3.14: A pictorial view of the on-line system.

3.7 Data Acquisition

The CPLEAR Data Acquisition System (DAQ) is based on a Valet-plus design, which is a VME based microprocessor system, controlled from a local VAX-cluster. Fig. 3.14 and Refs. [29, 34] give an overview of the system. Each sub-detector is controlled by its own Valet-plus, called Root Read Out (RRO), where monitoring tasks can be run and changes to the front end electronics settings done in parallel with data taking. In this sense, the DAQ treats the trigger processors as just another detector sub-system with its own RRO. When the event has passed all trigger levels the data stored in each RRO is transferred to the Event Builder of the experiment, which is another Valet-plus where the separate pieces of information of an event are put together. The data is then transferred to the counting room via an optical link where three more Valets are used for on-line monitoring and tape writing. The Data Distribution System (DDS) Valet gives data to the Tape Valet and Model Spider Producer (MSP) Valet. The Tape Valet writes the data on IBM 3480 cartridges using a Summit STK4280 cassette tape drive, with two separate units in order to minimize time losses due to tape mounting. The MSP selects

events and transfers them to the VAX-cluster for monitoring.

The size of a complete event with HWP information is roughly 2,4 kbytes. The tape system is capable of writing 1000 events/s, but normally only a few hundred events/s are written. At the moment, the bottleneck in the system is the transfer time of the data from the front end to the event-builder, after a read-out strobe has been issued by the trigger control. The detector system which takes the longest to read out is the drift chambers, presently about 1 ms.

3.8 Slow Control

A Slow Control system has been developed that helps in checking the hardware of the detector during data taking [35]. It is running on the VAX-cluster and is based on three software packages written by the slow control team of the Aleph collaboration [36].

All the high voltages of the experiment are monitored by this system, along with many other quantities like temperatures, magnetic field etc. Reference values for all monitored quantities are read in from a data base on the VAX. Two tolerance values exist: warning and alarm level. When the warning level is reached by some quantity a message is shown on a screen in the control room together with a beep. The alarm can be set to inhibit data taking until the device giving the alarm is cured.

The slow control is also used for lowering the HV values at the end of each spill and to raise them again after the beam arrives. This is done in order to protect the chambers against spikes that can appear when the beam is switched on. Furthermore, discriminator levels of different detector front end electronics can be changed from the control room.

3.9 Data Processing

Since the first beam arrived to the experiment in 1989 we have written several thousands of tapes. In this thesis data collected in different years have been used. Since the detector in the beginning was incomplete, the

data from 1989 (run period 5, P5) is only used for calibration studies. P7 to P9 from 1990 has been used both for calibration and data analysis. During 1991 we had four runs, P10 to P13 giving a total of 3000 tapes of data with 220 million events. It was decided to write this thesis on these data sets.

During 1992 we had 75 days of data taking, P15 to P23. During P21, a two week run, a grand total of 2000 tapes were written. The large amount of data written in this experiment necessitates a system for data processing and filtering. Four different kinds of data tapes exist in the experiment, both for data and MC generated events.

- RAW Raw data tapes, with all the detector information.

- Pre-DST Pre-filtered tapes where the standard CPLEAR software [37, 38] has been run on the events. The cleaning of the sample results in writing about 5% [39] of the events on the Pre-DST. Apart from the RAW information the result of the Pattern Recognition program [37] is stored.

- DST Loose filtering is performed on Pre-DSTs writing also the result of the Track Fit program [37] on the output tape.

- Mini-DST In order to speed up data processing, the DSTs are filtered and a new format is written, the Mini-DST [40]. Here, only the fitted values of the tracks are stored, along with PID and calorimeter information in a processed form. Several DST tapes are fitted on one mini tape.

ZEBRA [41] is used as the format for data storage both of data and calibration constants. The CPLEAR Monte Carlo simulation CPGEANT [42] is based on the GEANT3 [43] simulation package, with the complete detector configuration taken into account. The known $p\bar{p}$ annihilation branching ratios are put in and the K_L decays are generated using a flat lifetime distribution. Following a Dalitz plot analysis [44], each MC event is given a weight depending on the phase space variables. No CP -violation is put into our Monte Carlo. In order to keep track of all tapes, FATMEN [45, 46] is used extensively for all tapes. It is anyway difficult to keep track of tapes!

Chapter 4

Particle Identification

This chapter describes the performance of the Particle Identification Detector (PID) in more detail. Section 4.1 describes the scintillators and the time-of-flight and dE/dx measurements. Section 4.2 describes the use of the Cherenkov detector. Section 4.3 discusses the various calibration systems, whereas Section 4.4 describes a method of calibrating the positions of the detector.

4.1 The Scintillators

The inner scintillator (S1) is 3,1 m long and 3 cm thick. It has a trapezoidal shape, see Fig. 3.10 with an inner and outer width of 11,2 and 11,8 cm respectively. The outer scintillator (S2) has a rectangular cross section, $1,4 \times 13 \text{ cm}^2$, with the same length. Both are slightly smaller than the Cherenkov module to ensure that a particle passed through the active volume of the Cherenkov. The S1 is made of BC 408 (Bicron Corporation) and was developed by the Boston group whereas S2 is made of NE 102 (Nuclear Enterprise) by the Greek universities. The roughly 1 m long light guides that were manufactured by the Coimbra group are made of polymethyl methacrylate (PMMA), and guide the light out of the magnet end-caps to the photomultipliers. For the scintillators, one PM is sitting at each end, XP4222B and XP2232B for the S1 and S2, respectively.

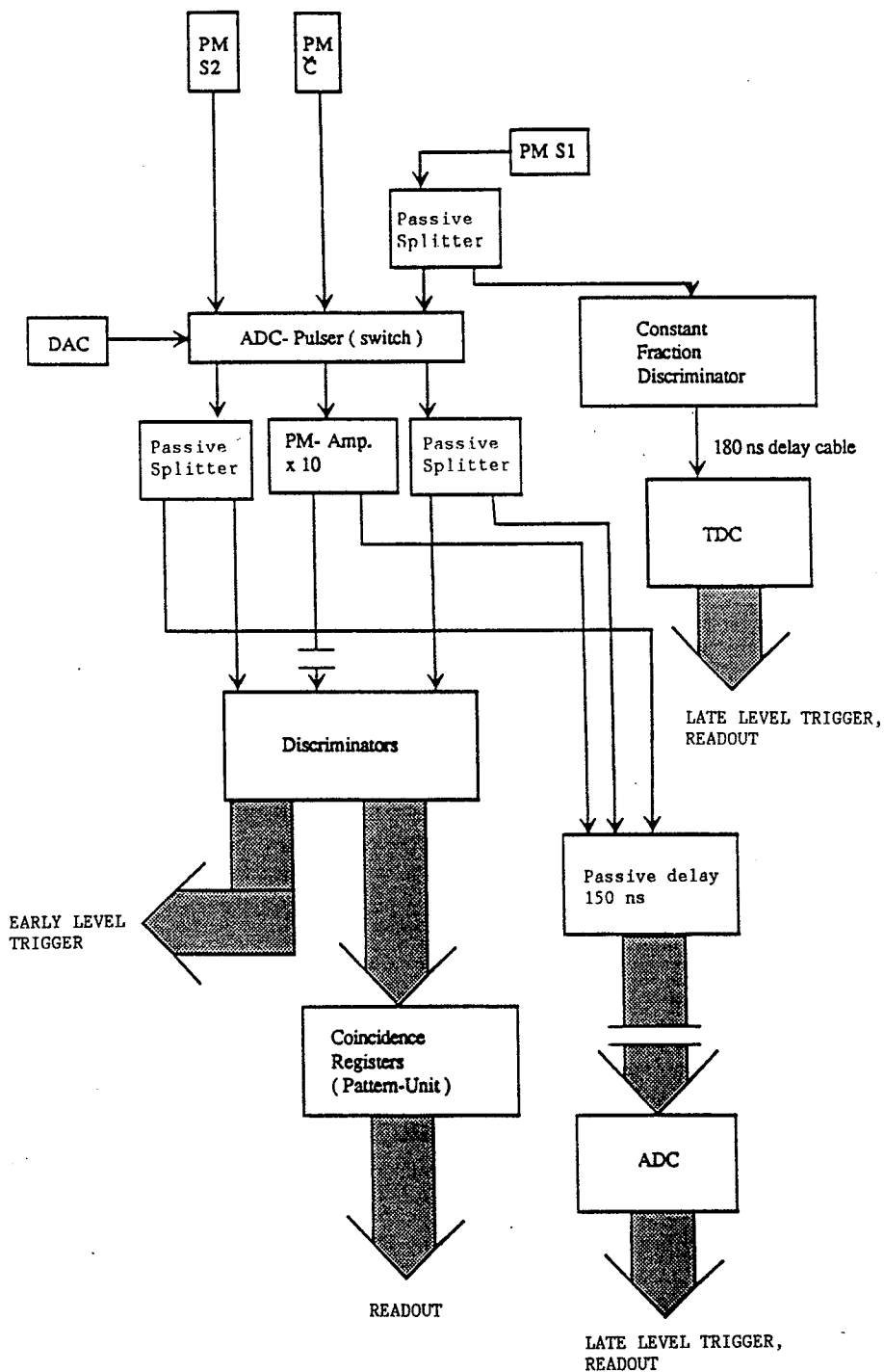


Figure 4.1: *PID read-out electronics. The early level trigger is the EDL described in Section 3.6.1 and the late level trigger is the HWP2, see Section 3.6.2.*

As stated before, the inner scintillator (S1) performs several tasks. Apart from giving the first multiplicity trigger of the event, the energy loss and time-of-flight of a particle passing through it is measured. The light collected by the PM-tube is first split by a passive splitter, see Fig. 4.1. Part of the signal is sent to a Constant Fraction Discriminator (CFD, Phillips 715), delayed 180 ns and, if the event is to be further processed, converted in $1.2 \mu\text{s}$ by a flash-TDC, developed at Boston. This information is used in HWP2 (Section 3.6.2) and sent to the event-builder of the experiment. The performance of the TOF-system is described in Section 4.1.2 below.

The second branch of the signal contains yet another passive splitter, that sends the signal to a discriminator (LeCroy 4413) and to a flash-ADC, developed by MSI and Swierk [47]. The discriminator has two outputs, one which is used for the EDL trigger, that checks the multiplicity and the presence of a $\overline{\text{SCS}}$ candidate in the event. This is done within 115 ns. The other output is sent to coincidence registers (pattern units, LeCroy 4448) to be sent to the event-builder. The flash-ADC branch is delayed 150 ns before conversion starts, something that is finished in 400 ns. The flash-ADC has an accuracy of 8 bits and the flash-TDC provides 10 bit accuracy with a 70 ns full scale.

The outer scintillator (S2) contributes to the EDL trigger by making sure that the trigger kaon candidate has passed through the Cherenkov module. But reading out the ADC signal makes it possible to measure the energy loss in this module as well. The signals from S2 are processed in a similar way to the ones from S1, see Fig. 4.1. Here, however, there is no need to split the signals for a TDC branch. Only the splitting between the discriminator and flash-ADC is performed. The discriminator signal goes to the trigger and to the pattern units. The ADC signal is delayed and converted if desired. ADC and pattern unit information are communicated to the event-builder.

4.1.1 Determining Energy Loss

Typical ADC spectra are shown in Fig. 4.2. The scintillator discriminator level corresponds roughly to the bottom of the valley between the pedestal and minimum-ionizing peak, as shown by the hatched areas. The ADC information of S1 was originally intended for pulse height corrections to

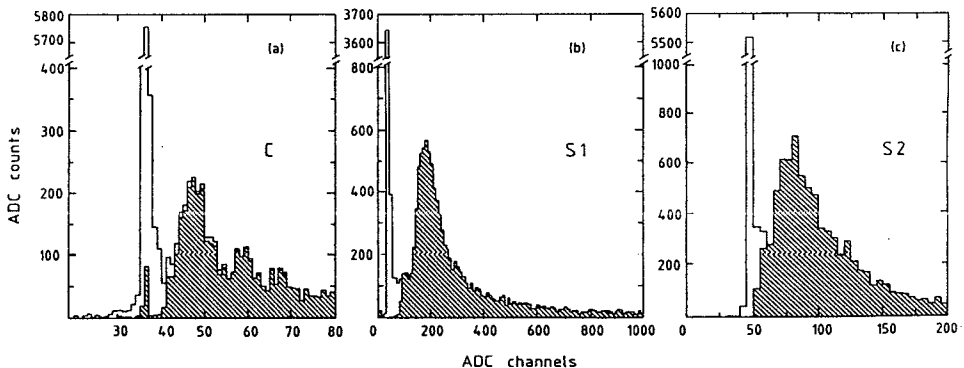


Figure 4.2: Typical PID ADC spectra, with pedestal. a) shows Cherenkov, b) Scintillator 1, c) Scintillator 2 spectra. The hatched areas are the signals that pass the discriminator cut for the trigger.

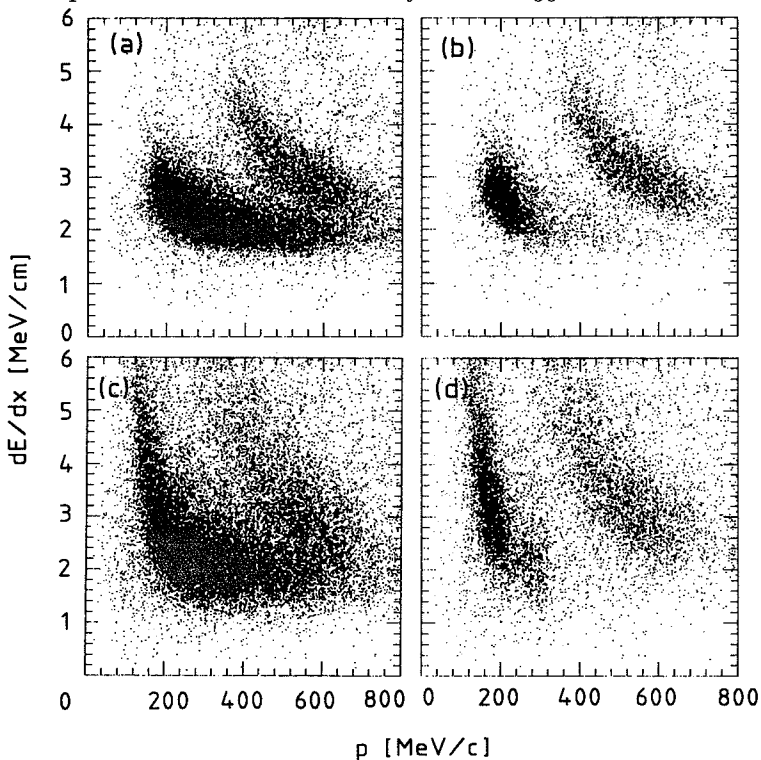


Figure 4.3: Scatter plot of the energy loss in the scintillators as a function of momentum, a) and b) for S1, c) and d) for S2. The upper band comes from kaons, the lower from pions with a) and c) showing all tracks from events with a kaon trigger (T_{433}), b) and d) only the track with a $S\bar{C}S$ signature. The momentum in S2 has been corrected for the energy loss in the PID.

the TDC signal. This has been shown to be unnecessary, see [48] and Section 4.1.2. The signal from both scintillators can also be used for particle identification, by measuring the energy loss (dE/dx) a particle suffers when passing through. This is shown in Fig. 4.3 where dE/dx is plotted as a function of momentum. One can clearly see the pion (lower) and kaon (upper) bands well separated up to 650 MeV/c. Also, the effect of the p_T cut is shown. By demanding that the kaon candidate has $p_T > 300$ MeV/c most of the low momentum pions are cut away. The reason that there are no kaons with momentum less than 350 MeV/c in Fig. 4.3 is that this is needed in order to reach S2. For S2 the separation between pions and kaons is increased by the energy loss the particles suffers when passing the Cherenkov, but since S2 is thinner the light output is lower and this advantage countermanded. This means that the particle identification in S2 is less efficient than the one in S1 but it is an independent complement.

The shapes of the pion and kaon distributions have been obtained by fitting Fig. 4.3 in narrow slices of momentum to Gauss functions [49]. The information on how many standard deviations a particle is away from being a pion or a kaon is then made available by a subroutine off-line. This information is also available to the trigger (see section 3.6.2) in the form of look-up tables in order to make a decision possible on-line.

4.1.2 Measuring Time of Flight

Since each S1 counter is equipped with a photomultiplier at each end, the time-of-flight (TOF) of a track can be measured by measuring the arrival times of the light pulses to the PMs and taking the average. In principle, this can be used together with the momentum of the track in order to calculate the mass of the particle. However, since the annihilation time of the event is only known with a r.m.s. spread of 0,8 ns (see Section 5.2), which is of the same magnitude as the time-of-flight of a particle to S1, this can not be used for particle identification. A different method that makes use of the full event topology has been tested, and is reported in Section 5.2. The normal way of using TOF in the CPLEAR experiment is to take the time difference between two tracks, where the annihilation time cancels. Here follows an evaluation of the pulse height effect on the TOF measured. This is a summary of [48].

The pulse height effect is caused by the triggering system of a discrim-

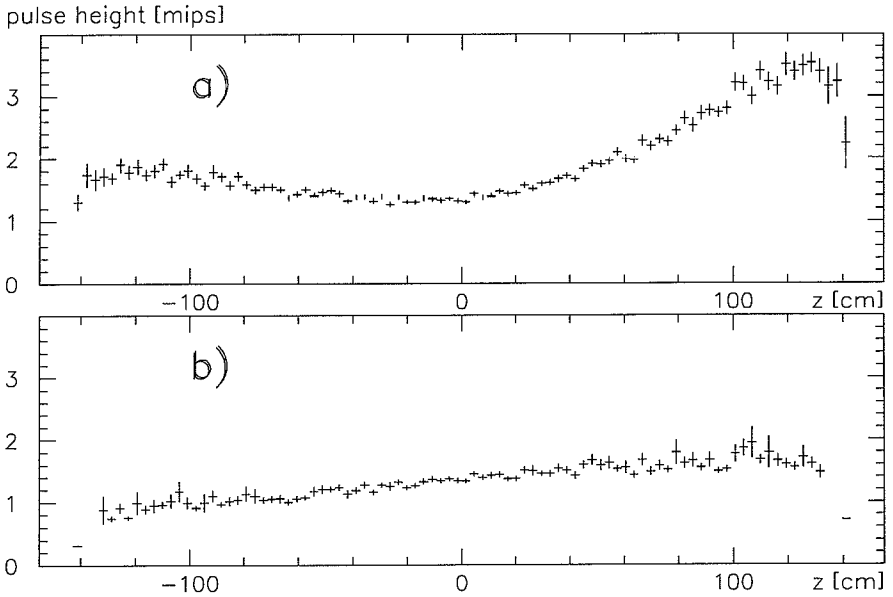


Figure 4.4: *ADC value in number of minimum ionizing particles (mips) as a function of where the particle hits the S1. a) shows raw signal, b) is normalized to pathlength. All PMs are sitting on the right hand side.*

inator. See e.g. [50, pages 317-320] for a good description. A Leading Edge discriminator can have a walk of as much as ± 10 ns for an amplitude range of 1 to 10. If not corrected for, this would make timing measurements in a high energy physics experiment impossible. In our experiment however, we use Constant Fraction Discriminators where this effect is much smaller.

The goal of this study was to select a clean sample of two track events with mainly pions. Therefore, the analysis has been done on minimum bias DST data from period 5, taken in 1989. During this period the detector was not fully operational. Instead of flash-TDCs, conventional ones were used and the z -coordinate had to be calculated using the DC6 value and assuming that the track originated from the centre of the detector. Several cuts were made in order to clean the event sample. For instance, each track had to pass within 1,5 cm in the xy -plane of the detector centre.

This left mainly pions with an ADC-value varying with z as given by Fig. 4.4a. In Fig. 4.4b the pulse height is normalized to the pathlength of the particles through the scintillator, where one can see a linear behaviour as a function of impact position. The attenuation length in this scintillator is 360 cm.

For each track one gets two time measurements, t_u^{meas} and t_d^{meas} from the upstream and downstream PM respectively. From this we calculate the transit time from the target to the scintillator,

$$t_u = t_u^{meas} - \frac{z_{max} + z}{v} \quad \text{and} \quad t_d = t_d^{meas} - \frac{z_{max} - z}{v},$$

where v is the effective velocity of light in the scintillator and z_{max} is the end of the scintillator plank. We define t as the arithmetic average,

$$t = \frac{t_u + t_d}{2} + \frac{z_{max}}{v} = \frac{t_u^{meas} + t_d^{meas}}{2}.$$

This is shown in Fig. 4.5a, solid line.

The error in each measured time t_u and t_d is expected to decrease with increasing number of detected photoelectrons. In order to examine the data for a possible pulse height effect one can calculate a weighted average where t_u and t_d are weighted with $1/\sigma^2 = n/const$ where n is the ADC signal in terms of number of minimum ionizing particles, mips. This yields

$$t' = \frac{n_u t_u + n_d t_d}{n_u + n_d} + \frac{z_{max}}{v} = \frac{n_u t_u^{meas} + n_d t_d^{meas}}{n_u + n_d} - \left(\frac{n_u - n_d}{n_u + n_d} \right) \frac{z}{v}$$

This is shown in Fig. 4.5a, dashed line.

Both distributions of Fig. 4.5a show a broad peak, with a r.m.s. spread of 1,4 ns. This comes from the time jitter in the beam counter start and different annihilation times, along with different momenta and path lengths of the two particles. To eliminate the jitter in the start one calculates $\Delta = t_1 - t_2$ and $\Delta' = t'_1 - t'_2$ as the time difference between the two tracks in the event. The distributions are shown in Fig. 4.5b, solid line representing Δ and dashed line Δ' . The major part of the remaining spread in these distributions (r.m.s. 1,3 ns) is due to momentum and path length differences.

Correcting for this the expected time t^{exp} for each track is calculated. This gives $t^c = t - t^{exp}$ and $t'^c = t' - t^{exp}$ which is plotted in Fig. 4.5c,

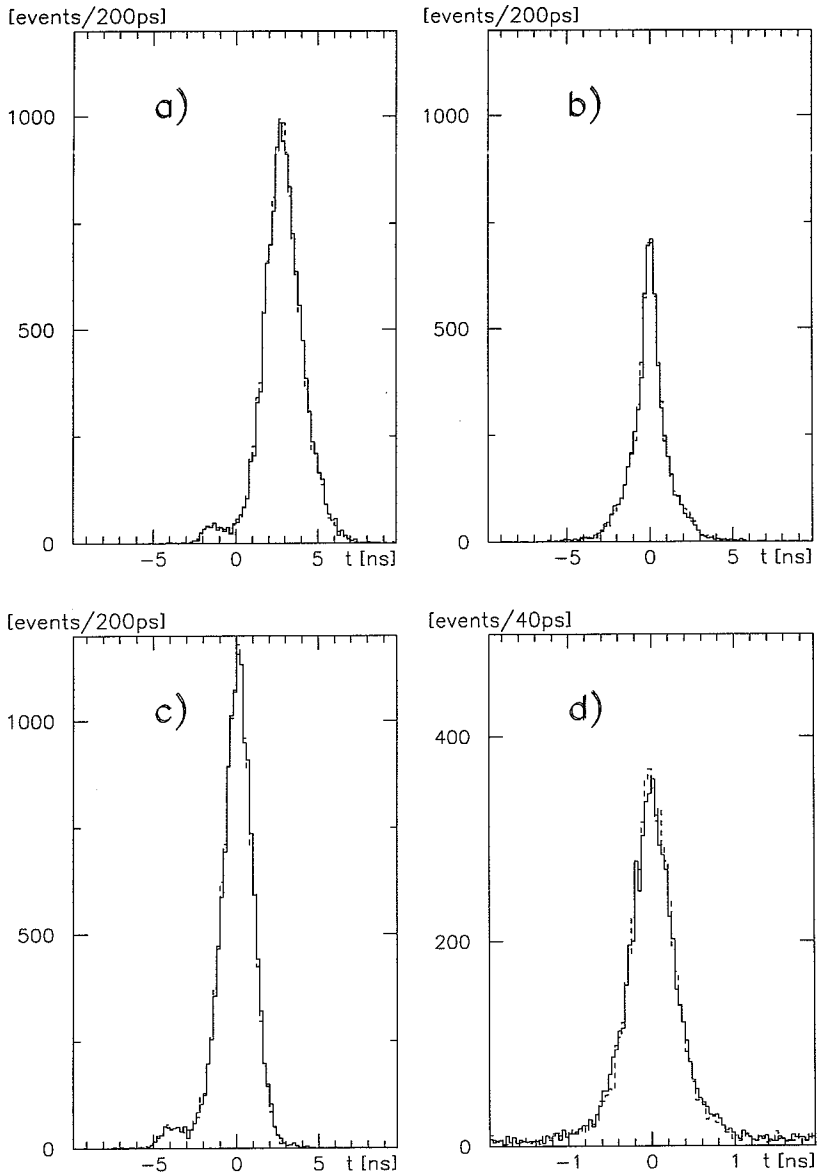


Figure 4.5: *Time-of-flight distributions and differences, solid line is geometrical average, dashed line weighted average. a) shows raw data distributions, b) shows the time difference between the tracks in a). c) shows the time distributions after subtracting the expected time-of-flight, d) shows the time difference between the tracks in c).*

Track 1 [mips]	Track 2 ADC signal [mips]				
	0-0,5	0,5-1,0	1,0-1,5	1,5-2,0	2,0-2,5
0-0,5		17 ± 30 284 ± 21	88 ± 28 269 ± 20	83 ± 52 237 ± 37	
0,5-1,0		30 ± 11 261 ± 8	29 ± 7 268 ± 5	22 ± 14 275 ± 10	-43 ± 26 289 ± 18
1,0-1,5			7 ± 8 269 ± 6	13 ± 11 275 ± 8	-58 ± 23 289 ± 16
1,5-2,0				51 ± 27 252 ± 19	-57 ± 35 283 ± 25

Table 4.1: *The means (top value) and r.m.s. spreads (bottom value) of the time difference distributions in ps, divided in bins of pulse height for each track. The quoted errors are statistical only. The means are everywhere consistent with zero and the spreads agree well within errors.*

still with the beam counter jitter which gives a r.m.s. spread of 1,2 ns. In the $\Delta_c = t_1^c - t_2^c$ and $\Delta'_c = t_1^{c'} - t_2^{c'}$ shown in Fig. 4.5d, a r.m.s. spread of about 280 ps is found. This corresponds to a time resolution of 200 ps per track.

So far, no difference has been found between the normal and the weighted average. One idea was to classify the tracks in a z -independent way in pulse height and to see if one could find an effect. Classifying the tracks on their ADC value, one has to bear in mind that each track has two pulse heights, corresponding to the two PMs. It was decided to choose the lower one in the calculation of Δ_c and Δ'_c . Dividing the pulse height interval 0 to 2,5 mips in 5 bins, one gets a 5×5 matrix, with a separate Δ_c in each bin. From these one can extract the mean and r.m.s. spread of each distribution. The results are given in Table 4.1 (three bins are excluded since the statistics were not large enough). The means are everywhere consistent with zero and the r.m.s. spreads agree well within errors. Similar results are obtained for Δ'_c .

The conclusion of this study is that by using Constant Fraction Discriminators, no correction for pulse height is necessary. A time resolution for the TDCs of 200 ps is also found. The resolution quoted in Section 3.4, 180 ns, comes from using a sample where one uses particle identification in order to clean the data. This is not done in this study.

4.2 The Cherenkov Detector

Each Cherenkov module is 3,1 m long. It has a trapezoidal cross section, see Fig. 3.10, with inner width 12 cm and outer width 13,6 cm and is made of 2,5 mm thick extruded PMMA. The development of the Cherenkov detector was a joint effort of Basel, MSI and CERN and the consequences of different materials and radiators are described in [51]. The radiator chosen was a liquid freon, FC72, see Section 3.4. It has a boiling temperature of 55°C, refractive index of 1,26 for wavelengths above 200 nm and a density of 1,68 g/cm³. Since each module contains 31 litres of liquid, it means that they are very heavy, about 60 kg each with wrapping and light guides. FC72 also has a very low achromaticity in the interesting wavelength region, corresponding to a velocity uncertainty of $\Delta\beta \approx 0,01$. Two PMs at each end of the counters, type XP3462, collect the light produced.

In order to match the wavelength of the Cherenkov light to the sensitivity of the PM, a wavelength shifter, diphenyl-oxazole (PPO), was added to a concentration of 20 mg/l. 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 with a quantum efficiency of about 70%. The shifted Cherenkov light is emitted isotropically, which tends to make the light collection efficiency more uniform along the length of the Cherenkov box. The uniformity of the efficiency is further improved by painting the outside of the middle 80 cm of the box with white reflecting paint, NE 561. This diffuses the light along the box axis and directs it towards the PM-tube.

The most important task of the Cherenkov detector is to quickly separate pions from kaons. The signals coming from the Cherenkov photomultipliers are sent through amplifiers (Phillips 776) and then fed into discriminators (LeCroy 4416) for the trigger, see Fig. 4.1. The discriminator level is adjusted such that it corresponds to one half photo electron. The high voltage of the PMs is individually set, using LeCroy 4032A power supplies, in order to have a high and similar gain of all tubes. A typical ADC pulse height spectrum is shown in Fig. 4.2a, where one can clearly see the pedestal and the first and second photo electron peaks. The trigger decision is taken within 115 ns. Apart from sending the signal to the discriminators, the PM-amplifiers also send signals to flash-ADCs [47]. After a delay of 150 ns, the ADCs start converting. A later stage of the trig-

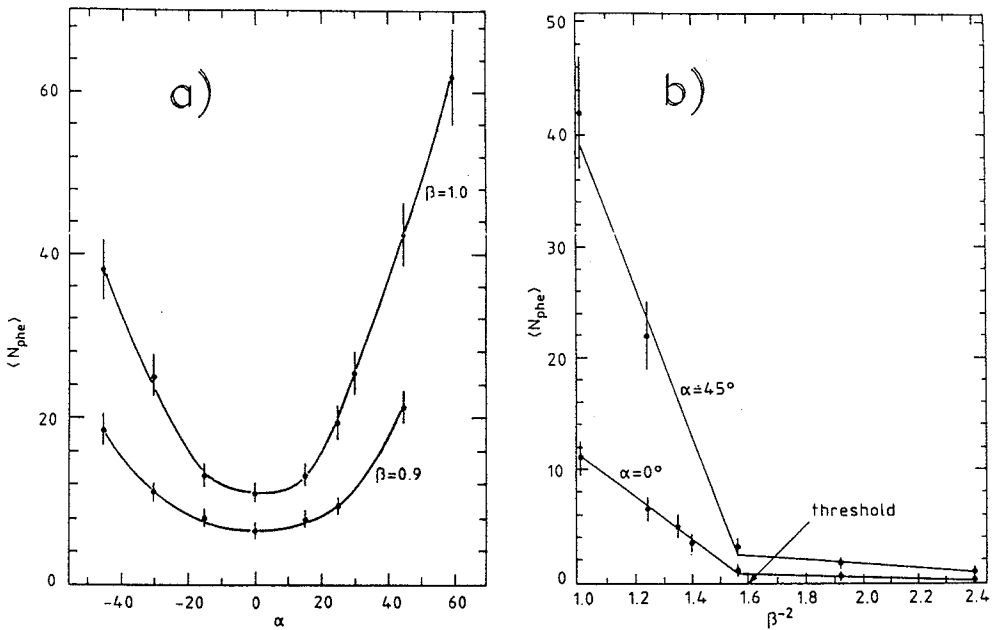


Figure 4.6: Left is shown the average number of photo-electrons as a function of the angle α that the particle hits the counter, right the same thing as a function of $1/\beta^2$ for two different angles. The lines are hand-drawn to guide the eye, the error bars show systematic errors rather than statistical.

ger, the HWP2 (section 3.6.2) makes use of this information and decides in $1,9 \mu\text{s}$ if the event should be kept. The ADC signal and discriminator decision (passed through pattern units) are sent to the event-builder. Off-line, the Cherenkov information can be used together with the S1 pulse height for distinguishing between $\pi^\pm$ and $e^\pm$, see Section 5.1.

Results from a prototype test with an unseparated beam of mainly protons are reported in [25]. The Cherenkov response as a function of the angle with which a particle hits the PID is shown in Fig. 4.6a. Even in the mid-section, with tracks perpendicular to the counter, $\beta = 0,9$ particles produce on average 8 photo-electrons. The response as a function of $1/\beta^2$ is shown to be linear in Fig. 4.6b, as expected for Cherenkov light. The threshold behaviour of the counter is also shown for two different incident angles. The reason that a larger angle gives more photo-electrons is not only that more Cherenkov light is produced but also that a larger fraction of the light is totally reflected in the Cherenkov box. A small background can be seen below the threshold, which was concluded to come from pion contamination of the proton beam. Using real data, the

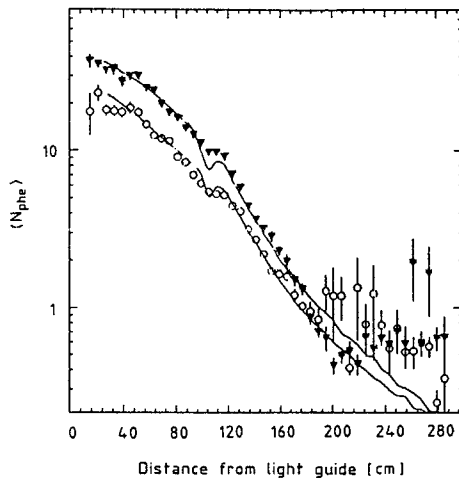


Figure 4.7: *Average number of photo-electrons as a function of distance away from the light guide for pions with $p = 300 \pm 10$ MeV/c (open circles) and $p = 600 \pm 10$ MeV/c (filled triangles). The curves show expected values from Monte Carlo simulations.*

average number of photo electrons measured as a function of distance away from the photomultiplier is shown in Fig. 4.7 for pions in two momentum intervals, 300 ± 10 MeV/c and 600 ± 10 MeV/c. The curves falls roughly exponentially with the distance and the effect of painting the mid part of the Cherenkov box is clearly visible, as a shoulder around $z = 110$ cm.

4.3 Calibration Systems

Calibrating the detector components can be done by using real data, off-line. However, it is often necessary to check the detector performance in between data taking and three systems are available that can be run as monitoring jobs from the VAX-cluster on the PID Valet-plus.

A green Light-Emitting Diode (LED) is glued to each light guide of the S1, Cherenkov and S2 modules. It can be flashed using a pulser system, with attenuators on the Cherenkov LEDs in order to bring down the signal to a level comparable to the one produced by real particles. This is a test of the whole detector subsystem, since the data is read out by the normal electronics chain, Fig. 4.1, and collected in histograms for calibration purposes.

Ultra-violet pulses from a nitrogen laser can be injected at the centre of each counter, with good time definition by the use of quartz fibres. This system is mainly used for the time-of-flight calibration of the S1, since the time definition of the light pulses is superior to the one using the LED system. The test on the operation of the sub-detector system is similar, however.

A set of DAC-controlled pulsers is used in order to inject a well defined charge into the front end electronics, see Fig. 4.1. For the scintillators SP687A is used, with a signal amplitude of 0,3–3 V and for the Cherenkov SP693 is used which has an amplitude range of 10–100 mV. This system is developed in Basel and used to check and calibrate the ADCs and the discriminators of the PID and can also be used when the high voltage is switched off.

4.4 Calibrating the Positions of Each Detector

4.4.1 Data Sample and Method

In a high-precision experiment it is necessary to know the positions of the individual detectors in a given reference system. In our experiment this system is defined by the drift chambers, Section 3.3.2. Using real fitted tracks detected by the chambers and fitted by an off-line program the position where the track hits the given PID-module is obtained. This can be used both for detector positioning and for measuring the efficiency of the scintillators.

The position analysis was performed on three sets of data, from run period 5 (1989) and 7 (1990), reported in [52] and from period 19 (1992), [53]. From P5 113000 minimum bias DST events were used, from P7 1,2 million events of minimum bias raw data and from P19, just as a check, 124000 events of minimum bias raw data were used. In order to get a threshold (in momentum) above which the scintillators can be considered to be efficient, the fraction of tracks that gives light is plotted as a function of momentum in Fig. 4.8. A track is defined to have given light in a scintillator when at least one of the two photomultipliers viewing it has triggered the corresponding pattern unit. A cut at 200(400) MeV/c

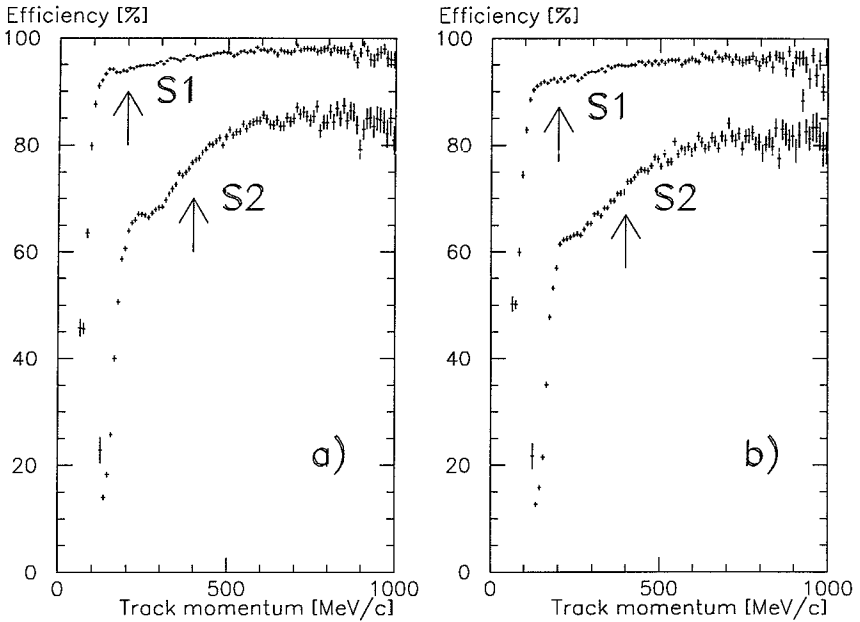


Figure 4.8: *Efficiency of the scintillators as a function of momentum for, a) P5 data, b) P7 data. The arrows indicates the cuts used in this analysis.*

was chosen for S1(S2). The higher cut for S2 is to make sure that a larger number of tracks actually reaches S2 and does not interact in the Cherenkov. There is a slight difference in the efficiency curve as a function of momentum for the DST data as compared to the raw data which comes from the fact that a filter was used selecting 2 or 4 track events with at least 5 hits in the chambers on the P5 data. This enhances the efficiency, but should not change the rest of the analysis.

The major difference between the run periods is that the drift chambers were taken out and put back in place again. For the scintillators, the photomultiplier tubes have been removed, along with the light tight box around the light guides. Before P19, everything except the calorimeter went out and back in. After reinstallation, the positions of the scintillators might have been affected. For comparison, 21000 unfiltered minimum bias Monte Carlo events were used.

Part of the inefficiency seen in Fig. 4.8 comes from the fact that the scintillators do not cover the full azimuthal angle φ , there are small gaps between two neighbours, see Fig. 3.10. S1 covers 91% of 2π and S2 roughly 89%. The following analysis was performed in order to locate these gaps.

The Track-fit part of the CPLEAR software was used to calculate φ for each track relative to the sector centre at the mid-radius of S1 and S2, respectively. Using this information, together with the p_x, p_y and p_z , a theoretical pathlength in the scintillator was calculated. Plotting the efficiency as a function of φ , overlaying all sectors in the same histogram one obtains Fig. 4.9. Looking carefully at this figure, one finds that the average gap position is shifted some 2 mrad ($0,1^\circ$) from its expected value $\varphi_0 = \frac{\pi}{32} = 0,0982$ rad. In order to quantify the shift, the spectrum was repeated and transformed so that the gap appeared as a peak. This peak was then fitted with a Gaussian with constant background, as is shown in Fig. 4.10, and the peak position thus extracted.

For the efficiencies, only channels 25 to 75 of the 100 channel histogram in Fig. 4.9 were used. Taking the average of these, an average efficiency of 98,9% is achieved for all S1 sectors during P5.

4.4.2 Results

Using the method of Section 4.4.1 independently for all sectors of both S1 and S2 one obtains Fig. 4.11 for the position of each scintillator. Note that φ_0 is subtracted from each gap position. A positive value means that the scintillator is displaced towards a greater value of φ . This is the case for sectors in the left half of the detector (9-24), whereas the rightmost ones are shifted the other way, something that can be explained by a relative shift of the drift chambers with respect to the PID.

The data in Fig. 4.11 is fitted by a sinusoidal in order to extract the parameters of this shift. The result of the fit to the S1 P7 data yields a movement of 4,5 mm in the direction 4,38 rad with a global rotation of 1,8 mrad of the whole PID cylinder with respect to the drift chambers. For P19 the shift is found to be 3,2 mm in the 4,28 rad direction with a rotation of 0,7 mrad from the fit to the S1 data. These results are put into the calibration banks for use in MC simulations and data analysis programs.

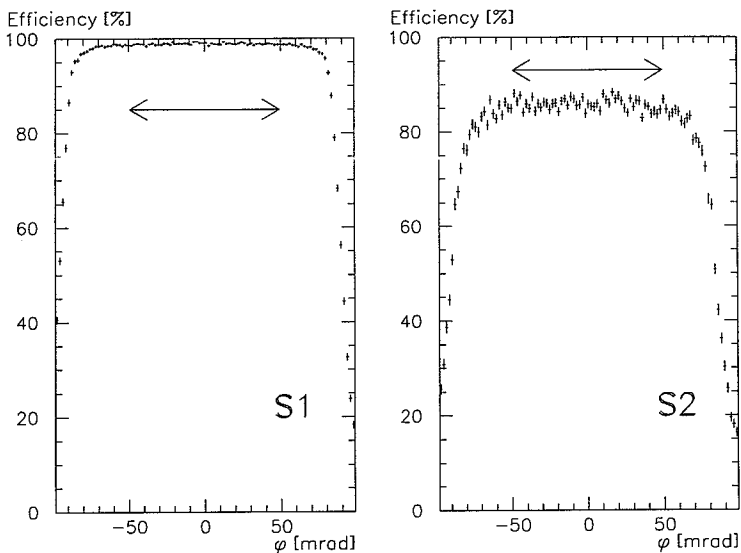


Figure 4.9: *Efficiency as a function of φ for all sectors using P5 data. The arrows indicate the channels used for calculating the efficiency.*

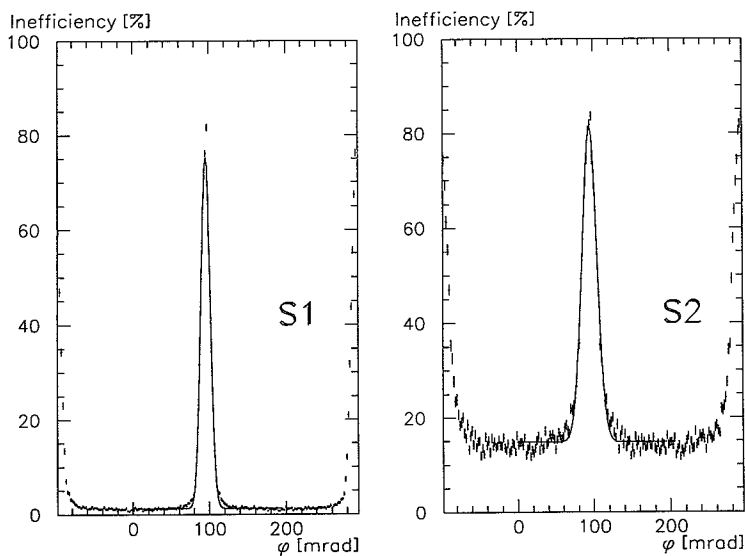


Figure 4.10: *The fit to the sector gap position as described in the text. Same histograms as in Fig. 4.9*

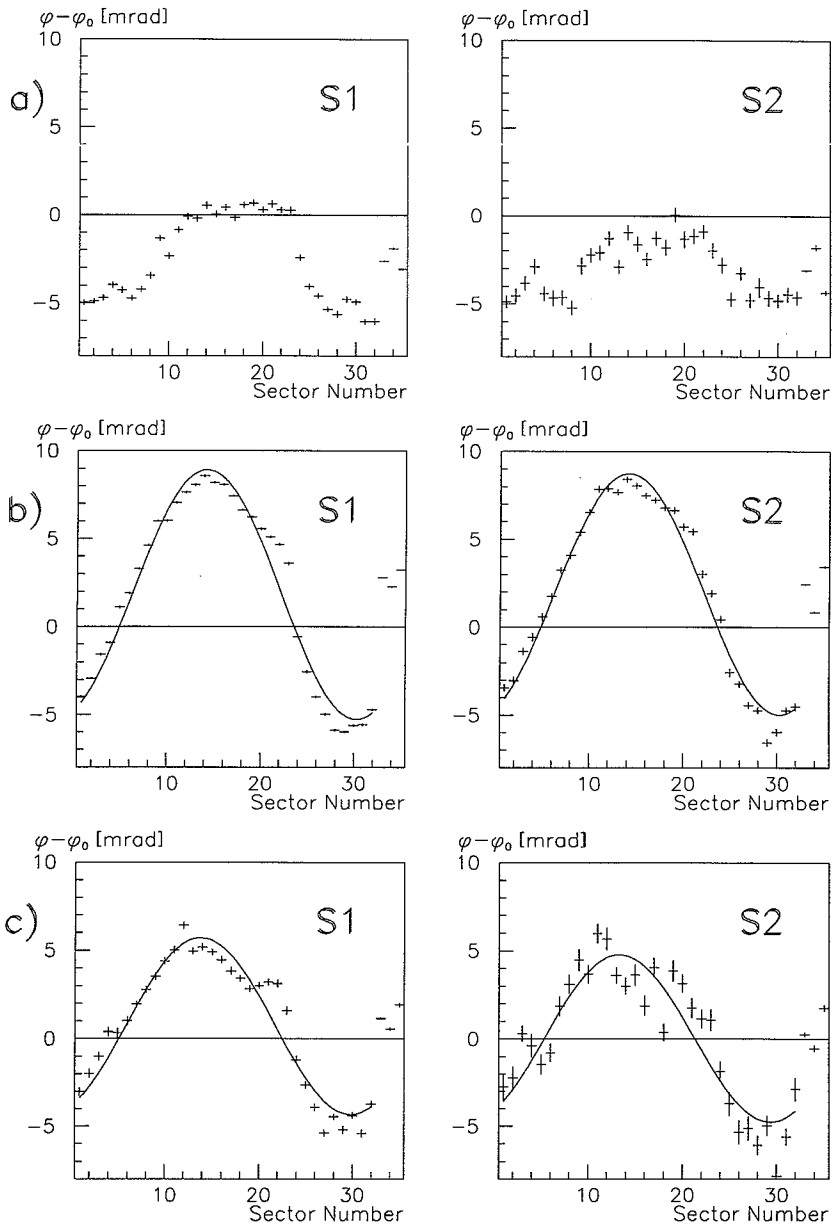


Figure 4.11: *Sector gap positions for a) P5, b) P7 and c) P19 data. Bin 33 shows the average of all sectors, 34 the average for all tracks with $z > 30$ cm, 35 the average for all tracks with $z < -30$ cm. The fits are fits with a sinusoid, as described in the text.*

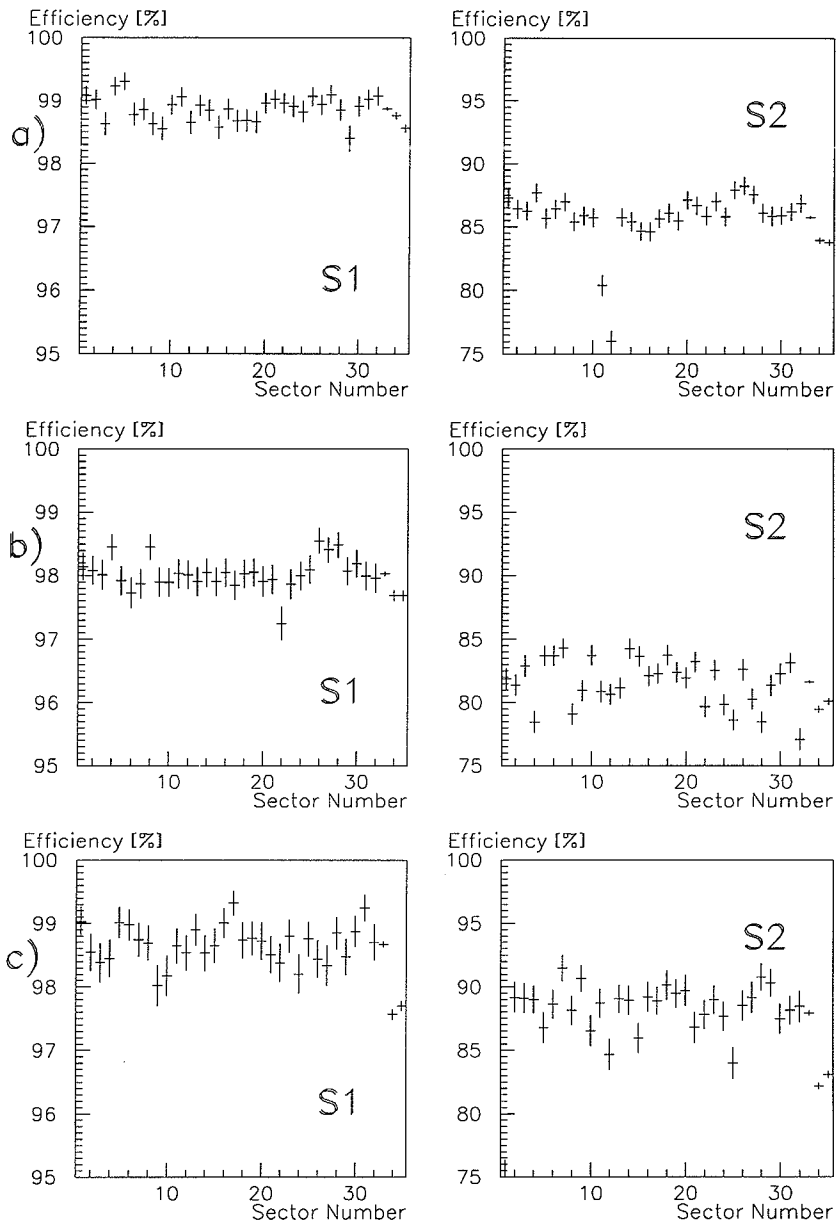


Figure 4.12: *Efficiencies per sector of the scintillators for a) P5, b) P7 and c) P19 data. Bin 33 shows the average of all sectors, 34 the average for all tracks with $z > 30$ cm, 35 the average for all tracks with $z < -30$ cm.*

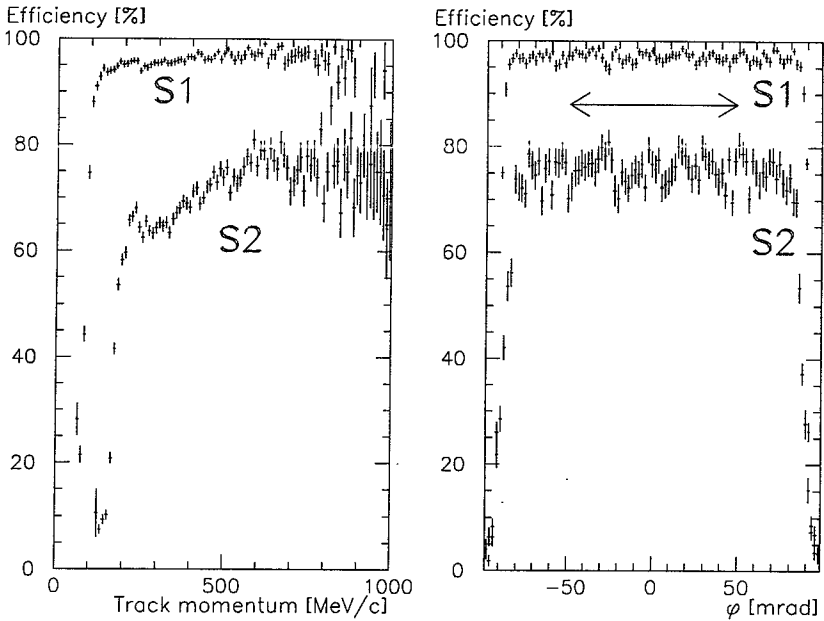


Figure 4.13: *Efficiencies as a function of momentum (left) and ϕ (right) from Monte Carlo calculations. The arrow indicates the channels used for calculating the efficiency.*

Looking carefully in Fig. 4.11, a possible twist of the scintillators can be seen. The last two bins of the histogram show the average of all sectors for tracks with $z > 30$ cm and $z < -30$ cm, respectively. The effect is very small, in P7 and P19 the upstream part of the scintillator has a ϕ that is larger than the downstream part.

The efficiencies are given in Fig. 4.12. For S1, efficiencies of $(98,88 \pm 0,03)\%$, $(98,03 \pm 0,04)\%$ and $(98,74 \pm 0,05)\%$ for P5, P7 and P19 are obtained. For S2, the values are $(85,8 \pm 0,2)\%$, $(81,6 \pm 0,2)\%$ and $(88,2 \pm 0,2)\%$ respectively for the three periods. The reason for the lower efficiency of S2 is that there is 11 cm of extra material in front of it and it is half the thickness of S1.

The efficiencies obtained are somewhat better than those from MC-simulations, $(97,0 \pm 0,2)\%$ and $(75,6 \pm 0,4)\%$ for S1 and S2 respectively. The reason for the poor efficiency of S2 is that if a particle interacts

strongly in the Cherenkov, it disappears from our Monte Carlo. The figures for MC corresponding to Fig. 4.8 and Fig. 4.9 can be found in Fig. 4.13.

4.5 When Disaster Struck

The Cherenkov system was designed as a closed system, each counter hermetically sealed. Dismounting was not planned for the duration of the experiment. However, FC72 boils at a relatively low temperature (55°C) and during the hot summer 1991 all the calorimeter electronics were for the first time switched on, in run period 12. This raised the temperature of the PID above 46°C, when air dissolved in the liquid will switch to gas phase and increase the pressure even more than just the thermal expansion of the liquid would. This resulted in the development of tiny cracks which allowed the freon to leave the counters.

The disaster was only realized a month later, in P13, when some Cherenkov counters started to contribute more to the $\overline{SCS}$ trigger than before. Inspection showed that three counters had lost about half of their FC72 contents. In order to check the time evolution of these leaks, a method similar to the one developed for the determination of the scintillator positions was used, see Section 4.4.1.

Tapes from different dates during P12 and P13 were analysed. Results are shown in Fig. 4.14 for one of the worst PIDs, number 31. One can clearly see how the leak starts to develop as an inefficiency hole on the side of the counter with a higher φ , that is to the top side of the counter in this case. The three sectors 14, 16 and 31 suddenly lost a lot of their freon, around August 17. After that they continued to leak slowly for the rest of P12 and P13, see Fig. 4.15.

Since other detector subsystems needed to be taken out during the winter shutdown of 1992 it was decided to remove all PID sectors and repair the damage. At the same time an expansion system was fitted connecting each Cherenkov box to its own expansion vessel in order to allow for circulation of liquid. A method was also developed for degassing the Cherenkov counters using ultrasound [54, 55] in order to decrease the light absorption of FC72. The pion rejection is now at the same level as before the accident.

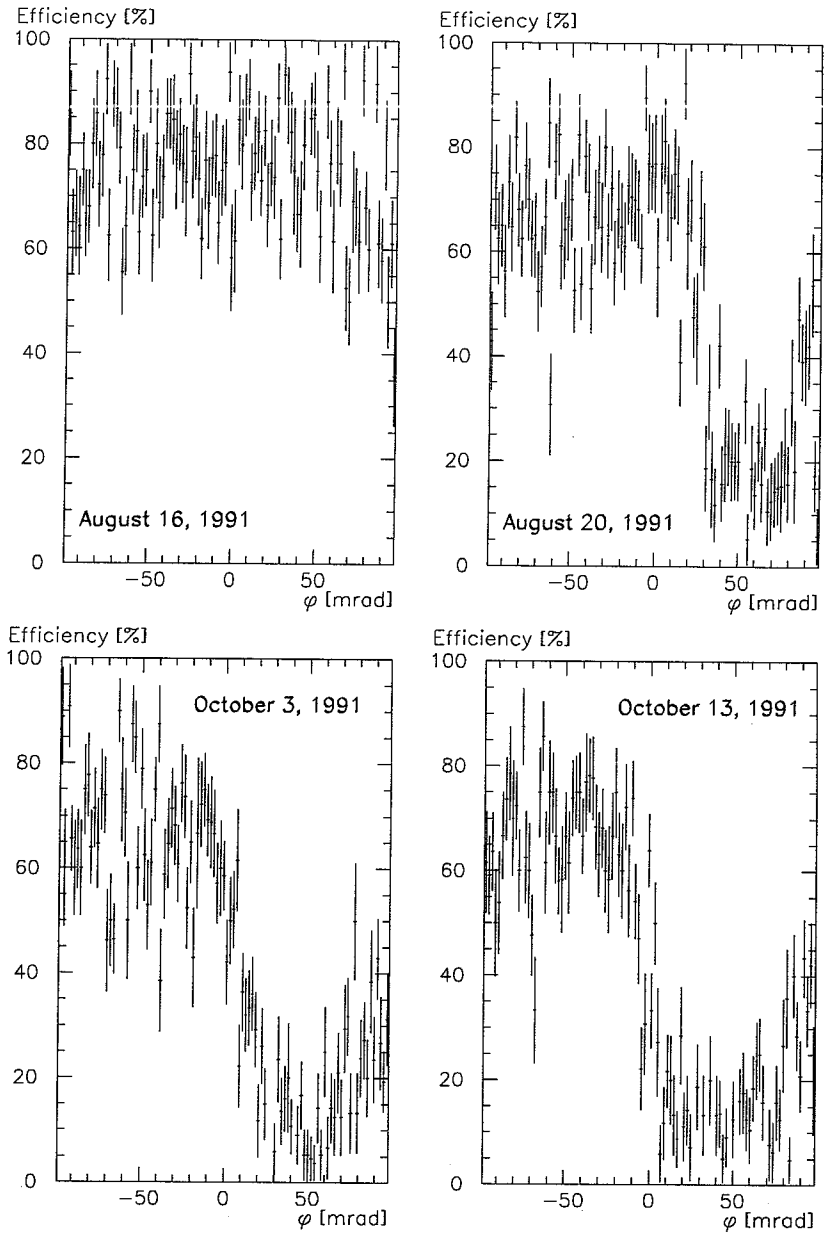


Figure 4.14: *Time evolution of one of the leaking Cherenkov modules. The two upper figures are from P12, the two lower ones from P13.*

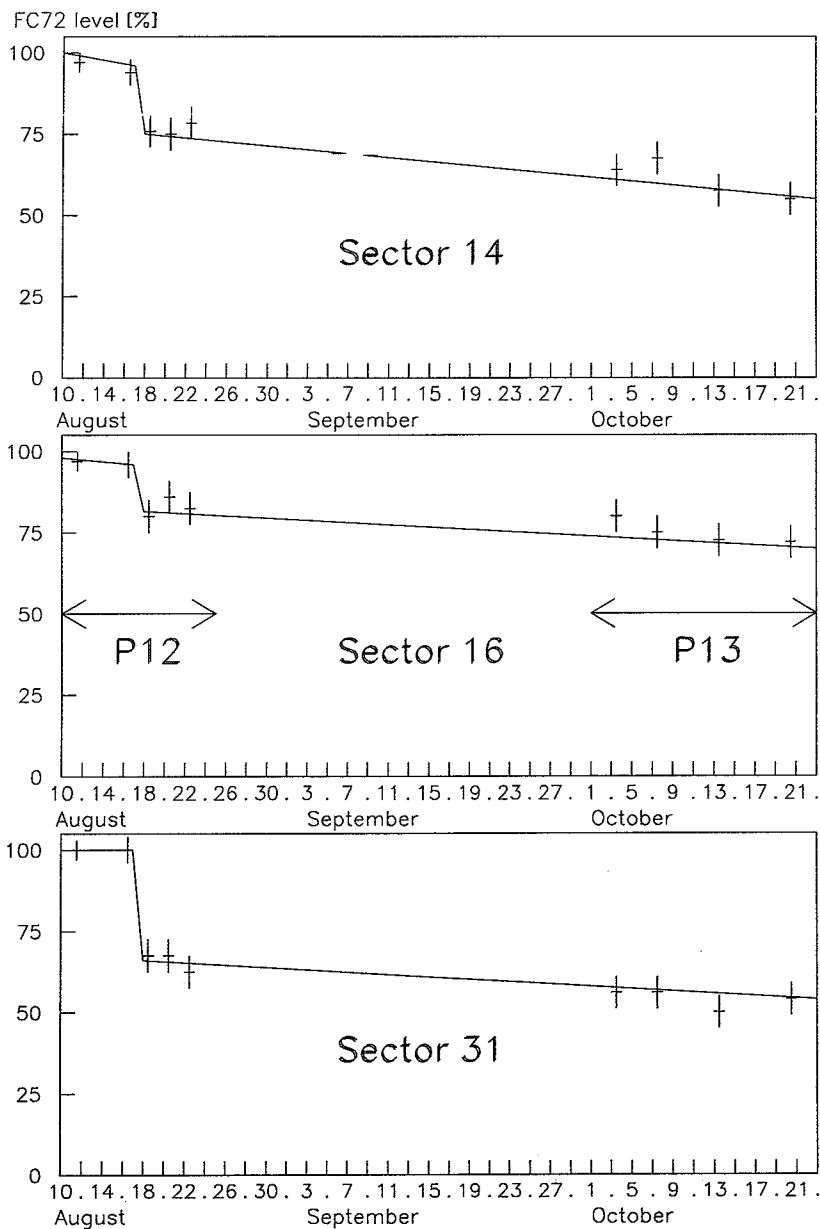


Figure 4.15: Leak rate of three Cherenkov counters during P12 and P13. The lines are hand drawn to guide the eye.

Chapter 5

How to Identify $e^\pm$

A central issue in detecting the semileptonic decays of neutral kaons is the identification of electrons and positrons. This is done by using the different subdetectors of the PID. The use of pulse heights (Cherenkov, dE/dx) is described in Section 5.1 and a time-of-flight method is described in Section 5.2.

5.1 Cherenkov Pulse Height vs dE/dx in S1

The electrons and positrons from $K^0(\overline{K}^0) \rightarrow \pi^\pm e^\mp \bar{\nu}_e(\nu_e)$ decays are relativistic. Consequently they are above the threshold for producing light in the Cherenkov and are minimum ionizing particles in the scintillators. Pions, on the other hand, are below the Cherenkov threshold for momenta below 180 MeV/c and their dE/dx signal is increasing with decreasing momentum. Combining the Cherenkov pulse height information with the energy loss in S1 provides a powerful tool to separate $e^\pm$ from $\pi^\pm$.

In order to evaluate this, test samples of electrons and pions are needed. Ideally, test-beam data should be used, where pure beams of different momenta and incident angles can be obtained. Such a test is planned [56]. When one PID was previously tested [25] the response to pions and protons was checked. The following section describes a way of obtaining samples of $\pi^\pm$ and $e^\pm$. Since a fraction of the semileptonic

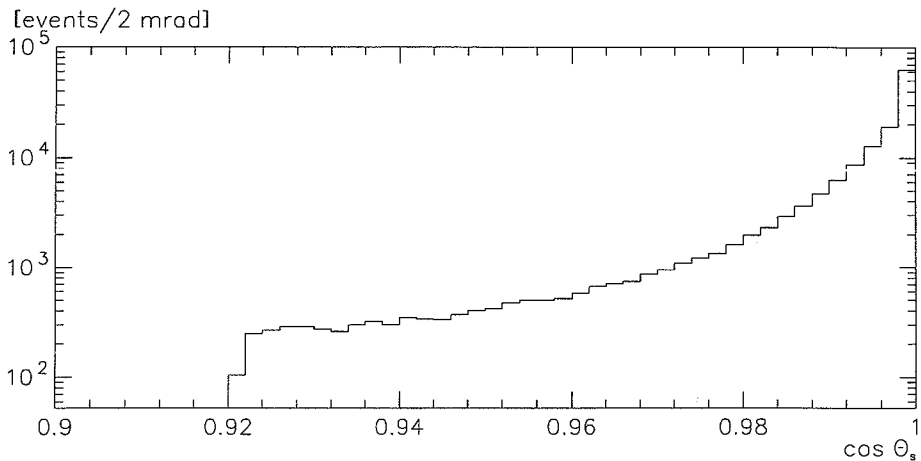


Figure 5.1: *Distribution of the opening angle between secondary tracks, θ_s , for T401 events. Note that already when producing the Mini-DST, a cut on $\cos \theta_s < 0.92$ is made.*

decays involves a $\mu^\pm$ instead of an $e^\pm$, a method of simulating muons by the use of pions is described in Section 5.1.2.

5.1.1 The S1/Cherenkov Cut

A special trigger was devised in order to enhance the number of events where a photon has converted and produced an e^+e^- pair. Several tapes were taken in P9 with trigger T403 and in P13 with trigger T401. Requiring two primary and two secondary tracks without identifying a kaon selects events with, for instance $\pi^+\pi^-\pi^0$, where one of the γ 's from the π^0 has produced an e^+e^- pair. The primary tracks can then be used as a pion sample. The disadvantage of this method is that all tracks are pointing towards the centre of the detector, which gives a very strong correlation between the angle with which a track hits the PID and its z coordinate. Also, for primary pions, very few tracks with momenta below 100 MeV/c are found, since this is roughly what is needed for a pion to reach and give signal in S1. In the case of K^0 decays however, pions with lower momenta can reach S1 since the decay is further out in the detector volume.

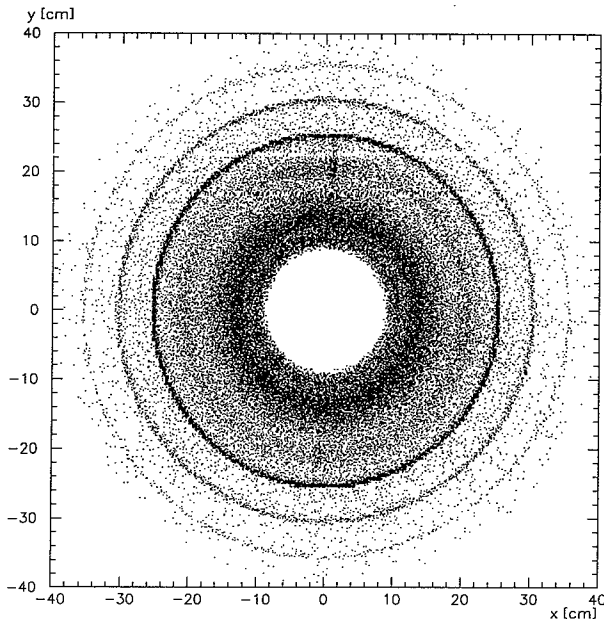


Figure 5.2: *Radial distribution of vertices from γ conversions. The rings come from conversions in PC1, PC2, DC support structure, DC1, DC2 and DC3.*

Mini-DST data from P9 and P13 were analysed. From P9, 49000 events of M1T403 data and from P13, 318000 events of both magnet polarities T401 were used. The most effective cut in order to get a clean sample of events with a γ conversion is to cut on the opening angle θ_s of the secondary particles. This angle is expected to be small if it is a true conversion, with $\cos \theta_s$ close to 1. The distribution is shown in Fig. 5.1 where one can see the characteristic e^+e^- signal above a flat background. A cut on $\cos \theta_s > 0,98$ is chosen. Since the PID information is to be studied, no two tracks are allowed to be extrapolated to the same S1 or Cherenkov module. After these cuts and cuts on the quality of tracks and vertices are made, see Fig. 5.2, 16555 events from P9 and 123203 events from P13 remain. The background from other processes in this sample of $\pi^+\pi^-e^+e^-$ events is estimated from Fig. 5.1 to be less than 2%.

The scatter plots of the dE/dx signal in S1 versus Cherenkov pulse height for different momentum intervals are shown in Fig. 5.3 for the electron and Fig. 5.4 for the pion sample. Fig. 5.4 clearly shows the Cherenkov

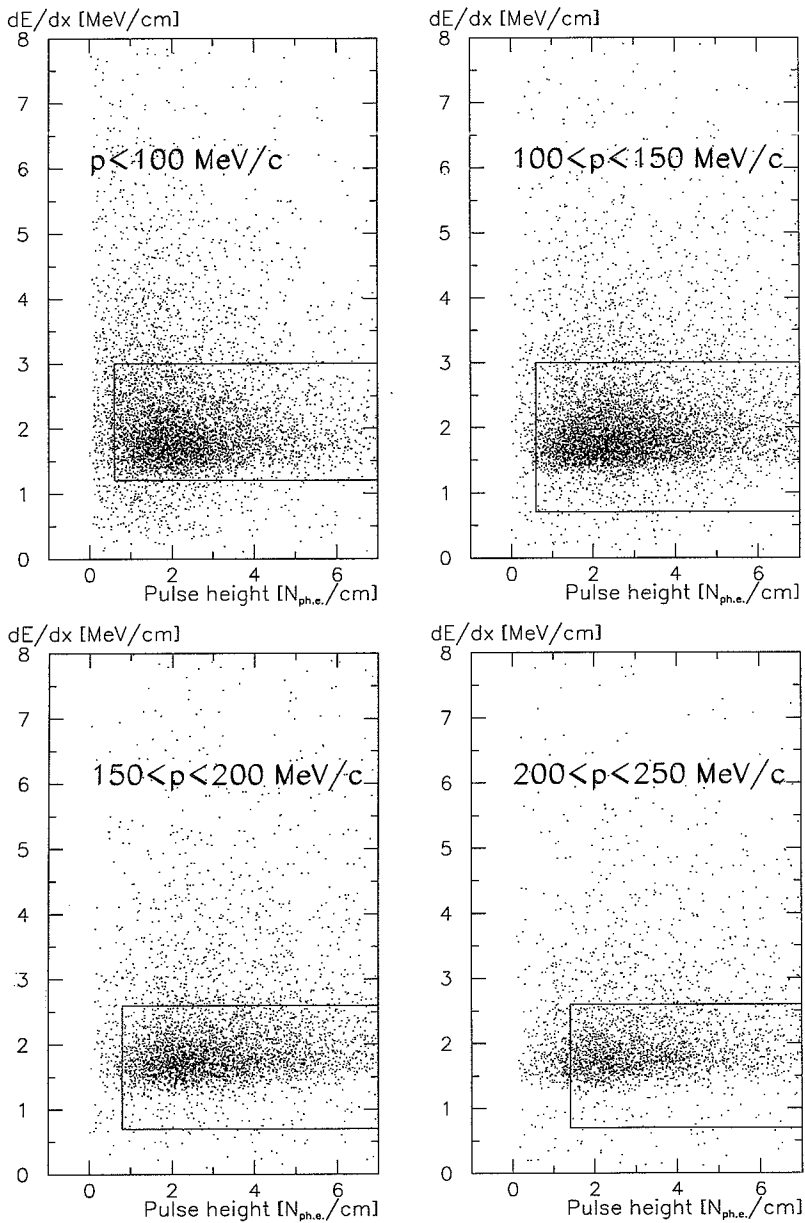


Figure 5.3: Scatter plot of dE/dx signal in S1 versus Cherenkov pulse height for $e^\pm$ for four different momentum regions. The lines indicate the region which is used to define electrons.

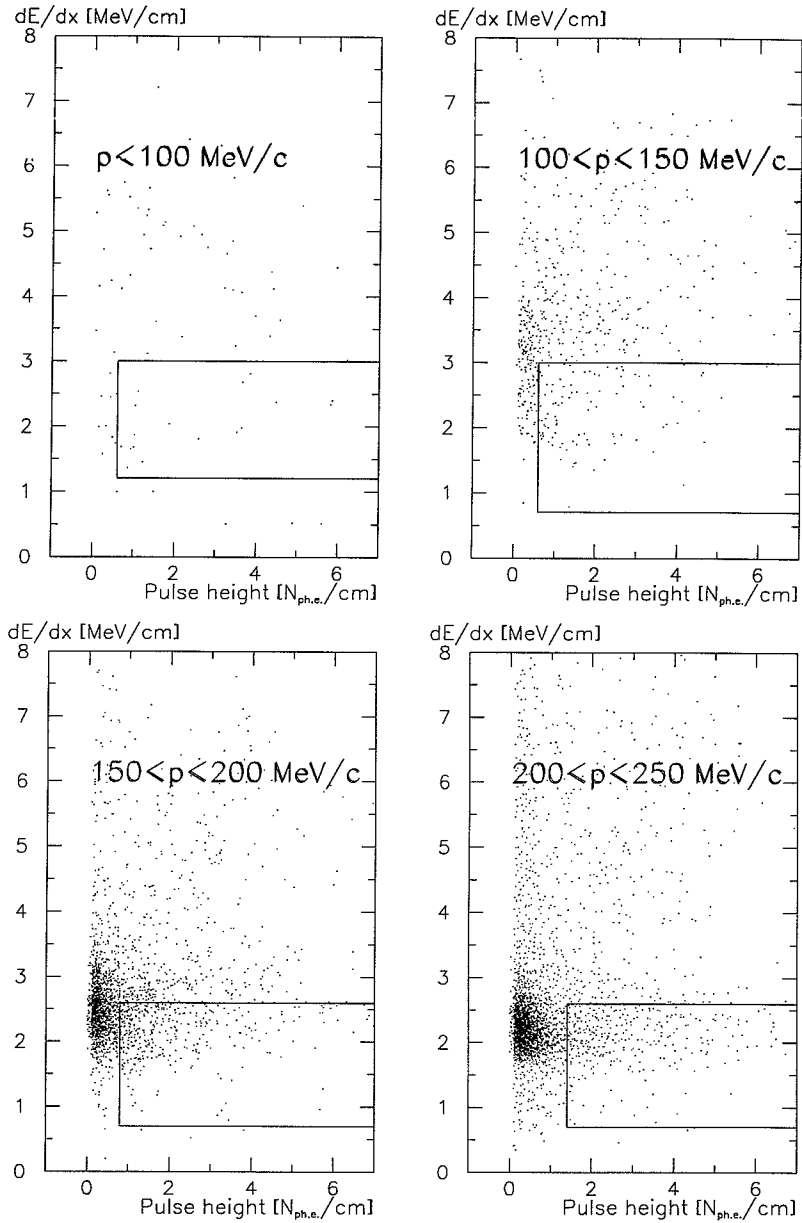


Figure 5.4: Scatter plot of dE/dx signal in S1 versus Cherenkov pulse height for $\pi^\pm$ for four different momentum regions. The lines indicate the region which is used to define electrons.

Period	Particle	0–50 [MeV/c]	50–100 [MeV/c]	100–150 [MeV/c]	150–200 [MeV/c]	200–250 [MeV/c]
P9M1	e^+	23,4 $\pm$ 2,2	64,6 $\pm$ 0,6	74,6 $\pm$ 0,6	69,9 $\pm$ 0,7	62,9 $\pm$ 0,8
	e^-	22,1 $\pm$ 2,1	61,3 $\pm$ 0,6	74,2 $\pm$ 0,5	67,6 $\pm$ 0,7	62,3 $\pm$ 0,8
	Total: $e^+e^-: \eta_e$	22,7 $\pm$ 1,5	63,0 $\pm$ 0,4	74,4 $\pm$ 0,4	68,7 $\pm$ 0,5	62,6 $\pm$ 0,6
P9M1	π^+		2 $\pm$ 2	2,6 $\pm$ 0,7	2,0 $\pm$ 0,2	1,7 $\pm$ 0,2
	π^-	–	0 $\pm$ 2	3,1 $\pm$ 0,7	1,8 $\pm$ 0,2	1,7 $\pm$ 0,2
	Total: $\pi^+\pi^-: \eta_\pi$	–	1 $\pm$ 1	2,9 $\pm$ 0,5	1,9 $\pm$ 0,2	1,7 $\pm$ 0,1
P13M1	e^+	6,6 $\pm$ 0,6	50,8 $\pm$ 0,3	70,1 $\pm$ 0,3	66,2 $\pm$ 0,4	49,1 $\pm$ 0,4
	e^-	6,7 $\pm$ 0,6	47,9 $\pm$ 0,3	67,9 $\pm$ 0,3	64,1 $\pm$ 0,4	51,2 $\pm$ 0,4
P13M2	e^+	6,4 $\pm$ 0,6	47,8 $\pm$ 0,3	67,8 $\pm$ 0,3	63,9 $\pm$ 0,3	48,7 $\pm$ 0,4
	e^-	6,8 $\pm$ 0,6	50,4 $\pm$ 0,3	70,8 $\pm$ 0,3	65,6 $\pm$ 0,3	50,6 $\pm$ 0,4
Total:	$e^+e^-: \eta_e$	6,6 $\pm$ 0,3	49,2 $\pm$ 0,1	69,1 $\pm$ 0,1	64,9 $\pm$ 0,2	49,9 $\pm$ 0,2
P13M1	π^+	–	3,8 $\pm$ 1,5	1,8 $\pm$ 0,4	2,6 $\pm$ 0,3	3,3 $\pm$ 0,3
	π^-	–	1,6 $\pm$ 0,9	1,4 $\pm$ 0,3	2,7 $\pm$ 0,3	3,5 $\pm$ 0,3
P13M2	π^+	–	2,3 $\pm$ 1,1	1,6 $\pm$ 0,3	3,1 $\pm$ 0,3	3,0 $\pm$ 0,2
	π^-	–	2,2 $\pm$ 0,9	1,9 $\pm$ 0,4	2,9 $\pm$ 0,3	3,6 $\pm$ 0,3
Total:	$\pi^+\pi^-: \eta_\pi$	–	2,4 $\pm$ 0,5	1,7 $\pm$ 0,2	2,8 $\pm$ 0,2	3,3 $\pm$ 0,1

Table 5.1: *Efficiencies (in %) for electrons (η_e) and pions (η_π) as a function of momentum to pass the S1/Cherenkov cut.*

threshold effect. In these plots is also shown a cut that is used to define electrons with an efficiency η_e of 60–70% with an acceptance of pions η_π of 2–3% [57]. This is called the S1/Cherenkov cut in the following. Table 5.1 gives the values for efficiencies in different momentum bins, for positive and negative particles and positive and negative magnetic field, respectively for the two periods. The efficiency is lower in P13, since some of the Cherenkov counters had lost freon, see Section 4.5. Very few pions are available in the lowest momentum bins. From Monte Carlo studies this is however also the case for pions from the signal $K^0(\bar{K}^0) \rightarrow \pi^\pm l^\mp \bar{\nu}_l(\nu_l)$ and from the background channels $K_S \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^+\pi^-\pi^0$. Since the values for η_e and η_π defined in Table 5.1 will be used later for checking how large fraction of these MC events that pass the S1/Cherenkov cut the extrapolated value in this momentum region is used. Above 250 MeV/c, pions produce so much Cherenkov light that it was deemed futile to go any higher in momentum with this cut.

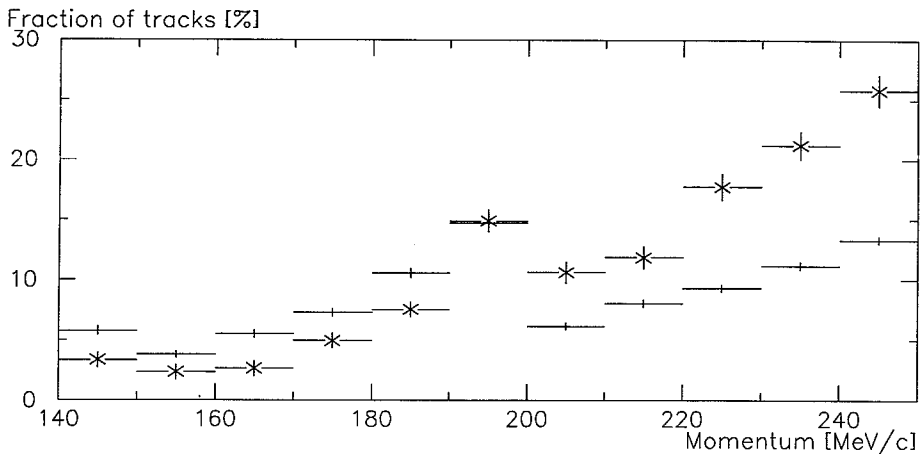


Figure 5.5: *Fraction of muons detected as electrons (η_μ) by the S1/Cherenkov cut as a function of momentum, for P9 (stars) and P13 (crosses). The discontinuity seen at $p = 200$ MeV/c is caused by the change of $e^\pm$ selection criteria, see Fig. 5.3.*

In calculating the asymmetries in the semileptonic decays the ratio of detection probabilities $\eta = P(e^-\pi^+)/P(e^+\pi^-)$ defined in Section 2.2.3 enters and must be known with a high precision. The calibration data in Table 5.1 is not good enough and does not cover all possible angles and z values, so awaiting high statistics calibration data, η is derived from the $K^0(\bar{K}^0) \rightarrow \pi^\pm l^\mp \bar{\nu}_l(\nu_l)$ data sample, see Chapter seven.

5.1.2 Muons in the PID

The branching ratio for $K_L \rightarrow \pi^\pm \mu^\mp \bar{\nu}_\mu(\nu_\mu)$ is 70% of the $K_L \rightarrow \pi^\pm e^\mp \bar{\nu}_e(\nu_e)$ branching ratio. This is the main source of muons in the CPLEAR experiment, but no subdetector is designed to look for them. The asymmetry signal from decays with a muon is expected to be identical to the one from decays with an electron, so if the muon is identified as an electron it would contribute to the signal. If the event is misidentified, $\mu^\pm \pi^\mp$ taken for $\pi^\pm e^\mp$ it would instead destroy the signal.

In order to determine the fraction of muons (η_μ) that is detected as

electrons by the S1/Cherenkov cut the pion test sample is used, scaling down the pion momentum since the dE/dx and Cherenkov signals depend on the velocity of a particle. Since both particles are roughly minimum ionizing in the 140–250 MeV/c range, the discrimination between $\mu^\pm$ and $\pi^\pm$ is mainly done by the Cherenkov. At 250 MeV/c, a muon produces 70% of the Cherenkov light compared to a $\beta = 1$ particle. Fig. 5.5 shows the fraction of muons that pass the S1/Cherenkov cut above the threshold for muons to produce light in the Cherenkov, 140 MeV/c. For the momentum bins 150–200 MeV/c and 200–250 MeV/c values of η_μ of 5,2%(8,9%) and 16,8%(9,8%) for P9(P13) are found, respectively.

Below threshold a muon can produce light in the Cherenkov mainly by decay. The low momentum muons will stop and decay in the PID, but since the lifetime is long, 2,1 μ s compared to the integration time of the flash-ADC, only the muons decaying in the first 100 ns will be counted in the event, i.e. less than 5%. For the Monte Carlo acceptance of this channel, the same PID acceptance as found for pions is used, but few events are available with muons below 100 MeV/c because of phase space limitations.

5.2 Using Time-of-Flight

The time-of-flight of a $\beta = 1$ particle taking the shortest route to S1 is about 2 ns. On the other hand, a slow kaon ($\beta = 0,7$) traveling at the maximum angle for detection in the PID would take 8 ns to reach S1. When dealing with time-of-flight, it is necessary to take into account not only the different annihilation times but also velocities and flight paths and to calculate an expected flight time, see Section 4.1.2. This section shows how this can be done.

In a four track event from T433 data the primary $K^\pm\pi^\mp$ pair can be used to calculate the annihilation time of the event. Correcting each measured time with the time expected for a pion or kaon, the annihilation time t_{ann} is defined by taking the average. This distribution is shown in Fig. 5.6 and has a r.m.s. spread of 0,8 ns due to the straggling of the antiprotons in the target. The error in the determination of the annihilation time is the same as was found in Section 4.1.2, 280 ps. Next, the flight time t_{K^0} of the K^0 is calculated using the missing quantities

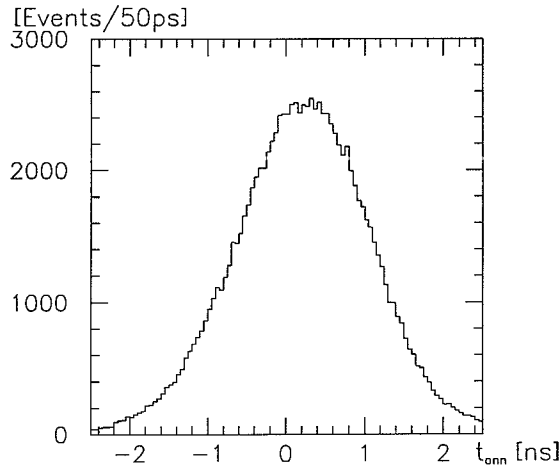


Figure 5.6: *Annihilation time distribution calculated from the two primary tracks.*

obtained at the primary vertex.

Now the time-of-flight t_i of the secondary tracks can be calculated $t_i = t_i^{meas} - t_{K^0} - t_{ann}$ and compared to the time expected if the particle is an electron $t_i^{exp,e}$ or a pion $t_i^{exp,\pi}$. The advantage is that each track can be checked separately against the pion or electron hypothesis, instead of calculating the time difference and comparing with time differences for $\pi\pi, e\pi$ or πe combinations. Taking Monte Carlo generated events of the $K_L \rightarrow \pi^\pm e^\mp \bar{\nu}_e (\nu_e)$ channel $t_i^e = t_i - t_i^{exp,e}$ and $t_i^\pi = t_i - t_i^{exp,\pi}$ can be calculated. Plotting the one against the other, Fig. 5.7 is obtained for electrons and pions, separately for different momentum regions. Electron tracks should be close to $t_i^e = 0$, pions should be found near $t_i^\pi = 0$. A strong correlation can be found in these plots, since if for instance $t_i^{exp,e}$ is underestimated then this will also be true for $t_i^{exp,\pi}$. In these plots are also indicated lines below which 95% of all electrons are found. As expected, the number of pions that fall in this category increases with momentum and already in the region 150–200 MeV/c one can see that TOF is not very efficient in separating pions from electrons.

A software routine has been developed based on this Monte Carlo study that given a level of electrons one is prepared to loose or the number of pions one is prepared to accept defines which cut should be used on

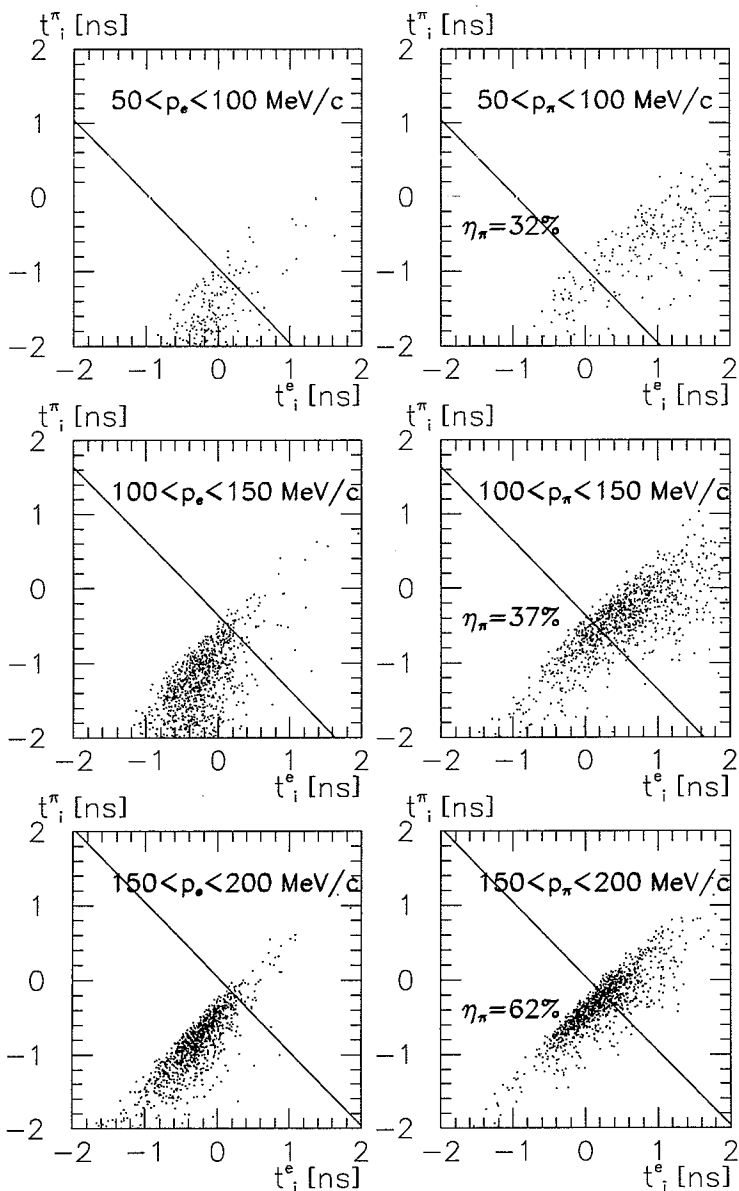


Figure 5.7: Scatter plot of t_i distributions of MC secondary tracks for three different momentum regions, left for electrons and right for pions. t_i assuming that the particle is a pion is plotted on the vertical scale, assuming electron is plotted on the horizontal scale. True electrons should be found near $t_i^e = 0$.

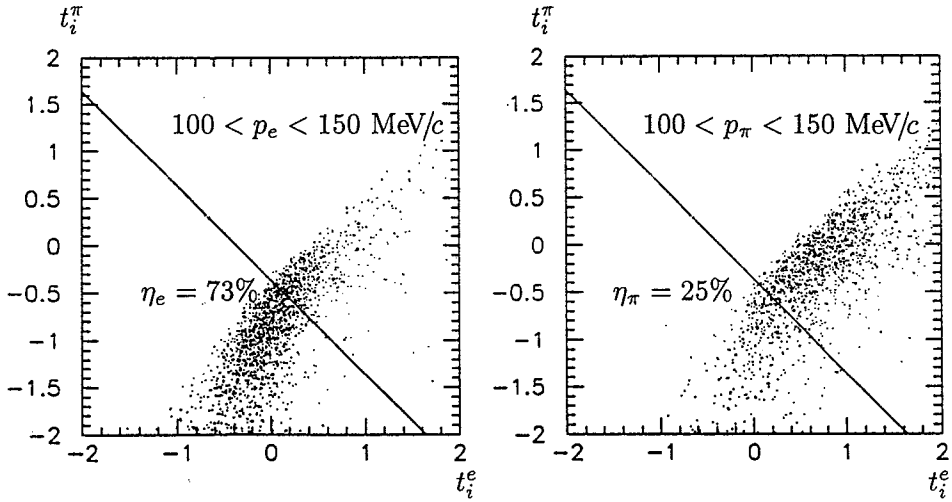


Figure 5.8: Scatter plot of t_i distributions of data secondary tracks for the 100 – 150 MeV/c momentum region, left for electrons and right for pions. t_i assuming that the particle is a pion is plotted on the vertical scale, assuming electron is plotted on the horizontal scale. True electrons should be found near $t_i^e = 0$. Electron identification has been performed using the S1/Cherenkov cut.

time-of-flight. Testing the routine on a T433 sample from period 8 using a MC cut level of 5% Fig. 5.8 is obtained. The electron in this sample has been identified by the S1/Cherenkov cut, but still a fraction of pions remains as can be seen from the fact that fewer electrons pass the cut. Even at a MC cut level of 5%, 26% of the data is cut away, increasing to 60% with a cut level of 20%. A lot of events are lost without much enhancement of the quality of the final data sample.

Since for a large fraction of the data studied in this thesis the time-of-flight information is missing, it was decided not to use this method for $e^\pm/\pi^\pm$ separation. When TOF information is more readily available, this is a method that could be applied for all four track final states.

Chapter 6

Analysing Calibration Data

The large amount of data from the CPLEAR spectrometer makes possible many detailed studies of branching ratios. Data taken with a kaon trigger have been used to determine the mass difference between K^{*0} and $K^{*\pm}$. The value obtained was $4,4 \pm 1,7$ MeV [21]. Several branching ratios, using minimum bias data, have been studied. For instance, the relative branching ratio of $p\bar{p} \rightarrow K^+K^-$ to $p\bar{p} \rightarrow \pi^+\pi^-$ has been determined to $0,205 \pm 0,016$ [29, 58]. This result and results of branching ratios involving ρ and f_2 mesons that will be covered in the following section, can be used to determine the fraction of P-wave annihilation in a 15 bar hydrogen target. This is described in Section 6.2. These studies are done in order to check the behaviour of our Monte Carlo simulation.

6.1 $p\bar{p} \rightarrow \rho\pi^0, \rho\pi^0\pi^0, \rho\pi^0\pi^0\pi^0, \rho\omega$ and $f_2\pi^0, f_2\eta$

This work is also reported in [59]. Here, results are given for annihilation into $\rho\pi^0, \rho\pi^0\pi^0, \rho\pi^0\pi^0\pi^0, \rho\omega, f_2\pi^0$ and $f_2\eta$, where ρ and f_2 decays into $\pi^+\pi^-$. Of these branching ratios none has been measured at the fraction of P-wave annihilation in the CPLEAR target and $\rho\pi^0\pi^0\pi^0$ has not been measured at all. Reliable values for these branching ratios are important for comparison with QCD based theoretical calculations [60].

Period	Events	2 tracks	Pass cuts	ρ -peak	f_2 -peak
P8M1T1	1081816	28,9%	14,6%	3,0%	0,85%
P8M2T1	1272182	32,0%	13,9%	2,8%	0,81%
P8 total	2353998	30,6%	14,2%	2,9%	0,83%
P9M1T1	435111	31,9%	13,4%	2,8%	0,77%
P9M2T1	302311	31,1%	11,5%	2,3%	0,67%
P9 total	737422	31,6%	12,6%	2,6%	0,73%
P8 & P9	3091420	30,8%	13,8%	2,8%	0,81%

Table 6.1: *The minimum bias data sample and the effect of the cuts. The peaks are defined as the tabulated mass value $\pm \frac{\Gamma}{2}$.*

6.1.1 Processing of Data and Monte Carlo

All minimum bias data from period 8 and 9 have been analysed. For P8, this means a total of 2,35 million events from 21 tapes of both magnet polarities. P9 data includes 10 tapes of both M1 and M2 giving 0,74 million events, see Table 6.1.

Only two track events (as defined by the Track Fit program) have been analysed. These events, 30,8% of the total minimum bias sample, have been subject to the following cuts:

- Opposite charge.
- The difference in φ between Track Fit and the hit wire in DC6 is less than 5 mrad.
- The χ^2 of the Vertex Fit is less than 2,5.
- The vertex position is found to be within a cylinder of 10 cm length and 1,5 cm radius.
- The shortest distance from each track to the common vertex is less than 4 cm.

Various final states of $p\bar{p}$ annihilation contributing to $\pi^+\pi^-$ events have been generated using the CPGEANT simulation program [42]. A list of these channels can be found in Table 6.2. The proposed $a_X(1565)$ [61] has also been included.

All Monte Carlo channels have been subject to the same cuts as the data, after first making sure that they pass trigger 1. The result can be

Channel	Events	Trigger 1	2 tracks	Pass cuts	ρ -peak	f_2 -peak
$\rho\pi^0$	250000	98,3%	82,9%	33,6%	16,5%	0,7%
$\rho\pi^0\pi^0$	100000	98,4%	82,0%	32,2%	16,2%	0,7%
$\rho\pi^0\pi^0\pi^0$	200000	98,4%	80,9%	30,5%	15,3%	0,7%
$\rho\eta$	137458	98,9%	59,6%	23,5%	11,9%	0,4%
$\rho\omega$	50000	99,7%	10,3%	3,3%	1,58%	0 %
$\rho\omega \rightarrow \pi^0\gamma$	150000	98,4%	83,0%	32,6%	17,2%	0,07%
$f_2\pi^0$	600000	83,4%	57,1%	22,4%	0,7%	9,35%
$f_2\eta$	400000	89,0%	47,4%	16,7%	0,6%	7,35%
$a_X\pi^0$	50000	82,7%	51,0%	19,0%	0,2%	2,0%

Table 6.2: *Generated minimum bias Monte Carlo channels and the effect of the cuts. The percentage of events in the different peaks is then the acceptance of the channel. The peaks are defined as the tabulated mass value $\pm \frac{\Gamma}{2}$.*

used for determining acceptances for the various channels, as well as giving the shapes of the distributions in the invariant mass and momentum spectrum, which will later be used for fits to the data.

Note that the ω and η mesons have decay branching ratios into neutrals of 8,5% and 70,8% respectively. Thus, their acceptances are correspondingly lower, since only events with two charged tracks pass the cuts.

6.1.2 Fitting the Invariant Mass Spectrum

After the cuts on data described in the previous section have been applied 13,8% of the events remain. For these events, the invariant mass is calculated assuming that both tracks are pions. The invariant mass distribution is given in Fig. 6.1. The cutoff at about 450 MeV/ c^2 is due to the detector acceptance. Above that, one can clearly see two peaks sitting on a falling background. The first one comes from $\rho \rightarrow \pi^+\pi^-$, the second one from $f_2 \rightarrow \pi^+\pi^-$. The background under these peaks has been fitted to various functions, see Table 6.3, together with two or three MC generated peaks for ρ , f_2 and a_X above 500 MeV/ c^2 . Including a_X improves the fit in all cases. This means that there is an excess of events for high invariant masses. The best form for the background is found to

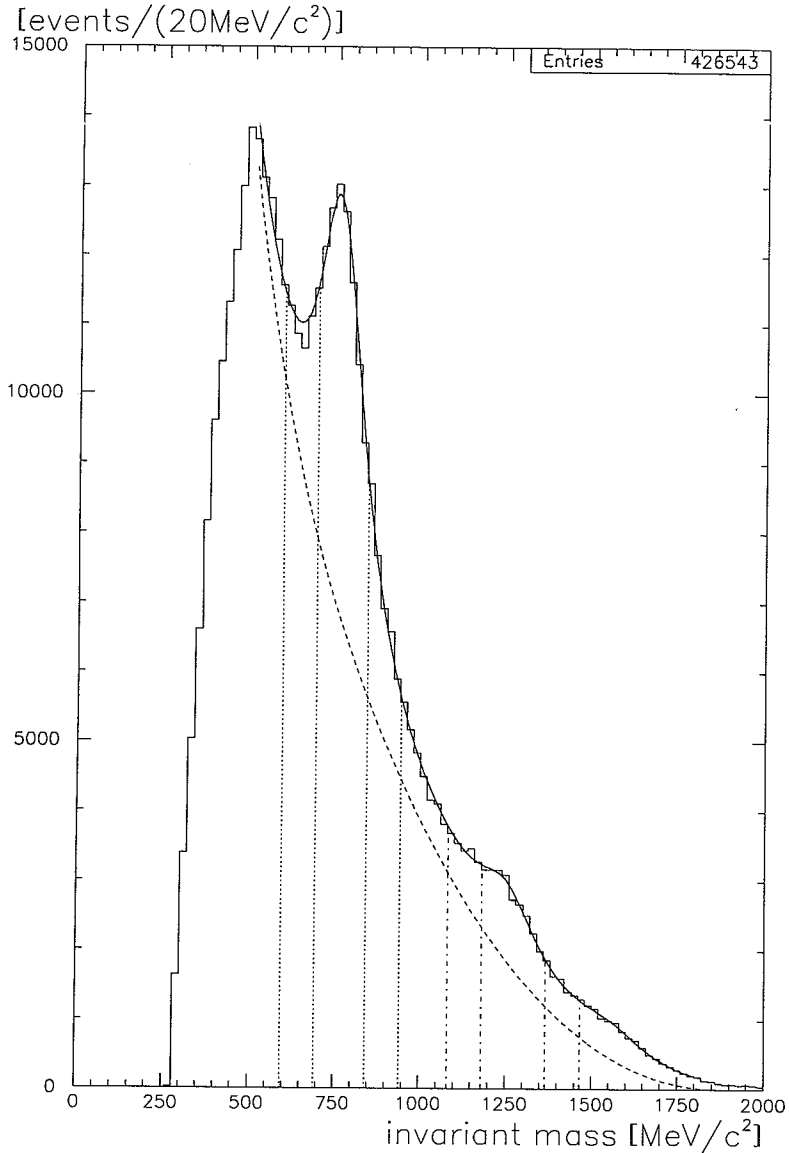


Figure 6.1: Invariant mass spectrum for the $\pi^+\pi^-$ tracks. The fit is background + three Breit-Wigner functions, as described in the text. The dashed line shows the background that is used for Fig. 6.2. The dotted bands are the slices used for the ρ -peak analysis, the dash-dotted ones are the slices in the f_2 case.

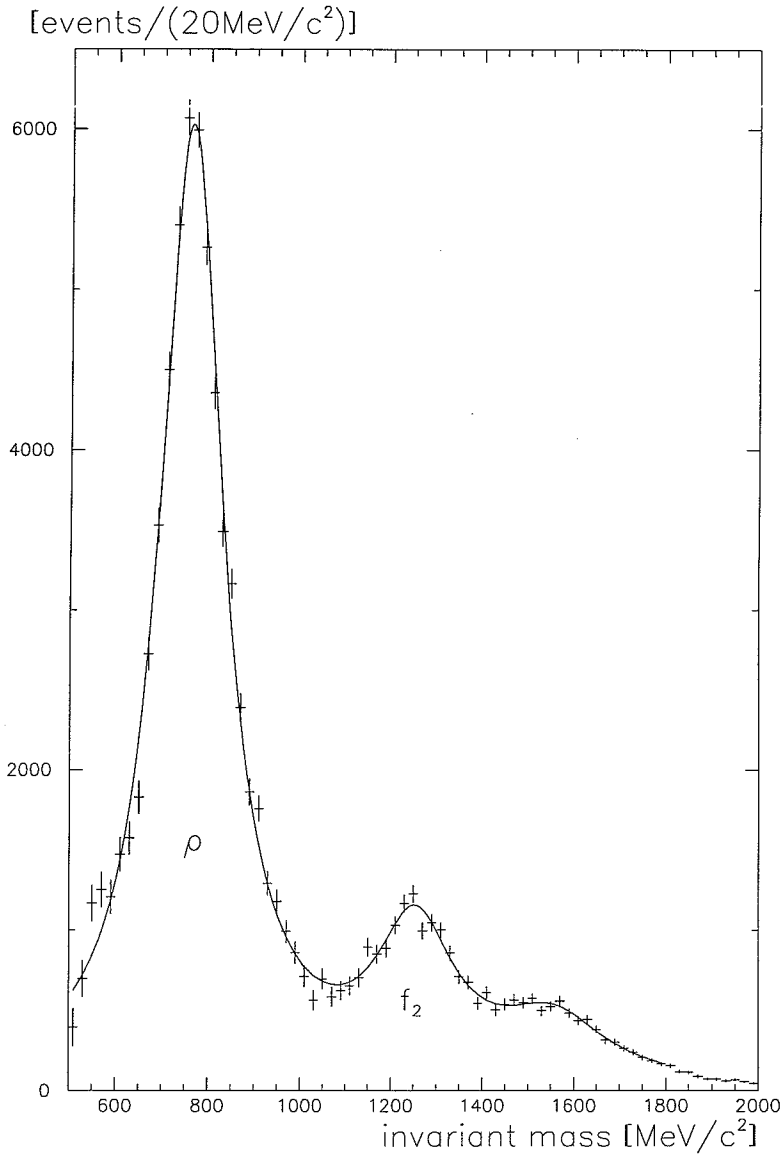


Figure 6.2: *Invariant mass spectrum for the $\pi^+\pi^-$ tracks after the background has been subtracted. The fit is by three Breit-Wigner functions, as described in the text.*

Power functions: $F(m) = (p_5 - m)^{p_1} e^{p_2} + (p_5 - m)^{p_3} e^{p_4}$					
Number of parameters	With a_X	$\chi^2/d.o.f.$	Events in ρ -peak [k]	Events in f_2 -peak [k]	Events in a_X -peak [k]
2		2428/68	$26,9 \pm 0,4$	$4,38 \pm 0,17$	
2	Y	454/67	$32,0 \pm 0,4$	$10,3 \pm 0,2$	$3,92 \pm 0,07$
3		820/67	$31,7 \pm 0,4$	$8,70 \pm 0,22$	
3	Y	330/66	$32,6 \pm 0,4$	$9,43 \pm 0,21$	$2,50 \pm 0,10$
4		341/66	$37,4 \pm 0,4$	$5,64 \pm 0,18$	
4	Y	325/65	$37,5 \pm 0,6$	$6,14 \pm 0,19$	$0,84 \pm 0,16$
5		336/65	$37,5 \pm 0,4$	$5,77 \pm 0,22$	
5	Y	268/64	$36,0 \pm 0,2$	$8,07 \pm 0,19$	$1,97 \pm 0,11$
Exponentials: $F(m) = e^{p_1 m + p_2} - p_4 e^{p_3(p_5 - m)}$					
Number of parameters	With a_X	$\chi^2/d.o.f.$	Events in ρ -peak [k]	Events in f_2 -peak [k]	Events in a_X -peak [k]
4		440/66	$34,2 \pm 0,4$	$7,55 \pm 0,25$	
4	Y	354/65	$34,2 \pm 0,4$	$8,35 \pm 0,19$	$1,24 \pm 0,10$
5		440/65	$34,2 \pm 0,9$	$7,55 \pm 0,37$	
5	Y	354/64	$34,2 \pm 0,3$	$8,36 \pm 0,20$	$1,24 \pm 0,10$
Polynomial: $F(m) = p_1 + p_2 m + p_3 m^2 + p_4 m^3 + p_5 m^4 + p_6 m^5$					
Number of parameters	With a_X	$\chi^2/d.o.f.$	Events in ρ -peak [k]	Events in f_2 -peak [k]	Events in a_X -peak [k]
6		314/64	$36,3 \pm 0,5$	$5,81 \pm 0,20$	
6	Y	274/63	$34,6 \pm 0,2$	$8,40 \pm 0,23$	$2,71 \pm 0,11$

Table 6.3: *Results of fits to the invariant mass spectrum. The fit includes background + one parameter for the scaling of each of the fitted MC peaks. m is the invariant mass variable and the number of events given are in units of 1000.*

be the power function in Table 6.3, also used in [62].

The invariant mass spectrum in Fig. 6.1 is now fitted with the selected background form and three Breit-Wigner distributions for the resonances. This is the fit shown in Fig. 6.1, with a χ^2 -sum of 103 for 50 degrees of freedom. Subtracting the background the spectrum is shown in Fig. 6.2, with the three Breit-Wigner functions plotted as a curve. The f_2 peak is slightly shifted to a lower mass compared to the world average value. This is however consistent with the MC generated peaks if one includes a non negligible fraction of $f_2\eta$ events, since the f_2 in this case is sitting near the edge of phase space and therefore the Breit-Wigner becomes distorted. The number of $f_2\eta$ events required to make the fit of the invariant mass spectrum acceptable is consistent with the amount of $f_2\eta$ found in the

momentum spectrum (Section 6.1.4).

The FWHM of the peaks are larger than the tabulated values [10] due to the detector resolution, but again this is confirmed by Monte Carlo. In the Monte Carlo case, these distributions are 5% (ρ) and 19% (f_2) broader than the results of the Breit-Wigner fit to the data. This is presently included in the systematic errors, since CPGEANT version 4.500 is not corrected for this effect. To estimate the number of events in the peaks in the invariant mass plot the area under the fitted Breit-Wigner $m \pm \frac{\Gamma}{2}$ (Fig. 6.2) is used, giving 36400 ± 900 events in the ρ -peak and 7240 ± 600 events in the f_2 -peak.

6.1.3 Fitting the Momentum Spectrum

In order to select final states with ρ meson production a cut of $\pm \frac{\Gamma}{2}$ has been made in the invariant mass spectrum around the tabulated [10] ρ -mass $768,3 \text{ MeV}/c^2$, see Fig. 6.1. The momentum distribution for the $\pi^+\pi^-$ system in this invariant mass range is plotted in Fig. 6.3. The background shape of the non ρ meson production was estimated in the following way: a slice of $100 \text{ MeV}/c^2$ on either side of the ρ -peak in the invariant mass distribution was selected (Fig. 6.1). The momentum distributions of the $\pi^+\pi^-$ system in these slices (Fig. 6.3) have been added together with the weights 0,69 for the left background and 0,80 for the right background. The weight factors correspond to the best fit of the data in Fig. 6.3.

The amount of events in each of the channels $\rho\pi^0, \rho\pi^0\pi^0, \rho\pi^0\pi^0\pi^0, \rho\omega$ is then given by a χ^2 -fit of Monte Carlo generated distributions of these channels to the data in Fig. 6.3. If the $\rho\pi^0\pi^0$ and $\rho\pi^0\pi^0\pi^0$ channels are omitted, the fit to the momentum spectrum fails to reproduce the correct number of ρ events, as found in Fig. 6.1. Channels with four or more π^0 's have not been included, since $\pi^+\pi^-4\pi^0$ is only about 10% of the $\pi^+\pi^-3\pi^0$ channel [63]. The $\rho\eta$ and $\rho\pi^0\pi^0$ channels give very similar momentum spectra of the ρ and can thus not be fitted simultaneously. The world average value $WA = 0,312 \pm 0,039$ is therefore used for the $\rho\eta/\rho\pi^0$ relative branching ratio obtained in experiments using liquid hydrogen [64, 65, 66, 67] and one result [68] which is an extrapolation to pure S-wave annihilation. The relative branching ratio $\rho\eta/\rho\pi^0$ has been shown to vary very little from S-wave to P-wave annihilation [60].

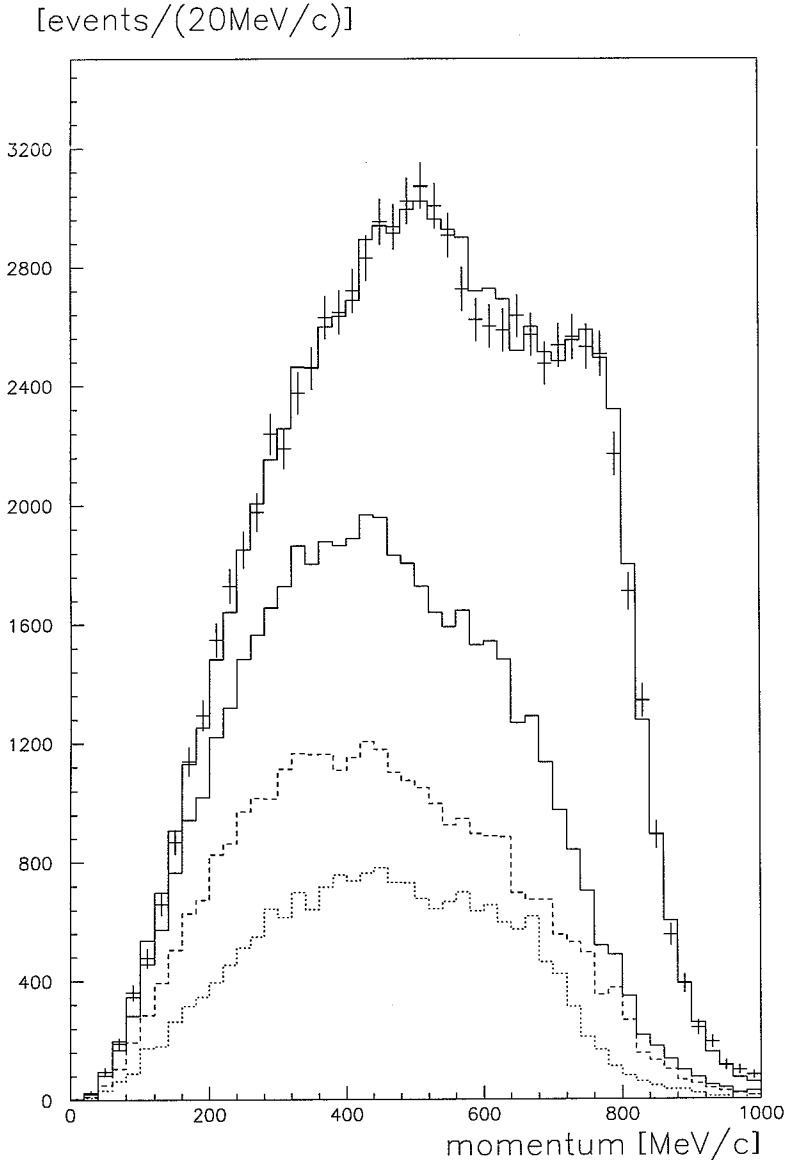


Figure 6.3: *Momentum spectrum of ρ and its background. The solid line through the data points is the best fit of background + Monte Carlo generated peaks. The dashed line is the background from the left slice, the dotted one is from the right slice. Adding the two gives the lower solid line. Note that the fitted MC distributions are not included in the figure but are shown in Fig. 6.4.*

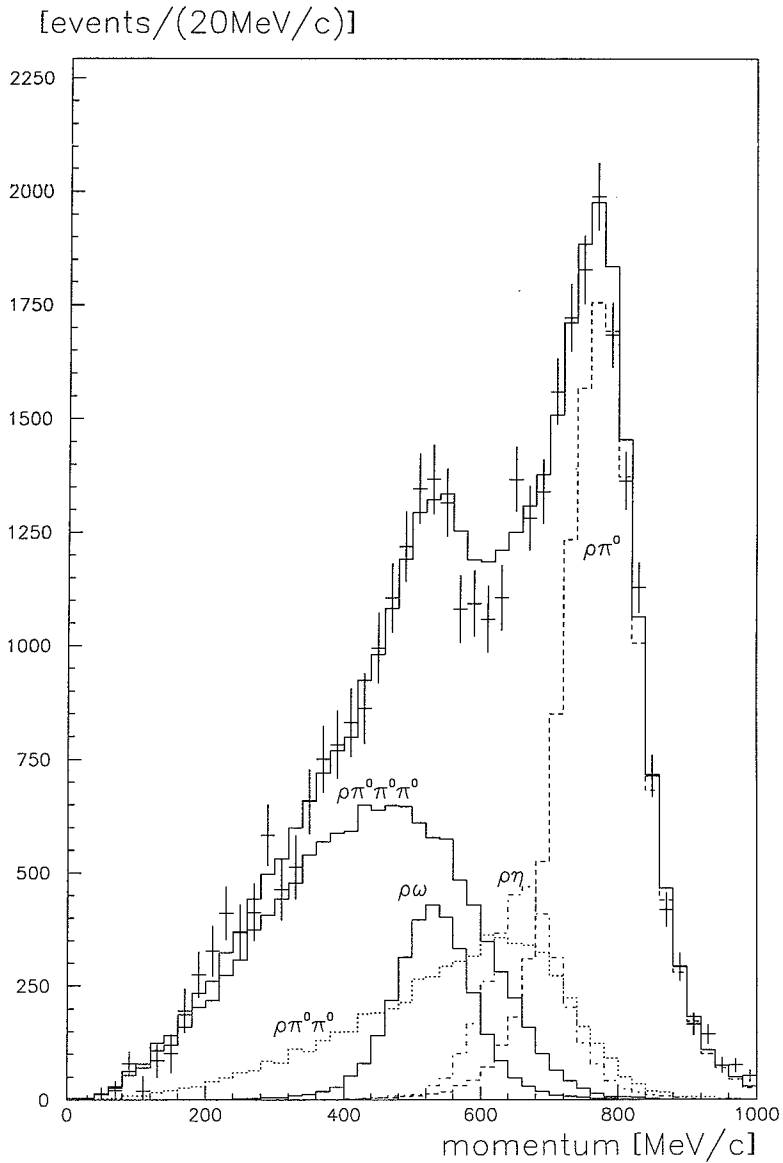


Figure 6.4: Momentum spectrum of ρ with subtracted background and fitted Monte Carlo peaks as described in the text.

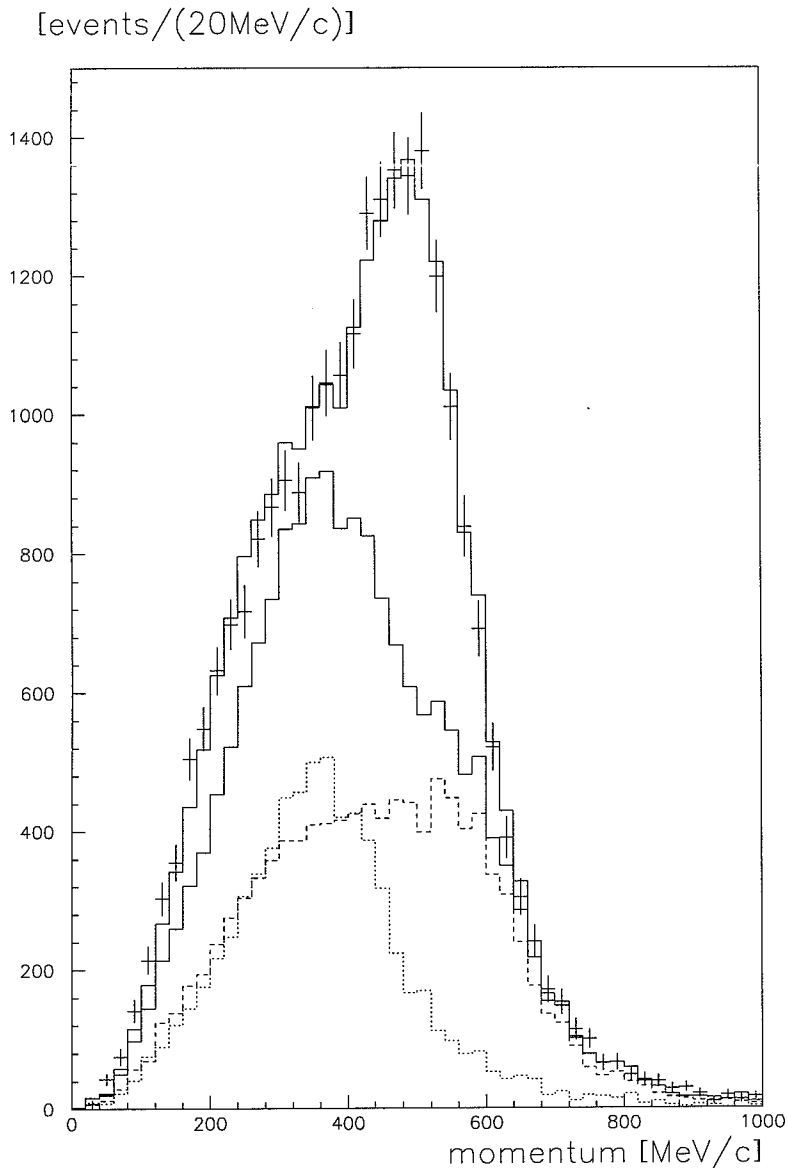


Figure 6.5: *Momentum spectrum of f_2 and its background. The solid line through the data points is the best fit of background + Monte Carlo generated peaks. The dashed line is the background from the left slice, the dotted one is from the right slice. Adding the two gives the lower solid line. Note that the fitted MC distributions are not included in the figure but are shown in Fig. 6.6.*

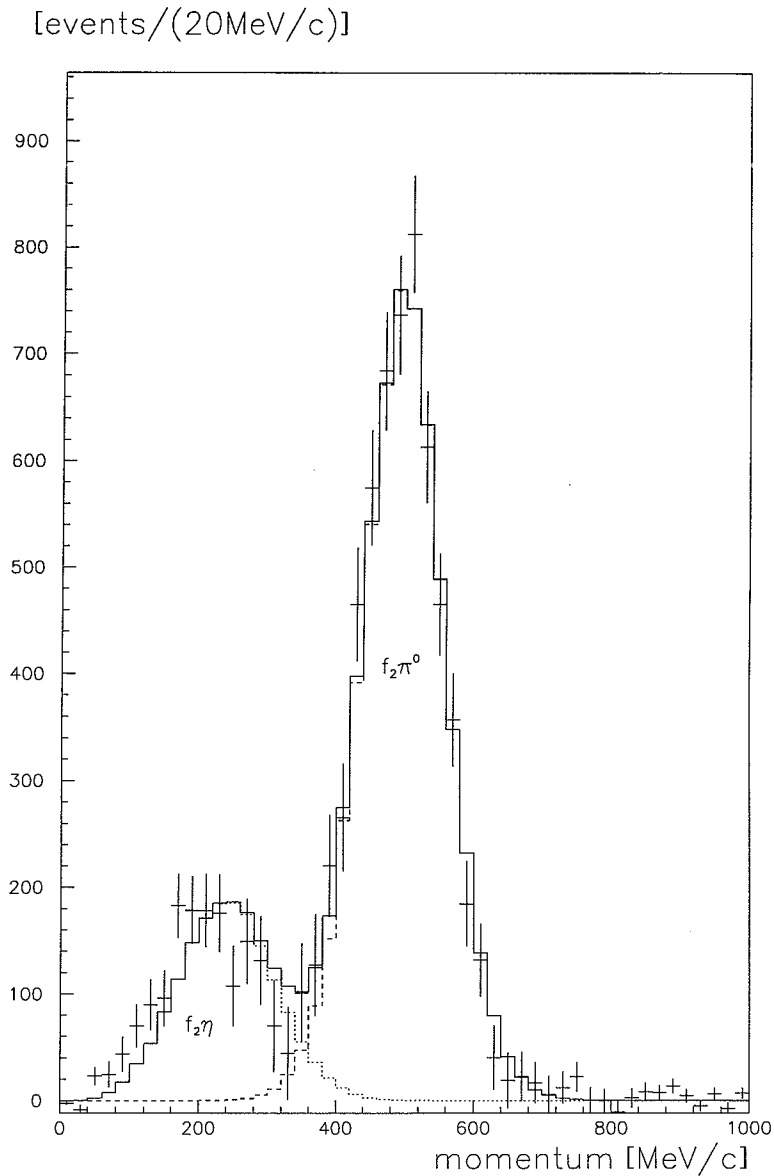


Figure 6.6: *Momentum spectrum of f_2 with subtracted background and two fitted Monte Carlo peaks as described in the text.*

Channel	Events	Statistical error	Systematic error
$\rho\pi^0$	73,7k	$\pm 3,1k$	$\pm 1,2k$
$\rho\pi^0\pi^0$	38,0k	$\pm 10,0k$	$\pm 5,0k$
$\rho\pi^0\pi^0\pi^0$	78,7k	$\pm 8,8k$	$\pm 10,0k$
$\rho\omega$	186,1k	$\pm 30,9k$	$\pm 8,4k$
$f_2\pi^0$	61,1k	$\pm 3,0k$	$\pm 1,0k$
$f_2\eta$	22,5k	$\pm 7,1k$	$\pm 7,1k$

Table 6.4: *Number of resulting events in each channel as defined in the text. The statistical errors are calculated using MINOS [69].*

The fitted momentum spectrum of ρ with the background subtracted is shown in Fig. 6.4.

The ratio of events $x(1)$ from $\rho\eta/\rho\pi^0$ and the number of events in the background $x(2)$ has been included in the χ^2 -sum of the fit as:

$$\frac{(x(1) - WA)^2}{0,039^2} + \frac{(x(2) - N)^2}{900^2}$$

where N is the number of events 49000 ± 900 in the background determined from the invariant mass spectrum. This gives a χ^2 -sum of 48 for 45 degrees of freedom, see Fig. 6.3.

In the f_2 case a similar method was used (Fig. 6.5-6.6) to determine the $f_2\eta/f_2\pi^0$ relative branching ratio. The number of events N in the background was set to 16040 ± 600 and was included in the χ^2 -sum of the fit in the same way. Since the Monte Carlo peaks in the invariant mass spectrum were seen to be around 20% too broad this has been corrected for. The χ^2 -sum is 64 for 47 degrees of freedom, see Fig. 6.5.

6.1.4 Branching Ratios and Discussion of Errors

The statistical error of the background, the peak and the Monte Carlo has been added quadratically bin by bin. The fitting of the observed spectra with the generated Monte Carlo peaks and the known acceptances then gives the number of “real” events for each channel, see Table 6.4. The values for the relative branching ratios are found in Table 6.5 together with the total error.

Branching ratio	This experiment	S-wave Ref. [60]	P-wave Ref. [60]	Liquid H_2 [64, 65, 72, 73]
$\rho\omega/\rho\pi^0$	$2,53 \pm 0,43$	$1,22 \pm 0,29$	16 ± 5	$1,45 \pm 0,17$
$\rho\pi^0\pi^0/\rho\pi^0$	$0,51 \pm 0,15$	-	-	$0,87 \pm 0,16$
$\rho\pi^0\pi^0\pi^0/\rho\pi^0$	$1,06 \pm 0,19$	-	-	-
$f_2\eta/f_2\pi^0$	$0,37 \pm 0,16$	$0,07 \pm 0,07$	$0,11 + 0,05$	-

Table 6.5: *Relative branching ratios in $p\bar{p}$ annihilation, from this experiment and compared with previous measurements, see Section 6.1.5.*

There are several sources of possible systematic errors. In the invariant mass spectrum of Fig. 6.2 it is clear that the ρ peak extends under the f_2 peak and vice versa. This has been corrected for by obtaining this (small) contribution from Monte Carlo simulations and subtracting it. Moreover, there is an amount of resonant events in the background slices chosen according to Fig. 6.1. This has been corrected for in the same way. Systematic errors could also be introduced by detector limitations; for example in the reactions $p\bar{p} \rightarrow \rho\pi^+\pi^-$ and $p\bar{p} \rightarrow \rho\pi^0\pi^+\pi^-$, which have high branching ratios, the detector could miss the two extra charged pions and such events would then contribute to the data sample. This error source has however been ruled out because in simulations of these channels it is seen that very few events survive the cuts. It is also seen from comparison of Monte Carlo simulations with the data that the contribution from the $\rho f_0\pi^0$ channel is negligible.

6.1.5 Comparison With Other Experiments

The results from this experiment for the ratios $\rho\omega/\rho\pi^0, \rho\pi^0\pi^0/\rho\pi^0$ and $\rho\pi^0\pi^0\pi^0/\rho\pi^0$ are given in Table 6.5 together with the earlier results from liquid hydrogen and the recent results from the Asterix experiment [60] extrapolated to pure S- and P-wave annihilation. The measurements in liquid hydrogen corresponds to a fraction of $(8,6 \pm 1,1)\%$ P-wave [70]. This, however, is contradicted by [71], where a value of $(18 \pm 2)\%$ is obtained.

For the $\rho\pi^0$ and $\rho\omega$ channels there are several published results from experiments in liquid hydrogen, both from bubble chambers and spectrometers. There is one earlier result on the $\rho\pi^0\pi^0$ [72] whereas the

$\rho\pi^0\pi^0\pi^0$ channel has not been measured before. The results obtained in this study for these channels can also be compared to the charged channels, $\rho\pi^+\pi^-$ and $\rho\pi^+\pi^-\pi^0$, which have large branching ratios, $(5,8^{+0,3}_{-1,3})\%$ and $(7,3 \pm 1,7)\%$, respectively [64]. The larger branching ratios for these channels compared to the case with two or three π^0 's can be understood since a larger number of states are available for the charged channels. For $\rho\pi^0$ [64] gives the branching ratio $(1,4 \pm 0,2)\%$ and [65] gives $(1,6 \pm 0,1)\%$. For $\rho\omega$ the most accurate measurement is reported by [73], which quotes a branching ratio of $(2,26 \pm 0,23)\%$. The $\rho\omega/\rho\pi^0$ ratio then becomes $1,45 \pm 0,17$ from these measurements. It is important to note that the quoted errors are statistical only.

6.2 Determining the Fraction of P-wave Annihilation

Estimates of the fraction of P-wave annihilation for different target densities can be used to check models for the de-excitation of protonium. The Asterix collaboration at LEAR has determined the absolute branching ratios for $p\bar{p}$ annihilation into $\rho\pi^0$ and $\rho\omega$ for initial S- and P-states separately [60] to: $\Gamma_S(\rho\pi^0) = (1,56 \pm 0,21)\%$, $\Gamma_P(\rho\pi^0) = (0,40 \pm 0,09)\%$, $\Gamma_S(\rho\omega) = (1,91 \pm 0,37)\%$, $\Gamma_P(\rho\omega) = (6,38 \pm 1,28)\%$. The result of the relative branching ratio R of $\rho\omega/\rho\pi^0$ then makes it possible to calculate the fraction of P-wave annihilation f_P at a pressure of 15 bar through the relation:

$$f_P = \frac{\Gamma_S(\rho\omega) - R\Gamma_S(\rho\pi^0)}{R(\Gamma_P(\rho\pi^0) - \Gamma_S(\rho\pi^0)) - (\Gamma_P(\rho\omega) - \Gamma_S(\rho\omega))}$$

The result is:

$$f_P = 0,28 \pm 0,086_{external} \pm 0,08_{internal} = 0,28 \pm 0,12_{total}$$

where the errors have been added quadratically. The dominant external error is coming from the uncertainties in the absolute branching ratios. This result is in good agreement with the previous measurement [58] of f_P through the relative branching ratio of the channels K^+K^- and $\pi^+\pi^-$ of $f_P = 0,379 \pm 0,086$ for 15 bar gaseous hydrogen. Combining the two measurements gives a value of $0,345 \pm 0,070$. This result is consistent with cascade calculations of [74, 75].

Chapter 7

Neutral Kaon Decays to $\pi^{\pm}l^{\mp}\bar{\nu}_l(\nu_l)$

In order to study the semileptonic asymmetries defined in Section 2.2.3 it is necessary to obtain the different decay rates $\bar{R}_+(t)$, $\bar{R}_-(t)$, $R_+(t)$ and $R_-(t)$, defined in eq. 2.15 and 2.16. In order to get these rates, the number of events in the different categories $\bar{N}_+(t)$ etc. has to be corrected for the acceptance of the detector. K^+ and K^- have different nuclear cross sections in matter, which causes the detector to see more of K^+ . The quantity $\alpha = N_{K^+}/N_{K^-}$ should be independent of trigger conditions, magnetic field, kaon momentum and decay geometry. A detailed study [76] using $K^0 \rightarrow \pi^+\pi^-$ events at early lifetimes finds the value $\alpha = 1,131 \pm 0,010$ after applying small corrections for the differences in phase space for this type of decay compared to $K^0(\bar{K}^0) \rightarrow \pi^{\pm}l^{\mp}\bar{\nu}_l(\nu_l)$. A model dependent check on this value has been done, using eq. 2.21, see Section 7.4.1.

It is also possible that the probability to detect an $e^+\pi^-$ pair and an $e^-\pi^+$ pair is not the same. For this analysis, the value of the parameter η defined in Section 2.2.3 is determined from data using eq. 2.20. Since this requires knowledge of the value of δ the world average value is used [10]. δ is determined using K_L decays for lifetimes greater than $14\tau_S$ and in order to stay compatible with this only the lifetime region $14-30\tau_S$ is used. The dependence of the values of η and Δm on the cuts made on data is checked in the following section. Δm is determined from a fit to

eq. 2.17 in the lifetime range $3\text{--}14\tau_S$ assuming no background. The final value of η is found to be very close to one, $\eta = 1,002 \pm 0,019$. Again, this is consistent with what is found using a model dependent fit to eq. 2.22, see Section 7.4.1.

In order to determine the amount of background in the final data sample Monte Carlo studies of the acceptances for the decay channels $\pi e \nu$, $\pi \mu \nu$, $\pi \pi$ and $\pi \pi \pi$ have been made, see Section 7.2. In Section 7.3 the fitting procedure is described and in Section 7.4 the results of fits to data using eq. 2.17, 2.18 and 2.19 are presented.

7.1 Cuts to Select Semileptonic Events

All events taken with triggers that give a secondary vertex outside PC1 or PC2 from P8 to P13 have been analysed. For P8 and P9 this means 1,3 M events on mini-DST with trigger T433. For 1991, P10–P13, mainly trigger T423 was used, but some tapes in P11 were taken with T90423 and in P13 T4423 was used with a total of 2,9 M events on mini-DST. The data from 1991 suffers from the fact that PC2 was dead and the Cherenkov boxes started to lose freon in P12, see Section 4.5. Also, the efficiency of the time-of-flight system was low, so it was decided not to use the method described in Section 5.2 at all. Equal amounts of M1 and M2 data have been analysed, thus reducing systematic errors coming from possible asymmetries in the detector.

In order to select events originating from semileptonic decays of the neutral kaons the following cuts were made:

- Four tracks found both by the Pattern Recognition and Track Fit programs, two primary (with hits in the PCs) and two secondary.
- Charge balance on the primary and secondary tracks.
- Track quality: at least 4 xy -points for primary tracks, at least 3 xy -points for secondary tracks and at least 2 z -points for all tracks.
- One of the primary tracks is a kaon defined by dE/dx in S1, Cherenkov pulse height and a loose cut on the TOF difference between the primary tracks. This track should have hit the same S1 and S2 sector.

- No two tracks with an extrapolated path length in the same PID module.
- A 1-constraint fit to the K^0 mass at the primary vertex has a probability greater than 10%.
- Testing a 5-constraint hypothesis, that selects $K^0 \rightarrow \pi^+\pi^-$ events, yields a probability less than 10%.
- The S1/Cherenkov cut defined in Section 5.1.1 finds one $e^\pm$. This introduces a momentum cut of 250 MeV/c.
- A 2-constraint fit, that assigns the missing momentum at the secondary vertex to a neutrino has a probability larger than 10%.
- With the improved parameters after the 2-constraint fit, the momentum of the kaon track should lie between 350 and 800 MeV/c. All other tracks should have a momentum of less than 750 MeV/c.

After these standard cuts 104000 events remain. The constrained fits mentioned are developed at Saclay [77]. So far, no cut on the vertices has been made. The reason is that the improved parameters from the 2-constraint fit should be used, where extrapolations of the track parameters give new vertices for the primary and the secondary tracks. The distributions of primary vertices are already shown in Fig. 3.6. Here, a cut has been chosen that cuts away 3% of the tail of each distribution, which results in cutting events with $r_p > 2,1$ cm and z_p outside $-6,8 < z_p < 7,4$ cm.

The cuts that remain to be made are cuts on the secondary vertex position and the following angles:

- θ_p The two primary tracks should not be close to parallel or back to back.
- θ_{K^0} The radius vector between the two vertices should be parallel to the flight direction of the K^0 . This can be checked both in the transverse plane ($\theta_{K^0}^T$) or in space (θ_{K^0}), with different resolutions for the two.
- $\theta_s^{K^0}$ The opening angle between the two secondary tracks in the K^0 rest frame should not be close to 180° . This cuts away events where the K^0 has decayed to a $\pi^+\pi^-$ pair, since they are necessarily back to back in the K^0 rest frame.

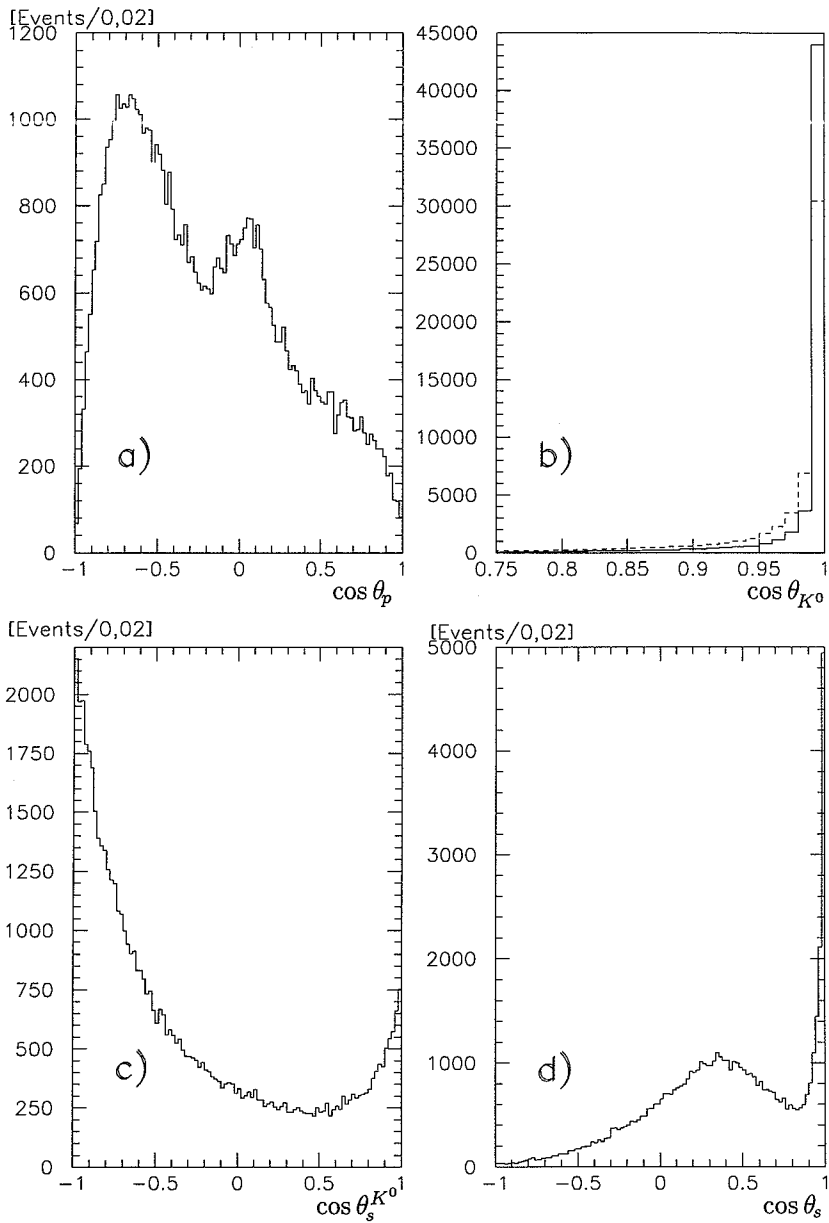


Figure 7.1: Distributions of a) $\cos \theta_p$ b) $\cos \theta_{K^0}^T$ (solid line), $\cos \theta_{K^0}$ (dashed line) c) $\cos \theta_s^{K^0}$ and d) $\cos \theta_s$ before any cuts on these variables are made.

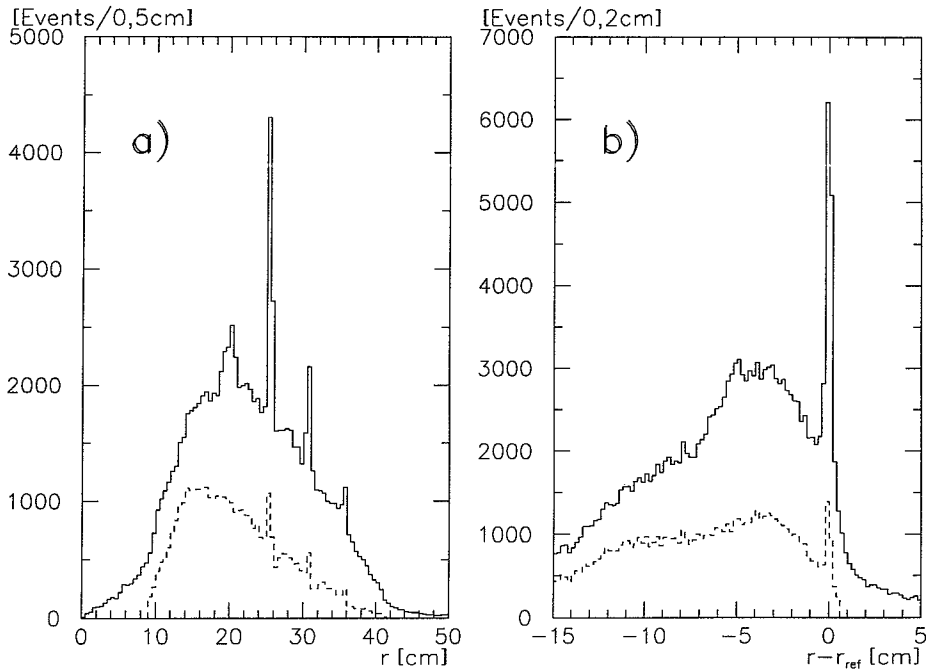


Figure 7.2: *Distribution of secondary vertices a) as a function of r , in b) $r - r_{ref}$ is shown. The peak at 20 cm is at the radius of the support structure of the DC, the three following peaks are at DC1, DC2 and DC3 radii. The dashed lines show the distributions after all cuts are made.*

θ_s The opening angle between the two secondary tracks should not be close to 0° . This can be used to reject events where a photon has produced an e^+e^- pair, see Section 5.1.1.

Fig. 7.1 shows these distributions before cuts are made. The distribution of secondary vertices as a function of r is given in Fig. 7.2a. The spikes seen in the figure come from DC1, DC2 and DC3 and stem mainly from photons that have converted to an e^+e^- pair in the chamber. Also, some of these vertices are caused by the fact that the fitting program prefers to put the vertex on a hit, and not in the region after. In the low r region no tracks ought to have $r < r_{PC}$ so it is necessary to cut away these events. Also, no vertex should be found outside DC4 since a minimum of three DC hits are required to make a secondary track. Since no track should have a hit associated to it inside the vertex, taking $r - r_{ref}$, where r_{ref}

Cut	Variable	1	2	3	4
A	$r_{PC} - r <$ $r - r_{ref} <$	0 cm	0,6 cm	1,2 cm	—
B	$ \cos \theta_p <$ $-\cos \theta_s <$	0,96	0,97	0,98	0,99
C	$\cos \theta_{K^0}^T >$	0,985	0,94	0,92	0,87
	$\cos \theta_{K^0} >$	0,95	0,85	0,81	0,75
D	$\cos \theta_s^{K^0} >$	-0,82	-0,86	-0,92	-0,96
E	$\cos \theta_s <$	0,86	0,89	0,92	0,95

Table 7.1: *Definition of cut values 1–4. A lower value means a harder cut, with events fulfilling the criteria above surviving the cut. Note that r_{PC} is the radius of PC2 in 1990 and PC1 in 1991, since PC2 malfunctioned.*

is the reference point or first chamber hit for each track (Fig. 7.2b) this quantity should always be less than zero. In this figure, the spike from the chambers is even more prominent. Since the 2-constraint fit has a non-zero vertex resolution, one should not cut at $r - r_{ref}$ less than zero but rather less than some value r_{res} greater than zero.

In order to test the quality of the data sample different combinations of cuts have been tested. A value is assigned to each level of a cut, with a lower value denoting a harder cut. Table 7.1 summarizes these values. Cut A has already been discussed, see Fig. 7.2. Cut B is performed in order to reject events where the primary tracks are back to back or parallel or the secondary tracks are back to back. This could happen when a primary track is back-scattered in the PID and the resulting track goes through the detector and is detected as two tracks by the pattern recognition program. As can be seen from Fig. 7.1a and d not many events have this problem. Cut C is done in order to assure alignment between the K^0 and the radius vector between the two vertices, see Fig. 7.1b. The resolution on this angle has been checked using MC generated events of $K_L \rightarrow \pi e \nu$. This distribution is shown in Fig. 7.3 and indicates that a very stringent cut is not needed. Cut D is made in order to reduce what is left of $K_S \rightarrow \pi^+ \pi^-$ background. The distribution of MC generated events of this channel and of the $\pi e \nu$ channel are shown in Fig. 7.4. In principle, these events should be cut away by the cut on 5-constraint fit probability, but if the fit fails

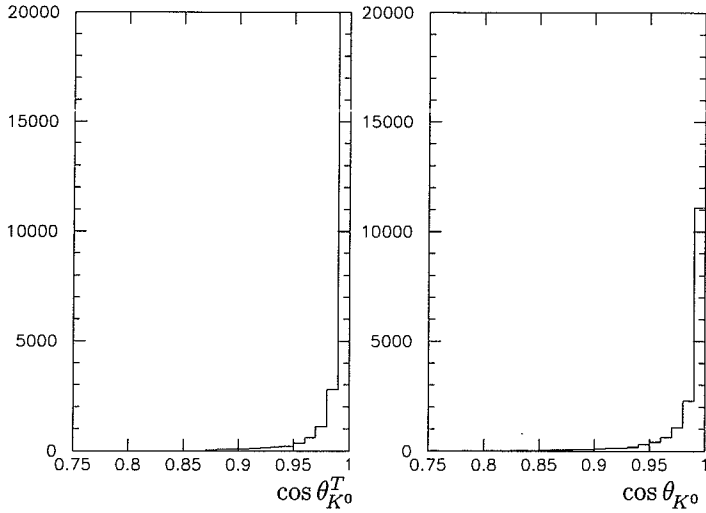


Figure 7.3: *Distributions of $\cos \theta_{K^0}$ in the transverse plane (left) and in space (right) from MC generated $K_L \rightarrow \pi \nu$ events.*

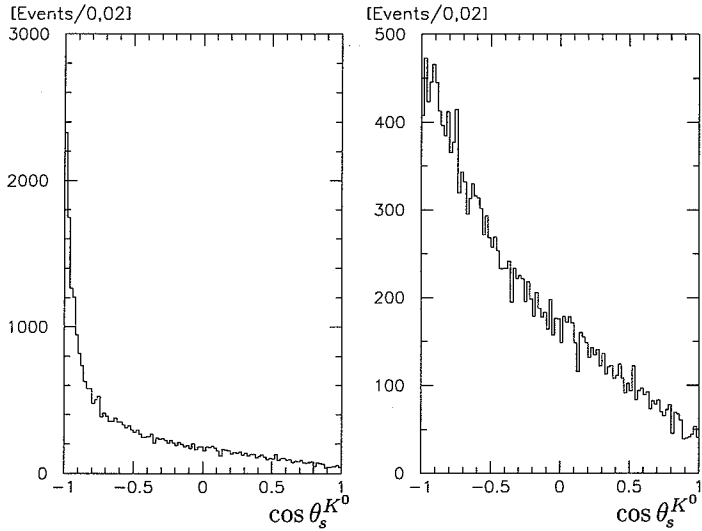


Figure 7.4: *Distributions of $\cos \theta_s^{K^0}$ for MC generated events of $K_S \rightarrow \pi^+ \pi^-$ (left) and $K_L \rightarrow \pi \nu$ (right).*

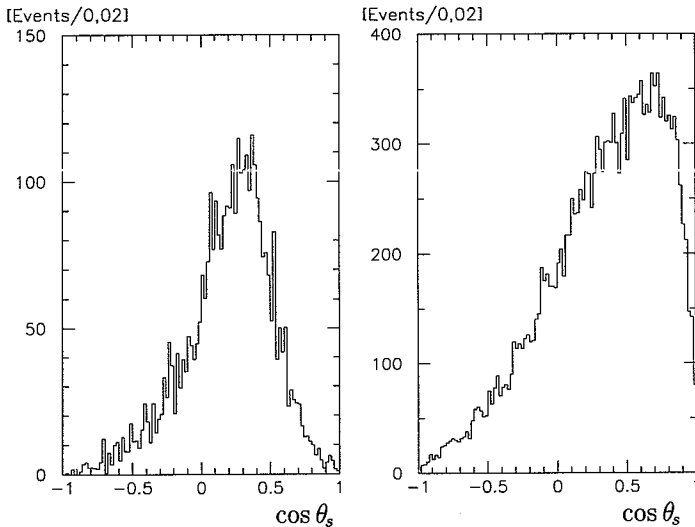


Figure 7.5: *Distributions of $\cos \theta_s$ for MC generated events of $K_S \rightarrow \pi^+ \pi^-$ (left) and $K_L \rightarrow \pi e \nu$ (right).*

the event is kept, which means that a fraction of the two-body decays survives. Fig. 7.1c shows this distribution for data, indicating that the 2π fraction is not too large in this data sample, but it is not possible to make a severe cut on this variable since a lot of the signal is then also cut away. Finally, Cut E is essential to make since it is not possible to model the channel $\gamma \rightarrow e^+ e^-$ correctly. A large fraction of the data is actually of this type, making a hard cut in this variable necessary, see Fig. 7.1d. Luckily, not much of the signal is found in this region, as is indicated by the Monte Carlo simulation of $K_L \rightarrow \pi e \nu$, see Fig. 7.5.

Varying the five cut parameters Table 7.2 is obtained. The total number of events after all the cuts varies from 29194 to 63521. Since the value of Δm is determined before to $\Delta m = (5,351 \pm 0,024)10^9 \hbar/s$ [10] this is used as a check on the quality of the data sample. The value of η is everywhere consistent within the errors. As the statistical error on η goes into the systematic errors of A_T , a cut configuration with many events is preferable. The two-body background at life-times larger than $14\tau_S$ is also negligible. The value of Δm varies little with the cut configuration but it is clear that the last three cannot be used because of the low value of Δm . As stated before, Cut E is the most crucial, since this

Cut A	Cut B	Cut C	Cut D	Cut E	η 14-30 τ_S	$\Delta m[10^9 \hbar/s]$
1 54938	1 54438	1 39388	1 26322	1 23496	1,006 $\pm$ 0,027 5698	5,47 $\pm$ 0,19
1 54938	4 54876	4 49854	4 45957	2 39132	0,992 $\pm$ 0,018 12700	5,15 $\pm$ 0,14
2 58286	3 58102	4 52451	2 41362	2 33766	1,004 $\pm$ 0,020 11009	5,48 $\pm$ 0,16
2 58286	3 58102	4 52451	2 41362	3 34518	1,005 $\pm$ 0,020 11161	5,37 $\pm$ 0,16
2 58286	3 58102	4 52451	2 41362	4 35742	1,010 $\pm$ 0,020 11363	5,38 $\pm$ 0,16
2 58286	3 58102	4 52451	3 44720	2 37027	1,002 $\pm$ 0,019 11988	5,26 $\pm$ 0,15
2 58286	3 58102	4 52451	3 44720	3 37794	1,002 $\pm$ 0,019 12141	5,25 $\pm$ 0,15
2 58286	4 58221	4 52543	4 48494	2 40691	1,000 $\pm$ 0,018 13457	5,16 $\pm$ 0,14
2 58286	4 58221	4 52543	4 48494	3 41471	1,001 $\pm$ 0,018 13614	5,15 $\pm$ 0,14
3 59484	3 59292	4 53401	3 45532	2 37597	1,005 $\pm$ 0,019 12275	5,21 $\pm$ 0,14
3 59484	3 59292	4 53401	3 45532	3 38385	1,005 $\pm$ 0,018 12432	5,20 $\pm$ 0,14
3 59484	3 59292	4 53401	3 45532	4 39655	1,010 $\pm$ 0,019 12650	5,21 $\pm$ 0,14
3 59484	4 59414	4 53495	4 49371	2 41322	1,003 $\pm$ 0,018 12392	5,11 $\pm$ 0,14
3 59484	4 59414	4 53495	4 49371	3 42123	1,004 $\pm$ 0,018 13930	5,10 $\pm$ 0,14
3 59484	4 59414	4 53495	4 49371	4 43414	1,008 $\pm$ 0,018 14150	5,11 $\pm$ 0,14

Table 7.2: η and Δm values for different cuts. The number of events in the 3-14 τ_S region, where Δm is determined is also given after each cut. The value of η is determined from the number of events in the 14-30 τ_S lifetime range. The cut configuration used is indicated by an extra box.

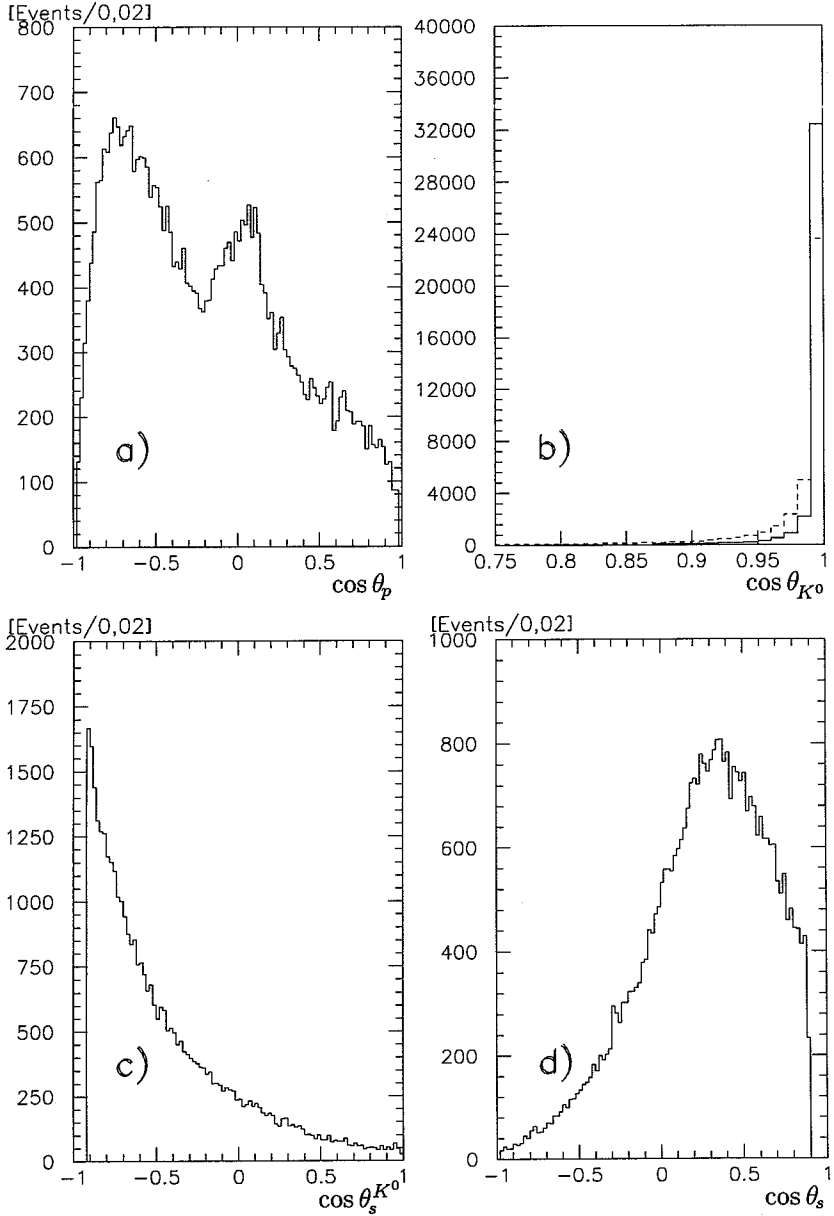


Figure 7.6: *Distributions of a) $\cos \theta_p$ b) $\cos \theta_{K^0}^T$ (solid line), $\cos \theta_{K^0}$ (dashed line) c) $\cos \theta_s^{K^0}$ and d) $\cos \theta_s$ after all the cuts on data are made.*

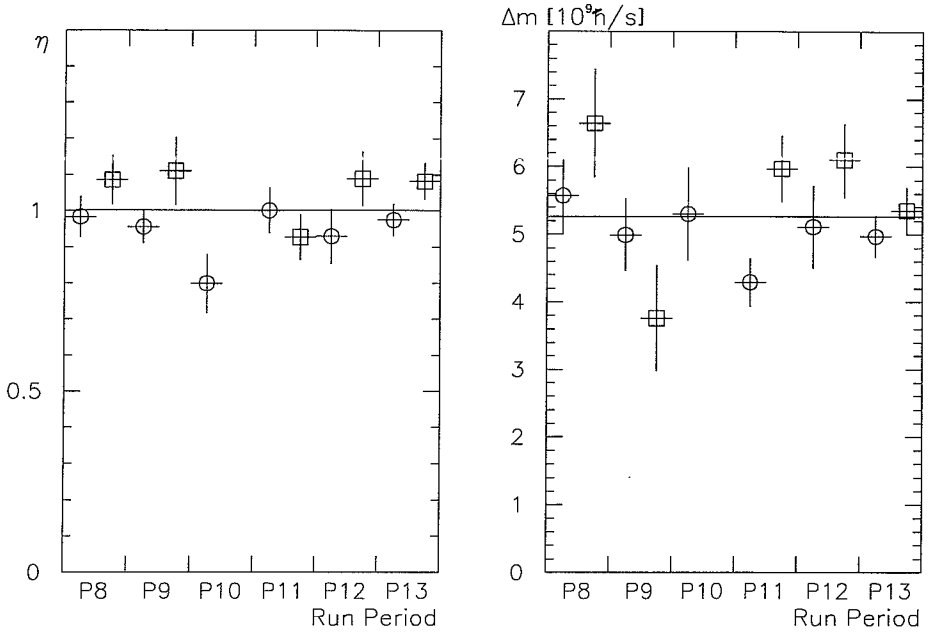


Figure 7.7: A check on the stability of η (left) and Δm (right) for different run periods and magnetic fields. Circles represent data taken with M1, squares data with M2. The lines are the fit values when fitting all data.

is not modeled in Monte Carlo. The remaining 2π background in the signal region can be included in the fit, see Section 7.3. As a final cut configuration, $A = 2, B = 3, C = 4, D = 3$ and $E = 2$ is chosen. This gives a value of $\Delta m = (5,26 \pm 0,15)10^9 \hbar/s$ with a χ^2 -probability of 90%. The angular distributions corresponding to Fig. 7.1 after all cuts are made are shown in Fig. 7.6.

As a further check on the stability of the data sample the values of η and Δm are determined separately for different run periods and magnetic fields, see Fig. 7.7. Unfortunately, both η and Δm determined from M1 and M2 data separately differs from the average with two standard deviations. No explanation for this is found, but if there is an effect varying from M1 to M2, taking equal amounts of data any such effect would cancel.

1990 conditions	$\pi e \nu$	$\pi e \nu$ -b	$\pi \mu \nu$	$\pi \mu \nu$ -b	$\pi^+ \pi^-$	$\pi^+ \pi^- \pi^0$
Events	127922	127922	31847	31847	57765	14130
After cuts	5776	5143	1349	1377	784	419
3-14 τ_S	3965	3498	929	935	540	296
S1/Cherenkov cut	2655	44	70	18	13	8
Acceptance [%]	2,1	0,035	0,22	0,058	0,022	0,057
$R_x/R_{\pi e \nu}$	1	1	0,70	0,70	4,72	0,32
$N_x/N_{\pi e \nu}$ [%]	100	1,7	7,4	1,9	5,1	0,88
% of signal		1,6		1,8	4,7	0,82
1991 conditions	$\pi e \nu$	$\pi e \nu$ -b	$\pi \mu \nu$	$\pi \mu \nu$ -b	$\pi^+ \pi^-$	$\pi^+ \pi^- \pi^0$
Events	118252	118252	185931	185931	104334	6177
After cuts	19059	17375	27253	27698	4286	536
3-14 τ_S	12859	11558	17968	18156	3055	357
S1/Cherenkov cut	7549	208	1205	463	94	12
Acceptance [%]	6,4	0,18	0,65	0,25	0,090	0,20
$R_x/R_{\pi e \nu}$	1	1	0,70	0,70	4,72	0,32
$N_x/N_{\pi e \nu}$ [%]	100	2,8	7,1	2,7	6,6	1,0
% of signal		2,6		2,5	6,2	0,92

Table 7.3: Acceptance of different Monte Carlo samples. $\pi e \nu$ -b stands for a background run, where the pion is identified as an electron and the electron is taken for pion. The same applies for $\pi \mu \nu$ -b. $R_x/R_{\pi e \nu}$ is the relative branching ratio of the two channels. In the case of $K_S \rightarrow \pi^+ \pi^-$ the factor also includes the differences in expected rates for K_S and K_L integrated over the 3-14 τ_S lifetime region. $N_x/N_{\pi e \nu}$ is the relative ratio of the acceptance for the studied channel to the $\pi e \nu$ channel multiplied by the relative branching ratio.

7.2 Monte Carlo Background Studies

In order to determine the fraction of different background channels in the final data sample the same analysis program was run on MC generated events of decays into $\pi e \nu$, $\pi \mu \nu$, $\pi^+ \pi^-$ and $\pi^+ \pi^- \pi^0$. Two samples of each are available, simulating the detector and trigger response during 1990 and 1991 respectively. Since the PID response to $\pi^\pm$, $\mu^\pm$ and $e^\pm$ is presently not properly simulated, the efficiencies for these particles to pass the S1/Cherenkov cut found in Section 5.1 are used together with the information of the particle momentum. The $\pi e \nu$ and $\pi \mu \nu$ data samples are analysed twice, first time calling the lepton electron and the second time the pion electron while misidentifying the lepton as a pion. If both pions in the 2π and 3π samples have a momentum below 250 MeV/c (which is

necessary for the S1/Cherenkov cut) each track is allowed to be misidentified as an electron. Table 7.3 summarizes the MC processing. Since there are equal amounts of data from 1990 and 1991, the main difference being the lower efficiency of the Cherenkov in P12 and P13, the average acceptance is used. Allowing for a 30% error, the $\pi e\nu$ mis-identification background is taken to be $(2,1 \pm 0,6)\%$, $\pi\mu\nu$ mis-identification $(2,2 \pm 0,6)\%$, $\pi^+\pi^-$ background $(5,4 \pm 1,6)\%$ and $\pi^+\pi^-\pi^0$ background $(0,9 \pm 0,3)\%$ of the combined $\pi e\nu$ and $\pi\mu\nu$ signal. These values are used when fitting the semileptonic asymmetries.

7.3 Fitting Procedure

A fitting program called MINUAS has been used [78]. It is an adaptation of MINOS [69] for the semileptonic analysis. The histograms used in the fit are the different $N_+(t)$, $N_-(t)$, $\bar{N}_+(t)$ and $\bar{N}_-(t)$ distributions shown in Fig. 7.8. N_+ stands for a K^0 decay to e^+ etc. First the different semileptonic asymmetries are built setting η and α equal to one. At the time of the fit these values are given as inputs together with the different background contributions found in the previous section. In order to get the rates from the number of events the following relations are used: $\bar{R}_+ \propto \bar{N}_+/\alpha$, $\bar{R}_- \propto \bar{N}_-/\alpha\eta$, $R_+ \propto N_+$ and $R_- \propto N_-/\eta$.

For the statistics presented in this analysis a bin width of $1\tau_S$ has been used, but the signal and background contributions have been integrated over the bin in order to reduce the error. In principle several parameters can be determined at the same time, but since data is scarce and only 11 bins are available, best results are obtained if one parameter is locked while the other is fitted.

7.4 Results

Results on Δm , $\Re(x)$, $\Im(x)$, $\Re(\varepsilon_S)$ and ε_T from 1990 and 1991 data have been reported before [79, 80]. The object of this study was to increase the statistics and to check the stability of the data. The increase in statistics due to cutting less hard is 22,5%. This affects both the statistical and the systematic error, since the error of η depends on statistics.

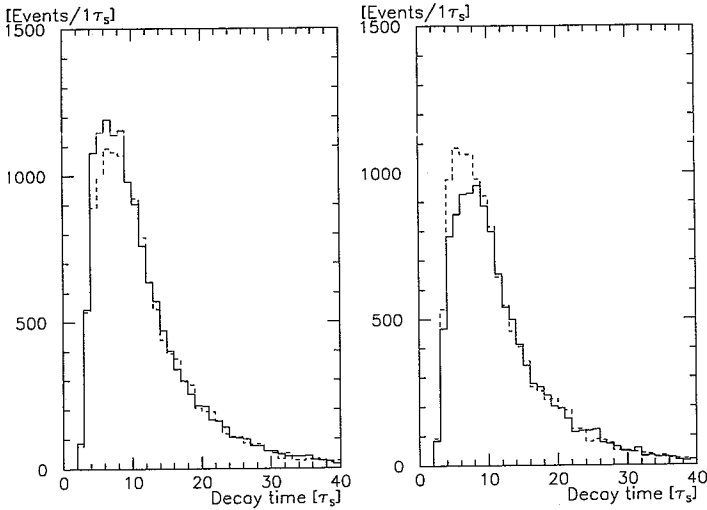


Figure 7.8: Number of events as a function of the kaon lifetime in units of τ_S . Left are shown distributions from $\bar{K}^0$ decays, right from K^0 , the solid lines from decays to e^+ , dashed lines to e^- .

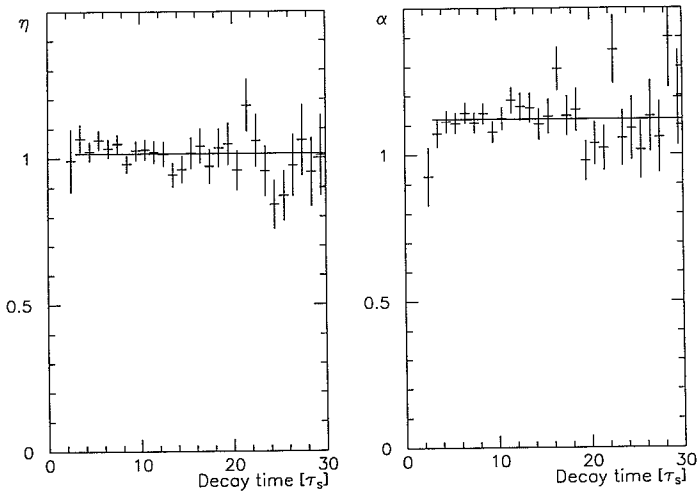


Figure 7.9: Model dependent fits of η (left) and α (right).

7.4.1 Model Dependent Determination of α and η

In order to cross check the values used in this analysis, the rate products (eq. 2.21 and 2.22) are fitted with a constant. If the value of x is zero, using eq. 2.21 one should find $\alpha = (1 - \Re(\varepsilon_L))/A_\alpha$ and fitting eq. 2.22 should give $\eta = (1 + \Re(\varepsilon_T))/A_\eta$. The fits are shown in Fig. 7.9. Fitting the 3–30 τ_S region, values of $\alpha = 1,120 \pm 0,010$ and $\eta = 1,015 \pm 0,009$ are found, with χ^2 -probabilities of 36% and 62%, respectively.

7.4.2 Results from the A_1 Asymmetry

Fitting the A_1 asymmetry of eq. 2.17 values of Δm and $\Re(x)$ can be obtained. This asymmetry depends only slightly on the accuracy of η and α , but is most sensitive to the amount of 2π background in the data sample. Fig. 7.10a shows this asymmetry if no background is assumed, Fig. 7.10b shows the same thing with background. The solid line shows the best fit when $\Re(x)$ has been fixed to zero, the dashed line shows the fit if $\Delta m = (5,351 \pm 0,024)10^9 \hbar/s$ and $\Re(x)$ has been allowed to vary. Table 7.4 gives the results of these fits.

A study of the systematic errors is reported in Table 7.5. A value of $\Delta m = (5,43 \pm 0,19_{stat} \pm 0,04_{syst})10^9 \hbar/s$ is found, and $\Re(x)$ is found to be consistent with zero, $\Re(x) = (-26^{+52}_{-64_{stat}} {}^{+12}_{-11_{syst}})10^{-3}$.

7.4.3 Results from the A_2 Asymmetry

The A_2 asymmetry (eq. 2.18) depends on $\Im(x)$ and $\Re(\varepsilon_S)$. Both quantities are sensitive to α and $\Im(x)$ is also sensitive to η . Neither depends on the amount of background. Fig. 7.11a shows this asymmetry if no background is assumed, Fig. 7.11b shows the same thing with background. The solid line shows the best fit when $\Re(\varepsilon_S)$ is fixed equal to $\Re(\varepsilon_L)$, the dashed line shows the fit assuming $\Im(x) = 0$ and allowing $\Re(\varepsilon_S)$ to vary. Table 7.6 gives the results of these fits.

The systematic errors on this determination are reported in Table 7.7. If $\Re(\varepsilon_S)$ is set equal to $\Re(\varepsilon_L)$ a value of $\Im(x) = (-36 \pm 32_{stat} \pm 10_{syst})10^{-3}$

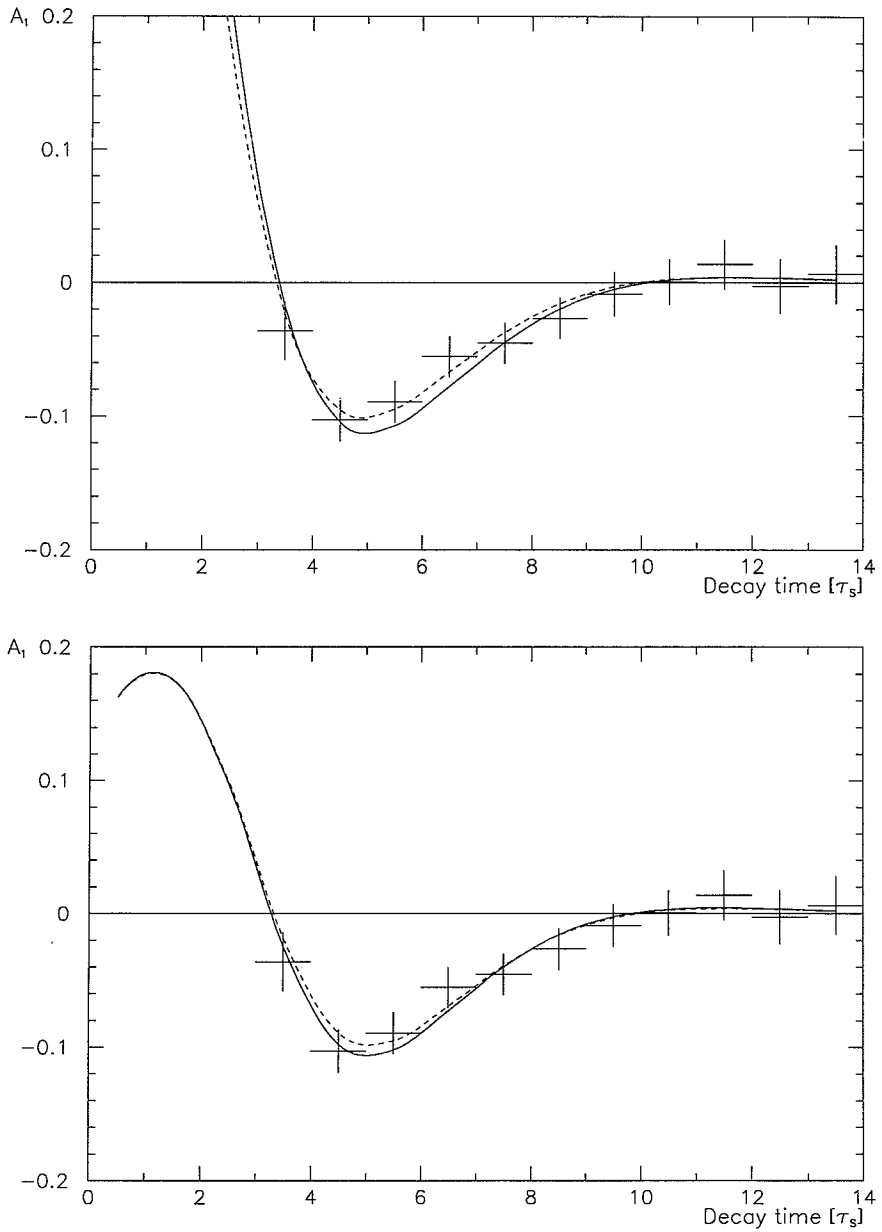


Figure 7.10: Fits to the A_1 asymmetry to determine Δm (solid line) and $\mathcal{R}(x)$ (dashed line). Top is shown fits assuming no background, bottom shows the fits assuming the background found in Section 7.2.

No background			
χ^2 -prob	$\Delta m[10^9 \hbar/s]$	$\Re(x)[10^{-3}]$	Corr.
90%	$5,26 \pm 0,15$	—	
99%	—	-84^{+54}_{-66}	
98%	$5,44 \pm 0,21$	-101^{+68}_{-83}	$-0,580$
With background			
97%	$5,43 \pm 0,19$	—	
97%	—	-26^{+52}_{-64}	
97%	$5,53 \pm 0,24$	-54^{+65}_{-80}	$-0,536$

Table 7.4: *Results of fits to the A_1 asymmetry as described in the text. Corr. stands for the correlation between the parameters. The background used is described in Section 7.2.*

Parameter	No background		With background	
	$\Delta m[10^9 \hbar/s]$	$\Re(x)[10^{-3}]$	$\Delta m[10^9 \hbar/s]$	$\Re(x)[10^{-3}]$
α	0	0	0	0
η	$+0$ $-0,01$	$+5$ -4	$+0$ $-0,01$	± 4
$K_S \rightarrow 2\pi$	$+0,11$	$+30$	$\pm 0,04$	± 8
$K_L \rightarrow 3\pi$	$+0,01$	$+5$	0	$+2$ -1
Mis-identification	$+0,04$	$+25$	$\pm 0,01$	$+7$ -6
Total	$+0,12$ $-0,01$	$+40$ -4	$\pm 0,04$	$+12$ -11

Table 7.5: *Systematic errors of Δm and $\Re(x)$. The variable studied has been varied one standard deviation in each direction. In the no background case the background found in Section 7.2 has been added in order to determine the systematic error, which results in a shift of the central value of the parameter fitted.*

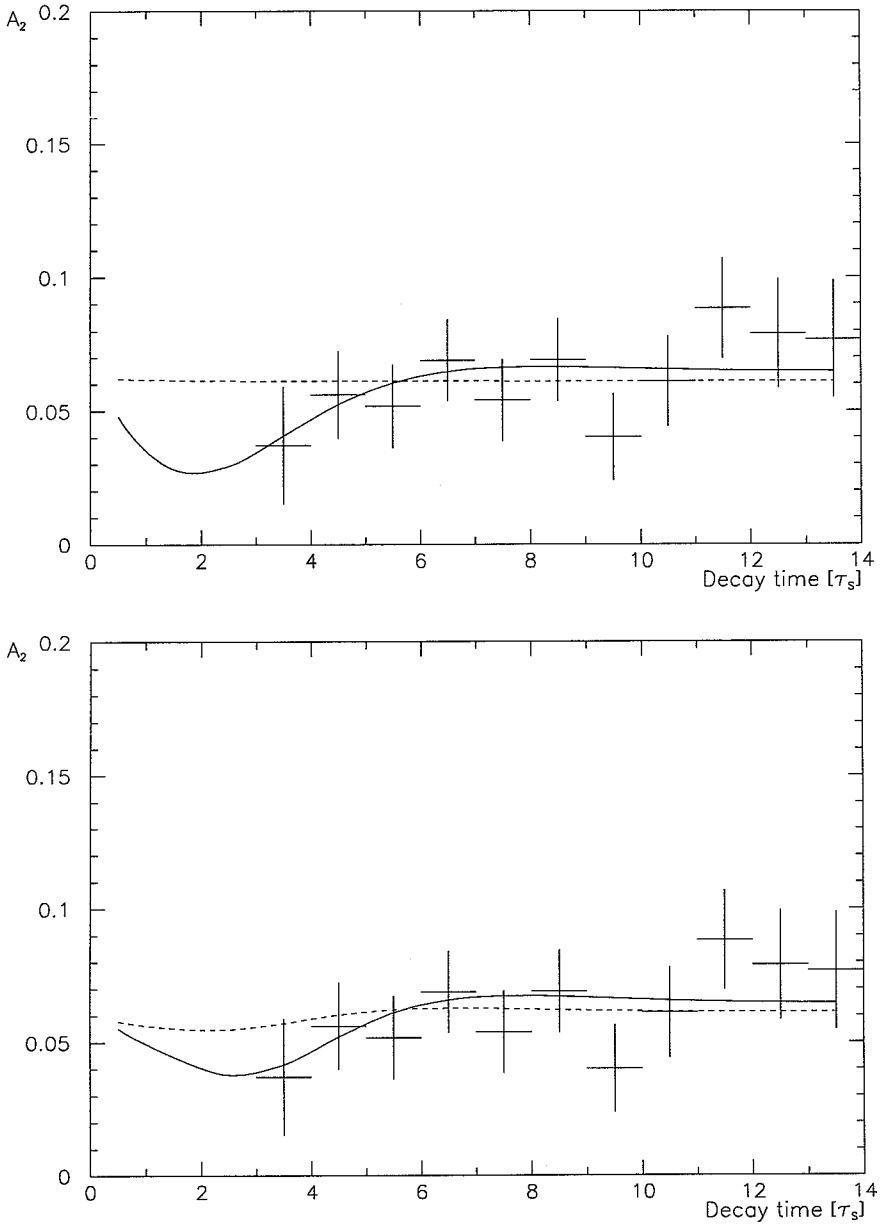


Figure 7.11: Fits to the A_2 asymmetry to determine $\Im(x)$ (solid line) and $\Re(\epsilon_S)$ (dashed line). Top is shown fits assuming no background, bottom shows the fits assuming the background found in Section 7.2.

No background			
χ^2 -prob	$\Im(x)[10^{-3}]$	$\Re(\varepsilon_S)[10^{-3}]$	Corr.
81%	-36 ± 26	—	
68%	—	$-0,2 \pm 2,6$	
74%	-34 ± 28	$1,0 \pm 2,8$	$-0,366$
With background			
79%	-36 ± 32	—	
72%	—	$-0,09 \pm 2,7$	
72%	-33 ± 34	$0,75 \pm 2,8$	$-0,306$

Table 7.6: *Results of fits to the A_2 asymmetry as described in the text. Corr. stands for the correlation between the parameters. The background used is described in Section 7.2.*

Parameter	No background		With background	
	$\Im(x)[10^{-3}]$	$\Re(\varepsilon_S)[10^{-3}]$	$\Im(x)[10^{-3}]$	$\Re(\varepsilon_S)[10^{-3}]$
α	∓ 8	$\mp 2,2$	∓ 10	$-2,2$ $+2,3$
η	$+2$ -1	$\pm 0,2$	$+1$ -2	$\pm 0,2$
$K_S \rightarrow 2\pi$	0	$+0,01$	0	0
$K_L \rightarrow 3\pi$	0	0	0	0
Mis-identification	0	0	0	0
Total	± 8	$\pm 2,2$	± 10	$+2,3$ $-2,2$

Table 7.7: *Systematic errors of $\Im(x)$ and $\Re(\varepsilon_S)$. The variable studied has been varied one standard deviation in each direction. In the no background case the background found in Section 7.2 has been added in order to determine the systematic error.*

is found, consistent with zero. This is currently the most precise single measurement of this quantity. Setting $\Im(x) = 0$ yields a value of $\Re(\varepsilon_S) = (-0,1 \pm 2,7_{stat}^{+2,3}_{-2,2_{stat}})10^{-3}$. This quantity has never been measured.

7.4.4 Results from the A_T Asymmetry

The asymmetry A_T defined in eq. 2.19 is special in that measuring a value different from zero is a direct proof of T -violation, something that never has been measured before. Unfortunately, this quantity is sensitive to both η and α . The background changes this asymmetry very little. Fig. 7.12 shows this asymmetry if no background is assumed. The variable $\Re(\varepsilon_T)$ is equal to this asymmetry divided by four. The value found is $\Re(\varepsilon_T) = (-1,9 \pm 1,8)10^{-3}$ (no background, 68% χ^2 -probability) and $\Re(\varepsilon_T) = (-1,8 \pm 1,9)10^{-3}$ (72% χ^2 -probability) using the background from Section 7.2. Table 7.8 summarizes the systematic errors in the determination of $\Re(\varepsilon_T)$. A value of $\Re(\varepsilon_T) = (-1,8 \pm 1,9_{stat}^{+2,5}_{-2,7_{syst}})10^{-3}$ is found. With this data, no statistically significant measurement of T -violation can be made, but with more data and controlling the systematic errors T -violation can be measured for the first time in the CPLEAR experiment.

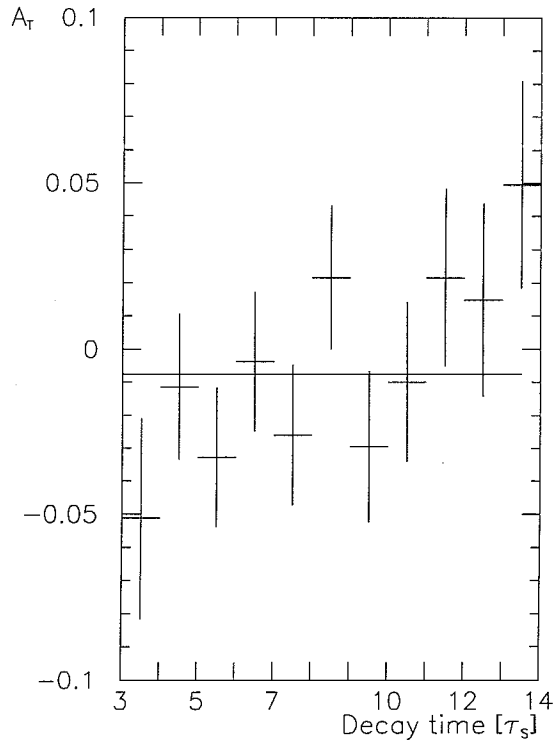


Figure 7.12: Fits to the A_T asymmetry that determines ϵ_T . If a value different from zero is found, this means that T-violation for the first time has been observed.

Parameter	No background	With background
α	$\mp 1,1$	$-1,2$ $+1,1$
η	$\pm 2,4$	$+2,3$ $-2,4$
$K_S \rightarrow 2\pi$	$+0,1$	$+0$ $-0,1$
$K_L \rightarrow 3\pi$	0	$-0,1$ $+0$
Mis-identification	0	$-0,1$ $+0$
Total	$\pm 2,6$	$+2,5$ $-2,7$

Table 7.8: Systematic errors in the determination of $\Re(\epsilon_T)$. The variable studied has been varied one standard deviation in each direction. In the no background case the background found in Section 7.2 has been added in order to determine the systematic error.

Chapter 8

Conclusion

The CPLEAR experiment has been described. It has been shown to be fully operational, with data taking underway. So far, 10000 data tapes have been recorded with first results being published. During 1993, 75 days of data taking has been approved in which a total of 15–20000 tapes will be written.

Several studies of the Particle Identification Detector (PID) performance are reported. Methods for using time-of-flight and pulse heights in Scintillator 1 and Cherenkov modules for separating particles have been developed and tested. A method to determine the exact positions of the different modules of the PID has been developed, which can also be used to monitor the liquid levels in the Cherenkov boxes. Calibration data from these studies have been used to determine relative branching ratios of several final states from $p\bar{p}$ annihilation involving ρ and f_2 mesons. These results have been used to determine the fraction of P-wave annihilation, f_P , in a 15 bar gaseous hydrogen target. A value of $f_P = 0,345 \pm 0,070$ is found, agreeing well with theoretical calculations.

A method to determine CP - and T -violation parameters from the semileptonic decays of neutral kaons has been described together with results from initial data taking during 1990 and 1991, see Table 8.1. Including data from 1992 and 1993, a direct determination of T -violation through the A_T asymmetry defined in eq. 2.19 seems to be within reach. To be able to measure A_T , a good control of the systematic uncertainties

Parameter	This work	World average
$\Delta m[10^9 \hbar/s]$	$5,43 \pm 0,19$	$5,351 \pm 0,024$
$\Re(x)[10^{-3}]$	-26^{+53}_{-65}	6 ± 18
$\Im(x)[10^{-3}]$	-36 ± 34	-3 ± 26
$\Re(\varepsilon_S)[10^{-3}]$	$-0,1 \pm 3,5$	—
$\Re(\varepsilon_T)[10^{-3}]$	$-1,8^{+3,1}_{-3,3}$	—

Table 8.1: *Results on parameters determined in this work compared to world average values [10]. The errors reported are total errors.*

is required, and a large part of this work has been to determine these. The acceptance factors η and α need to be determined to a high degree of accuracy, since the A_T asymmetry depends heavily on these variables. The $\Re(x)$ and $\Im(x)$ are less sensitive to systematic errors and a substantial reduction of the statistical error is expected. In the determination of Δm we can not compete with the precision of the existing measurements. With the expected increase in statistics, a statistically significant determination of $\Re(\varepsilon_S)$ seems possible.

Appendix A

Abbreviations and Materials Used

A.1 Abbreviations

ADC	Analog to Digital Converter
C	Charge operator
CFD	Constant Fraction Discriminator
DAQ	Data Acquisition system, see Section 3.7
DC	Drift Chamber, see Section 3.3.2
DST	Data Summary Tape
Δm	Mass difference $K_L - K_S$
EB	Event Builder, see Section 3.7
EDL	Early Decision Logic, see Section 3.6.1
FE	Front End electronics
FWHM	Full Width Half Maximum
HV	High Voltage
HWP	Hard Wired Processor
IDL	Intermediate Decision Logic, see Section 3.6.1
$\Im(x)$	Imaginary part of x
LEAR	Low Energy Antiproton Ring, at CERN
LED	Light Emitting Diode
M#	Magnetic field polarity, M1 normal field, M2 reversed
MC	Monte Carlo

MSI	Manne Siegbahn Institute
MWPC	Multi Wire Proportional Chamber
P	Parity operator
$P\#$	Run Period number
PC	Proportional Chamber, see Section 3.3.1
PID	Particle Identification Detector, see Section 3.4
PM	photomultiplier
PSI	Paul Scherrer Institut
$\Re(x)$	Real part of x
RRO	Root Read Out, see Section 3.7
σ	The r.m.s. spread of a distribution
$S\#$	Inner scintillator (S1) or outer scintillator (S2)
ST	Streamer Tube, see Section 3.3.3
τ_S	K_S lifetime
T	Time reversal operator
$T\#$	Trigger number, defined in Section 3.6.4
TC	Trigger Control
TDC	Time to Digital Converter
TOF	Time Of Flight
VME	Electronics standard

A.2 Materials Used

BC 408	Bicron Corporation scintillator
FC72	C_6F_{14} freon, trade mark of 3M
kevlar	Polyamide fibre, trade mark of Du Pont de Nemours
kapton	Polyamide film
mylar	Polyester film, trade mark of Du Pont de Nemours
NE 102	Nuclear Enterprise scintillator
NE 561	Nuclear Enterprise white reflective paint
PMMA	Polymethyl methacrylate
PPO	Diphenyl-oxazole wavelength shifter
rohacell	Polymethacrylamide hard foam, trade mark of Röhm

Acknowledgements

This work would not have been possible without the extensive help of my supervisor Prof Per Carlson. He has helped me over the years with everything from teaching me the ways of particle physics to practicalities like funding my trips to CERN. Without his encouragement this work would never have been finished.

CLEAR is a large experiment, I cannot mention all who I have met over the years that have helped me greatly. Thanking specially our spokesman Dr Panagiotis Pavlopoulos these thanks extend to all members of the collaboration.

The members of the CLEAR group at MSI in Stockholm have of course contributed enormously to this work. Drs Christer Fuglesang, Kerstin Jon-And and Andras Kerek have always been willing to discuss physics or electronics problems as well as helping me whenever I was facing a dead-end. They also helped me by reading draft versions of this thesis. Dr Lars Adiels was of great help, before he left for a job at Siemens. Dr Sandor Szilagy, now back in Hungary was also very fun to work with.

People leave and people come. Since PhD student Mats Danielsson joined the experiment I have worked closely together with him and we have shared the little triumphs and defeats, especially in the meson spectroscopy work. There, we have both benefited from close collaboration with Prof Ludwig Tauscher of Basel, who checked our work in detail and came up with new ideas.

The semileptonic analysis group is headed by Dr Claudio Santoni, whose help was essential for Chapter seven of this thesis. He also wrote the MINUAS fitting program, used heavily in the analysis. Dr Philippe Bloch has helped a lot with maintaining the CLEAR software and keeping the collaboration running. Dr John Fry was always willing to discuss physics and help me with my problems. The Boston group, headed by Prof Jim Miller and consisting of Drs Ted Lawry and Dave Francis (who previously was a post doc in Stockholm) together with PhD students Apollo Go and Dave Zimmerman all helped me getting a better understanding of the PID hardware.

The computer specialists Drs Bengt Lund-Jensen and Carl-Gunnar Lindén were always very helpful. Drs Christian Walck and Arne Nord-

mark always had time for a discussion on L^AT_EX when I got stuck. Arne also helped me print the whole shebang on a 600 dpi LaserJet IV. Mrs Elisabeth Oppenheimer and I had many a good discussion on English grammar.

It is always nice to be able to get help when you run into problems. Profs Karl-Erik Bergkvist, Ingmar Bergström and Cecilia Jarlskog have always helped in solving my problems very quickly. Karl-Erik is specially acknowledged for always asking the right questions, Ingmar for letting me use the photos of Lee and Yang (and for skating excursions) and Cecilia for always being prepared to answer my questions. Her understanding of *CP* related problems has been of great help to me since she is very good at explaining things. She was also kind enough to proof-read Chapter two for me.

The rest of the particle physics group at MSI are greatly acknowledged for their friendliness and for reading draft versions of my thesis. Drs Lydia Didenko, Tom Francke and Lars-Ove Eek together with PhD students Jesper Söderqvist, Göran Tranströmer and Niclas Weber all made my days at the institute or at CERN pass very quickly. It is always very nice to meet with people from other disciplines and MSI is the perfect place for that. Many coffee and lunch discussions have been made pleasant by the help of Prof Arne Johnson, Drs Peter Carlé, Johan Jeansson, Włodzimierz Klamra, Anders Källberg, Fredrik Lidén, Arne Nilsson, Lars-Olov Norlin, Ulf Rosengård, Ansgar Simonsson and Ramon Wyss (even though he uses our computer!). The administrative department has always been willing to help and pay my bills, whatever their amount. For this, their help is greatly acknowledged. Last, but not least, thanks to my family for their constant support!

The use of comma in numbers requires a special explanation. All countries have signed and agreed to follow the ISO 31-0 standard [81] which clearly states: "There shall be a comma on the line". Convincing L^AT_EX to do this is not easy, especially in math mode, but everything is possible.

I was the first one to get employed at the Institute when it changed name in 1988 from Atomforskningsinstitutet to its present name. How appropriate that I will be the last one to leave now that the Institute no longer will be an Institute of its own!

Appendix C

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