Measurement of $Re(\varepsilon'/\varepsilon)$ with a new calorimetry technique

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Introduction

NA48 is an experiment designed to measure the $CP$ violation parameter $Re(\varepsilon'/\varepsilon)$ in the $K^0$ decays in two pions at the CERN laboratories in Geneva.

The international collaboration that participates in the realization of this project has recently submitted a preliminary result based on the data collected during the year 1997. NA48 has collected a much larger data sample during the following two years and the relative analysis is now going on.

A group of physicists from the Scuola Normale Superiore and from the Pisa INFN section collaborate in the experiment. They have been in particular engaged in the development of the electro-magnetic calorimeter and the trigger system used for the detection of the four photons coming from the kaon decay in two neutral pions.

The calorimeter, almost completely active and filled with liquid krypton, is the most innovating component of the NA48 detector and the study of its properties turned out to be rich in physical and technical problems of notable interest.

I have been a member of Pisa group of the NA48 collaboration since 1991.

In the first year I worked on the prototypes of the calorimeter, studying the systematic effects linked to the particular scheme applied for the readout structure. Later I have been involved in the development and the study of the final detector. I have been responsible for the development of the central processor of the trigger system (the PeakSum system) that performs the principle calculations needed to select the relevant $K \to 2\pi^0$ decays. Since 1997 I’ve dedicated myself to the analysis of the data collected by the experiment. I first studied the performance of the calorimeter and the trigger, and later I dedicated myself to the development of a full analysis procedure to derive $Re(\varepsilon'/\varepsilon)$. The results of the analysis that I carried out together with 4 other people have been approved by the NA48 collaboration and retained among the few results used for computing the final value.

In the first chapter of this work I will briefly introduce the theoretical motivation of the $Re(\varepsilon'/\varepsilon)$ measurement.

In the second chapter I will expose the experimental requirements for NA48
and its setup.

In chapter 3 I will first describe the calorimeter prototypes: the tests, the results and the ideas that led to the planning and to the realization of the complex readout structure. I will then describe the final calorimeter.

Chapter 4 contains the description of the triggering system that has been developed to select the decays of the kaon into 2 neutral pions.

In chapter 5 I will describe the performances achieved by both the calorimeter and the trigger.

The last chapter will then be dedicated to the preliminary results for $Re(\varepsilon'/\varepsilon)$ obtained from the data collected in the 1997 data taking.
Chapter 1

Phenomenology of CP violation

Since 1964, year of the first observation of the two pions decay of the $K_L$ [1], the CP violation became a subject of keen interest both experimental and theoretical. Until today, however, after more then thirty years of experimental activity, evidence for the violation has been clearly observed only in $K$ decay.

1.1 The system $K^0 - \bar{K}^0$

The description of the $K^0 - \bar{K}^0$ system contained in this paragraph follows the line of Bell, Steinberger [2] and Kleinknecht [3] papers.

$K^0$ and $\bar{K}^0$ are produced by the strong interactions as strangeness eigenstates ($S = \pm 1$). If the time evolution of the states was ruled only by the strong and the electro-magnetic Hamiltonians, the two states would remain distinct in their time evolution. The weak interactions instead do not preserve the strangeness and thus induce transitions between the states of $K^0$ and $\bar{K}^0$.

The time evolution of a generic state is given by:

$$|K(t)\rangle = \alpha(t)|K^0\rangle + \beta(t)|\bar{K}^0\rangle.$$  \hspace{1cm} (1.1)

as induced by the Hamiltonian $H$:

$$i\frac{d}{dt}\begin{pmatrix} \alpha(t) \\ \beta(t) \end{pmatrix} = H \cdot \begin{pmatrix} \alpha(t) \\ \beta(t) \end{pmatrix}. $$ \hspace{1cm} (1.2)

The Hamiltonian can be parametrised as:

$$H = \begin{pmatrix} M_{11} + i\Gamma_{11}/2 & M_{12} + i\Gamma_{12}/2 \\ M_{21} + i\Gamma_{21}/2 & M_{22} + i\Gamma_{22}/2 \end{pmatrix} = M + i\Gamma/2.$$ \hspace{1cm} (1.3)

with $i,j=1$ referring to $|K^0\rangle$ and $i,j=2$ to $|\bar{K}^0\rangle$. 


M and \( \Gamma \) are hermitian matrices, as they represent measurable quantities (masses and decay widths). Moreover, assuming CPT invariance of the Hamiltonian, where CPT indicates the combination of charge conjugation (C) space parity (P) and time reversal (T) operators, one deduces:

\[
<K^0|H|K^0> = <K^0|CPT H CPT|K^0> = <\bar{K}^0|H|\bar{K}^0> \tag{1.4}
\]

that means:

\[
H_{11} = H_{22}. \tag{1.5}
\]

We can thus write:

\[
M_{11} = M_{22} = M_0 \tag{1.6}
\]

and:

\[
H = \begin{pmatrix}
M_0 + i \Gamma_0/2 & M_{12} + i \Gamma_{12}/2 \\
M_{12}^* + i \Gamma_{12}^*/2 & M_0 + i \Gamma_0/2
\end{pmatrix} \tag{1.7}
\]

Diagonalising \( H \) one finds the eigenstates of the time evolution:

\[
|K_{L,S} \> = \frac{1}{\sqrt{1 + |\alpha_{L,S}|^2}}(|K^0 \> + \alpha_{L,S} |\bar{K}^0 \> ). \tag{1.8}
\]

with \( \alpha_S = -\alpha_L = \alpha \) and \( \alpha^2 = H_{21}/H_{12} \).

In the base of \( |K_S \> \) and \( |K_L \> \) the matrix \( H \) reduces to:

\[
H = \begin{pmatrix}
M_S + i \Gamma_S/2 & 0 \\
0 & M_L + i \Gamma_L/2
\end{pmatrix} \tag{1.9}
\]

with \( M_{S,L} \) being the masses and \( \Gamma_{S,L} \) the lifetimes of the two eigenstates.

The \( L, S \) suffixes used to flag the eigenstates stay for Long and Short and they refer to the very different lifetime of the two states \([4]\):

\[
\tau_L = \frac{1}{\Gamma_L} = (5.15 \pm 0.04) \times 10^{-8} \text{ s} \tag{1.10}
\]

\[
\tau_S = \frac{1}{\Gamma_S} = (0.8940 \pm 0.0009) \times 10^{-10} \text{ s}. \tag{1.11}
\]

The mass difference between the two states is instead small and is measured to be \([4]\):

\[
M_L - M_S = (0.5311 \pm 0.0019) \times 10^{10} \text{ \( h / s \) } \tag{1.12}
\]

for an average value of \([4]\):

\[
M_{K^0} = (497.672 \pm 0.031) \text{ MeV/}c^2. \tag{1.13}
\]
1.1. **THE SYSTEM \( K^0 - \bar{K}^0 \)**

<table>
<thead>
<tr>
<th>channel</th>
<th>decay ratio</th>
</tr>
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<tbody>
<tr>
<td>( \pi^0 \pi^0 \pi^0 )</td>
<td>( (21.12 \pm 0.27) % )</td>
</tr>
<tr>
<td>( \pi^0 \pi^+ \pi^- )</td>
<td>( (12.56 \pm 0.20) % )</td>
</tr>
<tr>
<td>( \pi^+ \mu^+ \nu_\mu (K_{\mu 3}) )</td>
<td>( (27.17 \pm 0.25) % )</td>
</tr>
<tr>
<td>( \pi^+ e^+ \nu_e (K_{e 3}) )</td>
<td>( (38.78 \pm 0.27) % )</td>
</tr>
</tbody>
</table>

Table 1.1: Main decay channels for the \( K_L \)

<table>
<thead>
<tr>
<th>channel</th>
<th>decay ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^+ \pi^- )</td>
<td>( (68.61 \pm 0.28) % )</td>
</tr>
<tr>
<td>( \pi^0 \pi^0 )</td>
<td>( (31.39 \pm 0.28) % )</td>
</tr>
<tr>
<td>( \pi^+ \pi^- \gamma )</td>
<td>( (0.178 \pm 0.005) % )</td>
</tr>
</tbody>
</table>

Table 1.2: Main decay channels for the \( K_S \)

Tables 1.1 and 1.2 show the main decay channels and their relative branching ratios for the two eigenstates (the values are taken from [4]).

Defining:

\[
\varepsilon = \frac{1 - \alpha}{1 + \alpha}
\]  

(1.14)

one gets:

\[
|K_S> = \frac{1}{\sqrt{1 + |\varepsilon|^2}} (|K_1> + \varepsilon|K_2>)
\]  

(1.15)

\[
|K_L> = \frac{1}{\sqrt{1 + |\varepsilon|^2}} (|K_2> + \varepsilon|K_1>)
\]  

(1.16)

where \( K_1 \) and \( K_2 \) are the \( CP \) eigenstates:

\[
|K_1> = \frac{1}{\sqrt{2}} (|K^0> + |\bar{K}^0>) \quad (CP|K_1> = +|K_1>)
\]  

(1.17)

\[
|K_2> = \frac{1}{\sqrt{2}} (|K^0> - |\bar{K}^0>) \quad (CP|K_2> = -|K_2>)
\]  

(1.18)

From equations 1.16 and 1.15 it is evident that a value of \( \varepsilon \) different from 0 indicates that the eigenstates of the Hamiltonian (the physical states with defined masses and lifetimes) are not simultaneously eigenstates of the \( CP \) symmetry and by consequence that \( CP \) is violated.

We will refer to this \( CP \) violation effect as the violation in the “mixing” of the neutral kaon states.
At present the experimental observations on neutral kaons decays, with semileptonic and 2 pions final states, account for a value of the parameter $\varepsilon$ of $2.3 \times 10^{-3}$ with very high precision.

1.2 The $CP$ violation in kaons into two pions decay

A generic neutral state of two pions ($|\pi^0\pi^0>$ or $|\pi^+\pi^->$) can be expressed as overlap of states with defined isospin $I=0,1,2$.

From the Pauli principle for bosons one can deduce that the isospin wave function for two pions in a state of angular momentum 0, is necessarily symmetric and exclude by consequence $I=1$ states.

The two pions states originated by the decay of a $K$ (which has 0 spin) will then contain $I=0$ and $I=2$ components only. Moreover, given that:

$$CP |\pi^0> = -|\pi^0>$$  \hspace{1cm} (1.19) $$CP |\pi^+> = -|\pi^->$$  \hspace{1cm} (1.20)

we can derive that a neutral state of two pions in S-wave, is a $CP$ eigenstate with eigenvalue +1.

This observation reflects in the fact that the $K_S$, which is predominantly composed of the $CP$ positive eigenstate $K_1$, has a large branching ratio for the decay in two pions, while these decay channels are heavily suppressed for $K_L$. Actually the observation of $K_L \rightarrow 2\pi$ decays has been the first evidence of a $CP$ violation effect in the kaon system.

Denoting with $|n>$ the two pions state with isospin $I=n$ it turns out that:

$$|0> = \sqrt{\frac{1}{3}}(|\pi^-\pi^+> + |\pi^+\pi^-> - |\pi^0\pi^0>)$$  \hspace{1cm} (1.21)

$$|2> = \sqrt{\frac{1}{6}}(|\pi^-\pi^+> + |\pi^+\pi^-> + 2|\pi^0\pi^0>).$$  \hspace{1cm} (1.22)

Exploiting the Fermi-Watson theorem, the decay amplitudes in the two isospin states for the $K^0$ can be expressed by:

$$<0|T|K^0> = A_0 e^{i\delta_0}$$  \hspace{1cm} (1.23)

$$<2|T|K^0> = A_2 e^{i\delta_2}$$  \hspace{1cm} (1.24)

where $A_0$ and $A_2$ are the weak amplitudes for $|K^0> \rightarrow |0>$ and $|K^0> \rightarrow |2>$ transitions, and $\delta_0$ and $\delta_2$ are the phase differences produced by the strong elastic interaction in the final 2 pions states.
1.2. THE CP VIOLATION IN KAONS INTO TWO PIONS DECAY

Assuming CPT invariance for the decay amplitude it can be deduced:

\[ <0|T|\bar{K}^0> = A_0^* e^{i\delta_0} \]  \hspace{1cm} (1.25)
\[ <2|T|\bar{K}^0> = A_2^* e^{i\delta_2}. \]  \hspace{1cm} (1.26)

We can now define the quantities:

\[ \epsilon_0 = \frac{<0|T|K_L>}{<0|T|K_S>} = \frac{i \text{Im}(A_0) + \epsilon \text{Re}(A_0)}{\text{Re}(A_0) + i \epsilon \text{Im}(A_0)} \]  \hspace{1cm} (1.27)
\[ \epsilon_2 = \frac{<2|T|K_L>}{\sqrt{2} <0|T|K_S>} = \frac{i \text{Im}(A_2) + \epsilon \text{Re}(A_2)}{\sqrt{2}(\text{Re}(A_0) + i \epsilon \text{Im}(A_0))} e^{i(\delta_2 - \delta_0)} \]  \hspace{1cm} (1.28)
\[ \omega = \frac{<2|T|K_S>}{<0|T|K_S>} = \frac{\text{Re}(A_2) + i \epsilon \text{Im}(A_2)}{\text{Re}(A_0) + i \epsilon \text{Im}(A_0)} e^{i(\delta_2 - \delta_0)} \]  \hspace{1cm} (1.29)

If a common phase factor of the kaon states is redefined to have \( A_0 \) real (according to the Wu and Yang [5] convention) one gets:

\[ \epsilon_0 = \epsilon \]  \hspace{1cm} (1.30)

and (neglecting the \( \epsilon^2 \) terms):

\[ \epsilon_2 \approx \frac{\epsilon \omega}{\sqrt{2}} + \epsilon' \]  \hspace{1cm} (1.31)

where we have defined:

\[ \epsilon' = \frac{i}{\sqrt{2}} \frac{\text{Im} A_2}{A_0} e^{i(\delta_2 - \delta_0)}. \]  \hspace{1cm} (1.32)

With this phase convention we derive that:

\[ <0|T|K_2> \propto \text{Im}(A_0) = 0 \]  \hspace{1cm} (1.33)

and by consequence:

\[ <2|T|K_2> = <2\pi|T|K_2> \propto \text{Im}(A_2) \propto \epsilon' \]  \hspace{1cm} (1.34)

that means that \( \epsilon' \) is proportional to the amplitude of the decay of the kaon \( CP \) eigenstate with negative eigenvalue \( K_2 \) in a two pions state with positive \( CP \) eigenvalue.

It is then evident that measuring the parameter \( \epsilon' \) to be different from zero corresponds to the observation of what is called a “direct” \( CP \) violation, that means the \( CP \) violating decay of a \( CP \) eigenstate (distinct from the mass eigenstates \( K_L \) and \( K_S \)).
CHAPTER 1. PHENOMENOLOGY OF CP VIOLATION

We define the measurable quantities:

\[ \eta_{+-} = \frac{\langle \pi^+ \pi^- | T | K_L \rangle}{\langle \pi^+ \pi^- | T | K_S \rangle} \]
(1.35)

\[ \eta_{00} = \frac{\langle \pi^0 \pi^0 | T | K_L \rangle}{\langle \pi^0 \pi^0 | T | K_S \rangle} . \]
(1.36)

Straightforward algebra gives:

\[ \eta_{+-} = \frac{\varepsilon + \varepsilon_2}{1 + \omega/\sqrt{2}} \]
(1.37)

\[ \eta_{00} = \frac{\varepsilon - 2\varepsilon_2}{1 - \sqrt{2}\omega} . \]
(1.38)

The selection rule of the weak decays \( \Delta I = 1/2 \) implies \( \omega \approx 0 \). In this limit one obtains:

\[ \eta_{+-} = \varepsilon + \varepsilon' \quad \text{and} \quad \eta_{00} = \varepsilon - 2\varepsilon' . \]
(1.39)

Due to the smallness of \( \varepsilon' \) the phase of \( \varepsilon \) is given by:

\[ \theta_{\varepsilon} \simeq \theta_{\eta_{+-}} \]
(1.40)

while that of \( \varepsilon' \) is expressed in terms of the measured quantities \( \delta_0 \) and \( \delta_2 \):

\[ \theta_{\varepsilon'} = \frac{\pi}{2} + \delta_2 - \delta_0 \]
(1.41)

and their values are experimentally measured to be [4]:

\[ \theta_{\varepsilon} = (43.49 \pm 0.08)^\circ \]
(1.42)

\[ \theta_{\varepsilon'} = (48 \pm 4)^\circ . \]
(1.43)

1.3 CP violation models

Soon after the first observation [1], of CP violation a model was proposed that conjectured the existence of a new interaction named "Superweak" [6]. This model foresees the existence of a fundamental CP violating interaction with a coupling strength about a factor \( \varepsilon \) smaller than that of the weak interaction and \( \Delta S = 2 \) transitions at first order.

As a consequence the Superweak model foresees that mixing of the mass eigenstates, determined by \( K^0 \rightarrow \bar{K}^0 \ (\Delta S = 2) \) transitions, is the only manifestation of the CP violation, while direct violating \( K_2 \rightarrow 2\pi \ (\Delta S = 1) \) decays are not foreseen at the tree level of the interaction and hence are heavily suppressed.
In this hypothesis clearly the two ratios among the decay amplitudes in two pions of $K_L$ and $K_S$ ($\eta_{+-}$ and $\eta_{00}$) are equal and are determined only by $\varepsilon$:

$$\eta_{00} = \eta_{+-} = \frac{<2\pi \mid T \mid K_L>}{<2\pi \mid T \mid K_S>} = \varepsilon.$$  \hspace{1cm} (1.44)

An alternative model is the Milliweak one for which the $CP$ violation originates from second order processes of an interaction that violates the strangeness of one unity at first order. In the framework of such a model one can account for both “mixing” and “direct” $CP$ violating effects.

The Milliweak model can be incorporated in the Standard Model of the electroweak interactions which accounts the possibility of a $CP$ violation as the manifestation of a non trivial phase in the Cabibbo-Kobayashi-Maskawa [7] matrix whose coefficients describe the coupling strength among the 3 quarks doublets.

As shown before the characteristic parameter quantifying direct $CP$ violation in two pions neutral kaons decays is $\varepsilon'$. From equation 1.39 one can derive a relation between $Re(\varepsilon'/\varepsilon)$ and the measurable quantity $R$ (called double ratio):

$$R = \frac{\Gamma(K_L \rightarrow \pi^0\pi^0) \cdot \Gamma(K_S \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^+\pi^-) \cdot \Gamma(K_S \rightarrow \pi^0\pi^0)} \approx 1 - 6Re(\varepsilon'/\varepsilon)$$ \hspace{1cm} (1.45)

where $\Gamma$ indicates the width of a particular decay process.

Since the $\varepsilon$ and $\varepsilon'$ phases have similar value, $Re(\varepsilon'/\varepsilon)$ is essentially a measure of the modulus of $\varepsilon'$ and hence of the magnitude of the possible direct $CP$ violation.

The values of $Re(\varepsilon'/\varepsilon)$ measured by the previous generation of experiments are $(2.3 \pm 0.65) \cdot 10^{-3}$ and $(0.74 \pm 0.52 \pm 0.29) \cdot 10^{-3}$, respectively published by NA31 [8] (CERN experiment) and by E731 (FERMILAB experiment) [9].

The first value differs from zero by more than 3 standard deviations, and hence is indicating the presence of a direct violation effect, while the second is compatible with zero, and by consequence with no direct $CP$ violation.

The experimental situation therefore was not yet settled and an improvement in accuracy by at least a factor 2 is strongly felt to be needed.
Chapter 2

The NA48 experiment

NA48 is an experiment being performed at CERN laboratories at Geneva.

The experiment aims at measuring the $CP$ violation parameter $Re(\varepsilon'/\varepsilon)$, in the two pions decay of the neutral $K$ mesons, with a sensitivity of better than $2 \cdot 10^{-4}$.

2.1 Principle of the measurement

NA48 experiment has been designed [10] to measure the double ratio $R$ among four $K^0 \to 2\pi$ decay widths, and by consequence $Re(\varepsilon'/\varepsilon)$ (see equation 1.45).

Each individual width is experimentally given by:

$$\Gamma_{i,f} = \frac{N_{i,f} - N_{i,f}^B}{A_{i,f} \cdot \Phi_i}$$ (2.1)

where the subscripts $i$ and $f$ indicates the particular decay ($i = S, L$ for $K_S$ or $K_L$ and $f = 00, +-\pi^0 \pi^0$ or in $\pi^+ \pi^-$), $N_{i,f}$ and $N_{i,f}^B$ the total number of observed events and the number of background events, $\Phi_i$ the primary particles flux and $A_{i,f}$ the acceptance of the experimental apparatus.

The need to measure a double ratio of widths rather than the four widths separately, has been thoroughly considered when NA48 has been conceived and designed.

The basic idea is to observe the $K_L$ and $K_S$ decays of the same momentum and decay vertex position, both in the $\pi^+ \pi^-$ and in the $\pi^0 \pi^0$ modes, with the same detector (see figure 2.1) so that the acceptance factors of the four widths cancel out (at first order) in the ratio. The result will then be only slightly dependent on the uncertainty in their determinations, keeping Montecarlo corrections small.
The flux terms also cancels between charged and neutral decays of the same \( K_S \) or \( K_L \) beam.

To reduce the effects due to the differences in momentum distribution of \( K_L \) and \( K_S \) beams and the momentum dependence of the detector efficiencies, and to assure the best a priori cancellations of the acceptance terms in \( R_i \), it is necessary to calculate double ratios for events in small bins of kaon energy.

Given the large natural difference in the longitudinal distribution of decay vertex between \( K_L \) and \( K_S \) and the differences in vertex reconstruction resolutions, the same binning approach cannot be followed to reduce the effects due to the dependence of efficiencies on the decay vertex position.

An event-weighting technique (see section 2.1.1) is used to symmetrise \( K_L \) and \( K_S \) distribution, at the prize of a slight loss in statistical power.

This technique implies the necessity to reconstruct the relative momentum and position scales for \( \pi^+ \pi^- \) and \( \pi^0 \pi^0 \) events to an accuracy of \( \sim 2 \times 10^{-4} \). Using the known values of kaon and pion masses, momentum and position measurements can be related together, and the absolute scale is determined, independently for charged and neutral decays, by the reconstruction of the position of a veto counter, called AKS (see figure 2.2), composed of three scintillation counters preceded by an aligned iridium crystal, to allow an enhanced photon conversion [11], which induces a sharp edge in the \( K_S \) decays distribution.

The other fundamental choice of NA48 is that of having simultaneous \( K_L \) and \( K_S \) beams (spatially superposed at the position of the apparatus as shown in figure 2.3) thus reducing at the maximum possible extent the effects of relative differences among \( K_L \) and \( K_S \) due to time dependence of the apparatus response and to accidental activity in the detector.

The detector for the observation of the \( \pi^+ \pi^- \) decays is a magnetic spectrometer (see section 2.1.5) for the measurement of pion momenta, while the apparatus for the \( \pi^0 \pi^0 \) decays is a liquid krypton electro-magnetic calorimeter for the measurement of the energies and the impact point position of the 4 photons originated by the decays of the 2 \( \pi^0 \).

Two hodoscopes, are installed: one after the spectrometer and one inserted inside the electro-magnetic calorimeter, to provide a precise measurement of the event time. This time information is essential to distinguish between \( K_S \) and \( K_L \) decays (see section 2.1.4).

Anti-counters have been installed to allow the precise definition of the fiducial volume (see figure 2.1), and an hadron calorimeter followed by a muon veto system are installed at the end of the detector (see figure 2.1) to allow charged particles identification for background rejection.

The dominant background contribution for neutral decays comes from the \( K_L \to \pi^0\pi^0\pi^0 \) with just 4 observed photons. At the trigger level this contribution is largely reduced with a cut in the reconstructed longitudinal position of
the decay vertex. In the offline analysis a cut is applied on the reconstructed masses of two pairs of photons. In the case of decays $K \rightarrow 2\pi^0$, the values of the two masses are both equal to the $\pi^0$ masses, within the measurement accuracy. For the background events due to decay in three pions with 4 photons reconstructed there is almost no correlation among the values of the two invariant masses reconstructed. Montecarlo studies show that the distribution of those background events, plotted in a two-dimensional space, with $m_1$ and $m_2$ (the two invariant masses reconstructed) as coordinates, is uniformly distributed over a region much wider than the surface populated by $2\pi^0$ events.

![Detector scheme](image-url)
The number of background events that pass the final analysis cuts can then be evaluated and subtracted.

Concerning charged decays, a cut on the invariant mass of the 2 oppositely charged tracks, assumed to be pions, will strongly reduce the background due to the semileptonic decays. A subsequent reduction of $K \rightarrow \pi e \nu$ background events is obtained by the identification of the electron tracks, with the ratio of their measured momenta and of the energy deposited in the electro-magnetic calorimeter. The identification of the muons coming from $K \rightarrow \pi \mu \nu$ decays is
2.1. PRINCIPLE OF THE MEASUREMENT

Figure 2.3: NA48 experimental apparatus
based on the information of the muon anti-counter.

One of the principal contributions to the final error on the measurement is expected to come from the statistical error, dominated by the decays $K_L \rightarrow \pi^0\pi^0$, the rarest among the four taken into account. From equation 1.45 we can see that:

$$\sigma_{\text{stat}} \simeq \frac{1}{6} \cdot \frac{1}{\sqrt{\alpha_w N_{L,0}}}$$  \hspace{1cm} (2.2)

since the double ratio is a number almost equal to 1. $\alpha_w$ is a factor that estimates the reduction of statistical power due to the weighting technique ($\alpha_w \simeq 2/3$ as described in appendix A). In order to obtain a contribution of the statistical error of the order of $10^{-4}$ it will be necessary to collect about $3 \cdot 10^6$ events of $K_L$ decays into two neutral pions.

To be able to collect such a number of events in a period of the order of some months of real data taking, NA48 has decided to work with a $K_L$ beam intensity such that, during the beam spill, $\sim 10^6$ decays per second are produced between the beginning of the fiducial zone and the detector ($\sim 100$ m).

This implies that each part of the detector and especially the trigger system has to stand these frequencies. The NA48 collaboration has set-up a trigger and acquisition system based on the concept of the pipe-line.

### 2.1.1 The weighting technique

All the terms in equation 2.1 are in reality dependent on the kaon momentum $p_K$ and on the decay vertex position.

The actual number $N_{i,f}$ of measured events (after background subtraction) in a certain decay channel $(i, f)$ is given by:

$$\frac{dN_{i,f}}{dp_K' dz'_v} = \Gamma_{i,f} \cdot \int_{-\infty}^{\infty} dp_K \int_{-\infty}^{\infty} dz_v \left[ A_{i,f}(p_K, z_v, p_K', z'_v) \cdot \Phi_i(p_K) \cdot F_i(p_K, z_v) \right]$$  \hspace{1cm} (2.3)

where: $p_K$ and $z_v$ are the true values of kaon momentum and decay vertex position in the direction of the beam axis, $p_K'$ and $z'_v$ are the measured values of the same two quantities, $F_i$ the physical distribution function of the decays and $A_{i,f}$ is apparatus acceptance (i.e. the probability of detecting an event with measured $p_K'$ and $z'_v$ out of the true values $p_K$ and $z_v$).

The double ratio $R_{\text{raw}}$ of the measured numbers of decays is then given by:

$$R_{\text{raw}} = \frac{\int dp_K' dz'_v \frac{dN_{L,00}}{dp_K' dz'_v} \times \int dp_K' dz'_v \frac{dN_{S,++}}{dp_K' dz'_v}}{\int dp_K' dz'_v \frac{dN_{L,00}}{dp_K' dz'_v} \times \int dp_K' dz'_v \frac{dN_{S,00}}{dp_K' dz'_v}}$$  \hspace{1cm} (2.4)
2.1. **PRINCIPLE OF THE MEASUREMENT**

One can reasonably make the assumption that $A_{i,f} = A_f$ as the experimental apparatus is the same for $K_S$ and $K_L$ and the beams are almost exactly spatially superimposed at the position of the electro-magnetic calorimeter. The small differences in the acceptance between $K_S$ and $K_L$ decays are anyway going to be studied by an appropriate Montecarlo and a correction will be applied to calculate $R$.

At a similar level of accuracy (taking also into consideration that the production angle relative to direction of the incoming primary protons for $K_S$ and $K_L$ beams have been chosen such as to minimise the difference of the momentum spectra in the range of accepted kaon energy) the flux factors $\Phi_i$ cancel in $R_{raw}$.

Because of the large difference in the dependence of $F_i$ on $z_v$ (due to the difference in $K_S$ and $K_L$ lifetimes), and because of the finite and different apparatus resolutions for charged and neutral decays, the same “binning” approach cannot be used in $z_v$.

First of all one can realize (see discussion in appendix A) that, given the steep exponential distribution of $K_S$ decays, applying a software upstream fiducial cut in $z_v'$ would imply a too large sensitivity of $R$ to the systematic error in the vertex position reconstruction. The NA48 collaboration has thus chosen to install a converter and an highly efficient system of anti-counters (the already mentioned AKS veto system shown in figure 2.2) after the final $K_S$ beam collimator. All the $K_S$ events not in coincidence with an AKS signal will be accepted for the analysis even if their decay vertexes are reconstructed upstream of the AKS position.

This solution reduces to an acceptable level the sensitivity of the systematic error on $R$ to the definition of the beginning of the decay region for $K_S$ events. This is in fact the region from which most of the $K_S$ originates. In case of application of a software cut to define the beginning of the $K_S$ fiducial region, any error would result in the lost of a large fraction of the $K_S$ statistics. This wouldn’t be compensated in the double ratio by the lost of an equivalent fraction of $K_L$ events, as those are uniformly distributed over the all region. The net result would be an unacceptably large dependence of the error on $R$ to the resolution on the definition of the beginning of the longitudinal vertex decay.

Because of the sharp physical cut at the upstream edge of the accepted $K_S$ events, the $K_S$ decays distribution close to the AKS is dominated by the reconstruction resolutions and is hence different for charged and neutral decays. This implies that, over a significant portion of the $K_S$ decay distribution, the double ratio could not be calculated in bins of $z_v'$ as the resolution and acceptance differences between charged and neutral decays would not factor out. As an illustration of the problem one can ask himself to what $z_v'$ bin the events with a vertex reconstructed before the AKS position should be assigned. It is
CHAPTER 2. THE NA48 EXPERIMENT

thus clear that we have to calculate $R_{raw}$ integrating over the full $z'_v$ fiducial region.

An upstream software cut on $z'_v$ (at the level of the reconstructed position of the AKS) can instead be safely applied to $K_L$ events because their distribution is almost flat over distances much longer than the reconstruction resolution in $z_v$.

The same software cut on $z'_v$ is applied to define the downstream end of the acceptance region for both $K_S$ and $K_L$ events.

To assure under these circumstances the cancellation of the acceptance terms in the double ratio one can weight the $K_L$ events with a function $W(p'_K, z'_v)$ (ideally equal to $W(p_K, z_v)$) given by the ratio of the $K_S$ to $K_L$ 2 pion decay distributions:

$$W(p'_K, z'_v) \simeq W(p_K, z_v) = \frac{F_S(p_K, z_v)}{F_L(p_K, z_v)} = \frac{F(p_K, 6 + z_v)}{F(p_K, 120 + 6 + z_v)} \quad (2.5)$$

where 120 is the distance (in meters) between the targets of $K_S$ and $K_L$ beams and the longitudinal vertex position is measured from the centre of the AKS, and:

$$F(p, z) = e^{-z/\lambda_S} + |\eta|^2 e^{-z/\lambda_L} + 2|\eta|D e^{-z(1/\lambda_S + 1/\lambda_L)/2} \cos(\omega z - \phi) \quad (2.6)$$

$$\lambda_{L,S} = \gamma \beta c \tau_{L,S} \quad (2.7)$$

$$\omega = \frac{(m_{K_L} - m_{K_S})c}{\gamma \beta h} \quad (2.8)$$

The interference term is proportional to $D$ with:

$$D = \frac{N_{K^0} - N_{\bar{K}^0}}{N_{K^0} + N_{\bar{K}^0}} \quad (2.9)$$

where $N_{K^0}$ ($N_{\bar{K}^0}$) are the numbers of $K^0$ ($\bar{K}^0$) incoherently produced by the proton interactions in the target. $D$ has been measured in similar conditions by NA31 and can be checked by fitting directly the data.

Thus one gets a weighted double ratio $R_w$ given by:

$$R_w(\Delta p'_K) = \frac{\Gamma_{L,00} \Gamma_{S,+} \int d\omega d\Delta p_K W(p'_K, z'_v)F_L(p_K, z_v)A_{00}(p_K, z_v, \Delta p'_K, z'_v)}{\Gamma_{S,00} \Gamma_{L,+} \int d\omega d\Delta p_K F_S(p_K, z_v)A_{00}(p_K, z_v, \Delta p'_K, z'_v)} \simeq$$

$$= \frac{\Gamma_{L,00} \Gamma_{S,+} \int d\omega d\Delta p_K F_S(p_K, z_v)A_{00}(p_K, z_v, \Delta p'_K, z'_v)}{\Gamma_{S,00} \Gamma_{L,+} \int d\omega d\Delta p_K F_S(p_K, z_v)A_{00}(p_K, z_v, \Delta p'_K, z'_v)} \simeq \frac{\Gamma_{L,00} \Gamma_{S,+}}{\Gamma_{S,00} \Gamma_{L,+}} \quad (2.10)$$
2.1.2 The beam

As repeatedly mentioned the experiment is based on the concurrent observation of $K_L$ and $K_S$ decays with the same apparatus. This means, among other requirements, that the two $K$ beams [12] have to be spatially superimposed at the detector position (see figure 2.3), to avoid unwanted differences in acceptance.

The $K_L$ beam originates from a main proton beam with a momentum of 450 GeV/c impinging on a Beryllium target.

Among the reaction products the neutral component is selected at an angle of 2.4 mrad with respect to the incoming beam, to maximise the ratio between the number of $K_L$ and that of neutrons in the momentum range of interest.

The protons which have not interacted in the target, after deflection by a dipole magnet, are sent to impinge on a bent crystal which deflects the protons entering parallel to the crystallographic planes, through the "channelling" effect [13, 14, 15]. This allows to select an highly collimated proton beam, with an intensity about $10^4$ times smaller with respect to the main beam.

Other magnets subsequently bring these protons on the target of $K_S$, located only 72 mm above the direction of flight of the $K_L$.

Downstream of the $K_S$ target, the neutral component of the reaction products are selected at an angle of about 4.2 mrad with respect to the proton beam. This angle has been chosen so as to have a ratio among the $K_L$ and $K_S$ decays as much as possible independent from the kaon momentum. At this angle, in fact, the distribution of the number of produced $K$ versus the momentum is much softer than the one correspondent to the angle of production of the $K_L$. Moreover the channelling reduction factor of the primary protons allows to have comparable numbers of "good" 2 $\pi$ decays from $K_L$ and $K_S$, integrated over 2-3 $K_S$ decay lengths.

The final $K_S$ collimator is installed at a distance of 6 m from the $K_S$ target, followed by 8mm of lead (to induce the conversion of $\gamma$s from the 2 $\pi^0$ decays) and by the AKS anti-counter (see figure 2.2).

2.1.3 The decay region

The decay zone (see figure 2.4) is contained in a vacuum pipe 90 m long ending in a kevlar window 0.8 mm thick.

The material and the thickness of the window have been select taking into account the opposite necessities that the window is thick enough to satisfy all the security requirements still being as thin as possible in terms of radiation length.

The angular aperture of the decay zone is fixed by anti-counter rings of octagonal inner shape (see figure 2.5) which are used to reduce the background
Figure 2.4: Scheme of the decay region
2.1. PRINCIPLE OF THE MEASUREMENT

Figure 2.5: Scheme of the anti-counter rings

due to the $K_L \to 3\pi$ decays [16]. Each ring is divided in sectors, each realized from a sandwich of two scintillators embedding 2.5 cm of iron. The angular zone selected has an opening of 10.35 mrad.

2.1.4 The tagging

One of the most critical parts of the whole experiment is the attribution of the decays to a $K_L$ or to a $K_S$. NA48 strategy is to measure the time difference between the passage of the protons in the tagger counter [17, 18], before the $K_S$ target, and the time of the event in the detector.

$K_S$ events are defined as those whose time difference falls into a defined temporal window while all the others are assumed to be $K_L$ events.

The accidental activity in the tagging counter causes the attribution to $K_S$ of a $K_L$ event while the inefficiency in the time reconstruction of the event or in the time measure of the proton in the tagging counter will cause the opposite error.

If $\alpha_{LS}$ is the number of $K_L$ decays wrongly identified as coming from $K_S$ and if $\alpha_{SL}$ gives the number of oppositely reconstructed events it is reasonable to assume that:

$$\alpha_{LS}^{00} \simeq \alpha_{LS}^+$$  \hspace{1cm} (2.11)

as they depend mainly of the characteristics of the proton beam, while in general it is:

$$\alpha_{SL}^{00} \neq \alpha_{SL}^+$$  \hspace{1cm} (2.12)
This depends on the fact that the apparatus that observes the event (and that determines its time too) is different for the charged and for the neutral decays.

It is essential for the success of the experiment to hold under control these factors, but it is even more important to operate in a way that they are mutually equal. It is indeed possible to show that if $\delta_{SL}^{00} = \delta_{SL}^{+}$, the tagging error cannot artificially create a signal of direct $CP$ violation. When this signal is present, on the other hand, the tagging uncertainty causes an effect of dilution of $R$ (the double ratio) that has to be corrected.

To stand the proton beam rate of more than 10 $MHz$ the tagging detector has been realized with 12 counters arranged in staircase along the horizontal beam axis and 12 along the vertical axis (see figure 2.6), in a way that each of them has to stand a rate of about 1 $MHz$. Each tagger counter is equipped with photomultipliers on just one side (see figure 2.7). Every PM signal is read-out by two 8-bit 480 MHz FADCs running in interleaved mode. The intrinsic time resolution of a single tagging counter is of the order of $\sim 160$ ps as can be deduced from figure 2.8.
2.1.5 The apparatus for detecting charged decays

The detection of charged decays is assured by a magnetic spectrometer to measure the $\pi^+ \pi^-$ momenta and an hodoscope to measure their arrival time.

The magnetic spectrometer

The spectrometer is composed of four Multi Wire Proportional chambers \cite{19, 20} and an analysing dipole magnet \cite{21}.

The four chambers have an octagonal shape with a total width of 2.9 m. Each of them is composed of 8 planes of 256 parallel sense wires, arranged in 4 views (see figure 2.9). The gap between two sense wires of a same plane is 10 mm.
and the two planes of a same view are displaced by 5 mm (see figure 2.10). The gap between the sense wires is measured and known with a precision of 10 μm, and the resulting position resolution is measured to be about 120 μm for each plane. The magnet (see figure 2.11) has an opening of 2.45 m of width and 2.2 m of height, and yields an integrated field of around 0.8 T·m corresponding to a momentum kick of ∼ 250 MeV/c.

The measured momentum resolution of the spectrometer is [22]: \( \Delta p/p = (0.47 \oplus 0.01p[GeV/c]) \% \) that means a resolution in the \( K \) mass of nearly 3 MeV (see figure 2.12).
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Figure 2.9: Arrangement of the chamber views

The charged hodoscope

The time measure of the charged decay events is based on a hodoscope [23, 24] placed to about 1 m from the electro-magnetic calorimeter and composed of two planes of scintillators 50 cm apart from each other. Each plane is composed of four quadrants of 16 scintillators, 2 cm thick, each, horizontal in a plane and vertical in the other (see figure 2.13).

The dimensions of the different scintillators are adjusted so that each plane has an active octagonal surface that matches the acceptance surface of the electro-magnetic calorimeter.

Charged trigger

The trigger that selects charged decays [25] is structured as a classical two level system.

A first level of fast rate reduction is assured by a coincidence between planes in the hodoscope [26] and the requirement that a fast estimate of the sum of the total energy seen by the electro-magnetic and the hadronic calorimeter is greater that 30 GeV. This total energy information is obtained by a fast sum of
the calorimeters energy information performed by the electronics of the trigger for neutral decays.

The second level of trigger is composed of hardware coordinate builders followed by a farm of microprocessors (called Mass Box) that perform a basic reconstruction of the event characteristics.

Events are selected when having two tracks with a closest distance of approach smaller than 5 cm and a opening angle smaller than 15 mrad. Moreover the reconstructed proper decay time of the event is required to be smaller than 4.5 $K_S$ lifetimes and the reconstructed invariant mass is required to be greater than 95 % of the kaon mass.
2.1. PRINCIPLE OF THE MEASUREMENT

Magnet characteristics:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total weight</td>
<td>105 tons</td>
</tr>
<tr>
<td>Nominal current</td>
<td>1200 A</td>
</tr>
<tr>
<td>Total nb. of A-turns</td>
<td>$0.98 \times 10^6$</td>
</tr>
<tr>
<td>$B_y(0,0,0)$</td>
<td>0.3712 Tesla</td>
</tr>
<tr>
<td>Integrated $B_y(0,0,z)$</td>
<td>0.858 T.m</td>
</tr>
<tr>
<td>Magnetic energy</td>
<td>430 KJoules</td>
</tr>
<tr>
<td>Dissipated power</td>
<td>3.1 MW</td>
</tr>
</tbody>
</table>

Figure 2.11: The Magnet

The overall charged trigger chain produces an output rate of events of about 1 kHz.

Even if the charged trigger is intrinsically an asynchronous system, it receives, as all the data acquisition systems in the experiment [27], the global 40 MHz experiment clock. All the events are thus recorded together with a trigger time information (called time stamp), obtained by a counter of the main clock. The time stamp allows later reordering of the charged events.

The asynchronous architecture implies anyway that the trigger has a non negligible dead time. Whenever the Mass Box reaches its computing limit, the system has to stop accepting new inputs form the first level trigger.

In 1997 the system has been measured to have a dead time of $\sim 1\%$ of the pulse.

The Mass Box has been programmed to store for every period of the global
Figure 2.12: kaon mass resolution as obtained by charged decays detection

experiment clock a bit related to its status. This information can be used later in the analysis to correct for the possible asymmetries between charged and neutral events, induced by the dead time (see discussion in chapter /refchap:eprime).

2.1.6 The detection of neutral decays

For the detection of the neutral kaon decays the NA48 collaboration has realized an almost homogeneous (to minimise the sampling fluctuations) calorimeter with liquefied krypton as active medium.

The trigger system to select $K_L \rightarrow 2\pi^0$ decays is based on the calorimeter information itself and it has been realized in pipe-line (see following discussion) to have a dead-time free data acquisition.

This part of the apparatus is probably the most delicate as the $K_L \rightarrow$
2.1. PRINCIPLE OF THE MEASUREMENT

\[ \pi^0 \pi^0 \] is the rarest decay mode (thus dominating the statistical error on the measurement). Moreover the neutral decays detection can be quite sensitive to accidental effects and one has to get rid of the large background induced by \( K_L \to 3\pi^0 \) decays.

In the following chapters the calorimeter and the trigger system are presented in detail, and their achieved performances are discussed.
Chapter 3

The electro-magnetic calorimeter

The electro-magnetic calorimeter for the detection of the four photons coming from the decay of the two pions of the neutral channels is the most innovating element of the NA48 detector and the one of most difficult realization.

The development of the design and building of the final electro-magnetic calorimeter has been a major effort which has required many phases of production and test of different prototypes with implementation of different readout techniques.

The requirement of excellent energy resolution has led to the development of an almost homogeneous ionization chamber detector, with liquefied krypton as the active medium, described in this chapter.

3.1 Theoretical elements on ionization chambers

Ionization chambers are devices that allow to measure the ionization caused by the passage of charged particles in a material, in general a noble gas like argon, krypton or xenon, with sufficiently long lifetime before recombination.

Electric fields of suitable intensity force the free charges created by the ionization to drift toward the collection electrodes on which a current related to the amount of drifting charge is induced.

The detection of this current allows the measurement of the energy released in the material.

The electro-magnetic calorimeters exploiting this technique are ionization chambers with longitudinal and transverse dimensions chosen such as to contain most of the ionization produced by the shower initiated by the incident electron or photon.
The interested reader can find discussions on the properties of electro-magnetic
showers development in different materials in detailed review papers [28, 29].

The active volume of an ionization calorimeter can be divided into cells. In
each cell a current is produced proportional to the ionization created by the
particles inside it. This subdivision can be used to measure, in addition to the
energy, the position of the incident particles.

The electric fields that move the ionization charges are normally chosen of
an intensity such as to induce a saturation of the drift velocity of the ionization
electrons (which depends on the field and on the collisions the atoms of the
material that slow down it). For a parallel plate cell the drift velocity is constant
and uniform inside the cell, and perpendicular to the electrodes.

The positive ions velocity is slower by orders of magnitude with respect to
that of the free electrons, and doesn’t contribute appreciably to the current
immediately following the development of the shower and for times short (as
used by NA48 readout) with respect to the drift time of the electrons across the
cell.

The accumulation of ions in a cell, due to multiple shower occurrence in
times of the order of the drift time of the ions (in our case ∼0.5 s), gives rise
to a space charge effect, which can alter the magnitude and the uniformity of
the electric drift field. In the conditions of NA48 [30] the effect is small and we
neglect it in the following discussions.

For infinitely extended plane electrodes, every moving charge \( q \) induces a
constant current

\[
i_q = \frac{q}{t_d}
\]

no matter its distance from the readout electrode (see figure 3.1(a)). The con-
tribution of a charge to the total current ends when it reaches the surface of the
readout electrode and cannot move anymore.

The time \( t_d \) is given by:

\[
t_d = \frac{d}{v_d};
\]

where \( v_d \) is the electron drift velocity and \( d \) is the width of the cell in the
direction of the electric field (and of \( v_d \)).

With the above assumptions, and with the hypothesis that the ionization
charge is uniformly distributed inside a cell, the time behaviour of the induced
current is given by [31]:

\[
i(t) = \frac{Nq}{t_d} \cdot \left(1 - \frac{t}{t_d}\right) \quad (0 \leq t \leq t_d)
\]

where \( N \) is the number of ion-electron pairs created in the cell by the ionization
and \( q \) the elementary electron charge (see figure 3.1(c)).
3.1. THEORETICAL ELEMENTS ON IONIZATION CHAMBERS

Figure 3.1: Time behaviour of the current due to a single ion-electron pair (a) and to uniform ionization inside the cell (c).

This implies that the time behaviour of the charge induced on the electrodes is:

\[ Q(t) = Nq \left( \frac{t}{t_d} - \frac{1}{2} \left( \frac{t}{t_d} \right)^2 \right) \cdot (0 \leq t \leq t_d) \quad (3.4) \]

Thus if one integrates the induced current for a measurement time \( t_m = t_d \) the collected charge is:

\[ Q_m = Q(t_d) = \frac{1}{2} \cdot Nq \quad (3.5) \]

where \( Q_m \) is the total observed charge.

The need to work at high data acquisition frequency led us to realize a fast readout that collects the deposited charge in a time much smaller than the drift time. If the current signal is effectively integrated for a time \( t_m \ll t_d \) one gets [32]:

\[ Q_m \approx Nq \cdot \frac{t_m}{t_d} \quad (3.6) \]
Such a readout is called “current-sensitive” [33, 34] as one measures a signal proportional to the initial induced current $Nq/t_d$.

Equations 3.3 and 3.4 hold only in the hypothesis that the recombination lifetime $\tau_R$ of the ionization electrons is large with respect to $t_d$. If the recombination is taken into account by $N = N(t) = N_0 \cdot \exp(-t/\tau_R)$, equations 3.3 e 3.4 become (for $0 \leq t \leq t_d$):

$$i(t) = \frac{N_0 q}{t_d} \cdot e^{-t/\tau_R} \cdot \left(1 - \frac{t}{t_d}\right)$$

$$Q(t) = \frac{N_0 q \cdot \tau_R}{t_d} \cdot \frac{t_d}{t_d} \cdot \left[e^{-t/\tau_R(t + \tau_R - t_d)} - (\tau_R - t_d)\right].$$

This implies that in the hypothesis of $\tau_R \ll t_d$ the charge observed in a time $t_m \ll t_d$ but of the order of magnitude of $\tau_R$ is given by:

$$Q_m \simeq N_0 q \cdot \frac{\tau_R}{t_d} \cdot \left(1 - e^{-t_m/\tau_R}\right)$$

In practice the NA48 calorimeter krypton purification system maintains the electron lifetime $\tau_R \gg t_d \gg t_m$ [35] and the signal is practically not affected by $\tau_R$.

If now we relax instead the hypothesis of uniform distribution of the ionization charge inside the cell and we consider the number of ion-electron pairs $dN$ produced in an interval $x, x + dx$ (where $x$ is the distance from the cell anode electrode) to be given by $dN = N(|x - x_i|)dx$ (where $x_i$ is the distance of the primary photon or electron impact point), we get:

$$Q_m(x_i) = N'(x_i)q \frac{t_m}{t_d},$$

with:

$$N'(x_i) = \int_0^d N(|x - x_i|)W(x)dx.$$  (3.11)

$W(x)$ is the weighting function that takes into account the already mentioned fact that each drifting electron induces a constant current only while it is able to move, and its contribution to the signal terminates when it reaches the surface of the anode electrode.

One can easily see that if the current is integrated for a time $t_m < t_d$, all the free electrons induced at a distance $x$ from the anode electrode larger than $d \cdot t_m/t_d$ gives the same contribution to $Q_m$, while the ones induced near the anode are able to drift only for a fraction of the time $t_m$ and thus their contribution is less important. More precisely $W(x)$ is given by (see figure 3.2):

$$W(x) = \frac{x}{d \cdot t_m/t_d} \quad (0 \leq x < d \cdot \frac{t_m}{t_d})$$

$$W(x) = 1 \quad (d \cdot \frac{t_m}{t_d} \leq x \leq d).$$  (3.12)
3.1. THEORETICAL ELEMENTS ON IONIZATION CHAMBERS

The measured charge is given by:

\[ Q_m(x_i) = q \cdot t_m / t_d \cdot \int_0^d N(|x - x_i|) W(x) dx. \]

The shape of \( N(x) \) is indicative of the actual shower transverse distribution function should.

Figure 3.2: Behaviour of the charge collection weighting function \( W(x) \) inside a cell for different choices of \( t_m \).
### Chapter 3. The Electro-Magnetic Calorimeter

#### Table 3.1: Physical properties of the liquefied krypton

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number (Z)</td>
<td>36</td>
</tr>
<tr>
<td>Atomic weight (A)</td>
<td>84</td>
</tr>
<tr>
<td>Density</td>
<td>2.41 g/cm³</td>
</tr>
<tr>
<td>Radiation length ($X_0$)</td>
<td>4.7 cm</td>
</tr>
<tr>
<td>Molière radius ($R_M$)</td>
<td>4.7 cm</td>
</tr>
<tr>
<td>Interaction length ($\lambda_I$)</td>
<td>60 cm</td>
</tr>
<tr>
<td>Average ionization energy</td>
<td>20.5 eV</td>
</tr>
<tr>
<td>Critical energy ($E_c$)</td>
<td>21.51 MeV</td>
</tr>
<tr>
<td>Boiling temperature</td>
<td>119.8 K</td>
</tr>
<tr>
<td>Fusion temperature</td>
<td>116.0 K</td>
</tr>
<tr>
<td>Relative dielectric constant ($\varepsilon_r$)</td>
<td>1.62</td>
</tr>
<tr>
<td>Natural radioactivity</td>
<td>$\sim$ 500 Bq/cm³</td>
</tr>
</tbody>
</table>

It is easy to see that if one takes $N(|x - x_i|) = N/d$ (that means uniform ionization inside the cell) and assumes to collect the charge for a time $t_m = t_d$ or $t_m \ll t_d$, one deduces the same values of $Q_m$ as given by equations 3.5 and 3.6.

### 3.2 Main properties of NA48 calorimeter

The choice of liquid krypton as active medium has been driven by the requirement of using a noble gas (to be able to keep the recombination lifetime large) with a radiation length short enough to allow the building of a quasi-homogeneous detector (to minimise statistical fluctuations in the ionization charge deposition) and thick enough in the direction of the incident particles to contain most of an electro-magnetic shower (thus minimising the fluctuations due to charge leakage).

The main krypton properties are reported in table 3.1. The first idea of a xenon calorimeter has been abandoned in favour of krypton because of cost considerations.

A cooling system for the krypton liquefaction and a suitable cryostat to contain it at 120 K have been designed and built by the NA48 collaboration. The cryogenic system is not described here but the interested reader can refer to [35] and [36].

The active calorimeter thickness is 27 radiation lengths which means nearly 125 cm.

The reading structure for the collection of the ionization charge is arranged in longitudinal towers; the cells have a $2 \times 2$ cm² section.
3.2. **MAIN PROPERTIES OF NA48 CALORIMETER**

The calorimeter has a total number of 13248 channels; the active region has an octagonal shape with an inscribed circle of 128 cm radius. A circle of 8 cm radius in the centre of the detector is occupied by the beam pipe.

The choice of a reading structure arranged in longitudinal towers has been essentially determined by the necessity of a good separation of accidental clusters from the ones originated by the kaon decays. This provides a great reduction of the losses of good events due to accidental activity as required to deal with the great intensity of the NA48 beam.

The low cells capacitance ($\sim 100 - 200pF$) is essential to minimize signals rise time and to allow a “current sensitive” fast readout (see section 3.1), based on shaping electronics with an effective integration time much shorter than the total duration of the current induced by the ionization free charges.

The use of cold preamplifiers directly connected to the cells inside the cryostat allows the ionization signals not to be distorted by the parasitic inductance of long cable connections.

To avoid saturation effects in the electronics due to the high frequency of events, the preamplifiers have been designed to have a short restoring time (see section 3.5.1).

The signal from the analog electronics are continuously digitised by FADCs at a frequency of 40 MHz, to be able to reconstruct, in addition to the value of the initial current, the time information of the events, extrapolating the shape of the pulses from the time samples. This stream of time samples is sent to a dead-time free trigger and acquisition system based on the concept of the pipe-line (see section 4.1).

A readout structure with longitudinal towers implies the necessity of an extended dynamic range for the electronics of the cells. The properties of the lateral development of a electromagnetic shower in the liquid krypton are in fact such that the calorimeter cell correspondent to the position of impact of a photon, contains in average 40% of all the shower ionization charge. At the same time the need of minimize the charge leakage fluctuations requires to take into account, in the energy reconstruction, cells distant from the impact position and with a level of collected charge comparable to that of the electronic noise. Because the equivalent noise level is $\sim 5$ MeV and the accepted photon energies goes up to 100 GeV the readout electronics need to have dynamic range of about 80 db corresponding to approximately 14 bit.
3.3 The study of the calorimeter readout structure

Beginning from 1991 various calorimeter prototypes have been built and tested at CERN with electron beams.

The essential difference among the various prototypes has been the structure of the readout electrodes, that the we were forced to modify in order to eliminate unexpected effects of non uniform response observed on the first prototypes.

In all the cases however a cylindrical cryostat of 39 cm diameter and 140 cm length has been used. The thickness of the inner active zone was of 120 cm (similar to that of the final detector).

In total the prototype had 184 cells (see figure 3.3).

3.3.1 The dependence from the impact position

The first calorimeter prototype readout structure was made of flat electrodes, realized as a sandwich of copper and kapton [35, 37]. Each cell was horizontally divided in two semi cells with a common anode electrode (see figure 3.4). Vertically the cells were defined by the copper of the collecting electrode which was divided in strips 19 mm wide with a separation of 1 mm.

The results of a test of this structure showed that the response in energy
of the calorimeter to electrons of a monochromatic beam, was strongly dependent from the horizontal position of impact of the electron inside the cell (see figure 3.5).

A certain decrease of signal for particles impinging near to the central electrode was an expected effect, even if not of the observed magnitude. To understand the origin of such a dependence one has to refer to equations 3.10, 3.11 and 3.12 (see also figure 3.2). We observed that the electro-magnetic shower lateral profile in liquid krypton is very narrowly peaked around its centre (the direction of the primary photon or electron that generated it) over distances...
significantly smaller than the NA48 calorimeter semi-cell width (see figure 3.6 for a typical shower profile in NA48 calorimeter) while it becomes significantly flatter for large distances from the shower centre. This explains the observed reduction of signal when the primary particle impinges near an anode electrode and the shower core falls in the region were $W(x) < 1$.

An even more important unexpected effect was the large difference of the average response among two semi cells (see again figure 3.5). This could be understood [38] as caused by a slight different width for the two semi-cells. From
3.3. THE STUDY OF THE CALORIMETER READOUT STRUCTURE

equations 3.7 and 3.2 and under the hypothesis of drift velocity saturation, it can be seen that the current induced from the movement of the ionization charge is inversely proportional to the width of the semi cell in which it is produced.

In case of uniform ionization, with respect to the dimensions of a full cell, only a second order effect would be observed (in the response of a full cell the signal lost on one semi cell would be almost compensated by the gain in the other), but, as already mentioned, the transverse development of a shower close to its axis is actually strongly varying over distances of the order of the width
CHAPTER 3. THE ELECTRO-MAGNETIC CALORIMETER

Figure 3.7: Dependence of the response from the impact position after the introduction of kapton spacers between electrodes of our cells.

The main problem with such an effect is that, depending on the position of the electrodes, it is in general different among cells of different columns (i.e. delimited by different electrodes). This implies that one cannot hope to find a unique correction function, common to all the cells. Being the two semi-cells completely indistinguishable from the electronics point of view (there is a unique readout electrode), no electronics calibration could investigate the
3.3. The Study of the Calorimeter Readout Structure

cell differences around the detector, but one would be obliged to scan the full calorimeter with a collimated beam of electrons. Moreover it is not a priori sure that the position of the electrodes (and hence the entity of the effect) is not changing with time.

A quantitative treatment of this effect [38, 39] has shown that in order to be able to maintain the asymmetry, and then also the constant term of the energy resolution, at the level of the 0.5%, it is necessary to fix the widths of the semi-cells with an accuracy better than 100 \( \mu \)m.

3.3.2 The final readout structure

The search for a solution to the problem of the asymmetry among the semi cells and of the strong dependence of the response from the position of impact, led the collaboration to the realization of a quite different and innovative readout structure.

Instead of the copper-kapton electrodes, we choose to use ribbons of Cu(98%)-Be(1.8%)-Co(0.2%) alloy. Each ribbon is 18 mm wide, 1268 mm long and 40 \( \mu \)m thick. Horizontally the ribbons are positioned at a distance of 1 cm one from each other and a cell is then defined by the space among three consecutive electrodes. Vertically the strips are separate by 2 mm (see figure 3.8).

An important feature of the final NA48 calorimeter structure is that the cells are arranged in a way that photons originated by a decay occurring \( \sim 110 \) m far from the calorimeter (where the most part of the accepted kaon decays occurs) will impinge with the same incident angle relatively to the cell electrodes whatever their production angle could be. This “projective” behaviour is obtained adopting slight different transverse dimensions (\( \sim 1\% \) for both sides of the cell square section) between the front and the back of the calorimeter. Thus the resulting axes of the cells are all pointing to the same position on the beam axis.

Such an approach implies that, to a very good approximation the reconstructed angle of a photon with respect to the beam is independent of longitudinal shower fluctuations.

The electrodes ends are fixed to two circular plates of an epoxy-fibreglass composite material (STESALIT [40]), and stretched with a strain of about 2.5 N each. At the front face of the calorimeter, the ribbons are fixed to the plates by attaching them to suitable pieces of trapezoidal cross section which slide into grooves machined on the inner side of the plate. On the other plate, at the back of the calorimeter, there are holes through which pass the screws soldered to the end of the ribbons (see figure 3.9). These screws are used to fix the ribbons, to adjust their tension and to assure the electrical connection of the electrodes to the readout electronics.
For a good control of the tension and to restrict possible displacements of the ribbons from the optimal position, due to flaws in the system of support for the ribbons, we use "accordion" springs, with 2 mm pitch, worked out at the two ends of the ribbons (see figure 3.9). The springs at the entrance side of the calorimeter are 14 mm long for a measured elastic constant of about 160 N/mm while the ones at the opposite side are 27 mm long for an elastic constant of around 100 N/mm.

Beyond that, the ribbons are forced to pass across slits cut into 5 STESALIT plates 5 mm thick each and 20 cm apart the one from the other. The position of the slits at each plane is alternatively moved 10 mm horizontally with respect to the position of the previous one to force the ribbons to follow a "zig-zag"
3.3. THE STUDY OF THE CALORIMETER READOUT STRUCTURE

trajectory with an angle of around 50 mrad (see figure 3.10).

This arrangement is intended first of all to mediate (over the longitudinal development of the shower) the effect of the response dependence from the horizontal position of impact of the particles.

Another, and not less important effect of the zig-zag positioning of the ribbons is that of reducing the free length of the ribbons from 125 cm to 20 cm, thus allowing more precise geometrical tolerance on the electrodes positioning and assuring their stability in presence of the electric forces.

Figure 3.11 shows the residual impact point dependence observed after the adoption of the new readout structure. It can be seen that the residual dependence has been reduced at the 1% level, that the anode drop is significantly smoother and hence easier to correct and that no systematic difference is anymore observed between the two half of the cell.

The most important result anyway is the uniformity (within our calibration
precision) of the response dependence from cell to cell. This allows the derivation of a unique correction function, for all the calorimeter cells, to be applied using the impact point information deduced by the calorimeter itself.

At this level of accuracy, the dependence on the vertical impact position, that was negligible respect to the change due to the horizontal position in the old structures, becomes now significant. This vertical dependence is mainly due to the distortions of the electric field in the intermediate zones among two cells and to the fact that the drifting electrons don’t induce current only in the cells in which they travel, but also in the vertical neighbours. This effect was not taken into account in the discussion of section 3.1 where it was assumed that the vertical dimension of the cell was larger than the shower transverse dimension.

The vertical dependence is anyway observed to be uniform from cell to cell and is hence corrected like the horizontal dependence.
3.4 The neutral hodoscope

As already mentioned a neutral hodoscope is inserted inside the calorimeter structure to provide an additional time measurement.

This hodoscope is realized by mean of scintillating fibres, collected together in groups of 20 inside STESALIT tubes, fixed in the gaps between the electrodes (see figure 3.12), and readout by phototubes connected at their extremities and operating in the liquid krypton.

Figure 3.11: Dependence of the response on the impact position with the new structure
For the region of the 80 cell columns around the beam pipe, a phototube is connected to 10 fibre tubes, while in the periferical regions the phototubes read-out groups of 22 tubes. The neutral hodoscope is installed before the second spacer plate, were the shower mean charge deposition is expected to be about maximal for the accepted photon energies (5-100 GeV).

Figures 3.13 and 3.14 show the achieved time resolution of the device and its efficiency to reveal photon signals.

### 3.5 Readout electronics

The first stage of the analog readout electronics consists in a charge preamplifier directly connected to the cell structure (inserted inside the cryostat at the temperature of the liquefied krypton).

This preamplifier is based on an original design of V. Radeka [41], and is essentially a charge integrator with a restoring feedback.
The output signals from the preamplifiers are available on warm feed-through at the top of the calorimeter via RG178 coaxial cables, 6 m long, mostly immersed in the LKr.

Directly at the output of the feed-through, are connected the so-called “transceivers” amplifiers, that derivate the signal and perform a pole-zero cancellation to produce a signal with the same shape as the induced current on the electrodes. Their output drives shielded 100 Ω twisted pairs lines, 10 m longs, that carry the signal to the final shaping and flash digitising stage (see figure 3.15).
3.5.1 Cold electronics

The choice of using cold electronics has been made for several reasons:

- to avoid the use of long transmission line to carry the current signal induced on the electrodes out of the cryostat. This responds to the need of a fast readout.

- to exploit a property of ordinary silicon JFET, where the noise as a function of temperature has its minimum close to the liquid krypton temperature;

Figure 3.14: Neutral hodoscope efficiency
3.5. **READOUT ELECTRONICS**

- to profit of the good thermostatic properties of the liquid krypton bath to improve the long term stability, especially important for the accurate calibration needed for the experiment.

A dual hybrid version of cold charge integrating preamplifier, of BNL type [41], was designed for this project (see figure 3.16). The restoring time chosen is of 150 ns (to be compared with the $\sim 3\mu s$ drift time of the ionization).

The dispersion of the gains of the 13500 channels has been observed to be $\sim 0.9\%$.

Four hybrids are mounted on a single PCB card, to support them mechanically and to provide power and input/output connections.

The front-end cold electronics is assembled in units (called busses) containing 64 channels with their relative HV decoupling capacitors and resistors for high voltage biasing. The connection to the calorimeter electrode system is made by commercial connector pins inserted in a STESALIT profile. Each bus contains 64 pins for signals and 32 for a common ground connection.

The support for the 8 preamplifier cards (each containing 4 dual hybrid circuits) of a bus is a 18-layers printed circuit board that presents on its component side 8 calibration pulsers (see section 3.6) and 64 pads corresponding to

---

**Figure 3.15:** Scheme of the full calorimeter read-out chain
the preamplifier inputs. Each unit has power and voltage reference lines which pass along its length, allowing to connect one unit to the next one in the same column. Individual calibration trigger signals are sent to each unit.

To protect the front-end electronics from possible discharges occurring during the electrodes high voltage ramp-up, a system of switches has been implemented on each mother-board. Each set of switches consists of a long copper-beryllium spring that shorts all input pads to ground, once the springs are pressed against the pads by an actuator which employs liquid krypton as hydraulic fluid. Due to the very low inductance and high current capability of the springs, the switches provide a complete protection for the preamplifiers, even for continuous sparking in the electrode system and/or in the decoupling capacitors at least up to a voltage of 7 kV. During the first year of operation of the calorimeter, the protection system proved to be effective and reliable.
3.5.2 The transceivers

Transceiver boards [42] are mounted directly on the feed-through connector, enclosed by metallic boxes that extend the Faraday cage formed by the cryostat.

Their inputs presents 50 ohm AC termination for the coaxial cables coming from the preamplifiers.

The transceivers are implemented with discrete components in two stages (see figure 3.17).

In the first one, a zero-pole cancellation is performed to eliminate the 150 ns restoring time constant of the preamplifier. The signal produced has then the time shape of the current in the cell (see figure 3.18), amplified by a factor 15 and with a rise time of about 22 ns.

The second stage performs further amplification of the signal and then drives a shielded twisted pair line to the digitising electronics. Maximum care has been taken to minimise noise (1.9 nV/√Hz at the input) and the linearity, which is better than 0.1% both for the integral and the differential one.

The dispersion of the gains of the transceivers is ∼ 1.3%
3.5.3 The Calorimeter Pipeline Digitiser (CPD)

The CPD system [43, 44] is the final stage of the electronics chain, which provides the final shaping of the signals (to generate narrow pulses) and their 40 MHz flash digitisation. CPDs also take care of temporarily storing the produced digital information and of interfacing with the trigger electronics to send the relevant part of the data to the final storing facilities.

Every CPD modules handles 64 calorimeter channels, corresponding to a square region of 8 by 8 cells. This cabling scheme of the channels is due to the fact that the CPDs also provides signals to the Neutral Trigger electronics as it will be described in chapter 4.

Every CPD modules is implemented as a Fastbus module and it is mainly composed of:

- 32 CPDAS daughter cards, that contains the analogue and digitising circuitry for two calorimeter channels;
- 1 CPDTR analogue card, that provide outputs to the Neutral Trigger
electronics chain;

• 1 memory address card CPDMAC board, to provide the interface between the local data storing facility and the incoming trigger information;

• 1 FASTBUS interface card.

All the relevant signal processing of the CPD is provided by the CPDAS cards. Figure 3.19 shows the scheme of one of the two CPDAS channels.

The analogue processing of the input signals (see figure 3.18) consists of:

1. a differentiating stage followed by a 7 MHz sixth order Bessel-like analogue filter, to form the final pulse shape with a FWHM of $\sim 80$ ns (see figure 3.20) and following almost flat undershoot (see section 3.6.3 for a discussion on the characteristics of this undershoot);

2. a variable gain amplification stage that produces signals like the one shown in figure 3.22.

All this analogue processing is implemented in the KRYPTON Asic$^1$ that has been developed by the NA48 collaboration.

The produced analogue signals are sent to 10 bit 40 MHz FADC and the digital time samples are continuously stored in a circular memory buffer (see figure 3.19: Scheme of a CPDAS channel

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1 Asic stands for: application specific integrated circuit
Figure 3.20: Shape of the analog pulse sent to the switching gain CPD stage

figure 3.19) which is overwritten every 204.8 μs (8192 clock cycles). This is the holding time of the data and is the maximum time that the CPD system can wait for a trigger information.

Whenever a good event is found (by the Neutral Trigger or by another special trigger that one could set up), an event time information called “timestamp” (with the granularity of 25 ns, the clock period), has to be generated and sent by the trigger electronics to all the CPDMAC boards.

Those boards calculates the address of the circular buffer where the related time sample information has been stored. The data relative to the particular sample and of a programmable number of surrounding samples (normally set to 10) is transferred to the linear buffer where it is going to be readout and sent to the long term storing facility.

The switching gain logic

The switching gain amplifier stage is provided to increase the effective dynamic range of the electronics from the 10 bit of the FADCs to the 14 effective bits
3.5. READOUT ELECTRONICS

That is provided by 4 alternative gain stages (whose values are sketched in figure 3.21), that can be dynamically applied to the shaped pulses.

The selection of gain is done in parallel to the pulse processing in the Bessel filter and the gain is selected dynamically by comparing the instantaneous pulse height of the differentiated input signal with three thresholds. This scheme avoid the use of analog delay circuits, as the time needed by the comparing circuit is guaranteed by the intrinsic delay implied in the Bessel filtering.

The gain value can decrease but not increase every clock cycle. The lowest gain selected for a given pulse (corresponding to the highest point sampled by the gain selector) is held at least 3 clock cycles (i.e. 75 ns). The gain holding can be programmed to be extended up to 10 clock cycles.

The information of the current gain factor is stored with the data every clock cycle by mean of 2 additional bits. The data output of CPDs have then a 10+2 bit format but the required effective 14 bit dynamic range.

3.5.4 The data concentrator

The data concentrator receives the digital outputs of the ∼13500 CPD modules and applies programmable selection criteria to reduce the actual amount of data sent to the data storage.

The actual number of channels with relevant information for a given kaon...
Figure 3.22: Final output of the CPDs. Important: the figure doesn’t show the additional information of the CPD gain level as a function of time, that is produced together with the signal

decay event is in effect of the order of $\sim 100$ per every photon of the decay.

The basic data concentrator algorithm is based on the identification of those channels whose signal is above a programmable threshold and the subsequent selection of all the cells included in a halo of programmable radius and shape (within a limited range of possibilities).

Only the selected cells information is sent to the data storage facilities.

The Data Concentrator is programmed with different configurations (including a transparent one) that are dynamically applied to different categories of events according to their trigger codes.

The basic Data Concentrator algorithms are implemented in the Trigger and Zero Suppression Asic (TZSA) chip [45].
3.6 The calorimeter calibration

The calibration of the detector needs essentially two steps:

1. measure the absolute conversion factor between the amount of shower energy deposited in a cell and the resulting current;

2. measure the electronic gain of the readout channels, i.e. the ratio between the current at the input of the preamplifiers and the pulse height recorded by the readout electronics.

While the second relation is depending only on the characteristics of the components of the readout electronics for the different cells, the first depends on the physical properties of the detector (mean ionization energy, dimension of the cells, drift velocity), and is expected to be almost uniform over the calorimeter (see section 3.6.3).

3.6.1 The electronics calibration system

The response and stability of the electronics over the \( \sim 13500 \) calorimeter cells is measured to better than 0.5% by a precise calibration system.

Every cell is equipped with an individual calibration circuit which can inject, directly at the input of the cold preamplifiers, current signals of precisely programmable magnitude and with a shape very similar to that of the current pulses induced by physical events.

The system has been implemented installing in the front end electronics buses one pulse generator per each group of 8 cells, controlled by DC reference voltages for amplitude and digital signals for trigger (see figure 3.23).

Since the calibration pulses are produced locally they do not suffer distortion or cross-talk due to transmission over long lines.

They are generated by the discharge of a capacitor, driven by the trigger signal sent on the gate of a MOS transistor acting as a switch.

The initial shape of the discharge is chosen to be close to \( t/t_d \). The initial current amplitude is determined by the value of \( V_{ref} \) (see figure 3.23) that is controlled by a very stable 15-bit accurate DAC.

In each calibration pulse generator a compensation circuit [46] provides a correction for the parasitic pick-up due to the trigger signal (10 Volts amplitude). Without the correction the pick-up would have an amplitude corresponding to \( 3 \div 5 \) times the electronic noise. The compensation reduces this effect well below the noise level.

The combination of triggers and reference DAC values sent to the calibration circuits, allow a large variety in the geometrical patterns of calibration that can be produced by the system.
The reference DAC range (0-20 V) has been chosen to be able to produce calibration pulses over the full dynamic range covered by physical signals.

3.6.2 Measurement of the calibration circuits parameters

The measurement of the values of the single components of the calibration circuits is unpractical both for the number of measurements and for the difficulty of measuring them at 120 K, while it is clear that any uncertainty on those parameters reflects directly on the calibration error. Instead, the global effect of the calibration circuit has been measured at room temperature and at 120 K with a comparison technique.

The goal of this method is to measure on a test bench a global constant for each channel, by equalising the calibration signal, as produced by a given DAC value pulsing the calibration circuit, to the signal obtained injecting directly a well known current (see figure 3.24).

The injected current is generated via an external pulser and a high precision
resistor. The ratio of the slopes of the two different ways of calibration gives the wanted calibration constant (expressed in $\mu$A/V), i.e. the amount of initial current injected in correspondence of a given value of the DAC voltage.

The constants were measured, to better than 1% accuracy, for each channel, at room temperature and at 120°K.

The variation of the calibration constant between the two temperatures was rather uniform, centred at a value of $(1.93 \pm 0.43\%)$ (see figure 3.25).

The technique used simulates the behaviour of the real physics current pulse, including the attenuation due to the HV decoupling capacitor, the capacity of the cell and the capacitive coupling of adjacent cells.

The stability of the capacitors of the calibration pulse generators is assured by their construction as element of a multi-layer printed circuit board and by operating at the fixed 120 K temperature of the liquid krypton.
The resistors are selected SMD\(^2\) of high stability.

### 3.6.3 Final calibration corrections

As previously mentioned, once the gains of the electronic chain for the different cells are known, one has still to measure what a certain level of induced current means in terms of deposited energy, because that is the quantity that we want to measure.

Assuming first that the detector has been built such that no differences in physical and geometrical properties between different cells are significant and that the temperature and purity of the liquid krypton are sufficiently uniform over the whole detector volume, one can measure an overall conversion factor that relates charge and energy. This absolute calibration factor is derived by the fit of the known position of the AKS, from the \(K_S \to 2\pi^0\) decay data.

After this absolute calibration it’s anyway necessary to study and correct the residual non-uniformity of the calorimeter response.

Significant variations could arise from uncertainties in the calibration system constants, from an insufficient control of mechanical tolerances or from local variations of the medium properties, like temperature or pressure, that could induce differences in the electron drift velocity.

All the effects of changes of physical parameters on the current response of the cells reduces to changes in the drift time.

A measure of the drift time in each cell can be performed in the framework of NA48 with a slight change of the running conditions. The method is based on the fact that the narrow pulse produced by the current step immediately following the shower development, is followed after the time \(t_m\) by a small but visible undershoot, lasting for exactly a time \(t_d\) (see figure 3.26), due to the gradual current decrease.

Special data taking periods have been allocated in which a large number of time samples (instead of the usual 10) were recorded in coincidence with an event, such that the full electronics signal was visible, up to the end of the negative undershoot. Recording a sufficient number of such events allows the precise measurement of \(t_d\) in different zones of the calorimeter to investigate the physical uniformity of the detector.

Various series of drift time measurements have been performed \([47]\), especially during test runs and using electron beams and for different values of the electrodes high voltage.

Measurements have also been performed during warming up operations of the krypton in order to investigate the dependence of the drift time on the

\(^2\)Surface Mounted Devices
3.6. THE CALORIMETER CALIBRATION

197 PCBs - 12608 channels

Figure 3.25: Spread of the calibration constants
CHAPTER 3. THE ELECTRO-MAGNETIC CALORIMETER

The results in term of drift velocity in the liquid krypton (extrapolated assuming the width of the cell gap), have been compared to published measurements [48, 49] and with measurements performed in a laser chamber, resulting in good agreement. Figure 3.28 shows the comparison between the drift velocity measurements performed on a calorimeter prototype and independent laser chamber measurements.

The ultimate inter-calibration of the cells can be achieved with electrons
3.6. THE CALORIMETER CALIBRATION

Figure 3.27: Drift time measurement as a function of the temperature for different high voltage values

of known momentum (monochromatic calibration electron beams or electrons from Ke3 decays with momentum reconstructed with the spectrometer) as well as reconstructing, imposing invariant mass constraints, multi-photon decays of mesons (e.g. $K \rightarrow 2\pi^0$, $\pi^0 \rightarrow 2\gamma$, $\eta \rightarrow 2\gamma$, $\eta \rightarrow 3\pi^0$) whose decay vertexes are independently known.

All the listed approaches have been followed to control to the best possible extent the response of the calorimeter.
CHAPTER 3. THE ELECTRO-MAGNETIC CALORIMETER

Figure 3.28: Drift velocity measurement in krypton as a function of the high voltage

The drift velocity $V_d$ changes by $-1\%$ per $+1$ K temperature variation.
Chapter 4

The Neutral Decay Trigger

The so-called Neutral Trigger [50] (also referred as NUT) has been designed to select $K \rightarrow \pi^0\pi^0$ decays and heavily suppress background events, mainly due to the dominant $K_L \rightarrow 3\pi^0$ decays.

To stand the high rate of neutral events expected at NA48 nominal beam intensity the collaboration designed and built a fully pipe-lined trigger.

4.1 The pipe-line concept

In a pipe-line scheme the information of all the detectors is continuously flash-digitised and stored on temporary buffers. In parallel a reduced set of flash-digitised information (possibly produced by the same detector) is continuously monitored by the trigger electronics and a trigger decision is produced every clock cycle. In case of a positive decision, the acquisition system record on tape the complete flash-digitised information, relative to a number of clock cycles centred around the trigger, that was previously stored in the temporary buffers by the detector read-out electronics (see figure 4.1).

Such an architecture allows to have a quasi “dead-time free” trigger.

The actual NUT implementation is based on a 40 MHz pipe-lined digital electronic chain. At each clock cycle every component of the chain perform a partial calculation and transmit the results to the following stage. Such a scheme implies that the time needed to perform the complete trigger calculation depends only on the complexity of the implemented algorithm and is constant from one event to another.
4.2 The Algorithms

The Neutral Trigger pipe-lined electronics performs calculations based on the information of the electro-magnetic calorimeter.

The information complexity is reduced by summing (see sections 4.3.1 and 4.3.2) the 13340 cell pulses into 64 vertical and 64 horizontal strips. That means dividing the calorimeter in rows and columns 4 cm wide.

The obtained pulses are then flash-digitised with a 40 MHz clock like in the standard read-out electronics and sent to the NUT computing chain.

Four quantities are reconstructed every clock cycle by the trigger electronics and used to perform cuts and take a decision:

1. The number of 1-dimensional clusters in the calorimeter (both in X and Y view). To reduce $K_L \rightarrow 3\pi^0$ background we cut on the maximum number of clusters in both views. Moreover the system reconstruct the time of every cluster found with a granularity of 3.125 ns. Thus the clusters cut can be applied only to near-in-time clusters (i.e. clusters in coincidence within a programmable time window), to limit the number of good events lost because of accidental activity in the detector. The full peak finding algorithm is described in detail in section 4.3.5.

2. The total energy $E$ measured by the calorimeter. The system sums the strips energy information independently for X and Y view. The total energy is then defined as the mean of the two values obtained by the
two views. This reconstructed energy is required to be above a (programmable) threshold.

3. The centre of gravity of the energy distribution $\text{COG} = \sqrt{(M_{1X}^2 + M_{1Y}^2)}$

where we define:

$$M_{1X} = \frac{\sum_i x_i \cdot E_{Xi}}{\sum_j E_{Xj}}, \quad M_{1Y} = \frac{\sum_i y_i \cdot E_{Yi}}{\sum_j E_{Yj}} \quad (4.1)$$

$E_{Xi}$ and $E_{Yi}$ represent the energy reconstructed from the $i$-th horizontal and vertical strip, and $x_i$ and $y_i$ the strip centre coordinates. This quantity is used to cut away decays of scattered kaons (either in collimators or in the material of the AKS) and cases where one or more of the kaon decay photons misses the calorimeter. This cut value has to be chosen taking into account the beam divergence which is slightly different for $K_S$ relative to $K_L$.

4. The $K^0$ proper lifetime $\tau_K = (d_{AKS} - d_K)/\gamma\beta c$ where $d_{AKS}$ is the distance between the AKS and the calorimeter and $d_K$ the distance between the decay vertex and the calorimeter. For kaons in the accepted energy and proper lifetime range, decaying in $nc$ photons, to an accuracy of better than $10^{-4}$ the invariant mass is given by (see discussion in section 5.1.3):

$$m_{nc} = \frac{\sum_{i=1}^{nc} E_{ci}}{d_K} \cdot \sqrt{M_{2cX} + M_{2cY} - M_{1cX}^2 - M_{1cY}^2} \quad (4.2)$$

where $M_{1cX}, M_{1cY}, M_{2cX}$ and $M_{2cY}$ are the X and Y components of the first and second moments of the energies of the $nc$ clusters in the calorimeter. Using instead the energies $E_{Xi}$ and $E_{Yi}$ and the coordinates $x_i$ and $y_m$ of the centres of each column and row, one obtains:

$$M_{2cX} + M_{2cY} - M_{1cX}^2 - M_{1cY}^2 = M_{2X} + M_{2Y} - M_{1X}^2 - M_{1Y}^2 - \Delta^2 \quad (4.3)$$

where:

$$M_{2X} = \frac{\sum_i x_i^2 \cdot E_{Xi}}{\sum_j E_{Xj}}, \quad M_{2Y} = \frac{\sum_i y_i^2 \cdot E_{Yi}}{\sum_j E_{Yj}} \quad (4.4)$$

and where the quantity $\Delta^2$, proportional to the number of photons, fluctuates rather normally around a value which is determined by the transverse size of the energy deposition by photons and to minor extent by the size of calorimeter cells. For the trigger purposes we can neglect $\Delta^2$ and calculate the (slightly overestimated) distance $d_K$ between the calorimeter and the decay vertex, as:

$$d_K = \frac{E}{m_K} \cdot \sqrt{M_{2X} + M_{2Y} - \text{COG}^2}. \quad (4.5)$$
CHAPTER 4. THE NEUTRAL DECAY TRIGGER

This quantity is used to select just those events decaying upstream of a programmable longitudinal position located between the AKS and the calorimeter. The actual value of this edge, is defined in terms of the Kaon proper lifetime, and is thus dependent on the Kaon momentum. This cut is very powerful to reduce the number of $K_L \to 3\pi^0$ decays with less than six photons detected by the calorimeter. The missing energy of the lost photon tends in fact to decrease $d$ and by consequence to reconstruct a longer proper lifetime. This can also be seen from figure 5.24.

All the cuts on the above listed variables are programmable, providing the possibility of adapting the trigger selection criteria to different categories of events other that the “good” $K \to 2\pi^0$ decays (like the $\eta \to 2\gamma$ or $\pi^0 \to 2\gamma$ decays used to check the absolute energy scale, as discussed in chapter 4).

All the cuts are eventually performed in parallel.

4.3 The Neutral Trigger Chain

The trigger system is implemented as a chain of different pipe-lined electronic systems. Figure 4.2 shows a scheme of the different stages of the Neutral Trigger chain.

Every stage of the chain elaborate the information and reduces the amount of data to pass to the next stage. The process terminates with the generation of a trigger word for every time slice. The logic scheme of such a process is shown in figure 4.3.

4.3.1 The CPD Trigger Outputs

The analog signals coming from the liquid krypton calorimeter cells are processed by the CPDTR (CPD TRigger output) section of the CPD modules (see section 3.5.3). Each CPDTR handles 64 cells corresponding to a $8 \times 8$ square matrix on the front surface of the calorimeter. The analog information from the calorimeter cells is summed by the CPDTR (after the shaping stage) in $2 \times 8$ and $8 \times 2$ super-cells [51] for subsequent addition in $2 \times 128$ and $128 \times 2$ columns and rows. This analog super-cells information is then sent to the rest of the trigger chain by output differential drivers, via twisted pair cables, to reduce noise and inter-channels cross talk.

The circuits used for summing the individually shaped pulses consist of a 6 bit programmable attenuator and two amplifiers with current outputs (transconductance amplifiers) as shown in figure 4.4. Noisy trigger channels can be disabled by means of a 7th bit. The serial digital control can vary the attenuation by a factor in the range 0.48 to 0.82, which corresponds to $\sim 26\%$ gain.
4.3. THE NEUTRAL TRIGGER CHAIN

Figure 4.2: Scheme of the Neutral Trigger chain

variation or 0.8% per LSB of digital control. This facilities allows an online inter-calibration of the individual calorimeter channels before entering them in the sum circuits, thus improving the resolution of Neutral Trigger calculations.

The transconductance amplifier consists of a differential amplifier with an improved linearity obtained with the help of two operational amplifiers (see figure 4.5).

4.3.2 The FADC and Filter modules

The Vienna Filter Modules (VFM) system processes the 2×8 super-cell analog signal coming from the CPD modules to produce the digitised information of the horizontal and vertical projections of the energy deposition in the calorimeter.

Signal processing is implemented in three different stages:

1. the digitisation of the 2×8 super-cell signals;

2. a digital filtering to reduce baseline and noise effects;
CHAPTER 4. THE NEUTRAL DECAY TRIGGER

Figure 4.3: Information elaboration in the NUT chain
3. the summing of the filtered signal of the super-cells belonging to the same column or row.

The VFM system is housed in 4 VME 9U crates, each containing 16 VFM modules, 1 Filter Control Module (FCM). Purpose of the FCM module is to
distribute the clock, to control the test cycles and to provide various control signals to the 16 VFM modules in its crate, that perform the actual signal processing.

The modules are controlled and programmed via the standard VME bus. The user definable part of the VME backplane connectors is customised to provide the necessary intercommunication between the 16 VFM modules, required to allow the possible application of complex filtering algorithms (see section 4.3.3) and to distribute to all the modules the 40 MHz clock signal and non VME standard power voltages. Moreover the VME backplane is equipped with the output connectors that are used to connect the system with the following element in the chain. A special on board test equipment allows the generation of analog pulses at the input of the VFM modules and the local recording of the relative digitised outputs, to study the system behaviour.

4.3.3 VFM modules operations

A scheme of the operations logic is shown in figure 4.6.

Each VFM module consists of a mother board and 32 daughter boards.

FADC daughter board

The VFM module is equipped with Philips TDA8760 FADC chips mounted on separate small daughter boards. Signal enters the FADC after passing through a band-pass filter. The FADC receives its input and clock in differential TTL standard. A signal of 1.1 mV corresponds to one LSB. The input sensitivity is adjustable using software programmable DAC’s in a range of ±6.8 %.

Mother board

The main components of the mother board are 8 filter and 2 adder Xilinx [52] chips. Each filter Xilinx is able to process 4 channels and can be operated in a transparent mode for testing purposes.

The filtering algorithm performs the following operations:

- select digitised signal higher than an individually adjustable threshold (0-255 LSB) for at least two consecutive time slices of 25 ns, to reduce noise fluctuations;

- subtract from the time samples individually adjustable (0-255 LSB) pedestal values; negative values are set zero;
4.3. THE NEUTRAL TRIGGER CHAIN

Figure 4.6: Scheme of the VFM operations
• for every channel find time local maxima (i.e. sample counts that are greater than previous and following one) and apply one of the following selection criteria:

1. set to zero every sample but the maximum and the higher of the neighbouring time slices
2. set to zero every sample but the maximum and both neighbouring time slices
3. set to zero every sample but the maximum plus two time slices before and one after the maximum

An additional “mask logic” is provided to allow the setting of large noise filtering threshold values with reduced effects in the subsequent trigger calculation resolution. When this option is switched on, the geometrically neighbouring channels of a channel with a valid signal are passed through the filter even if they did not fulfill the filter conditions above.

The signals from the 4 channels of one filter Xilinx are finally summed and passed as a 12 bit word to the adder Xilinx. Both sides of the mother board are equipped with one adder Xilinx which sums together the data of 4 filter Xilinx’s. Each of the two outputs of the module represents the sum of 16 input channels in a 12 bit form. The whole system thus produces the digital information of the 64 rows and 64 columns of the LKr calorimeter.

The results of the summation are transmitted in a kind of ECL twisted pair signal to the next stage of the trigger system. Additional parity and strobe bits are computed and sent with the data to allow the following part of the trigger chain to test the data integrity.

### 4.3.4 SPY and PMB modules

SPY and PMB modules provide to the digital section of the system a complete self-testing and an online monitoring facility. SPY modules [53] are general purpose 9U VME pipelined input/output registers that have been developed in collaboration between NA48 collaborators and a private firm. Each module has 4 digital inputs, each of 14 bits, and can be programmed via the VME bus to work in acquisition or in pattern generation mode.

In acquisition mode the 4 pipelined inputs are fanned out to 4 principal outputs (sent to the rest of the trigger chain) and 4 monitoring outputs (sent to PMB modules). Moreover 2 of the 4 inputs are fanned out to 2 auxiliary outputs, needed by the PeakSum system (the following element in the trigger chain) to properly perform the cluster finding algorithm (see next section for a detailed discussion).
The relative time skew of all the SPY module output bits is guaranteed to be smaller than 2 ns.

The module is equipped with an acquisition memory that allows the possibility of recording the complete input data for 131072 clock cycles. This acquisition facility can be triggered by an external signal and the modules can be programmed to perform an online zero-suppression (i.e. record only data different from zero), or to select data to be recorded according to the consistency check on the input pattern parity. The content of a clock counter is stored in parallel to the data to allow the recovery of data in case of filtered storage.

In pattern generation mode the SPY memory locations can be filled via the VME bus with known patterns and the modules can be programmed to generate those patterns on the outputs at the full clock frequency. This facility allowed the development of an online testing procedure of the algorithms of the following part of the trigger chain. Ad-hoc sequences of test patterns are generated by the SPY modules and the resulting trigger decisions are checked against the ones predicted according to the expected behaviour of the trigger electronics.

PMB (Pipeline Memory Board) modules \[54, 55\] are VME 9U modules designed and produced by NA48 collaborators. Every module has 8 inputs of 24 bits. The input data are temporarily stored on local FIFO buffers and can be successively sent to the NA48 DAQ system according to a delayed trigger information. This modules receive input by the SPY modules and by all the following stages of the trigger chain, thus recording the complete digital information of all the trigger calculation steps. This information is then sent to the DAQ stream whenever a positive trigger decision is taken, allowing the monitoring of the trigger electronics behaviour.

### 4.3.5 The PeakSum System

The PeakSum System \[56\] is the part of the chain performing all the basic calculations on the calorimeter projections information, that are:

- counting the number of energy clusters in the calorimeter
- reconstructing the time of each cluster with a granularity of 3.125 ns
- computing the total energy deposited in the calorimeter and the first and second moments of its distribution.

These calculations are performed independently and in parallel by two identical systems one for the horizontal and one for vertical projection.
Moments algorithms

The system is designed to calculate the following quantities:

\[ E_S = \sum_{i=-32}^{31} E_i = M0 \]  
\[ W_S = \sum_{i=-32}^{31} E_i \cdot i = M0 \cdot M1 \]  
\[ Q_S = \sum_{i=-32}^{31} E_i \cdot i^2 = M0 \cdot M2 \]

where \( E_i \) represent the i-th strip energy information of a projection. It is evident that the moments calculation has a slight left-right and top-bottom asymmetry. Having an even number of calorimeter strips in both vertical and horizontal projections, the origin for the momenta calculation cannot be assigned to the actual centre of the detector.

This asymmetry doesn’t affect the vertex position reconstruction. As can be easily verified from equation 4.5, the vertex calculation is independent of the choice of the origin for the moments calculation, as long as this is the same for first and second moment.

Concerning the COG calculation, this asymmetry just shifts its origin away of the actual centre of the calorimeter both vertically and horizontally, by half the width of a row (column). This shift could be taken into account by the look-up table modules following the PeakSum system and computing the trigger decision, but actually the cut performed is so loose that the shift doesn’t make any effect.

Peak Finding Algorithms

The peak finding algorithms are more complicated and delicate than those for moments calculation.

As pointed out before the system has to find the number of one dimensional clusters in the calorimeter projections. Such a cluster is defined by the simultaneous occurrence of a spatial and temporal peak in a projection. The system functionality is then based on the spatial and temporal analysis of adjacent calorimeter strips. The criteria for finding a space peak in a projection is the fulfilling of the following conditions:

\[ E_i(t_j) > E_{i-1}(t_j) \]  
\[ E_i(t_j) \geq E_{i+1}(t_j) \]
where $E_i(t_j)$ represents the $j$–th time slice of the $i$–th strip flash-digitised information. The conditions for the detection of a time peak are instead:

\[ E_i(t_j) > E_i(t_{j+1}) \]  
\[ E_i(t_j) \geq E_i(t_{j-1}) \geq E_i(t_{j-2}). \]

An additional condition is required to limit the possible effects of noise fluctuations on peak finding algorithms:

\[ E_i(t_j) > T \]

where $T$ is a programmable threshold. This particular threshold can be set to larger values than the VFM system one, because it affect only the peak finding criteria and doesn’t reduce the level of information used in the moments calculation.

**Fine time reconstruction**

To reduce the influence of near-in-time accidental activity on the selection of good events the system performs, for every detected cluster, the reconstruction of the timing information with a granularity of a 1/8 of the sampling clock period (3.125 ns). The intrinsic response of the calorimeter individual channels and of the readout electronics is defined in time to a similar accuracy (see section 5.2.2).

This time measurement is performed by analysing the sampled pulse of the strips where a cluster was detected and by reconstructing for every one of them the time at which the pulse-height reaches some reference value

\[ E_{ref_i} = \alpha \cdot E_i(t_{jm}) \]

where $E_i(t_{jm})$ is the maximum time sample of the $i$–th strip pulse-height and the fraction $\alpha$ is given by:

\[ \alpha = \frac{1}{2} + b_8 \cdot \frac{1}{8} + b_{16} \cdot \frac{1}{16}. \]

and $b_8$ and $b_{16}$ are 1-bit programmable registers that allow to slightly change the value of $\alpha$. For a given pulse shape the difference between $t_{ref}$ and the time of the peak is independent on the pulse height, depending only on the value of $\alpha$. The choice of having $\alpha$ of the order of 1/2 reflects the choice of reconstructing the time information from a region where the pulse derivative tend to be maximal, to minimise measurement fluctuations.
The system performs an approximate reconstruction of the pulse by linear interpolating between the two time samples preceding the maximum and the maximum itself (see figure 4.7). A simulation study has shown that such a linear algorithm gives a better intrinsic time resolution than finding the peak time with a parabola interpolation over the 3 time samples around the maximum.

A limitation of the algorithm is due to the fact that in cases in which \( E_{\text{ref}} < E_i(t_{jm-2}) \) the fine time \( t_{\text{ref}} \) is reconstructed to \( t_{jm-2} \) without further calculations. This means that the reconstruction resolution is decreasing for very large pulses (compared to the sampling period). It is now clear the role of \( b_8 \) and \( b_{16} \), provided to possibly increase the reference value, and by consequence to reduce the algorithm limitations.

Additional features of the peak algorithm are:

- a masking procedure to veto the possibility of detecting peaks in the two
neighbouring strips of a previously detected peak and with the reference
time reconstructed in the same or the following time slice. That means
that if a peak if detected in the strip $i$ and his reference time is recon-
structed in time slice $j$ ($t_j \leq t_{ref} < t_{j+1}$), the algorithm disables the
possibility of detecting a peak in slice $i+1$ or $i-1$, with a reference time
reconstructed in time slice $j$ or $j+1$. This procedure is provided to avoid
double counting of peaks due to possible important time skews between
neighbouring strip channels.

- a counting of possible “anomalous situations” per every time slice. These
  situations are flagged in case that a strip $j$ is known to have hardware prob-
  lems (in which case a special bit is set by VFM modules) and two almost-
simultaneous peaks (that means that reference time is reconstructed in
  the same time slice interval) are detected in the neighbouring strips $j-1$
  and $j+1$. Such a situation is ambiguous because peaks could originate
  from two real physics clusters as well as by just a single one centred in
  the faulty channel. The obvious danger concerning trigger algorithms is
  that a “good” 5 cluster event could be seen like a 6 cluster one and by
  consequence discarded. The “anomalous situation” counting is then pro-
  vided to increase peaks cut upper limit in coincidence with the detection
  of such dangerous patterns.

The Hardware implementation

A full PeakSum System is composed of 9 VME 9U boards, 8 of which are called
PeakSum Boards and 1 is called FinalRecombinator. Figure 4.8 shows a scheme
of the system.

Each PeakSum module has 8 principal 14 bit (12 signal bit, a channel flag
and a parity) inputs plus 2 auxiliary ones, coming from SPY modules. The 8
principal inputs take the information of 8 adjacent calorimeter strips. The 2
auxiliary inputs contains the duplicated information of the last principal input
of the preceding module and of the first principal input of the following one.
These inputs are used in peak finding algorithm to allow the PeakSum to be
able to find clusters centred at the edges of the modules (see later).

The 8 PeakSum modules are connected to form two daisy-chains, each deal-
ning with the strips coming from half of the calorimeter. Modules first indepen-
dently apply the full PeakSum algorithms to their 8 input strips, then combine
their partial results with the ones possibly coming from previous modules in the
chain and eventually pass the result to next modules.

Eventually the FinalRecombinator merges results coming from the two chains
and produces the final output for the Look-Up-Table system.
All the system modules are interfaced with VME protocol for configuration and checks.

The PeakSum operations are fully pipe-lined so that for every clock cycle the system accepts the information of the $i$th time slice $t_i$ for the 64 strips, and produces the results for time slice $t_{i-n}$, where $n$ indicates the overall latency of the system.

The single PeakSum module itself is organised as two parallel pipe-lined daisy-chain (see figure 4.10), one executing peak finding algorithms and the other momenta calculations. The base element of these local daisy-chains is the Neutral Trigger Processor (NTP) chip, the real heart of the system. The NTP chip is a VLSI semi-custom CMOS standard cell device especially developed by NA48 collaborators. A logical scheme of such a device is shown in figure 4.9. PeakSum modules are equipped with 6 identical NTP chips while FinalRecombinator modules house 2 of them. Every NTP chip can be programmed to work in 6 different configurations: Local Peak, Local EWQ, InterBoard Peak, InterBoard EWQ, FinalRecombinator Peak and FinalRecombinator EWQ. Peak and EWQ designate the mode of operation respectively for peak finding (and fine
4.3. THE NEUTRAL TRIGGER CHAIN

Figure 4.9: NTP chip internal structure scheme. EWQ_gen and Peak_gen blocks perform peak detection and momenta calculation. Merger block combines results from different chips or modules. Programmable pipelines allow temporal alignment before merging.

time reconstruction) and energy momenta calculation.

Local EWQ configured chips handle 4 strip channels each, calculating momenta according to the values of configuration registers $W$, which can take value from 0 to 15 and define the position of the 4 strips in the calorimeter, and $PN$ that is just a bit used to take into account the already mentioned slight asymmetry in momenta calculations. We thus have:

$$ ES = \sum_{i=0}^{3} E_i $$  \hspace{1cm} (4.16)
Figure 4.10: PeakSum Module scheme

\[ WS = \sum_{i=0}^{3} (4 \cdot W + i + PN) \cdot E_i \]  

\[ QS = \sum_{i=0}^{3} (4 \cdot W + i + PN)^2 \cdot E_i \]  

where \( E_i \) indicates the \( i-th \) chip input channel\(^1\).

The succession of input channels can also be inverted (0 ↔ 4, 1 ↔ 2 ...) setting CROSS configuration bit. This option is to be set together with PN for channels belonging to the calorimeter side with negative weights. The actual local WS calculation is performed with only positive weights, letting the FinalRecombinator eventually subtract the two partial calculations coming from

---

\(^1\)beware \( E_i \) doesn’t necessarily correspond to the \( i-th \) calorimeter strip; i is just indicating a relative position between the 4 chip inputs
the two PeakSum System daisy-chains (that means the two opposite side of the calorimeter).

After calculation, results are converted to a special *mantissa + exponent* format:

\[
\begin{align*}
\text{exponent} = 0 & \Rightarrow \text{value} = \text{mantissa} \\
\text{exponent} > 0 & \Rightarrow \text{value} = (\text{mantissa} + 2^9) \cdot 2^{\text{exponent}-1}
\end{align*}
\]  

(4.19) (4.20)

This means an effective precision of 10 bits. *Mantissas* are always 9 bit long while *exponents* are 3, 4 and 5 bit longs respectively for ES WS and QS. A parity bit is generated and added to the 3 words for successive communication checks.

This format is equivalent to that of the final outputs sent by the system to the Look-Up-Table system, a part from an additional sign bit added by the FinalRecombinator to WS information. Local Peak chips perform peak finding algorithms on their 4 principal inputs.

To be able to find a peak in their first or last input PeakSum modules obviously need to know the content of their neighbouring channels (refer to equations 4.9 and 4.10). That explains the need to provide to every Peak-Sum module the inputs relative to last channel of previous module and first of following one. A internal splitting of channels 3 and 4 is also needed (see figure 4.10).

The number of peaks detected is coded in 8 groups of 3 bit (one group for every 1/8 fraction of the clock period). Peak information related to slice \( j \) refers to peaks whose reference time \( t_{\text{ref}} \) is reconstructed between \( t_j \) and \( t_{j+1} \). That means that the \( i-th \) 3-bit number of slice \( t_j \) represents the number of one projection clusters revealed with:

\[
t_j + (i-1) \cdot \frac{T}{8} \leq t_{\text{ref}} < t_j + i \cdot \frac{T}{8}
\]  

(4.21)

where \( T \) is the clock period. An additional group of 3 bits is produced for the “anomalous situations” count plus a bit of checksum of all input channels parities (0=ok 1=problems). Once again an overall parity bit is generated and added to the output.

Both Peak and EWQ Local chips combine results of their calculations with the possible output of the previous chip of the chain and send the merged results to the following one.

InterBoard chips (both Peak and EWQ) interface the module local daisy-chain with the system one, that is needed to merge results evaluated by the local board chain with results coming from previous board.
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FinalRecombinator configured chips, which are obviously the ones equipping FinalRecombinator module, are dedicated to the eventual combination of peak and momenta information coming from the two half of the calorimeter.

Local chips have an internal computation pipe-line latency of 11 clock periods and a merging latency of 3. InterBoard merging operation is taking 3 clock periods. That leads (for modules located at the beginning of a daisy-chain) to a latency of 17 clock periods due to Local 0 and 1 parallel computation plus Local 1 merging with Local 0 output and the eventual InterBoard latency.

At every daisy-chain step InterBoard chip has to be programmed to delay data coming from Local 1 chip in order to take into account previous board InterBoard latency to combine coherent data (originated by the same time slice). This implies 3 additional clock periods of latency for every step, leading to a daisy-chain overall latency of 26 (17 + 3 \cdot 3).

FinalRecombinator merging is instead taking 5 clock periods due to the increase of complexity involved in taking into account negative numbers for $W_S$. The overall PeakSum latency ends up to be 31 clock periods, that means 775 ns for a 40 MHz clock.

4.3.6 The Look-Up-Table system

The system [57] consists of a series of 8 identical FASTBUS boards connected in cascade (see figure 4.11), each equipped with six identical memory look-up table units.

A look-up table unit has 18-bit inputs and 12-bit outputs; it contains all the 12-bit precomputed ‘answers’ to each of the 262144 possible ‘questions’ on the 18 input bits.

The six memories on each board are connected together in pairs in a three stage pipeline (see figure 4.12). Each look-up tables pair is separated from the others and from the board inputs and outputs by field programmable gate arrays (FPGA). FPGAs allow to route in a programmable way the outputs from one stage to the inputs of the next stage; they can also be used for simple boolean logic functions and for delaying data by one or more pipeline stages as needed by some algorithms. A 18-bit direct path from one FPGA to the next one is also provided.

LUT programming

Memories are downloaded from a control computer via the FASTBUS interface on the board; Xilinx FPGAs may be either downloaded using FASTBUS block transfer or loaded from an on-board ROM. A set of programs to generate memory and FPGA data ready for downloading from a specification file written in...
a homemade specification language has been developed on purpose.

These programs can also generate a simulation code to check on test events that the generated LUT logic behaves as required.

Routing functions in FPGAs can be built up using the specification language: a group of signals (a bus) is defined by a basic statement which also specifies where these signals are routed to. Combinatorial logic functions can be performed adding tokens to the statement, and pipeline step delays may be specified on statements.

An example of LUT programming is shown in figure 4.13.

**Algorithms**

The eight modules in figure 4.11 performs different calculations. The functions are all implemented by reprogramming identical basic modules.

**NPX** This module processes the peak data, i.e. the number of peaks seen in
time bins of 3.125 ns, coming from the PeakSum System \(X\)-view. The module looks at the number of peaks in time windows composed of three consecutive 3.125 ns time bins. For every 25 ns pipe-line step, the eight windows centred around the eight 3.125 ns time bins are investigated. The module determines the maximum number of peaks seen within one of the windows with the constraint that there is nothing in the 3.125 ns time bin preceding and following it. This last condition is applied to reduce the probability of loosing events due to close in time accidental activity.

**NPY**  This is a copy of the NPX module for the \(Y\)-projection peaks.

**A0M**  This module computes the average of the total energies coming from the two projections: \(M_0 = (M_{0X} + M_{0Y})/2\). Incoming data are encoded in the PeakSum output format (see equation 4.20). The addition is thus done by adjusting the normalisation of the smaller number, adding the mantissas directly and then encoding the result into 9 bits which are sent to the ECT module.
4.3. THE NEUTRAL TRIGGER CHAIN

In this module the first moment informations of the two views are combined for the centre of gravity calculation: \( M1 = \sqrt{M1^2_X + M1^2_Y} \). The technique is similar to that for A0M.

This module combines the second moment informations of the two projections for the calculation of \( M2 = M2_X + M2_Y \). The same technique as A0M is used.

This module receives the outputs of NPX and NPY and uses them to issue the final peak-trigger decision. Several decision bits are generated for different peak conditions in order to defer the final decision to a later stage in the pipeline. Moreover the NPK module also receives a digitised sum from the hadronic calorimeter and combines it with the electro-magnetic energy in order to produce a total energy trigger for hadronic events and a hadronic energy veto for rare-decay studies.

Inputs to this module are \( M0, M1 \text{ and } M2 \). The energy \( E = \alpha M0 \) is constructed; \( \alpha \) is a correction factor whose value is 1.0 for pipeline.
steps not containing any energy peak and is slightly larger than 1.0 when there is an energy peak. This factor compensates for the dependence of the reconstructed event energy on the phase between the event time and the 40 MHz clock. This correction factor is extrapolated approximating the $M_0$ behaviour around a peak with the parabola passing through the maximum and the two neighbouring time samples. The ECT module also computes the centre of gravity $COG = M_1/M_0$ and the factor of the decay vertex position $d$ which does not contain $E$.

**FIN** This module completes the $d$ calculation including the $E$ factor and perform the final selection of the events.
Chapter 5

Performances of the Neutral apparatus

As pointed out in chapter 2, in view of measuring $\text{Re}(\varepsilon'/\varepsilon)$, the electro-magnetic calorimeter and the Neutral Trigger must provide a highly efficient and accurate detection of $K \rightarrow 2\pi^0 \rightarrow 4\gamma$ events.

The construction of the final NA48 calorimeter and the full installation of the trigger system was completed at the beginning of 1997. The detector has operated since then with the combined $K_L + K_S$ beam.

In this chapter we report and compare the performances of the full calorimeter (more than 13500 cells) with that of the latest prototype (184 cells) and discuss the performances of the trigger.

5.1  Calorimeter performances

5.1.1  Resolutions achieved in prototype tests

For the tests of the final prototype, data were collected with almost monochromatic electrons beams, with energies from 8 to 80 $GeV$ and a resolution in energy $\Delta E/E < 0.5\%/\sqrt{E}$.

The electrodes operating high voltage was set to 5 kV.

For the studies of the spatial resolution two drift chambers were used (see figure 5.1) which allowed the reconstruction of the impact position with a precision of about 100 $\mu$m.

The equivalent thickness of material present in front of the calorimeter was nearly 0.6 radiation lengths.

Figure 5.2 shows the initial current response for a beam energy of 20 GeV.
The shown resolutions were derived by fitting a Gaussian function to the energy distributions reconstructed for the different beam energies and the quoted values are the $\sigma$ of these Gaussian functions. The trend of the obtained resolution as a function of the beam energy is shown in figure 5.3 and has been parametrised as:

$$\frac{\Delta E}{E} = \frac{3.5\%}{\sqrt{E}} + \frac{40\text{MeV}}{E} + 0.42\%.$$  \hspace{1cm} (5.1)

The term proportional to $1/\sqrt{E}$ takes into account the contribution of the statistical fluctuations, the constant term the contribution of the calibration error and the last term the contribution of the electronic noise. The electronic noise has been measured independently, observing the fluctuations of the events of pedestal, i.e. events registered without addressing any electronic signal to the preamplifiers. The other two coefficients of expression 5.1 have been extrapolated from the energy dependence of the resolution (figure 5.3).

The term that accounts for the fluctuations ($3.5\%/\sqrt{E}$) is in excellent agreement with a detailed simulation [58] that includes the description of the structure, of the signal formation (with a realistic mapping of the electric field), of the response of the electronics and of the shower development which considers all the relevant physical processes. The simulation takes also into account the presence of material in front of the calorimeter.

Detailed analysis has shown that the best resolution for the reconstruction of the impact position is obtained using the information of a window of $3 \times 3$ cells centred around the cell of impact.

The resolutions for the X and Y coordinates as a function of the beam
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Figure 5.2: Calorimeter response to 20 GeV electrons. The HV is set to 5 kV energy are shown in figure 5.4. The trends have been expressed as function of the energy (in GeV) as follows:

\[
\Delta x = \left( \frac{4.1}{\sqrt{E}} \oplus 0.5 \right) \text{ mm} 
\]

(5.2)

\[
\Delta y = \left( \frac{4.4}{\sqrt{E}} \oplus 0.5 \right) \text{ mm} 
\]

(5.3)
Figure 5.3: Energy resolution versus energy

5.1.2 Final detector resolutions

The installation of the final detector in the experimental area has been completed in the first half of 1997. The detector response has been recorded over the whole data taking period for the 1997 run.

One particular problem has affected the performances of the full calorimeter during 1997: the blocking capacitors that decouples the readout electronics from the electrode high voltage (see figure 3.8) have been observed to leak current for voltages greater than 1.8 kV. The working high voltage has thus then be set
Referring to the drift velocity measurements reported in figure 3.28, and to equations 3.1 and 3.2 one can easily see that the signal/noise ratio is reduced by 30% as compared with the running conditions for the prototype test (the prediction is confirmed by 1997 electron beam data). The results from the full calorimeter presented in the following parts of this chapter thus suffer from this unexpected behaviour, resulting in an increased constant term in the resolution trend as function of the particles energy.
All the capacitors have been replaced before the 1998 run period, and the calorimeter has been operated since then at the requested 3 kV voltage.

Figure 5.5 shows the energy resolution achieved during the 1997 data taking period. For technical reasons this plot is obtained summing the energy over a 7×7 box. The extrapolation of the energy resolution to the standard 11×11 box gives [59] the result of:

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{125 MeV}{E} \oplus 0.5\%$$

(5.4)
where E is the energy expressed in GeV. Of course this extrapolation procedure and the dependence on the knowledge of the spectrometer resolution induce a significant systematic error on the resolution measurement, but one can anyway appreciate the very good agreement between the performances of the prototype and those of the final calorimeter.

In the perspective of calculating $R$, the most important features of the performances are best evaluated looking at reconstructed events, rather than at individual showers. This is done in the following sections.

### 5.1.3 The neutral events selection and reconstruction

The basic physical information used to reconstruct neutral decays is the energy deposition in the liquid krypton calorimeter. The reconstruction algorithm is based on the identification of energy deposition clusters in the calorimeter in the appropriate time window ($\sim 300$ ns) relative to the trigger, and on the subsequent assignment of energy, position and time of occurrence for each of these clusters.

In figure 5.6 the LKr calorimeter information for a typical 4 photons event is shown.

In correspondence to each trigger, the digital (zero suppressed) information of the calorimeter cells is recorded on tape. For every cell a programmable number of consecutive time samples (centred around the event time delivered by the trigger logic), is recorded. For standard $\pi^0$ events the number of samples is usually set to 10.

The first step in the offline event reconstruction algorithm is that of calibrating every time sample information. That means that the time sample information has to be converted from ADC counts to an equivalent level of deposited energy. For the $i$-th cell and for every time sample the calibrated sample information $s_i$ is evaluated:

$$s_i = K \times g_i(c_i,(bits\,11:12)) \times \left[ c_i,(bits\,1:10) - p_i(c_i,(bits\,11:12)) \right]$$

(5.5)

where $c_i$ is the 12 bit (10 bit amplitude + 2 bit of gain range) information coming from CPDs, $g_i$ and $p_i$ are the gain factor and the pedestal value for channel $i$ in the specified gain range (as measured by the electronic calibration system) and $K$ is the overall factor that converts from induced current to deposited energy in the cell.

The following step is the cluster reconstruction, where the groups of cells candidates to represent individual electro-magnetic showers are identified, and their energy, position and time are reconstructed.

In the final stage photons coming from pion decays are identified, separated from the accidental activity in the detector and when possible associated in
pairs. Full kinematic reconstruction is then carried out selecting two pairs of reconstructed photons considered as candidates to represent a $K \rightarrow 2\pi^0$ decay.

The cluster finding algorithms

To identify clusters the whole calorimeter is scanned.

First of all a correction for possible local pedestal shift (due to superposition of the pulse on the undershoot of a preceding pulse) is computed. The first 3 calibrated samples (that are expected to be pedestal values) of a cell are
mediated if they all are in the lowest gain range. If the obtained mean value is different from zero by more than 3 times the noise level, this mean value is subtracted from every following time sample of the same cell.

The cluster search is then performed on the resulting corrected value of $s_i$. A cell is considered as a cluster seed candidate whenever in channel $i$ for time slice $t_j$ the following conditions are satisfied:

1. $s_i(t_j) > \text{Threshold (now set to 0.2 GeV)}$;
2. $s_i(t_j) > s_j(t_j)$
   for $j$ looping over the 8 surrounding cells;
3. $s_i(t_j) > \alpha + \beta s_{av}(t_j)$
   with $s_{av}(t_j)$ indicating the average of the energy readout by the 8 surrounding cells for time slice $t_j$, $\alpha = 0.18$ GeV and $\beta = 1.8$. This values have been optimised for the transverse shower profile in the liquid krypton and for the NA48 calorimeter cell dimensions.

This procedure is performed over all the 10 time slices recorded for an event and only the cluster seeds that correspond to a local time maximum of the pulse samples are retained. A detailed description of the complete algorithm can be found in [60].

Starting from all the identified seeds in space and time a cluster is constructed including all the cells in a radius of 11 cm.

The energy and time information of the pulse of the $i$-th cell contributing to a cluster is reconstructed with a digital filtering algorithm:

$$E_i = \sum_n a_n \cdot s_n$$  \hspace{1cm} (5.6)

$$T_i = \sum_n \frac{b_n \cdot s_n}{E_i}$$  \hspace{1cm} (5.7)

were $n$ loops over the 3 time samples centred on the time maximum of the cluster seed pulse. The quantities $a_n$ and $b_n$ are sets of constants obtained from the typical electronic pulse shape with the constraint of minimising the noise contribution to the pulse reconstruction. According to a detailed study of the variation of the pulse shapes over the calorimeter cells 11 categories have been identified [60]. Each category has its own set of constants.

In case of overlapping clusters, an interactive procedure is followed to share the energy contribution of the cells belonging to more than one cluster box based on a parametrisation $W(x, y)$ of the measured shower transverse development in liquid krypton. The same function is used to estimate the signal of those cells, known to have electronic problems, included in the cluster region. The
next step is the reconstruction of the global energy, time and impact position information of the clusters.

The energy $E_{cj}$ of the $j$-th cluster is simply obtained summing the derived contribution $E_i$ of all the cells belonging to it.

The global cluster time information is assumed to be the reconstructed time $T_i$ of the central cell of the shower. Detailed studies \[61\] have shown that one can get a small improvement of time resolution combining the information extracted by other cells of the shower. This information is indeed added to compute the final mean of the cluster times that gives the overall event time.

Concerning the impact position coordinates of the $j$-th cluster, a first estimate $(x_{cogj}, y_{cogj})$ is obtained by

$$x_{cogj} = \frac{\sum_i x_i E_i}{\sum_i E_i}$$  \hspace{1cm} (5.8)

$$y_{cogj} = \frac{\sum_i y_i E_i}{\sum_i E_i}$$  \hspace{1cm} (5.9)

where the sum over $i$ has to be intended as a sum over the cells belonging to a $3 \times 3$ region centred on the cluster seed, and $x_i, y_i$ are the coordinates of the centre of the $i$-th cell.

The vertical coordinate $y_{cogj}$ is then corrected as:

$$y_{cj} = A \cdot \tgh(B \cdot y_{cogj}).$$  \hspace{1cm} (5.10)

The correction function is derived in the hypothesis that the transverse shower development has an exponential behaviour and that the sum in equation 5.9 is performed over all the shower development. The coefficients $A$ and $B$ are derived by the data.

To correct the horizontal coordinate one has to introduce by hand various terms in the correction function, to take into account the effect of the electrodes zig-zag. The resulting correction function currently applied is \[60\]:

$$x_{cj} = A' \cdot \tgh\left(B' x_{cogj} + C' x_{cogj}^2\right) + D' + E' x_{cogj} + F' x_{cogj}^2.$$  \hspace{1cm} (5.11)

The 6 coefficient are derived from actual data. They are logarithmic functions of the cluster energy $(E_{cj})$ due to the logarithmic variation of the longitudinal position of the cluster core.

Once found the values of $x_{cj}, y_{cj}$, to take into account the variation of current induced as a function of the distance of the core of the shower from the anode of cluster seed cell (discussed in section 3.3.1), the energy value $(E_{cj})$ is corrected with a function $F(x_{0j} - x_{cj}) \cdot G(y_{0j} - y_{cj})$ (where $x_{0j}$ and $y_{0j}$ are the coordinates
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of the centre of the j-th cluster seed cell) equal for all cells and derived from the data.

Finally a small correction, derived from detailed Montecarlo studies of the shower shape, is applied to situation in which two clusters partially overlap, to correct for imprecise sharing of the energy between the two.

Other small corrections are applied to compensate for the effect of space charge accumulation during the burst [30] and for the difference between the photon direction and the cell projectivity angle.

Event reconstruction algorithms

Among the clusters found, a preliminary selection of the possible photon candidates is performed requiring them to have energies in defined interval and to be near-in-time (see section 5.1.4).

All the events with at least four photon candidates are fully reconstructed. The reconstruction process is then organised as two nested loops:

1. over all the possible 4 clusters combinations out of all the photon candidates

2. given the 4 clusters loop over the three possible two by two associations of them.

Given a group of 4 clusters identified as photon candidates the energy of the possible originating kaon is given by:

$$E_K = \sum_{i=1}^{n_c=4} E_{c_i}.$$  \hfill (5.12)

The invariant mass $m_{nc}$ of a particle decaying in $n_c$ photons, in the approximation of small angles of the photon momenta with respect to the particle beam axis, is given by:

$$m_{nc} = \frac{1}{d} \cdot \sqrt{\sum_{i=1}^{n_c} \sum_{j>i} E_{c_i} \cdot E_{c_j} \cdot [(x_i - x_j)^2 + (y_i - y_j)^2]},$$  \hfill (5.13)

or equivalently:

$$m_{nc} = \frac{\sum_{i=1}^{n_c} E_{c_i}}{d} \cdot \sqrt{M_{2cX} + M_{2cY} - M_{1cX}^2 - M_{1cY}^2},$$  \hfill (5.14)

where $E_{c_i}$ represents the measured energy of the i-th photon, $x_i$ and $y_i$ represent the coordinates of its impact point on a plane perpendicular to the beam direction, $d$ is the distance between such plane and the vertex of the decay and:

$$M_{1cX} = \frac{\sum_{i=1}^{n_c} E_{c_i} \cdot x_i}{\sum_{i=1}^{n_c} E_{c_i}}.$$  \hfill (5.15)
\[ M_{2cX} = \frac{\sum_{i=1}^{nc} E_{c_i} \cdot x_i^2}{\sum_{i=1}^{nc} E_{c_i}} \] (5.16)

and similar for \( M_{1cY} \) and \( M_{2cY} \).

Imposing to the invariant mass to have the value of the kaon mass, we derive the distance of the possible kaon decay vertex \( d_K \):

\[ d_K = \frac{E_K}{m_K} \cdot \sqrt{M_{2cX} + M_{2cY} - M_{1cX}^2 - M_{1cY}^2} \] (5.17)

and from that the longitudinal position \( z_v \) of the decay vertex relatively to the AKS position:

\[ z_v = d_{AKS} - d_K \] (5.18)

where \( d_{AKS} \) indicates the distance of the AKS from the reference plane of the calorimeter.

It can be noticed that the calculated value of \( z_v \) is largely independent on the choice of the reference plane due to the projective geometry implemented for the calorimeter.

To test the requirement that the 4 photons originate from a decay in 2 pions we associate the clusters two by two. The invariant masses of the different photon pairs are again calculated with equation 5.14 imposing now that \( d = d_k \):

\[ m_{c_i c_j} = \frac{(E_{c_i} + E_{c_j})}{d_K} \cdot \sqrt{M_{2cX} + M_{2cY} - M_{1cX}^2 - M_{1cY}^2}. \] (5.19)

To perform a first choice on the most probable association of photons a \( \chi^2 \) variable is constructed:

\[ \chi^2_m = (m_{c_i c_j} - m_\pi)^2 + (m_{c_k c_l} - m_\pi)^2 \] (5.20)

where \( i, j, k, l \) are the index of the photon candidates. The “good” association of photons in pairs (out of the 3 possible ones) is taken as the one minimising \( \chi^2_m \). Figure 5.7 shows the distribution of the “good” reconstructed masses for a run with a beam of \( K_S \) only, while figure 5.8 shows the distributions obtained from the same events with the other two possible associations of the photons.

It is observed that the physical region for the bi-dimensional distribution of the two pion masses has an elliptical shape (see figure 5.7). This can be reproduced by Montecarlo simulation and can also be easily explained by the fact that our reconstruction algorithm imposes to the invariant mass of the 4 photons to take exactly the value of the kaon mass, thus inducing a strong constraint to the distribution of the sum of the two reconstructed pion masses, while the difference is basically unconstrained.
One can thus compute the quantity:

\[ R_{\text{ellipse}} = \left( \frac{(m_1 - m_2)/2}{3 \cdot \sigma_-(E_{\gamma\text{min}})} \right)^2 + \left( \frac{(m_1 + m_2)/2 - M_\pi}{3 \cdot \sigma_+(E_{\gamma\text{min}})} \right)^2 \]  

(5.21)

The \( \sigma_-(E_{\gamma\text{min}}) \) and \( \sigma_+(E_{\gamma\text{min}}) \) are the standard deviations of the pion masses semi-difference and semi-sum distributions. The \( R_{\text{ellipse}} \) can be interpreted as a reduced \( \chi^2 \) distribution.

It is observed that the resolutions on the sum and the difference of the reconstructed pion masses are strongly dependent on the value of the energy of

Figure 5.7: Distribution of the reconstructed pion masses.
the minimum-energetic photon ($E_{\gamma_{\text{min}}}$), as an effect of the energy dependence of the calorimeter resolution. Figure 5.9 shows the $\sigma_+$ and $\sigma_-$ behaviour.

It is thus evident that the most accurate selection of the “good” photon pair combination is given by the minimisation of $R_{\text{ellipse}}$ more than $\chi^2_m$. This method allows a better background rejection and is thus the followed approach.

Another reconstructed quantity is the time of the event. For the analysis presented in this chapter I calculated it as the weighted mean of the four photon candidate times:

$$t_{\text{evt}} = \frac{\sum_{i=1}^{4} t_i / \sigma_{t_i}^2}{\sum_{i=1}^{4} 1/\sigma_{t_i}^2}$$  \hspace{1cm} (5.22)

where $t_i$ is the reconstructed time of the i-th cluster and $\sigma_{t_i}$ is an estimate of the time measurement fluctuations which can be taken as:

$$\sigma_{t_i} \propto \frac{1}{\sqrt{E_{c_i}}}$$  \hspace{1cm} (5.23)

The final algorithm used for the $R$ calculation is more sophisticated, as it includes in the mean the times of the most energetic lateral cells of the showers. Figure 5.10 shows the dispersion of the difference between $t_{\text{evt}}$ and the time of the 4 individual clusters for $K_S$ events.
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5.1.4 $K \rightarrow 2\pi^0$ events selection

The principal criteria applied are:

- a fiducial region for clusters to be considered as photon candidates is defined. A cut is performed around the beam pipe at a radius of 15 cm. The outer geometrical cut selects clusters included in a region of octagonal shape (as the calorimeter active area shape) with an inscribed circle of 110 cm of radius. All the individual cells with problems in the readout electronics are taken into account cutting a circular region of 2 cm of radius around each of them. Finally a region of 4 consecutive columns is eliminated to compensate for the missing High Voltage of two of them (this introduces $\sim$15% of loss in the acceptance).

- the energy of the cluster selected as photon candidates is required to be smaller than 100 GeV, to avoid electronics non-linearity effects, and to be greater than 3 GeV, to have an acceptable energy resolution.

- the four selected clusters are required to be in-time. That means that the differences between the event time $t_{\text{evt}}$ calculated for the selected clusters and their individual times $t_i$ are required to be smaller than 5 ns. The
actual value of this cut is determined by the narrow dispersion of the reconstructed times of the photons coming from a kaon decay (see 5.10).

- the kaon energy is required to be in an interval of 70 to 170 GeV. This interval is the one that minimises the energy spectrum differences between $K_S$ and $K_L$ component of the beam.

- the distance from the beam axis of the calculated C.O.G. of the 4 photon
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Figure 5.11: Distribution of Centre Of Gravity for $K_S$ beam (a) and for $K_S + K_L$ combined beam (b)

at the reference plane of the calorimeter is required to be lower than 10 cm (see figure 5.11). This criteria is intended to cut decays of scattered Kaons and events with missing $p_t$ due to $K_L \rightarrow 3\pi^0$ decays with only 4 clusters detected in the calorimeter.

- events having at least two of the four selected clusters being closer than 10 cm are rejected. This criterion is introduced to avoid problems in the reconstruction of the energy information from the calorimeter in case of overlapping showers.

- $K_S$ events in coincidence (in a window of $\pm$2 ns) with some activity in the AKS counters are rejected. This is the only cut to define the upstream limit of the region of acceptance for the $K_S$ decay vertex. No software cut on $z_v$ is performed for $K_S$. The importance of such a choice was discussed in section 2.1.1. $K_L$ events are instead cut upstream of the reconstructed AKS position.

- a downstream cut on the kaon decay vertex distribution is instead applied for both $K_S$ and $K_L$. The distance between the AKS reconstructed position and the downstream edge of the vertex fiducial region is defined,
Figure 5.12: Distribution of lifetime $n_\tau$ for $K_S$ beam (a), and for $K_S + K_L$ combined beam (b).

depending on the Kaon momentum, as a multiple $n_\tau$ of the value of a $K_S$ decay length $\lambda_S$. This decay length is defined as: $\lambda_S = \gamma \beta c \tau_S$ ($\tau_S$ is $K_S$ proper lifetime) and the cut is performed on the value of $n_\tau = z_v / \lambda_S$. $n_\tau$ has to be chosen as a compromise between the need to minimise the statistical error on $K_L \rightarrow 2\pi^0$ decays and the level of the physical background due to $K_L \rightarrow 3\pi^0$. It is easy to find out (see appendix A) that, assuming a uniform acceptance and a small dilution term $D$ (see equation 2.6), the weighting technique applied to $K_L$ decays (see section 2.1.1) implies that the statistical error for $K_L \rightarrow 2\pi^0$ decays is:

$$\sigma_{L}^{(\text{stat.})} \propto \sqrt{1 - e^{-2N_\tau} \frac{1 - e^{-N_\tau}}{1 - e^{-N_\tau}}}.$$ (5.24)

On the other hand, it is clear from equations 5.12, 5.17 and 5.18, that the background of $K_L \rightarrow 3\pi^0$ with only 4 photons detected tends to be reconstructed with large $z_v$ due to the underestimation of $E_K$. Figure 5.12 shows the distribution of $\tau_K$ for the $K_S$ and for the combined beam. In the final analysis a cut has been applied at $n_\tau = 3.5$.

- events with one or more extra clusters in-time with the 4 “good” clusters are rejected. With extra clusters I mean all the clusters seen by the calorimeter in coincidence with a trigger, that don’t belong to the 4 “good” ones. This is a very powerful cut to reduce the amount of physical
background due to $K_L \to 3\pi^0$ events. A $K_L \to 3\pi^0$ event reconstructed as a $K_L \to 2\pi^0$ event will often have at least one extra cluster in time with the 4 “good” ones. A simple cut requiring to have exactly 4 clusters per event would spoil excessively the statistics, given the rate of accidental activity in the calorimeter. To reduce this effect events are rejected only in presence of extra clusters with reconstructed time closer to $t_{\text{cut}}$ than 3 ns. To avoid the effect of shower fluctuations, that could simulate in time extra clusters, the check is performed just on clusters with energy greater than 1.5 GeV. Figure 5.13 shows the effect of the cut on the lifetime distribution for $K_S + K_L$ beam events. No appreciable decrease in statistic is observed in the background free region (low $n_\tau$).

- a cut on the value of $R_{\text{ellipse}} < 1.5$ is performed as the final physical selection criteria. This cut eliminate $\sim 7\%$ of $K_S$ events as well. This fraction of events is mostly composed of events with a pion Dalitz decays or photon conversions. These effects are symmetric between $K_S$ and $K_L$ and thus produce no effect on the double ratio.

- additional cuts are applied to symmetrise some dead time of the charged apparatus to the neutral events to ensure a good cancellation of possible related systematic effects in the double ratio. These cuts are discussed in more detail in the following chapter.

### 5.1.5 Reconstruction resolutions

To understand the real performances of the calorimeter for the $Re(\varepsilon'/\varepsilon)$ measurement we can now look at the resolutions in the reconstruction of the pion mass (remember that the kaon mass is imposed by the reconstruction algorithm) and of the longitudinal position of the decay vertex.

Figure 5.14 show the resolution in the reconstruction of pion mass. As already mentioned the resolution depends on the energy of the lowest energetic photon of the decay (see figure 5.9).

For all decays with photons more energetic than 3 GeV (the photon candidate selection threshold described in section 5.1.4), the calorimeter pion mass resolution is measured to be $\leq 1\%$ even if affected by the described high voltage problem of 1997 run.

The resolution for the reconstruction of the longitudinal decay vertex, can be extrapolated by the fit of the AKS edge in a $K_S$ beam data.
The distribution of the reconstructed position of the decay vertex close to the position of the AKS for $K_S$ data is reported in figure 5.15. The distribution is fitted with the function:

$$f_{AKS}(x) = A \cdot \int_{C}^{\infty} e^{-\frac{(x'-C)}{B}} \cdot e^{-\frac{(x-x')^2}{2D^2}} \, dx'$$

(5.25)

that describe the convolution of an exponential decay function with origin in $C$ and decay length $B$ with the apparatus resolution function in $z_v$, parametrised
by a Gaussian distribution, with $\sigma = D$. The vertex position resolution at distances of $\sim$120 m from the calorimeter is thus $\sim D = 60$ cm hence $< 1\%$ of the distance from the calorimeter to the decay vertex.

### 5.1.6 Systematic effects

The main systematic effects linked to the calorimeter response have been studied in great detail. A detailed discussion of all the effects goes beyond the scope of this work. I'll just discuss briefly what are the effects that we took into...
account and what is the uncertainty that we estimate that they induce on the measurement of $R$.

The precision with which the position of the AKS itself can be reconstructed and that determines the precision in the absolute energy calibration of the calorimeter can be made much smaller than the resolution in $z_{v}$. At a certain level however, systematic uncertainties in the fitting procedure will dominate.

This absolute calibration is kept under control with dedicated data taking.
conditions, in particular detecting pair of photons of known invariant mass from
decays of \( \pi^0 \) or \( \eta \) produced by negative pion beams in relatively thin targets
located close to the AKS position.

The overall error on \( \text{Re}(\varepsilon'/\varepsilon) \) due to the measurement of the absolute energy
scale calibration factor has been estimated to be of \( \sim 5 \times 10^{-4} \) on \( R \).

The transverse scale is studied as well. We use \( K_{e3} \) events, comparing the
electron impact point position reconstructed by the calorimeter and the one ex-
trapolated by the drift chambers following the magnet. The systematic uncer-
tainty on \( R \) arising from the transverse scale measurement precision is estimated
to be \( 3 \times 10^{-4} \).

The uniformity of response over the detector and the non-linearity in the
energy measurement are studied with \( K_{e3} \) events (where the electron energy is
independently measured by the spectrometer) as well as with decays of \( \pi^0 \) or \( \eta \)
in two photons of the same energy from the special run periods described above.
The overall non linearity is measured to be within 0.3 % in the energy range of
the selected photons (3-100 GeV) [59].

We estimated that part of it is induced by the loss of energy of the photons
in the material preceding the calorimeter. The mean energy loss is estimated
to be \( \sim 20 \) MeV. No direct correction is applied to the data to compensate for
this small non linearity. The uncertainty linked to this effect is estimated to be
\( \pm 9 \times 10^{-4} \) on \( R \).

Finally the uncertainty linked to the small correction applied in the photon
energy reconstruction is estimated to be \( \pm 4 \times 10^{-4} \) on \( R \).

5.2 Neutral Trigger performances

The neutral trigger installation has been completed in the first half of 1997.
The trigger system has operated since then in very stable conditions.

After an initial period of test during which different trigger conditions have
been tried out, since the beginning of august 1997 the final trigger conditions for
the \( K \to 2\pi^0 \) decays have been decided and set up. The values of the principal
cuts have been programmed to:

- \( E > 50 \) GeV ;
- \( \text{COG} < 15 \) cm ;
- \( \tau_K < 5.5 \tau_S \);
- number of peaks < 5 in a window \( \Delta t = 3 \times 3.125 \) ns .
The cut on the number of peaks was performed independently for the peaks in the X view and the ones in the Y view.

The resulting rate was of about 4500-5000 triggers per burst, that means \(~2\) KHz. Considering that the expected rate of kaon decays in the detector is of the order of 500 KHz, the current Neutral Trigger setup assures a rate reduction factor of about 250.

5.2.1 Trigger calculations resolutions

To investigate the trigger system performances one has to consider the resolution in the reconstruction of the physical quantities that are used to elaborate the trigger decision.

To study those resolutions one can compare the physical quantities reconstructed online by the Neutral Trigger with the same quantities extrapolated offline by the complete calorimeter information.

Figure 5.16 shows the comparisons for the reconstructed lifetime.

There is a clear indication that, apart from the effect of the worse intrinsic resolution of the online calculations (and the small \(\Delta^2\) shift in the lifetime distribution as from equation 4.3), the Neutral Trigger tends to systematically underestimate the values of lifetime.

This is understood as an effect of the wrong assumption on the cells size (assumed to be 2 cm instead of the effective value of 1.974 cm due to the projective geometry).

One observes as well that the distribution has large asymmetric tails. The Neutral Trigger lifetime is in fact largely underestimated when some accidental activity overlaps with the event. The accidental clusters induce an overestimation of the reconstructed kaon energy (see figure 5.17) and thus an underestimation of the reconstructed kaon lifetime. It is important to note that this error on the reconstruction of the lifetime value has no effect on the efficiency of the cuts, as the lifetime is required to be smaller than the cut value and its underestimation pushes the events to be accepted.

The same effect happens for the energy cut. The energy measurement has large asymmetric tails due to accidental activity that increases the Neutral Trigger energy estimate (see figure 5.17) but again these tails extend on the side opposed to the one where the trigger cut is applied.

These considerations reflects the fact that the trigger system has been designed to reduce at the minimum level the losses of events due to close in time accidental activity. Those events can in fact be properly reconstructed offline when the information of the single cells of the calorimeter is used.

Figure 5.18 shows the trigger-to-offline difference for the reconstructed COG. The shown resolution is the ideal one that one could obtain correcting in the
Figure 5.16: Difference between the Kaon lifetime reconstructed online by the Neutral Trigger and the one obtained from the offline reconstruction. The narrower peak contains the events with four clusters and no accidental activity while the large tail is dominated by events with accidental activity. As expected the presence of accidental clusters increase the overall measured energy and thus induces an overestimation of the reconstructed distance between the vertex and the calorimeter (see equation 4.5) and hence an underestimation of the reconstructed lifetime.

LUT for the slightly asymmetric choice of $M1$ calculation origin discussed in section 4.3.5. This correction was actually not implemented in LUT programs during 1997 data taking and the shown distribution is obtained instead calcu-
Figure 5.17: Difference between the energy information reconstructed by the Neutral Trigger electronics and the energy of the decaying Kaon as extrapolated offline by the calorimeter complete information. The tendency to overestimate the kaon energy is a consequence of the presence of accidental activity and the fact that the trigger electronics sums up the energy measured in the full calorimeter.

Figure 5.19 shows the real difference that we got in running conditions. As the cut on COG was chosen to be highly conservative (due to the intrinsic dif-
Figure 5.18: Difference between the COG calculated online by the Neutral Trigger and the same quantity calculated offline with the complete calorimeter information.

5.2.2 PeakSum time resolution

The online calculation of the clusters time is really the most interesting feature of the PeakSum system and of the trigger system in general. This is essential to reduce the amount of accepted $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$, that are the dominant $K_L$ neutral decay channel, without the risk of a large inefficiency due to accidental

It is evident that the better one is able to reconstruct cluster times, the smaller one can take the time window to consider the clusters as coincident and thus the lower is the trigger inefficiency due to accidental activity in coincidence with the 4 photons of a $K \rightarrow 2\pi^0$ decay.

Figures 5.20 and 5.21 shows the time resolution for the X and the Y view obtained comparing the time information calculated by the trigger for the four “good” clusters of $K \rightarrow 2\pi^0$ events with the event time reconstructed by the
As the PeakSum system doesn’t produce any information about the geometrical position of a cluster, but provides just the series of reconstructed times for all the event clusters, I had to select only clean 4 clusters events with no accidental activity in the calorimeter over many clock periods. I could thus assume that all the peaks found by the trigger for those events (most of the times 4 but sometimes less due to geometrical superposition on a projection), were related to one of the 4 event cluster. The plots thus contains for every event the differences between the individual times of the trigger peaks and the

Figure 5.20: PeakSum X view time resolution.
Both views have a time resolution of better than 3 ns. To understand how good this result is, we have to remember that these resolutions are obtained with no geometrical selection criteria on the photon impact positions, and thus include all the effects of possible skew between different calorimeter channels.

As previously discussed the coincidence window has been programmed to be $\sim 10$ ns, that corresponds to more than 3 times the PeakSum intrinsic resolution.
5.2.3 Trigger efficiency

The most relevant parameter of a trigger system is with no doubts its efficiency in selecting good events.

This parameter is also essential to evaluate the systematic error induce by the trigger on the final measurement.

The approach that one can follow to study a trigger efficiency is that of setting up a simple less selective independent trigger (that I’ll call minimum-bias trigger), to downscale it and to send those selected events to the DAQ.

One can then analyse offline this data set and count the number of times that an event passing the analysis cuts had also been selected by the main trigger, and how many time it had been lost. The efficiency is simply given by the ratio of good events selected by both the minimum-bias trigger and the main trigger over the total number of good events selected by the minimum bias trigger.

Such a simple trigger is not required to be highly efficient but it has to be as much as possible unbiased. That means that its possible inefficiency has to be uncorrelated to particular events characteristics and to the behaviour of the main trigger.

In the frame of NA48 experiment we set up an independent trigger for neutral decays based on the neutral hodoscope information. Because of the very good hodoscope efficiency (see figure 3.14) and of the complete independence of neutral hodoscope readout and calorimeter readout, a trigger based on this information fits all the requirements for a precise measurement of the main trigger efficiency.

The actual trigger conditions required the coincidence of a signal above a threshold in the top and bottom half or in the right and left half of the hodoscope surface.

Moreover, to reduce the produced rate the anti-coincidence with the signals in the AKL counters and in the muon vetos was required in the first part of the run. This requirements have been released in the second half, because they were observed not to reduce the rate by a large amount and we were worried about possible biases in the efficiency measurement.

A downscaling factor of 100 was applied to this trigger.

Some care has to be taken to avoid the effect of “double triggers” on the measurement. Because of the independence of the Neutral Trigger and the hodoscope trigger it is unavoidable to have a certain fraction of events triggered by the two systems in two consecutive clock periods instead that in the same one. In a pipeline data acquisition architecture this results in a double triggering of the same event. I thus had to take care of identify all the hodoscope events that had been also triggered by the Neutral Trigger in a preceding or following clock period to avoid a large overestimation of the trigger inefficiency.
Figure 5.22 shows the measured efficiency for $K_S$ and $K_L$ events as a function of the offline lifetime cut. The difference between the two for large values of the lifetime cut is due to the fact that the region of large lifetime are basically populated only by $K_L$ events as the $K_S$ have mostly already decayed.

In correspondence of the value of the final lifetime cut (3.5 in the plots horizontal scale), the combined $K_S + K_L$ efficiency is measured to be $(99.88 \pm 0.03)\%$.

The sources of the very small inefficiency have been studied and clearly
5.3. RESIDUAL BACKGROUND LEVEL

identified and are dominated by accidental activity effects. The basic physical phenomena influencing the trigger response are:

1. high energetic Λs decaying far upstream in the $K_L$ beam line and relatively close in time (within 40 ns) to the good event. The configuration of magnets, along the beam $K_L$ line, used to select the secondary protons for the $K_S$ target, deflect the protons from the Λs decaying in a defined longitudinal region, such that they can reach the calorimeter. The energy deposition of those isolated high energetic protons cause the Neutral Trigger centre of gravity to be reconstructed as being larger than the cut value (15 cm).

2. Accidental $K_L$ neutral decays occurring within 10 ns (the width of the peak finding time window) of a good event. This causes the counting of a number of peaks in time larger than 6 and the consequent rejection of the event.

Some losses of good events are as well induced by a bit error in the transmission of the digitised information of a calorimeter strip within the Neutral Trigger chain, as well as by some erratic cell response. Those losses are of course intrinsically symmetric between $K_S$ and $K_L$ events.

Given the fact that the accidental effects are symmetrised to a very good approximation between $K_S$ and $K_L$ events. This implies that no correction is needed on $R$ because of the neutral trigger.

The two values that I measure are:

$$\varepsilon_{KS} = (99.86 \pm 0.04)\%$$  \hspace{1cm} (5.26)

$$\varepsilon_{KL} = (99.93^{+0.07}_{-0.05})\%$$  \hspace{1cm} (5.27)

As expected the two efficiencies are compatible within the error even if the very low number of inefficient $K_L$ events (2 over 2952 minimum bias triggers) doesn’t allow a very precise comparison. I thus checked the same efficiency over the data collected in 1998, that have become available some time ago, and with a much larger statistics I found a perfect agreement between the two efficiencies.

5.3 Residual background level

The residual amount of background due to $K_L \rightarrow 3\pi^0$ events not eliminated by the trigger and the data selection criteria has to be extrapolated and subtracted from the signal region from the $K_L$ sample.
Figure 5.23: $R_{\text{ellipse}}$ distribution $K_S$ (corrected for the tagging dilution), $K_L$ and $K_{L_w}$ weighted events. The two $K_L$ distributions are renormalised to the $K_S$ one.

5.3.1 The $K_S$ tagging

The identification of the events originated by the $K_S$ beam is assured by the coincidence (in a window of ±2 ns) of the reconstructed event time and the time of impact of the protons impinging in the $K_S$ target (see section 2.1.4).

All the other $\pi^0 \pi^0$ events selected by the reconstruction are assumed to be coming from the $K_L$ beam. The probability ($\alpha_{LS}$) of accidental coincidence
5.3. RESIDUAL BACKGROUND LEVEL

between a proton passing in the tagger detector and a $K_L$ event time is measured to be $\sim 11\%$. The precise measurement of this probability of accidental $K_S$ tagging (I’ll refer to it as tagging dilution in the following sections) and its effect on the measurement are discussed in more detail in the following chapter.

Figure 5.24: Distribution of $R_{\text{ellipse}}$ for lifetime weighted $K_L$ data and for the background estimation obtained subtracting the $K_S$ signal shape.
5.3.2 Background determination

From the experience of NA31 [62] one expects the $K_L \rightarrow 3\pi^0$ background to be uniformly distributed in the variable $R_{\text{ellipse}}$.

To measure the background level one first has to obtain a pure signal distribution from the $R_{\text{ellipse}}$ distribution for events tagged as $K_S$ (assumed to be background-free) to which one has to subtract the $R_{\text{ellipse}}$ distribution for events tagged as $K_L$, scaled by a factor $\alpha_{LS}/(1 - \alpha_{LS})$, to correct for the contamination of $K_L$ events on the tagged $K_S$ events.

Figure 5.25: Reconstructed background level as a function of the event energy.
5.3. RESIDUAL BACKGROUND LEVEL

Figure 5.23 shows the $R_{\text{ellipse}}$ distribution for $K_S$ events (corrected for tagging dilution), for $K_L$ events, and for $K_L$ weighted events.

The background free $K_S$ signal distribution (properly re-normalised) is then subtracted from the $K_L$ distribution (lifetime weighted as described in section 2.1.1). The resulting distribution is to good approximation that of the physical background.

One thus extrapolate the background level under the signal region from a control region of $R_{\text{ellipse}}$ (between 4 and 14) where on one hand the background level is larger than the residual level of signal (thus minimising the error due to the subtraction) and on the other the distribution is not affected by the preliminary cuts on the pion mass applied by the first stage of data processing (the so called “Level 3” [63]). The extrapolation is done assuming an uniform distribution of $R_{\text{ellipse}}$ for the background events.

Figure 5.24 shows the complete $K_L$ events and the estimated background resulting from the difference.

It is interesting to note that the $K_L$ lifetime weighting mechanism has the positive side effect of reducing the effective background level. The $K_L \rightarrow 3\pi^0$ background events have in fact undetected clusters, and thus the total energy of the event is generally underestimated. This implies (see equation 5.17) that the vertex position for those events tends to be reconstructed closer to the calorimeter than it should be. The background events tend thus to be distributed preferentially in the region of large lifetime and thus to be in general more suppressed by the weights than the good $K_L \rightarrow 2\pi^0$ events.

For the final background estimation a correction factor of $1.2\pm0.2$, calculated using $K_L \rightarrow 3\pi^0$ Montecarlo events, is applied to the linear extrapolation.

Figure 5.25 shows the resulting values of the background level as a function of the event energy.

The global background level is $(0.096 \pm 0.016)\%$. 
Chapter 6

Preliminary result on $Re(\varepsilon'/\varepsilon)$

This chapter describes the analysis that I performed to calculate $Re(\varepsilon'/\varepsilon)$ from the data collected in 1997. The selection of charged decay events and the determination of the corrections to be applied to the raw ratio are briefly discussed and the result is presented. A more detailed description of all the studies that led to the optimisation of the selection of charged events goes beyond the scope of the present work. The interested reader will be able to read more on dedicated works that are in preparation.

6.1 Charged events selection

The detection of charged events is based on the charged spectrometer.

Hits in the drift chambers planes are first combined to reconstruct all the charged tracks.

A time information is associated to every track, reconstructing the time of the hit in the hodoscope geometrically associated to the extrapolation of the track on the hodoscope plane.

The momentum of every track is reconstructed from the deflection induced by the magnetic field. A measured detailed map of the magnetic field [64] is used in the extrapolation to minimise the uncertainty.

A small correction on the tracks has to be applied to deal with the magnetic field present in the evacuated decay region.

The tracks with momentum $>10$ GeV/c$^2$ are retained as charged pion track candidates.

Every pair of selected charged tracks with opposite charge is then assigned a vertex which is determined as the medium point of the closest distance of approach of the two tracks. Tracks are associated to construct vertex candidates just if the mean of the two track times is close (in a window of $\pm20$ ns) to the
trigger time, to avoid taking into account accidental tracks.

The pairs of tracks fulfilling all the physical requirements, described later in this section, are retained as $K \rightarrow \pi^+\pi^-$ event candidates. If more than a pair of tracks associated with the same trigger pass all the selection cuts, a single event is counted.

To reduce the possible error induced by the uncertainty in the determination of the magnetic field map, the total energy of the event (and by consequence its proper lifetime) is computed from the angle between the two tracks:

$$E = \frac{\sqrt{(m_K^2 - m_\pi^2) \cdot R}}{\theta}$$  \hspace{1cm} (6.1)

where $\theta$ is the angle between the tracks and $R$ is given by:

$$R = \frac{(E_+ + E_-)^2}{E_+ \cdot E_-}$$  \hspace{1cm} (6.2)

with $E_+,-$ being the energy of the two tracks.

The principal physical cuts applied to select the event candidates are:

- The closest distance of approach is required to be smaller that 3 cm to avoid the construction of events from uncorrelated tracks.

- A cut is performed on the asymmetry $A$ of the momenta of the two tracks, to eliminate events with tracks very close to the beam hole, for which one would need a very accurate Monte Carlo simulation of the apparatus. The asymmetry is defined as $A = |p_+ - p_-|/(p_+ + p_-)$, where $p_+$ and $p_-$ are the momenta of the two tracks. The requirements on the asymmetry are: $A < 0.62$ and $A < (1.08 - 0.0052 \cdot E_K)$

where $E_K$ is the Kaon energy expressed in GeV. A side effect of this cut is to eliminate all the $\Lambda$ and $\bar{\Lambda}$ decays originating from the $K_S$ beam.

- The invariant mass of the system of the two charged particles ($m_{+-}$) is required to be compatible with the Kaon mass. A maximum difference of $\pm 3\sigma_m$ with the value of the Kaon mass is allowed for $m_{+-}$, where $\sigma_m$ indicates the spectrometer mass resolution. Its observed dependence on the Kaon energy can be parametrised as:

$$\sigma_m(E_K) = 1.7610^{-3} \text{ GeV } + 0.737 \cdot E_K,$$

where the Kaon energy $E_K$ is expressed in GeV. To allow the better reduction of background the cut is thus performed as a function $E_{+-}$ where $E_{+-} = E_+ + E_-$ is the sum of the energy of the two tracks.
6.2 SYMMETRIC CUTS

- A large reduction of the background due to semileptonic decays of the Kaon is assured by a cut on the reconstructed kaon transverse momentum $p_t$. To minimise the asymmetry between $K_S$ and $K_L$, due to different $p_t$ resolution, the actual cut is performed on the variable $p'_t$ defined as the component of the kaon momentum orthogonal to the line joining the production target and the extrapolated point where the kaon trajectory would cross the plane of the first chamber. Of course such a cut procedure requires the identification of the events as originating from the $K_S$ target or from the $K_L$ one. This is provided by the reconstruction of the vertical position of the decay vertex. As described later, the two targets are separated vertically by much more than the two beam spot radiuses, thus allowing a not ambiguous identification of the $K_S$ and $K_L$ charged decays.

- A further reduction of $K_L \rightarrow \pi \mu \nu$ semileptonic decays is allowed by the muon veto counters installed at the end of the apparatus. Events are rejected if a hit is found in the muon counters, close to the extrapolated impact point of a track, and reconstructed to be in time (within $\pm 4ns$) with the same track.

- The $K_L \rightarrow \pi e \nu$ decays, are instead reduced cutting all the events with a track having a ratio between the reconstructed energy and momentum greater than 0.8.

Cuts are applied as well to discard events close to the limits of apparatus geometrical acceptance. A radial cut of 12 cm around the axis of the beam pipe is performed on the reconstructed impact point position of the tracks in the first, second and fourth drift chamber of the spectrometer (the third chamber is not needed in the event reconstruction and it is thus used only for specific studies).

Cuts are as well performed on the extrapolated impact point of the tracks on the muon veto planes, to avoid events hitting regions of low efficiency for the muon identification.

The efficiency of the charged reconstruction algorithms has been carefully studied. We estimate that the related systematic error on $R$ is $\pm 5 \times 10^{-4}$.

6.2 Symmetric cuts

The master idea of NA48 is to keep as symmetric as possible all the systematic uncertainties between the four decay modes.
To avoid asymmetries between the charged and neutral events instantaneous intensities, induced by the charged trigger dead time, we decided to apply in the analysis the Mass Box dead time to the neutral events. Thus the neutral events are discarded from the analysis whenever they are recorded in a period in which the Mass Box was in a busy state.

This procedure has the disadvantage of reducing by $\sim 1\%$ the amount of data of $K_L \rightarrow 2\pi^0$ decays, but assures a much better control on systematic effects.

Another type of inefficiency arises from the charged tracks detector. An overflow condition occurs in the drift chambers when more than 7 hits are measured in the same plane in a maximum time interval of 100 ns. Such a condition has been observed to affect the efficiency of the drift chamber readout electronics.

Many overflow conditions are generated during the burst because of electromagnetic showers originated by accidental particles in some material upstream of the spectrometer, thus generating a large number of hits in the following drift chambers. To assure that the data are collected in a clean situation and to avoid the need of a detailed simulation of the phenomena that induces overflows, all the overflow conditions occurred in the 400 ns preceding and following any triggered event are recorded. This is done for both charged and neutral events. We thus discard from the analysis all the events whenever an overflow condition was recorded within $\pm 312$ ns of the trigger time.

This cut has again the effect of symmetrising the possible effects induced by the overflows between charged and neutral decays (the residual possible differences are included in the accidental correction that I describe later). Unlike the dead time this overflow cut produces a very large loss of good events ($\sim 20\%$).

The other cuts symmetric between charged and neutral decays, are those that define the fiducial region for the decays. A downstream cut is applied on the reconstructed longitudinal vertex position corresponding to a kaon proper lifetime of $3.5 K_S$ lifetimes.

As discussed in section 5.1.4 for the neutral event selection, an upstream cut is performed at the level of the reconstructed position of the AKS for $K_L$ decays, while $K_S$ decays are discarded if they are in coincidence with an AKS hit.

In applying those cuts one has to take into account that the effective position of the AKS is reconstructed with an intrinsic difference of 21 mm between charged and neutral decays. This is due to the fact that charged decays occurring upstream of the AKS counter are always detected while neutral decays are detected only if one of the photons converts in the preceding material. Thus the fiducial region for charged and neutral decays are slightly displaced. The
good cancellation of acceptances in the double ratio is anyway assured between $K_S$ and $K_L$ decays of the same mode. The total lengths of the fiducial regions have anyway to be the same to provide the cancellation of the flux terms. As described in the previous section, to reduce the effects of possible incorrect reconstruction of the magnetic field, the proper lifetime is reconstructed using the energy information derived from the angle between the tracks (see equation 6.1).

To increase again the symmetry of the data taking, the fiducial cuts applied to the photon showers are applied as well to the extrapolation of the charged tracks on the calorimeter surface.

A cut requiring the centre of gravity of the event to be closer than 10 cm to the axis of the beam pipe is applied to both charged and neutral events. For neutral events the centre of gravity is defined as the energy weighted mean of the cluster positions on the calorimeter surface. For charged events the same weighted mean is computed from the extrapolation at the calorimeter surface of the charged tracks measured before the magnet.

### 6.3 The tagging procedure

One of the most delicate aspects of the NA48 experiment is the procedure applied to distinguish $K_S$ from $K_L$ decays.

As described in chapter 2, the $K_S$ events are identified from the coincidence (in a window of ±2 ns) of the event time with a proton hit in the tagging counter. To ensure the greatest symmetry between the four decay modes the same tagging mechanism applied to the neutral decays is also applied to the charged ones.

Figure 6.1 shows the distribution of the difference between the event time and the “best” proton time given by the tagging counters for charged decays produced by the combined $K_S + K_L$ beam. The “best” proton is simply defined as the one whose time minimises the difference with the event time after the correction for the time offset due to the distance between the tagging counters and the detector.

It is worthy to note, however, that for charged decays this tagging mechanism would be not strictly needed. Figure 6.2 shows the distribution of the reconstructed y and z coordinate of the decay vertex for $K_S$ and $K_L$ charged events. The two beams appear to be clearly separated in the vertical direction over all the longitudinal length of the fiducial region. It is thus clear that one can distinguish without any ambiguity the $K_S$ and the $K_L$ charged decays from the reconstruction of the vertex vertical coordinate. I’ll call this procedure the “vertex tagging”.

Such a clear procedure allows an independent way to measure the tagging
Figure 6.1: Time difference between the “best” proton time and the event time for $K_S$ and $K_L$ charged decays.

inefficiency for $K_S$ events and the probability of accidental tagging a $K_L$ as a $K_S$ event. Those effects have to be carefully studied in order to evaluate the corrections to be applied on the measurement of $R$ as will be shown in the following sections.
6.4 Calculation of $R$

This section describes how the measurement of $R$ is carried out and how the principal corrections are calculated.
6.4.1 Tagging effects

The two parameters that accounts for the possible tagging errors are: the tagging efficiency $\varepsilon_T$ and the mistagging probability $\alpha_{LS}$.

The first one is the efficiency for measuring the hit in the tagging counters of the proton that produces a $K_S$, in time with the reconstructed arrival time of the event in the detector. An inefficiency can possibly be induced both by an inefficiency in measuring the time of either the proton or the event, as well as by resolution effects in the time reconstruction that could induce a difference larger than the coincidence window. This effect induces a number of $K_S$ to be identified as $K_L$, and is expected to be very small.

We call mistagging instead the probability of an accidental coincidence between the time of a $K_L$ event and the hit time of an uncorrelated proton in the tagging counters. The mistagging induces $K_L$ events to be identified as $K_S$ events. Given the large intensity of the proton beam on the $K_S$ target, the mistagging effect is expected, unlike the tagging efficiency, to be quite a large effect.

While the small tagging inefficiency can possibly be different between charged and neutral decays, the mistagging probability, that depends mainly on the rate of protons in the tagging counters is expected to be almost the same for the two decay modes.

To understand the effect of the tagging errors on $R$, one can easily derive that:

$$ N_{S,++}^m = \varepsilon_T^- \cdot N_{S,++}^t + \alpha_{LS}^+ \cdot N_{L,++}^t \quad (6.3) $$

$$ N_{L,++}^m = (1 - \varepsilon_T^+) \cdot N_{S,++}^t + (1 - \alpha_{LS}^-) \cdot N_{L,++}^t \quad (6.4) $$

where $N_{S,++}^t$ and $N_{L,++}^t$ indicate the true numbers of $K_S \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^+\pi^-$ decays while $N_{S,++}^m$ and $N_{L,++}^m$ the corresponding measured values. The same equations can be written for neutral decays.

The scenario is actually slightly complicated by the fact that the tagged $K_S$ and $K_L$ events are treated differently in the analysis. The tagged $K_S$ events are selected with no upstream cut on the longitudinal vertex position while the tagged $K_L$ are weighted (see section 2.1.1).

Taking into account these differences, we can invert equations 6.3 and 6.4 to obtain:

$$ N_{S,++}^t = \frac{1}{(\varepsilon_T^- - \alpha_{LS}^{-})} \cdot \left[ (1 - \alpha_{LS}^{-}) \cdot N_{S,++}^m - \alpha_{LS}^+ \cdot N_{L,++}^{m(S)} \right] \quad (6.5) $$

$$ N_{L,++}^t = \frac{1}{(\varepsilon_T^+ - \alpha_{LS}^{+})} \cdot \left[ \varepsilon_T^- \cdot N_{L,++}^m - (1 - \varepsilon_T^+) \cdot N_{S,++}^{m(L)} \right] \quad (6.6) $$
where $N_{S,+}^{m(L)}$ is the measured number of events tagged as $K_S$ but treated as $K_L$ (cut upstream in the vertex distribution and weighted), and $N_{L,+}^{m(S)}$ is the measured number of events tagged as $K_L$ but treated as $K_S$ (not cut upstream in the vertex distribution and not weighted). Again an analogous equation holds for the neutral decays.

**Measurement of $\varepsilon_T$ and $\alpha_{LS}$**

In the charged decays the vertex tagging allows the very precise measurement of both quantities. Figure 6.3 shows the separation of the $K_S$ and $K_L$ components of figure 6.1.

Selecting the vertex tagged $K_S$ decays one can measure the fraction of $K_S$ charged events not in coincidence with a proton hit in the tagging counter. From 1997 data I measure:

$$\varepsilon_T^{(ch)} = (99.985 \pm 0.001)\%.$$

The mistagging probability for the charged events is instead measured selecting vertex tagged $K_L$ and counting what fraction of them is accidentally in coincidence with a proton hit in the tagging counters. I thus measure:

$$\alpha_{LS}^{(ch)} = (11.20 \pm 0.03)\%.$$

The analogous measurements for neutral decays are of course more complicated as we don’t have any independent tagging mechanism.

A direct measurement of tagging efficiency in neutral decays is obtained from the analysis of neutral events with either a $\pi^0 \to e^+e^-$ Dalitz decay or the conversion of one of the photons in the Kevlar window at the end of the vacuum tube. Those events can be tagged at the same time by the vertex of the electron-positron pair, and with the usual coincidence between the proton hits and the event time reconstructed from the remaining 3 photons. The precision of such a direct measurement is limited by the amount of useful events. The result obtained from 1997 data [65, 66] is: $\varepsilon_T^{00} = (2.3^{+3.0}_{-1.0}) \times 10^{-4}$.

A better estimate can be obtained if one just tries to measure the difference $\varepsilon_T^{00} - \varepsilon_T^{+\pm}$. Detailed studies have shown in effect that the tagging inefficiency is dominated by the inefficiency of the tagging counters more than by problems in the event time reconstruction. This means that the difference in efficiency between charged and neutral events is expected to be very small. Using the same Dalitz decays one can compare, for the same event, the time reconstructed by the charged hodoscope with the one reconstructed by the electro-magnetic
calorimeter. This comparison shows [67] that the neutral tagging inefficiency is equal to the charged one, with an accuracy of $\pm 1 \times 10^{-4}$.

The same differential approach is used to investigate the mistagging probability for neutral events. The difference $\alpha_{LS}^{00} - \alpha_{LS}^{+-}$ is measured looking at the accidental coincidences between the events and protons passing in the tagging counter at times shifted relatively to the true coincidence time. This means...
that one looks, for both charged and neutral decays, for coincidences in a time window that is artificially shifted from its proper centre value.

The actual measurement is carried out with 3 different windows. To perform such a measurement one has to consider the effects linked to the beam temporal structure and to the fact that the offset intervals could have a different contamination of accidental activity than the central one. A detailed study of this latter effect has been carried on [68] and a correction has been applied to the measurement. From 1997 data I measure: $\alpha^0_{LS} - \alpha^+_{LS} = (9 \pm 5) \times 10^{-4}$.

From this measurements I find out a global correction on $R$ due to the tagging of:

$$\Delta R = (+75 \pm 9) \times 10^{-4}. \quad (6.7)$$

### 6.4.2 Charged trigger efficiency

The charged trigger efficiency is measured, like the neutral trigger one, looking at a downscaled sample of the events triggered by an auxiliary minimum-bias trigger.

The number of those events passing all the selection criteria is checked to find out the fraction of events that had not been selected by the main trigger. The ratio between the number of good events being triggered by both the minimum-bias trigger and the main one, over the total number of good events triggered by the minimum-bias only, gives the trigger efficiency.

The charged trigger efficiency has varied quite a lot between the first and the second half of 1997 data taking period. A timing misalignment in the trigger logic has affected the efficiency for a non negligible part of the run. The global efficiency for 1997 data results thus to be $\sim 91.5\%$. Such a low efficiency has the effect of increasing the statistical error on the efficiency measurement, resulting in a relative large error for the correction factor for $R$. This is computed as the ratio of the measured efficiency for charged $K_L$ events over the efficiency for the $K_S$ events.

As explained later the correction (like most of the corrections) is actually computed as a function of the kaon energy (like most of the corrections).

The total shift on $R$ averaged over the complete energy range turns out to be:

$$\Delta R = (+11 \pm 22) \times 10^{-4}. \quad (6.8)$$

### 6.4.3 Background in the $K_L \to \pi^+\pi^-$ mode

The residual background due to $K_L$ semileptonic decays passing all the selection criteria is extrapolated looking at the distribution of signal, $K_{e\bar{e}}$ and $K_{\mu\bar{\mu}}$ events...
in the bi-dimensional plot of the reconstructed invariant mass versus $p_t^2$ (see figure 6.4).

The sample of $K_{e3}$ events is selected requiring that one of the two charged tracks has a $E/p$ value of more than 0.8.

The $K_{\mu3}$ events are instead selected requiring that one of the two tracks is in time with a hit in the muon veto.

All the other selection criteria for the charged events are required to be
fulfilled by those semileptonic event candidates. Thus one select a sample of events that are distributed as the background events.

In the resulting distributions of $m_{\pi\pi}$ versus $p_t^2$ one defines 2 control regions where there is negligible contribution from the $K \rightarrow \pi^+\pi^-$ signal, as can be verified looking at the distribution of the background-free $K_S$ events. From the content of events of the 2 control regions, using the knowledge of the shape of the background events contribution, one can extrapolate the amount of residual background present under the signal region.

Figure 6.5 shows the extrapolated distributions of the background components and the global distribution of the $K_L \rightarrow \pi^+\pi^-$ candidates as a function of $p_t^2$. One can see that the total background is dominated by the $K_{e3}$ component.

I measured the total amount of background events due to $K_{e3}$ to be $(0.20 \pm 0.01(stat))\%$ and the $K_{\mu3}$ one to be $(0.01 \pm 0.01(stat))\%$.

The uncertainty in the extrapolation is studied calculating the background using different control regions and measuring the differences in the result. The method has also been cross-checked on Montecarlo data. The systematic error on $R$ induced by the extrapolation method has been evaluated to be $\pm 5 \times 10^{-4}$.

### 6.4.4 Correction for accidental activity

The concurrent measurement of the four relevant decay modes induces a very low sensitivity of $R$ on the effects due to accidental activity.

The accidental activity is essentially originated by the most intense $K_L$ beam, but $K_S$ events should see the same activity as $K_L$ one, as they are generated simultaneously to the generation of the $K_L$ beam. Yet one expects that a residual effect could arise from possible small differences in the $K_S$ and $K_L$ beams instantaneous intensities, as well as from the slight difference in the beams geometrical and kinematical characteristics.

To measure the residual effect of accidental activity, NA48 has set up a procedure that was first used in the NA31 experiment. During the normal data taking period, a sample of data is collected to study the accidental activity in the beams. Two pseudo random triggers are set up to select events in proportion to the $K_S$ and the $K_L$ intensities. No condition on the event characteristics is imposed, thus most of the triggers actually select events with no physical content apart from the possible accidental contribution.

The $K_S$ trigger is generated downscaling and delaying by 69.3 $\mu$s the $K_S$ monitor hits. The $K_S$ monitor is a system of scintillators surrounding the interaction point of the secondary proton beam with the $K_S$ target. The rate of counts in the $K_S$ monitor is thus proportional to the rate of protons and thus to the rate of $K_S$ events.
CHAPTER 6. PRELIMINARY RESULT ON $\text{RE}(\varepsilon'/\varepsilon)$

Figure 6.5: Distribution of $p_t^2$ for $K_S$ and $K_L$ event candidates, and the extrapolated distribution of the $K_{e3}$ and $K_{\mu3}$ background components. The $K_S$ distribution is renormalised to the $K_L$ one.

A similar trigger is set up using the hits in the beam monitor counters, installed on the beam direction at the end of the vacuum tube. This counters have a rate of hits that is proportional to the total beam intensity, and thus to the $K_L$ intensity which is much larger than the $K_S$ one.

The delay is applied to the two triggers to have no direct correlation between the trigger and some possible in-time activity induced directly by the same proton hitting the counter. The value of 69.3 $\mu$s corresponds to 3 SPS periods,
6.4. **Calculation of R**

and to the intrinsic periodicity of the accelerated beam characteristics. After such a time one is thus confident to take events produced in the same beam conditions as when the proton hit was measured.

The events selected with this procedure provide an accurate sampling of the beam activity.

During the data processing, a fraction of the $K_L$ and $K_S$ events selected by the standard triggers are superimposed to such random selected events, and the resulting events (called overlay) are recorded.

From those events one can study the effect of the accidental activity. The overlay events are analysed like the normal triggered events and the net variation in the number of good events of a certain mode induced by accidental activity can thus be measured as:

$$\delta_{i,f} = \frac{\Delta N_{i,f}}{N_{i,f}} = \frac{\sum_{k \in \text{gains}} w'_k - \sum_{k \in \text{losses}} w_k + \sum_{k \in \text{commons}} (w'_k - w_k)}{\sum_{k \in \text{commons}} w_k + \sum_{k \in \text{losses}} w_k} \quad (6.9)$$

where $N_{i,f}$ is the weighted number of events of the decay mode $(i, f)$, $w_k$ are the weights of the original events triggered by the main trigger, and $w'_k$ are the weights of the overlaid events. The *commons* category contains the events that fit all the selection requirements before as well as after being overlaid, the *losses* category contains the events that where originally selected and are discarded after the overlay procedure, and the *gains* category contains the events that were discarded originally but are found to pass the cuts after the overlay procedure.

Appendix A.3 contains the formula that I derived to calculate the error on $\delta$. The resulting correction factor for $R$ is calculated to be:

$$\alpha_{\text{accidentals}} = \frac{(1 + \delta_{S,00}) \cdot (1 + \delta_{L,+-})}{(1 + \delta_{L,00}) \cdot (1 + \delta_{S,+-})}. \quad (6.10)$$

Some care is required to deal with the large fraction of losses ($\sim 20\%$) of good events due to the rejection of the drift chambers overflow conditions (see section 6.2). Such a large number would dominate the measured effects and induce a very large error in the measurement. Considering the fact that the probability of having an overflow condition in a random event is independent of the original event that will be superimposed on it, one can demonstrate that the correction on $R$ can be calculated excluding all the randoms with an overflow condition.

One thus finds out that the residual variation of events induced by accidental activity is of the order of $-2\%$ for charged events and $-2.5\%$ for neutral events. I studied the contribution of the different physical cuts to the losses of good events and I found no possible sources of asymmetries between $K_S$ and $K_L$ decays in the same mode.
I measure the resulting correction for $R$ to be:

$$\Delta R = (-3 \pm 16) \times 10^{-4}.$$  \hfill (6.11)

The result confirm that the accidental effects are indeed symmetrised by the NA48 data taking technique.

### 6.5 Other corrections

The differences in acceptance between $K_S$ and $K_L$ events of the same mode are strongly reduced by the weighting technique (see section 2.1.1). The residual correction to $R$ is studied with a detailed simulation of the NA48 apparatus and of the beam.

A small contamination of $K_L$ events is induced by $K \to 2\pi$ decays in which the kaon scatters and regenerates in the beam collimators. Those events are characterised by a large value of transverse momentum and are thus excluded by the charged sample while they survive the neutral cuts. A correction has been calculated [69] to compensate for those events.

### 6.6 Result for $Re(\varepsilon'/\varepsilon)$

The total amount of events (weighted and unweighted) selected in the four decay modes is shown in table 6.1

The final value of $R$ is calculated in 20 bins of the kaon energy (in the acceptance range 70-170 GeV). The corrections for the tagging, the charged trigger efficiency, the background and the acceptance are as well computed and applied in energy bins.

The final mean $R$ over the energy bin is calculated as

$$\log(R) = \frac{\sum_{i=1}^{20} \log(R_i)}{\sum_{i=1}^{20} \frac{1}{\sigma_i^2/R_i^2}}$$  \hfill (6.12)

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Unweighted</th>
<th>Weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \to \pi^0\pi^0$</td>
<td>$435 \times 10^4$</td>
<td>$122 \times 10^4$</td>
</tr>
<tr>
<td>$K_S \to \pi^0\pi^0$</td>
<td>$1041 \times 10^3$</td>
<td></td>
</tr>
<tr>
<td>$K_L \to \pi^+\pi^-$</td>
<td>$953 \times 10^3$</td>
<td>$267 \times 10^3$</td>
</tr>
<tr>
<td>$K_S \to \pi^+\pi^-$</td>
<td>$2219 \times 10^3$</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1: Number of selected events without corrections.
Figure 6.6: Distribution of the measured $R$ versus the energy of the selected kaons.

where $R_i$ is the double ratio calculated in the $i$–th energy bin and $\sigma_i$ its error.

The numerator and the denominator of equation 6.12 are calculated using an unbiased estimator.

The choice of calculating the mean of the logarithms instead of the mean of the single $R$ values has been driven by the observation of a reduced value of the residual bias.

Figure 6.6 shows $R$ versus the energy of the selected kaons.

Detailed studies, that won’t be discussed in this work, have been carried
CHAPTER 6. PRELIMINARY RESULT ON $Re(\varepsilon'/\varepsilon)$

<table>
<thead>
<tr>
<th>Tagging</th>
<th>+75 ± 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged trigger</td>
<td>+11 ± 22</td>
</tr>
<tr>
<td>Charged background</td>
<td>+20 ± 3</td>
</tr>
<tr>
<td>Neutral Background</td>
<td>-8 ± 2</td>
</tr>
<tr>
<td>Accidental activity</td>
<td>-3 ± 16</td>
</tr>
<tr>
<td>Scattered events</td>
<td>-12 ± 3</td>
</tr>
<tr>
<td>Acceptance</td>
<td>+28 ± 11</td>
</tr>
<tr>
<td>Neutral reconstruction</td>
<td>± 12</td>
</tr>
<tr>
<td>Charged reconstruction</td>
<td>± 5</td>
</tr>
<tr>
<td>Global systematic error</td>
<td>± 34</td>
</tr>
</tbody>
</table>

Table 6.2: Corrections and systematic errors on $R$.

on to exclude possible systematic dependences of the measurement on different quantities like the energy of the selected kaons or the data taking time.

The correction for accidental activity and for the scattered events have instead been applied to the global $R$ value.

The effects on $R$ of the applied corrections (in units of $10^{-4}$) are reported in table 6.2 together with the related systematic errors.

The final result that I obtain is:

$$Re(\varepsilon'/\varepsilon) = (18.6 \pm 4.6_{\text{stat.}} \pm 5.6_{\text{syst.}}) \times 10^{-4}$$

It is important to point out that most of the contributions to the systematic error are of statistical nature. The trigger efficiency correction and the accidental activity correction, that are the two most relevant sources of systematic error, are clearly of that kind. It is thus clear that the analysis of the full NA48 data sample will significantly decrease the systematic error as well as the statistical one.

The NA48 collaboration has recently published a paper [70] quoting a preliminary result of $Re(\varepsilon'/\varepsilon) = (18.5 \pm 7.3) \times 10^{-4}$. This result has been obtained combining the results from the different independent analysis that have been carried on. All the individual results have been found to be in very good agreement.

This preliminary result confirms that the experimental technique and the very innovative apparatus for the detection of neutral kaon decays, of the NA48 experiment, allow a very precise measurement of $Re(\varepsilon'/\varepsilon)$.

Moreover the result confirms the occurrence of direct $CP$ violation in the decays of the neutral Kaons.
Appendix A

Statistical errors for weighted events

A.1 Fluctuations for weighted events

The statistical fluctuations of a weighted sum of events:

\[ N_W = \sum_i w_i \]

where \( i \) is the event index, are estimated, for \( N_W \) large enough, by:

\[ \sigma(N_W) = \sqrt{\sum_i w_i^2}. \]

In the case of the measurement of an efficiency \( \varepsilon \) given by:

\[ \varepsilon = \frac{n_W}{N_w} \]

where \( n_W \) is the weighted sum of the efficient events, and \( N_W \) is the weighted sum of all the events, one can split \( N_W \) in the sum of two uncorrelated terms \( m_W \) (the sum of the weights of the inefficient events) and \( n_W \). Thus one obtains:

\[ \varepsilon = \frac{n_W}{n_W + m_W} \]

and consequently for the error:

\[ \sigma(\varepsilon) = \sqrt{\frac{m_W^2 \cdot \sigma(n_W)^2 + n_W^2 \cdot \sigma(m_W)^2}{(n_W + m_W)^4}} \]
where \( \sigma(n_W) \) is of course calculated as the sum of the squares of the weights. It is interesting to note that in the limit case in which all the weights are equal to one (that is of course equivalent to the absence of weights) and \( N_W = N \) the formula for the error reduces to the well known formula:

\[
\sigma(\varepsilon) = \sqrt{\frac{\varepsilon \cdot (1 - \varepsilon)}{N}}
\]

### A.2 Statistical error on \( R \)

The statistical error on \( R \) is dominated by the number of \( K_L \rightarrow 2\pi^0 \) events (the rarest decay mode).

Given the fact that the weights for \( K_L \) events are given by:

\[ w_i \simeq e^{-x_i} \]

where \( x_i \) is the reconstructed proper lifetime (in units of \( K_S \) lifetimes) of the \( i \)th event, and that the distribution of \( K_L \) events can be assumed to be flat in \( x_i \), one gets for the statistical error on \( K_L \rightarrow 2\pi^0 \) events:

\[
\sigma_{L,00} = \sum_i w_i^2 \simeq \frac{N_{L,00}}{3.5} \times \int_0^{3.5} e^{-2x} \, dx
\]

where \( N_{L,00} \) is the unweighted number of \( K_L \rightarrow 2\pi^0 \) events.

Considering that the weighted number \( N'_{L,00} \) is:

\[
N'_{L,00} \simeq \frac{N_{L,00}}{3.5} \times \int_0^{3.5} e^{-x} \, dx
\]

one gets that the statistical error on \( R \) is given by:

\[
\sigma_R^{(stat)} \simeq \frac{\sigma_{L,00}}{N'_{L,00}} = \frac{1}{\sqrt{N_{L,00}}} \times \frac{\sqrt{3.5 \cdot (1 - e^{-2 \times 3.5})}}{\sqrt{2 \cdot (1 - e^{-3.5})}} \simeq \frac{1.4}{\sqrt{N_{L,00}}}
\]

### A.3 Error for the overlay measurement

In the more complicated case of the study of the effect of accidental events (see section 6.4.4) with the overlay method, the error on the effect (see equation 6.9)

\[
\delta = \frac{m_W - n_W + p_W}{q_W + n_W}
\]
where $m = \sum_{i \in \text{gains}} w_i', n = \sum_{i \in \text{losses}} w_i, p = \sum_{i \in \text{commons}} (w_i' - w_i), q = \sum_{i \in \text{commons}} w_i$, can be calculated (disregarding the negligible effect of the random statistics) to be given by:

\[
\sigma(\delta) = \left[ p^2(q + n)^2 + q^2(m + p - m)^2 + m^2(q + n)^2 + 
+n^2(m + p + q)^2 - r^2(q + n)(m + p - n) \right] / (q + n)^4
\]

where: $n^2 = \sum_{i \in \text{losses}} w_i^2, m^2 = \sum_{i \in \text{gains}} w_i'^2, p^2 = \sum_{i \in \text{commons}} (w_i' - w_i)^2, q^2 = \sum_{i \in \text{commons}} w_i^2$ and $r^2 = \sum_{i \in \text{commons}} w_i(w_i' - w_i)$. 

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