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**Rate Effects in the Measurement of
the Direct CP Violation
with the NA48 Experiment at CERN**

PHD THESIS

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Abstract

This thesis is devoted to an experimental investigation of the direct violation of CP symmetry in the neutral kaon system. The data, taken in 14 weeks during 1998 by the NA48 experiment at CERN, are used to compare the amplitudes of the K_S and K_L neutral kaon decays into $\pi^+\pi^-$ and $\pi^0\pi^0$. From the comparison, the direct CP violation parameter $Re(\epsilon'/\epsilon)$ is measured:

$$Re(\epsilon'/\epsilon) = (10.4 \pm 2.9_{(stat.)} \pm 2.9_{(syst.)}) \cdot 10^{-4}$$

where the first error is statistical and the second is systematic. The non-zero result corroborates the previous measurement, published by NA48, based on the data taken in 1997, and establishes definitively the direct CP violation in the neutral kaon decay. The combined result:

$$Re(\epsilon'/\epsilon) = (12.0 \pm 3.6) \cdot 10^{-4}$$

is the most precise measurement of $Re(\epsilon'/\epsilon)$ up to now.

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Introduction

This thesis concerns an analysis on the data took by the NA48 experiment at CERN in 14 weeks, during 1998. NA48¹ published in 1999 a new measurement of direct CP violation in two pion decays of the neutral kaon [48].

The determination of the value of $\text{Re}(\epsilon'/\epsilon)$ by NA48 proceeds [12] through the measurement of the double ratio $\mathcal{R}$ of the decay widths:

$$\mathcal{R} \equiv \frac{\Gamma(K_L \rightarrow \pi^0 \pi^0)/\Gamma(K_S \rightarrow \pi^0 \pi^0)}{\Gamma(K_L \rightarrow \pi^+ \pi^-)/\Gamma(K_S \rightarrow \pi^+ \pi^-)} \approx 1 - 6 \cdot \text{Re}(\epsilon'/\epsilon)$$

The simultaneous collection of the four decay modes in the same fiducial volume leads to the cancellation of acceptance and efficiency effects, which are very similar for $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$. The actual experimental challenge is then to measure the residual systematic effects, which do not cancel in the double ratio.

The experimental analysis task involved long and accurate work of many people. This dissertation is the result of two years of work, which consisted first in detailed, personal studies of various systematic effects on the measurement. Of course, several discussions with many members of the collaboration were essential to each studied subject. Secondly, the work consisted in the developement of software tools to perform the complete analysis to measure $\text{Re}(\epsilon'/\epsilon)$. This second part of the job was done in collaboration with dr. G.Graziani. For the procedures not developed by ourself, we followed those developed inside the collaboration.

The dissertation proceeds as follows. After a brief theoretical introduction in Chapter 1, the NA48 method and experimental setup are described in Chapter 2. Chapter 3 presents the data collection, with particular emphasis on the trigger system. The selection of data samples, and the strategy to analyze the several systematic effects, are described in detail in Chapters 4 and 5.

The following chapters concern studies of my own, which are overviewed in Chapter 6. Mainly, the rate effects on the measurement are studied. Specifically, these effects matter both with the trigger, reconstruction, and selection of the events, and with the identification of the decay from the KS or the KL beam (kaon tagging).

¹The NA48 collaboration is formed by groups from: Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Vienna, Warsaw.

All these effects involve deeply both the beam accidental particles, which cross the detectors, and the time structure of the beam intensity.

Thus the study proceeds (Chapter 7) through a tentative “phenomenological” description of the particle fluxes, and the measurement of their rates, and geometrical distribution over the detector. Here the crucial idea is introduced of studying the extra-activity in the detector by analyzing information recorded in the read-out time windows.

Chapter 8 is devoted to the study of the time structure of the beam intensities. The intensity fluctuations of the beams are measured at the high level of 50% rms. In spite of this, the measurement of the time correlation between the K_S and the K_L beam points to a very small (less than 1%) de-correlation. This measurement is a crucial test for the simultaneity of the beams, which the cancellation of the rate effects in the double ratio relies upon. A description of the known beam structures and their origin is also carried out.

The trigger inefficiencies are studied in detail in Chapter 9, where a small correction on $\mathcal{R}$ due to the trigger inefficiency is measured. The charged trigger dead-time is measured not to affect the double ratio; this is achieved by the symmetrization of the dead-time with the neutral events, i.e. by rejecting also the neutral events, which are taken during charged trigger dead-time. Chapter 10 consists in a brief summary about the overflow condition, which is an important ($\sim 25\%$) dead-time cause for the DCH read-out, and affects both the trigger and the reconstruction. My personal point of view is presented about this matter, which is still subject of investigations. The utmost importance of the symmetrization of this dead-time by the neutral events is underlined here. In particular, the symmetrization reduces to a small level the difference between the selected intensity of the neutral and the charged events.

Chapter 11 outlines the effects on kaon decays, due to accidental particles which are generated by the same primary proton which produced the kaon. The effects of this in-time background are measured to a very small level by an independent analysis. My personal analysis is also described, which addresses the problem from a different point of view, but which is not finished yet.

In Chapter 12 all the previous results are collected, and conclusions are drawn about the rate effects on $\mathcal{R}$. Various methods are used to measure the effects, and

some cross-checks of the results are shown, regarding the stability of $\mathcal{R}$ with respect to variations of the intensity conditions. Effects on $\mathcal{R}$ are also studied, which may come from the different spatial correlation of K_S and K_L decays with the accidental particles.

Finally, in Chapter 13, the measurement of $\text{Re}(\epsilon'/\epsilon)$ is discussed.

1 Phenomenology of the neutral kaons

Overview

The weak interactions drastically violate the discrete symmetries of Charge conjugation (C) and Parity (P). Their product CP is conserved in almost all the physical processes: the 1964 observation by Christenson, Cronin, Fitch and Turlay [36] of a few dozen decays of the long-lived kaon into two pions revealed that CP symmetry is violated to a small degree ($\sim 2 \cdot 10^{-3}$). Only the combination of the C, P and the Time reversal symmetries (CPT) seems to be exactly conserved.

CP violation has important implications for understanding the predominance of matter over antimatter in the universe, after the Big Bang [97]. However the violation observed in the K meson system is not sufficiently large to be responsible for the observed abundance of matter. This suggests that also other systems could exhibit the CP violation, although so far, it has been established only in the decay of neutral kaons.

Therefore our present understanding of CP violation is quite poor: we do not yet know whether CP violation is simply an accident, proper to the neutral kaons, or if it is a general property of weak interactions, which could affect also other weak decays.

In the Standard Model (SM) of strong and electroweak interactions, CP violation comes from the single phase occurring in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. Like fermion masses and quark-mixing angles, the origin of the CKM phase lies in the more obscure part of the SM Lagrangian: the scalar sector. The present experimental observations are in agreement with the SM expectations; nevertheless, the correctness of the CKM mechanism is far from being proved.

A brief outline of the CP violation in the neutral kaon system is given in this chapter, following [91, 92]. The subject may be found in many reviews [15, 25, 26, 68, 69, 72, 82, 85, 96].

1.1 The neutral Kaon System

If there were not weak interactions, the neutral kaon system could be described as a simple two-state quantum mechanical system: given the strong interaction Hamiltonian $\mathcal{H}_s$, the system is defined by the two eigenstates $|K^0\rangle$, and its

antiparticle, CP conjugate, $|\bar{K}^0\rangle$, which are distinguished by their different quark content ($|K^0\rangle = d\bar{s}$, $|\bar{K}^0\rangle = s\bar{d}$), with opposite strangeness (flavour) quantum number.

But the weak interactions are there: they do not conserve the flavour, and allow a K^0 state to be transformed into its antiparticle $\bar{K}^0$. The weak interactions are responsible for the decays of the kaons, whose observed mass eigenstates are called K_S and K_L . In fact additional states are reachable by the $|K^0\rangle$ and $|\bar{K}^0\rangle$ states. Any CP-violation effect is generated by the interference between different amplitudes contributing to the same physical transition. This interference can occur either through meson-antimeson mixing or via final-state interactions, or by a combination of both effects.

1.1.1 K^0 - $\bar{K}^0$ Mixing

On assuming that CPT holds, one can write the 2×2 K^0 - $\bar{K}^0$ mixing matrix as follows:

$$\mathcal{M} = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}, \quad (1.1)$$

where the diagonal parameters M and Γ are real.

Some of the mixing matrix parameters are measured:

$$M = \frac{M_L + M_S}{2} = (497.672 \pm 0.031) \text{ MeV} \quad (1.2)$$

$$-2\text{Re}M_{12} \approx \Delta M \equiv M_L - M_S = (3.510 \pm 0.018) \text{ MeV} \quad (1.3)$$

$$\Gamma - \text{Re}\Gamma_{12} \approx \Gamma_L = (1.273 \pm 0.010) \cdot 10^{-14} \text{ MeV} \quad (1.4)$$

$$2\text{Re}\Gamma_{12} \approx \Delta\Gamma \equiv \Gamma_S - \Gamma_L = (7.361 \pm 0.010) \cdot 10^{-12} \text{ MeV} \quad (1.5)$$

Table 1.1 shows the main decay modes for the K_L and K_S states.

If CP were conserved, the parameters M_{12} and Γ_{12} would also be real. The physical eigenstates of $\mathcal{M}$ are

$$|K_{S,L}\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}} [p|K^0\rangle \mp q|\bar{K}^0\rangle], \quad (1.6)$$

with

$$\frac{q}{p} \equiv \frac{1 - \bar{\varepsilon}}{1 + \bar{\varepsilon}} = \left(\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}} \right)^{1/2}. \quad (1.7)$$

K_S		K_L	
Decay mode	Branching ratio (%)	Decay mode	Branching ratio (%)
$K_S \rightarrow \pi^+ \pi^-$	68.61 ± 0.28	$K_L \rightarrow \pi e \nu$	38.78 ± 0.28
$K_S \rightarrow \pi^0 \pi^0$	31.39 ± 0.28	$K_L \rightarrow \pi \mu \nu$	27.18 ± 0.25
$K_S \rightarrow \pi^+ \pi^- \gamma$	0.178 ± 0.005	$K_L \rightarrow \pi^0 \pi^0 \pi^0$	21.13 ± 0.27
$K_S \rightarrow \pi e \nu$	0.072 ± 0.014	$K_L \rightarrow \pi^+ \pi^- \pi^0$	12.55 ± 0.20
$K_S \rightarrow \pi \mu \nu$	0.0469 ± 0.007	$K_L \rightarrow \pi^+ \pi^-$	0.2056 ± 0.0033
		$K_L \rightarrow \pi^0 \pi^0$	0.0927 ± 0.0019

Table 1.1: The main decay modes for the states K_L and K_S .

If M_{12} and Γ_{12} were real, then $q/p = 1$, and $|K_{S,L}\rangle$ would correspond to the CP-even (K_1) and CP-odd (K_2) states $|K_{1,2}\rangle \equiv (|K^0\rangle \mp |\bar{K}^0\rangle) / \sqrt{2}$ where the phase convention $CP|K^0\rangle = -|\bar{K}^0\rangle$ is used. Notice that the flavour quantum number is conserved by strong interactions, thus the phases of the flavour eigenstates can be defined somehow arbitrarily. One can define:

$$|K_\zeta^0\rangle \equiv e^{-i\zeta}|K^0\rangle, \quad |\bar{K}_\zeta^0\rangle \equiv e^{i\zeta}|\bar{K}^0\rangle,$$

which satisfy $CP|K_\zeta^0\rangle = -e^{-2i\zeta}|\bar{K}_\zeta^0\rangle$. Both basis are of course trivially related: $M_{12}^\zeta = e^{2i\zeta}M_{12}$, $\Gamma_{12}^\zeta = e^{2i\zeta}\Gamma_{12}$ and $(q/p)_\zeta = e^{-2i\zeta}(q/p)$. Thus, in general, $q/p \neq 1$ does not necessarily imply CP violation. CP is violated in the mixing matrix if $|q/p| \neq 1$, i.e. $\text{Re}(\bar{\varepsilon}) \neq 0$ and $\langle K_L|K_S\rangle \neq 0^1$.

If the K^0 - $\bar{K}^0$ mixing violates CP, the two mass eigenstates are no longer orthogonal:

$$\langle K_L|K_S\rangle = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} \approx 2\text{Re}(\bar{\varepsilon}). \quad (1.8)$$

The signal of $|p/q| \neq 1$ can be observed, by a CP-violating asymmetry in a flavour-specific decay, i.e. a decay into a final state (f) which can only be reached either from an initial K^0 or from a $\bar{K}^0$, but not from both. A rate asymmetry can be defined as:

$$\mathcal{A}_{mix} \equiv \frac{\Gamma(P_1 \rightarrow f) - \Gamma(P_2 \rightarrow f)}{\Gamma(P_1 \rightarrow f) + \Gamma(P_2 \rightarrow f)} = \frac{1 - |p/q|^4}{1 + |p/q|^4} \quad (1.9)$$

¹Notice that $\langle K_L|K_S\rangle_\zeta = \langle K_L|K_S\rangle$. Another phase-convention independent quantity is $\frac{q}{p} \frac{\bar{A}_f}{A_f}$, where $A_f \equiv A(K^0 \rightarrow f)$ and $\bar{A}_f \equiv A(\bar{K}^0 \rightarrow f)$, for any final state f .

For instance the semileptonic decays of the neutral kaons:

$$K^0 \rightarrow \pi^- l^+ \nu_l, \quad \bar{K}^0 \rightarrow \pi^+ l^- \bar{\nu}_l. \quad (1.10)$$

exhibit a similar asymmetry: on assuming that, $|A(\bar{K}^0 \rightarrow \pi^+ l^- \bar{\nu}_l)| = |A(K^0 \rightarrow \pi^- l^+ \nu_l)|$; then one can define the asymmetry:

$$\delta \equiv \frac{\Gamma(K_L \rightarrow \pi^- l^+ \nu_l) - \Gamma(K_L \rightarrow \pi^+ l^- \bar{\nu}_l)}{\Gamma(K_L \rightarrow \pi^- l^+ \nu_l) + \Gamma(K_L \rightarrow \pi^+ l^- \bar{\nu}_l)} = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = \frac{2\text{Re}(\bar{\varepsilon})}{(1 + |\bar{\varepsilon}|^2)}. \quad (1.11)$$

The experimental measurement [65], $\delta = (3.33 \pm 0.14) \times 10^{-3}$, implies

$$\text{Re}(\bar{\varepsilon}) = (1.63 \pm 0.06) \times 10^{-3}. \quad (1.12)$$

Since CP is violated, the decay eigenstates of the kaon system (K_S and K_L) are not identical to the CP eigenstates.

Notice that the $\pi^+\pi^-$ and $2\pi^0$ states are even under CP, thus only the K_1 state could decay into 2π if CP were conserved. A third π would be required to allow a hadronic decay of the K_2 . Therefore, owing to the phase-space suppression of the $K_L \rightarrow 3\pi$ decay mode, the $K_L \approx K_2 + \bar{\varepsilon}K_1$ state has a much longer lifetime than the $K_S \approx K_1 + \bar{\varepsilon}K_2$.

It is also clear that the state $K_L(K_S)$ violates CP decaying into 2(3) pions due its contamination of $K_1(K_2)$ (see figure 1.1).

K^0 - $\bar{K}^0$ mixing implies that a state which was originally produced as a K^0 or a $\bar{K}^0$ will not develop in time in a purely exponential fashion. The time-dependent amplitudes for the decay into a given final state f are given by:

$$A(K^0 \rightarrow f) \sim \{A(K_S \rightarrow f) e^{-iM_S t} e^{-\Gamma_S t/2} + A(K_L \rightarrow f) e^{-iM_L t} e^{-\Gamma_L t/2}\}, \quad (1.13)$$

$$A(\bar{K}^0 \rightarrow f) \sim \{A(K_S \rightarrow f) e^{-iM_S t} e^{-\Gamma_S t/2} - A(K_L \rightarrow f) e^{-iM_L t} e^{-\Gamma_L t/2}\}. \quad (1.14)$$

In terms of the ratio

$$\eta_f \equiv \frac{A(K_L \rightarrow f)}{A(K_S \rightarrow f)} \equiv |\eta_f| e^{i\phi_f}, \quad (1.15)$$

the time evolution of the decay rates can then be written as:

$$\Gamma(K^0 \rightarrow f) \sim e^{-\Gamma_S t} + |\eta_f|^2 e^{-\Gamma_L t} + 2|\eta_f| \cos(\phi_f - \Delta M t) e^{-(\Gamma_L + \Gamma_S)t/2}, \quad (1.16)$$

$$\Gamma(\bar{K}^0 \rightarrow f) \sim e^{-\Gamma_S t} + |\eta_f|^2 e^{-\Gamma_L t} - 2|\eta_f| \cos(\phi_f - \Delta M t) e^{-(\Gamma_L + \Gamma_S)t/2}. \quad (1.17)$$

By measuring the decay rate as a function of time, the both the modulus and the phase of the ratio η_f are measured. The mass-difference ΔM is also obtained.

1.1.2 Direct CP Violation

An indication that CP is directly violated in the decay amplitude would come from any observed difference between the decay rate $\Gamma(P \rightarrow f)$, and its CP conjugate $\Gamma(\bar{P} \rightarrow \bar{f})$, if the flavour of the decaying meson P is known.

Let us write the amplitudes for the transitions $P \rightarrow f$ and $\bar{P} \rightarrow \bar{f}$ as the sum of two amplitudes:

$$A[P \rightarrow f] = A e^{i\phi} e^{i\delta} + A' e^{i\phi'} e^{i\delta'}, \quad (1.18)$$

$$A[\bar{P} \rightarrow \bar{f}] = A e^{-i\phi} e^{i\delta} + A' e^{-i\phi'} e^{i\delta'}, \quad (1.19)$$

where the $e^{i\phi}$, $e^{i\phi'}$ describe the phases-shifts due to the weak Lagrangian, the $e^{i\delta}$, $e^{i\delta'}$ describe the phases-shifts due to strong final-state interactions, and A , A' are the magnitude of the matrix elements. The rate asymmetry is then given by

$$\mathcal{A}_{dir} \equiv \frac{\Gamma[P \rightarrow f] - \Gamma[\bar{P} \rightarrow \bar{f}]}{\Gamma[P \rightarrow f] + \Gamma[\bar{P} \rightarrow \bar{f}]} = \frac{-2AA' \sin(\phi - \phi') \sin(\delta - \delta')}{|A|^2 + |A'|^2 + 2AA' \cos(\phi - \phi') \cos(\delta - \delta')}. \quad (1.20)$$

which shows how the following requirements are needed in order to generate a direct-CP asymmetry:

- At least two interfering amplitudes.
- Two different weak phase-shifts $[\sin(\phi - \phi') \neq 0]$.
- Two different strong phase-shifts $[\sin(\delta - \delta') \neq 0]$.

In the charged kaon system, direct violation CP asymmetries can be searched for in decays such as $K^\pm \rightarrow \pi^\pm \pi^0$, where the charge of the final pions clearly identifies the flavour of the decaying kaon. No positive signal has been reported up to date.

In the neutral kaon system, direct CP violation has been searched for in decays where K^0 - $\bar{K}^0$ mixing is also involved, and both direct and indirect CP-violation need to be taken into account, simultaneously. The K_L decay into 2π is used as both direct and indirect CP-violation signal.

The 2π final state is described in terms of isospin states: only two values of isospin are allowed by Bose symmetry for the final 2π state, which yield:

$$|2\pi\rangle = \sqrt{1/3} |2\pi\rangle_{I=0} + \sqrt{2/3} |2\pi\rangle_{I=1} \quad (1.21)$$

The $K \rightarrow 2\pi$ isospin breaking amplitudes are parametrized as follows:

$$A[K^0 \rightarrow (2\pi)_I] \equiv iA_I e^{i\delta_I}, \quad A[\bar{K}^0 \rightarrow (2\pi)_I] \equiv -iA_I^* e^{i\delta_I}, \quad (1.22)$$

are described by the A_I decay amplitudes, and the δ_I strong phase-shifts of isospin $I = 0, 2$.

The following asymmetries yield then the signals of CP-violation:

$$\eta_{+-} \equiv \frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)} \equiv |\eta_{+-}| e^{i\phi_{+-}} \approx \varepsilon + \frac{\varepsilon'}{1 + \omega/\sqrt{2}}, \quad (1.23)$$

$$\eta_{00} \equiv \frac{A(K_L \rightarrow \pi^0 \pi^0)}{A(K_S \rightarrow \pi^0 \pi^0)} \equiv |\eta_{00}| e^{i\phi_{00}} \approx \varepsilon - \frac{2\varepsilon'}{1 - \sqrt{2}\omega}, \quad (1.24)$$

where terms, quadratic in the small CP-violating quantities, have been neglected, and the following definitions are used:

$$\varepsilon \equiv \bar{\varepsilon} + i\xi_0, \quad (1.25)$$

$$\varepsilon' \equiv \frac{i}{\sqrt{2}} \omega (\xi_2 - \xi_0), \quad (1.26)$$

$$\omega \equiv \frac{\text{Re}(A_2)}{\text{Re}(A_0)} e^{i(\delta_2 - \delta_0)}, \text{ and} \quad (1.27)$$

$$\xi_I \equiv \frac{\text{Im}(A_I)}{\text{Re}(A_I)}. \quad (1.28)$$

Figure 1.1 illustrates the two CP violation effects on K_L decay.

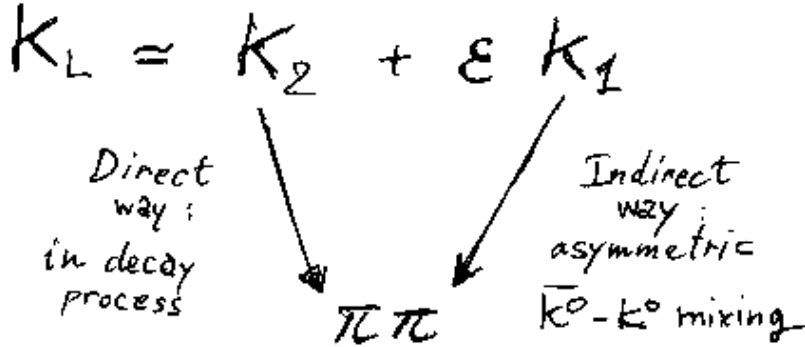


Figure 1.1: The two ways that CP violation can lead to $K_L \rightarrow 2\pi$.

The parameter ε relates to the indirect CP violation. Notice that ε is a measurable quantity, independent of the the phase-convention, while $\bar{\varepsilon}$ is not².

² $\varepsilon = \bar{\varepsilon}$ in the phase convention $\text{Im}(A_0) = 0$; however, $\text{Re}(\varepsilon) = \text{Re}(\bar{\varepsilon})$ in any convention.

From the eigenvector equations (see expr. (1.2) to (1.5)) for K_S and K_L the relation is obtained:

$$\bar{\varepsilon} \approx e^{i\phi_{SW}} \frac{\text{Im}(M_{12}) - \frac{i}{2}\text{Im}(\Gamma_{12})}{\sqrt{\Delta M^2 + \frac{1}{4}\Delta\Gamma^2}}, \quad (1.29)$$

where

$$\phi_{SW} \equiv \arctan\left(\frac{-2\Delta M}{\Delta\Gamma}\right) = 43.49^\circ \pm 0.08^\circ, \quad (1.30)$$

is the so-called superweak phase. Since $\Delta\Gamma \approx -2\Delta M$, one has $\phi_{SW} \approx \pi/4$. Moreover, Γ_{12} is dominated by the $K^0 \rightarrow (2\pi)_{I=0}$ decay mode; therefore, $\text{Im}(\Gamma_{12})/\text{Re}(\Gamma_{12}) \approx -2\xi_0$. Using these relations, one gets the approximate result

$$\varepsilon \approx \frac{e^{i\pi/4}}{\sqrt{2}} \left\{ \frac{\text{Im}(M_{12})}{2\text{Re}(M_{12})} + \xi_0 \right\}. \quad (1.31)$$

Direct CP violation is measured through ε' , which depends on the phase difference between the two isospin amplitudes through the term $\xi_2 - \xi_0$.

The CP-conserving parameter ω gives the relative size between these two amplitudes. From the analysis of the $\pi - \pi$ scattering, a big enhancement of the $I = 0$ channel is found, with respect to the $I = 2$ one, which is known as the $\Delta I = 1/2$ rule:

$$|\omega| \approx \frac{1}{22.2}, \quad \delta_2 - \delta_0 = -42^\circ \pm 4^\circ. \quad (1.32)$$

It's worth noticing that the $I = 0$ states feel an attractive interaction, while the $I = 2$ states feel a repulsive interaction. This feature is the origin of the enhancement of the $I = 0$ channel. In spite of its experimental evidence, the $\Delta I = 1/2$ selection rule is not justified by any general symmetry consideration. Although it is common understanding that its explanation must be rooted in the dynamics of the strong interactions, there is no up to date derivation of this effect from first principle QCD.

The small size of $|\omega|$ strongly suppress ε' , thus even if CP were maximally violated, its effects, in the kaon system, would appear to be small.

Notice that $\delta_2 - \delta_0 + \pi/2 \approx \pi/4$, i.e.

$$\varepsilon' \approx \frac{e^{i\pi/4}}{\sqrt{2}} |\omega| (\xi_2 - \xi_0). \quad (1.33)$$

Thus, owing to the particular numerical values of the neutral-kaon-decay parameters, the phases of ε (see expr. 1.31) and ε' (see expr. 1.33) are nearly equal, and hence $\text{Re}(\varepsilon'/\varepsilon) \approx \varepsilon'/\varepsilon$.

The experimental world-averages quoted by the Particle Data Group [65] are

$$|\eta_{+-}| = (2.268 \pm 0.023) \times 10^{-3}, \quad (1.34)$$

$$|\eta_{00}| = (2.253 \pm 0.024) \times 10^{-3}. \quad (1.35)$$

These two numbers are equal within errors, showing that indeed $|\varepsilon'| \ll |\varepsilon|$ as expected from the $|\omega|$ suppression. Moreover, from Eqn. (1.12) and $\arg(\varepsilon) \approx \pi/4$, we have $|\varepsilon| \approx 2.3 \times 10^{-3}$, in good agreement with the value extracted from $K^0 \rightarrow 2\pi$.

From the analysis of the time evolution of the decay rates (see eqn. 1.16), for the 2π modes, the phases of η_{+-} and η_{00} are measured:

$$\phi_{+-} = (43.5 \pm 0.5)^\circ, \quad (1.36)$$

$$\phi_{+-} - \phi_{00} = (0.1 \pm 0.8)^\circ, \quad (1.37)$$

which are very close to $\pi/4$, as expected.

The ratio ε'/ε can be determined through the relation

$$\frac{\varepsilon'}{\varepsilon} \approx \text{Re} \left(\frac{\varepsilon'}{\varepsilon} \right) \approx \frac{1}{6} \left\{ 1 - \left| \frac{\eta_{00}}{\eta_{+-}} \right|^2 \right\}. \quad (1.38)$$

Ten years ago, two different experiments [13, 54] reported a measurement of this quantity:

$$\text{Re} \left(\frac{\varepsilon'}{\varepsilon} \right) = \begin{cases} (23.0 \pm 6.5) \times 10^{-4} & \text{NA31 [13],} \\ (7.4 \pm 5.9) \times 10^{-4} & \text{E731 [54].} \end{cases} \quad (1.39)$$

The NA31 measurement provided evidence for a non-zero value of ε'/ε (i.e. direct CP violation), with a statistical significance of more than three standard deviations. However, this is not supported by the E731 result, which is compatible with $\varepsilon'/\varepsilon = 0$, thus with no direct CP violation. The probability for the two results being statistically compatible is only 7.6%.

The new experiments NA48 at CERN, KTeV at FNAL, and KLOE at Frascati, are built with a better sensitivity, in order to resolve this discrepancy.

1.2 The Cabibbo-Kobayashi-Maskawa Mechanism of CP Violation

CP violation requires the presence of complex phases. The only place one can insert complex phases to give CP violation in the Standard Model (SM) Lagrangian

is in the Yukawa interaction, which is introduced to generate the fermion masses:

$$\mathcal{L}_{Yukawa} = - \left(\overline{U}'_L \mathbf{m} U'_R + \overline{D}'_L \tilde{\mathbf{m}} D'_R + h.c. \right) \left(1 + \frac{\Phi_o}{v} \right). \quad (1.40)$$

Here Φ_o stands for the scalar Higgs field and v is its vacuum expectation value. The quark fields $U'_{L,R}$ and $D'_{L,R}$ are the 3-component vectors in flavour space for the up- and down-type quarks respectively,

$$U'_{L,R} = \left(\frac{1 \mp \gamma_5}{2} \right) \begin{pmatrix} u' \\ c' \\ t' \end{pmatrix}, \quad D'_{L,R} = \left(\frac{1 \mp \gamma_5}{2} \right) \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}, \quad (1.41)$$

and $\mathbf{m}$, $\tilde{\mathbf{m}}$ are 3×3 mass matrices of arbitrary complex numbers, the elements of which are $m_{ij} = -\frac{v}{\sqrt{2}}Y_{ij}$ and $\tilde{m}_{ij} = -\frac{v}{\sqrt{2}}\tilde{Y}_{ij}$ where Y_{ij} and $\tilde{Y}_{ij}$ are the Yukawa coupling constants with $i \equiv u, c$ or t and $j \equiv d, s$ or b .

In general, $\mathbf{m}$ and $\tilde{\mathbf{m}}$ are not diagonal. The diagonalization of the quark-mass matrices, $\mathbf{m}_D = V_L \mathbf{m} V_R^\dagger$ and $\tilde{\mathbf{m}}_D = \tilde{V}_L \tilde{\mathbf{m}} \tilde{V}_R^\dagger$, defines the physical (mass-eigenstates) fermion fields $U_{L,R} = V_{L,R} U'_{L,R}$ and $D_{L,R} = \tilde{V}_{L,R} D'_{L,R}$ where $V_{L,R}$ and $\tilde{V}_{L,R}$ are unitary matrices.

The coupling of the physical quarks to the neutral Z preserves the observed absence of flavour-changing neutral currents (FCNC), while their coupling to the charged $W^\pm$ introduces the mixing between families. The charged-current couplings are:

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \{ \overline{U}_L \gamma^\mu W_\mu^+ \mathbf{V} D_L + \overline{D}_L \gamma^\mu W_\mu^- \mathbf{V}^\dagger U_L \}, \quad (1.42)$$

where $\mathbf{V} \equiv V_L \tilde{V}_L^\dagger$ is an unitary 3×3 matrix called the quark-mixing or Cabibbo-Kobayashi-Maskawa (CKM) matrix [28, 73]:

$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \quad (1.43)$$

The values of the matrix elements can in principle all be determined from weak decays of the relevant quarks, or from deep inelastic neutrino scattering. Using

the constraints discussed below together with unitarity, and assuming only three generations, the 90% confidence limits on the magnitude of the elements of the complete matrix are [65]:

$$\mathbf{V} = \begin{pmatrix} 0.9742 \text{ to } 0.9757 & 0.219 \text{ to } 0.226 & 0.002 \text{ to } 0.005 \\ 0.219 \text{ to } 0.225 & 0.9734 \text{ to } 0.9749 & 0.037 \text{ to } 0.043 \\ 0.004 \text{ to } 0.014 & 0.035 \text{ to } 0.043 & 0.9990 \text{ to } 0.9993 \end{pmatrix}. \quad (1.44)$$

The Yukawa couplings Y_{ij} and $\tilde{Y}_{ij}$ are completely arbitrary complex numbers; therefore, the resulting quark masses and CKM matrix elements cannot be predicted in any way. In general, a unitary $n \times n$ matrix can be characterized by n^2 independent real parameters. Not all these parameters are, however, physical observables. Given the number n of fermion families, $(2n - 1)$ phases can be re-absorbed by appropriate $U(1)$ transformations of the quark fields. Thus, the most general CKM matrix contains $(n - 1)^2$ real parameters: $n(n - 1)/2$ mixing angles and $(n - 1)(n - 2)/2$ phases. With more than two families, the elements of $\mathbf{V}$ can be complex numbers which allow the possibility for generating CP violation through the interference of two diagrams involving different matrix elements.

With $n = 3$, the CKM matrix is described by 3 angles and 1 phase. The Particle Data Group [65] recommends the use of the following representation of the matrix as the “standard” CKM parameterization:

$$\mathbf{V} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}. \quad (1.45)$$

Here $c_{ij} \equiv \cos \theta_{ij}$ and $s_{ij} \equiv \sin \theta_{ij}$, with i and j being “generation” labels ($i, j = 1, 2, 3$). The real angles θ_{12} , θ_{23} and θ_{13} can all be made to lie in the first quadrant, by an appropriate redefinition of quark field phases; then, $c_{ij} \geq 0$, $s_{ij} \geq 0$ and $0 \leq \delta \leq 2\pi$.

The CKM matrix shows a hierarchical pattern, with the diagonal elements being very close to one, the ones connecting the two first generations having a size $\lambda \simeq \sin \theta_C \approx 0.2196 \pm 0.023$, the mixing between the second and third families being of order λ^2 , and the mixing between the first and third quark flavours having a much smaller size of about λ^3 . It is then quite practical to use the so-called

Wolfenstein [112] approximate representation of V :

$$\mathbf{V} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) . \quad (1.46)$$

The values of A , ρ and η are poorly measured: $A = 0.819 \pm 0.053$ and $\sqrt{|\rho|^2 + |\eta|^2} = 0.36 \pm 0.09$. In this representation CP is violated if $\eta \neq 0$.

Since $\delta(\eta)$ is the only possible source of CP violation, the SM predictions for CP-violating phenomena are quite constrained. Moreover, the CKM mechanism requires several necessary conditions in order to generate an observable CP-violation effect. With only two fermion generations, the quark-mixing mechanism cannot give rise to CP violation; therefore, for CP violation to occur in a particular process, all 3 generations are required to play an active role. In the kaon system, for instance, CP-violation effects can only appear at the one-loop level, where the top-quark is present. In addition, all CKM-matrix elements must be non-zero and the quarks of a given charge must be non-degenerate in mass. If any of these conditions were not satisfied, the CKM-phase could be rotated away by a redefinition of the quark fields. CP-violation effects are then necessarily proportional to the product of all CKM-angles, and should vanish in the limit where any two quark-masses of equal-charge are taken to be equal. All these necessary conditions as a single requirement on the original quark-mass matrices $\mathbf{m}$ and $\tilde{\mathbf{m}}$ [70]:

$$\text{CP violation} \iff \text{Im}\{\det[\mathbf{m}\mathbf{m}^\dagger, \tilde{\mathbf{m}}\tilde{\mathbf{m}}^\dagger]\} \neq 0 \quad (1.47)$$

Without performing any detailed calculation, one can make the following general statements on the implications of the CKM mechanism of CP violation:

- Owing to unitarity, for any choice of i, j, k, l (between 1 and 3),

$$\text{Im}[V_{ij}V_{ik}^*V_{lk}V_{lj}^*] = \mathcal{J} \sum_{m,n=1}^3 \epsilon_{ilm}\epsilon_{jkn} , \quad (1.48)$$

$$\mathcal{J} = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13} \sin \delta \approx A^2 \lambda^6 \eta < 10^{-4} . \quad (1.49)$$

Any CP-violation observable involves the product $\mathcal{J}$ [70]. Thus, violations of the CP symmetry are necessarily small.

- In order to have sizeable CP-violating asymmetries $[(\Gamma - \bar{\Gamma})/(\Gamma + \bar{\Gamma})]$, one should look for very suppressed decays, where the decay widths already involve small CKM matrix elements.
- In the SM, CP violation is a low-energy phenomena in the sense that any effect should disappear when the quark-mass difference $m_c - m_u$ becomes negligible.

1.2.1 Standard Model Predictions

The CKM mechanism generates CP-violation effects both in the $\Delta S = 2$ K^0 - $\bar{K}^0$ transition (see “box” diagrams in figure 1.2) and in the $\Delta S = 1$ decay amplitudes (see “penguin” diagrams in figure 1.2). Although a straightforward and well-defined technique, which makes use of the Operator Product Expansion, is available for a short-distance analysis of these interactions, the final quantitative predictions are obscured by the presence of hadronic matrix-elements of weak four-quark operators, which are governed by long-distance physics.

1.2.1.1 Computation of ε

In the analysis of the K^0 - $\bar{K}^0$ mixing only one hadronic matrix-element appears. Including the short-distance QCD corrections, the “box” diagram calculation of M_{12} yields

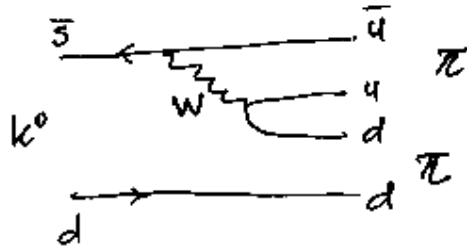
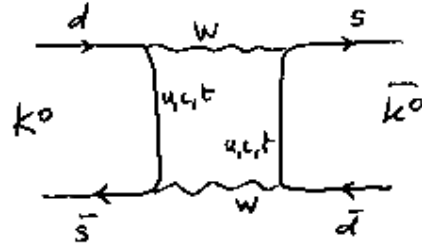
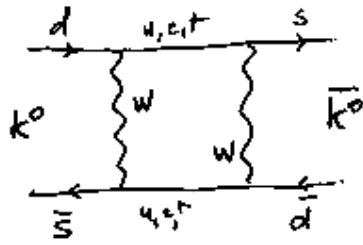
$$M_{12} = \frac{G_F^2 M_W^2}{16\pi^2} \{ \lambda_c^2 \eta_1 S(r_c) + \lambda_t^2 \eta_2 S(r_t) + 2\lambda_c \lambda_t \eta_3 S(r_c, r_t) \} \\ \times \frac{1}{2M_K} \alpha_s(\mu^2)^{-2/9} \langle \bar{K}^0 | (\bar{s} \gamma^\mu (1 - \gamma_5) d) (\bar{s} \gamma_\mu (1 - \gamma_5) d) | K^0 \rangle, \quad (1.50)$$

where

$$\lambda_i \equiv V_{is} V_{id}^* \quad (i = u, c, t), \quad (1.51)$$

and $S(r_i)$, $S(r_i, r_j)$ are functions of $r_i \equiv (m_i/M_W)^2$. Owing to the unitarity of the CKM matrix, $\lambda_u + \lambda_c + \lambda_t = 0$, and the contributions of the up, charm and top quarks to the “box” diagram add to zero in the limit of massless quarks (GIM mechanism [55]). The loop functions $S(r_i)$ and $S(r_i, r_j)$ are then very sensitive to the quark masses [$S(r_i) \approx r_i$, for $r_i \ll 1$]. For large m_t the second term in Eqn. (1.50) dominates.

"BOX" DIAGRAMS : $|\Delta S| = 2$

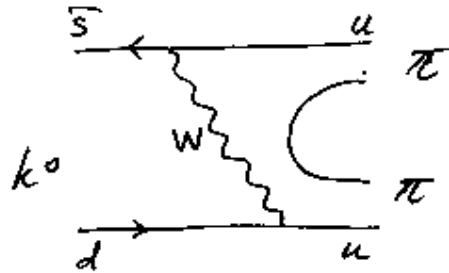


"SPECTATOR"

DIAGRAM : $|\Delta S| = 1$

$$\Delta I = 1/2 \rightarrow A_0 A_0$$

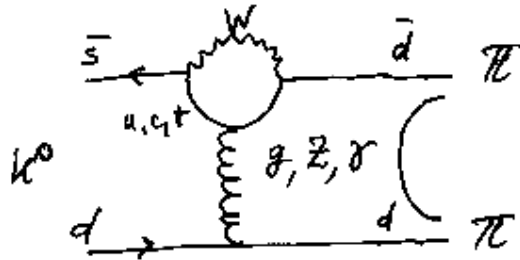
$$\Delta I = 3/2 \rightarrow A_2 A_2$$



"EXCHANGE"

DIAGRAM : $|\Delta S| = 1$

$$\Delta I = 1/2 \rightarrow A_0 A_0$$



"PENGUIN"

DIAGRAMS : $|\Delta S| = 1$

$$g, Z, \gamma : \Delta I = 1/2 \rightarrow I_m A_0$$

$$Z, \gamma : \Delta I = 3/2 \rightarrow I_m A_2$$

Figure 1.2: The "box" diagrams, responsible of the transition $K^0 - \bar{K}^0$, with $\Delta S = 2$ are shown on top. The diagrams ("spectator", "exchange", and "penguin") responsible of the $\Delta S = 1$ transition, in the $K \rightarrow 2\pi$ decay amplitude, are shown in the middle and on bottom.

The factors η_i represent short-distance QCD corrections to the lowest-order “box” diagram calculation ($\eta_i = 1$ in the absence of QCD effects): $\eta_1 \approx 0.85$, $\eta_2 \approx 0.57$ and $\eta_3 \approx 0.36$ [27]. In addition, one needs to compute the hadronic matrix element of the $\Delta S = 2$ four-quark operator in Eqn. (1.50), which is usually parametrized in terms of the so-called B_K parameter:

$$\alpha_s(\mu^2)^{-2/9} \langle \bar{K}^0 | (\bar{s}\gamma^\mu(1 - \gamma_5)d) (\bar{s}\gamma_\mu(1 - \gamma_5)d) | K^0 \rangle \equiv 2 \left(1 + \frac{1}{3}\right) \left(\sqrt{2}f_K M_K\right)^2 B_K. \quad (1.52)$$

$B_K = 1$ corresponds to the factorization approximation, which consists in splitting the matrix element in a product of two currents, by inserting the vacuum in all possible ways [$\langle \bar{K}^0 | (\bar{s}\gamma^\mu(1 - \gamma_5)d) | \emptyset \rangle \langle \emptyset | (\bar{s}\gamma_\mu(1 - \gamma_5)d) | K^0 \rangle$]. Clearly, this approximation can only be taken as an order-of-magnitude estimate, since it completely ignores the renormalization-group factor $\alpha_s(\mu^2)^{-2/9}$, where μ is an arbitrary renormalization scale. The total product (and therefore B_K) in Eqn. (1.52) is of course μ -independent, because the dependence on the renormalization scale is exactly canceled by the hadronic matrix element. Unfortunately, it is very difficult to make a calculation of this matrix element from first principles. The present uncertainty associated with the size of the hadronic matrix element is reflected in the broad range (from 0.2 to 1.0, depending on the computation method) of calculated B_K values.

In order to compute ε , $\text{Im}(M_{12})$ is obtained from Eqn. (1.50) while $\text{Re}(M_{12})$, which is much more sensitive to long-distance effects, is taken from the measured neutral-kaon mass difference ΔM . The result depends on the values of the CKM elements. Using the Wolfenstein parameterization (1.46), the experimental value of ε specifies a hyperbola in the (ρ, η) plane [27]:

$$\eta \left[(1 - \rho) A^2 r_t^{0.76} + P_C \right] A^2 B_K = 0.50, \quad (1.53)$$

where $P_C \approx 2/3$ contains the cc and tc “box” diagram contributions³.

The approximated expression :

$$\varepsilon \approx \frac{\text{Im}M_{12}}{\text{Re}M_{12}}$$

³The power-like dependence on r_t represents a numerical fit to the exact loop functions [27]. In the range $100 \text{ GeV} < m_t < 200 \text{ GeV}$, the exact result is reproduced to an accuracy better than 3%.

and the relations:

$$\begin{cases} \text{Im}M_{12} = \text{Im}V_{ts}V_{td}^*V_{cd}V_{cs}^* \approx A^2\lambda^6 \\ \text{Re}M_{12} = |V_{cd}V_{cs}|^2 \approx \lambda^2 \end{cases} \quad (1.54)$$

yield the order of magnitude estimate $\varepsilon \approx 10^{-3}$.

1.2.1.2 Computation of ε'/ε

The $\Delta S = 1$ contributions, shown in figure 1.2, have to be considered in the computation of ε' . The “spectator” and “exchange” diagrams are responsible of the large decay probability of the $K \rightarrow 2\pi$ process. The main contribution to the quark coupling comes from the amplitude:

$$A(s \rightarrow du\bar{u}) \propto V_{us}V_{ud}^* \approx \lambda$$

On the other hand, the “penguin” diagrams induce the direct CP violation, due to the imaginary amplitudes:

$$\begin{cases} A(s \rightarrow dc\bar{c}) \propto V_{cs}V_{cd}^* \approx -\lambda + i\eta A^2\lambda^5 \\ A(s \rightarrow dt\bar{t}) \propto V_{ts}V_{td}^* \approx (\rho - 1)\eta A^2\lambda^5 - i\eta A^2\lambda^5 \end{cases} \quad (1.55)$$

where the strong “penguin” contribute to the final $I = 0$ states only. Notice that a difference in the weak phase between A_0 and A_2 is a result of the fact that A_0 has contributions from both strong and weak “penguin” diagrams, with intermediate c and t quarks.

For a very naive order of magnitude estimate one can see that the parameter ε'/ε is suppressed by the two factors

$$|A_2/A_0| \approx 1/22.2 \quad \text{and} \quad |A_0^{\text{penguin}}/A_0^{\text{tree}}| \approx 0.05$$

which yield $\varepsilon'/\varepsilon \approx 10^{-3}$. Notice that a small value of ε'/ε comes from small hadronic matrix-elements, and not from small CP violating parameters.

The actual estimate of ε'/ε is much involved, since ten four-quark hadronic operators need to be considered in the analysis. Furthermore, cancellations between different contributions tends to amplify the sensitivity to the long-distance effects.

Due to the value of the top-mass, the weak “penguin” contributions tends to cancel the contributions of the strong “penguin”, and suppress the expected value

of ε'/ε . This is illustrated by the simplified, approximate relation:

$$\varepsilon'/\varepsilon \approx 10^{-4} \cdot \left[16B_6^{(1/2)} - 8B_8^{(3/2)} \left(\frac{m_t}{165} \right)^{2.5} \right] \left(\frac{110}{m_s} \right)^2$$

where m_t is the top quark mass, m_s is the strange quark mass evaluated at 2 GeV, and $B_6^{(1/2)}$ and $B_8^{(3/2)}$ are conventionally defined factors, giving the “penguin” long-range contributions to the interaction. The computation of the long-range amplitudes is addressed in different ways:

- The Monaco group [24] uses a phenomenological approach, which takes advantage of the measurement of ε'/ε related parameters. Two estimates are given, based on two different renormalization schemes:

$$\text{Re} \left(\frac{\varepsilon'}{\varepsilon} \right) = \begin{cases} (5.2_{-2.7}^{+4.6}) \times 10^{-4} \\ (7.7_{-3.5}^{+6.0}) \times 10^{-4} \end{cases} \quad (1.56)$$

- The Roma group [37,38] takes advantage of the lattice QCD simulation, and estimates:

$$\text{Re} \left(\frac{\varepsilon'}{\varepsilon} \right) = (4.6 \pm 3) \times 10^{-4} \quad (1.57)$$

- The Trieste group [18] approach is based on the Chiral Quark Model, and yields:

$$\text{Re} \left(\frac{\varepsilon'}{\varepsilon} \right) = (17_{-10}^{+14}) \times 10^{-4} \quad (1.58)$$

Conclusions

CP violation is a crucial topic both for particle physics and cosmology. Measurements of CP provide provide tests for the Standard Model, which accommodates CP violation with the following features:

- A single source is needed, namely one complex phase (δ) in the CKM matrix;
- CP violation appears only in the flavour-changing charged-current interactions of quarks;
- CP is explicitly broken (it comes from the complex Yukawa couplings), and is not an approximate symmetry of the weak interactions: the phase is $\delta \approx \mathcal{O}(1)$; small measured parameters (ε and ε') are due to the small flavor violation in the first two quark generations;

CP violation is also a sensitive probe for new physics. In particular the measurement of ε/ε' is sensitive to the superweak scenario [111], and to some models of approximate CP [47].

This thesis presents a measurement of the direct CP violation in the neutral kaon system, where the characteristic parameter is $\text{Re}(\epsilon'/\epsilon)$.

2 The NA48 experiment: experimental method and apparatus

2.1 The experimental method

The NA48 experiment [12] aims to determine $Re(\epsilon'/\epsilon)$ through the measurement of the double ratio $\mathcal{R}$ of the widths of neutral kaon decays into two pions:

$$\mathcal{R} = \frac{\Gamma(K_L \rightarrow \pi^0 \pi^0)/\Gamma(K_S \rightarrow \pi^0 \pi^0)}{\Gamma(K_L \rightarrow \pi^+ \pi^-)/\Gamma(K_S \rightarrow \pi^+ \pi^-)} \approx 1 - 6 \cdot Re(\epsilon'/\epsilon) \quad (2.1)$$

The NA48 experimental setup is shown in figure 2.1; it consists of:

- i) Two beams, later referred to as **KS** and **KL** beams, which are simultaneous, almost collinear, and have a similar energy spectrum;
- ii) A detector, later referred to as tagging station, or tagger, which measures the crossing time of the protons hitting the **KS** target, allowing to recognize the K_S decay fragments.
- iii) A magnetic spectrometer, to detect the $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ charged decay products;
- iv) A liquid Krypton calorimeter, to detect the neutral decay products;
- v) A hadron calorimeter followed by a muon filter.

The basic measurement is to count the number of events ($N_L^{\pi^0 \pi^0}$, $N_S^{\pi^0 \pi^0}$, $N_L^{\pi^+ \pi^-}$, and $N_S^{\pi^+ \pi^-}$), for each of the four decay modes, and carry the double ratio:

$$\mathcal{R}_{raw} = \frac{N_L^{\pi^0 \pi^0} / N_S^{\pi^0 \pi^0}}{N_L^{\pi^+ \pi^-} / N_S^{\pi^+ \pi^-}} \quad (2.2)$$

The simultaneous collection of the four decay modes in the same fiducial volume, and by the same detector, leads to the cancellation of acceptance and efficiency effects, as they are very similar for K_S and K_L decays. Thus the relation $\mathcal{R}_{raw} \sim \mathcal{R}$ holds in first approximation. The actual experimental challenge is to measure the systematic second order effects, residual from imperfect cancellation. The wanted accuracy on the measurement of $\mathcal{R}$ is $\sim 1 \cdot 10^{-3}$, which corresponds to an error on $Re(\epsilon'/\epsilon)$ of $\sim 2 \cdot 10^{-4}$.

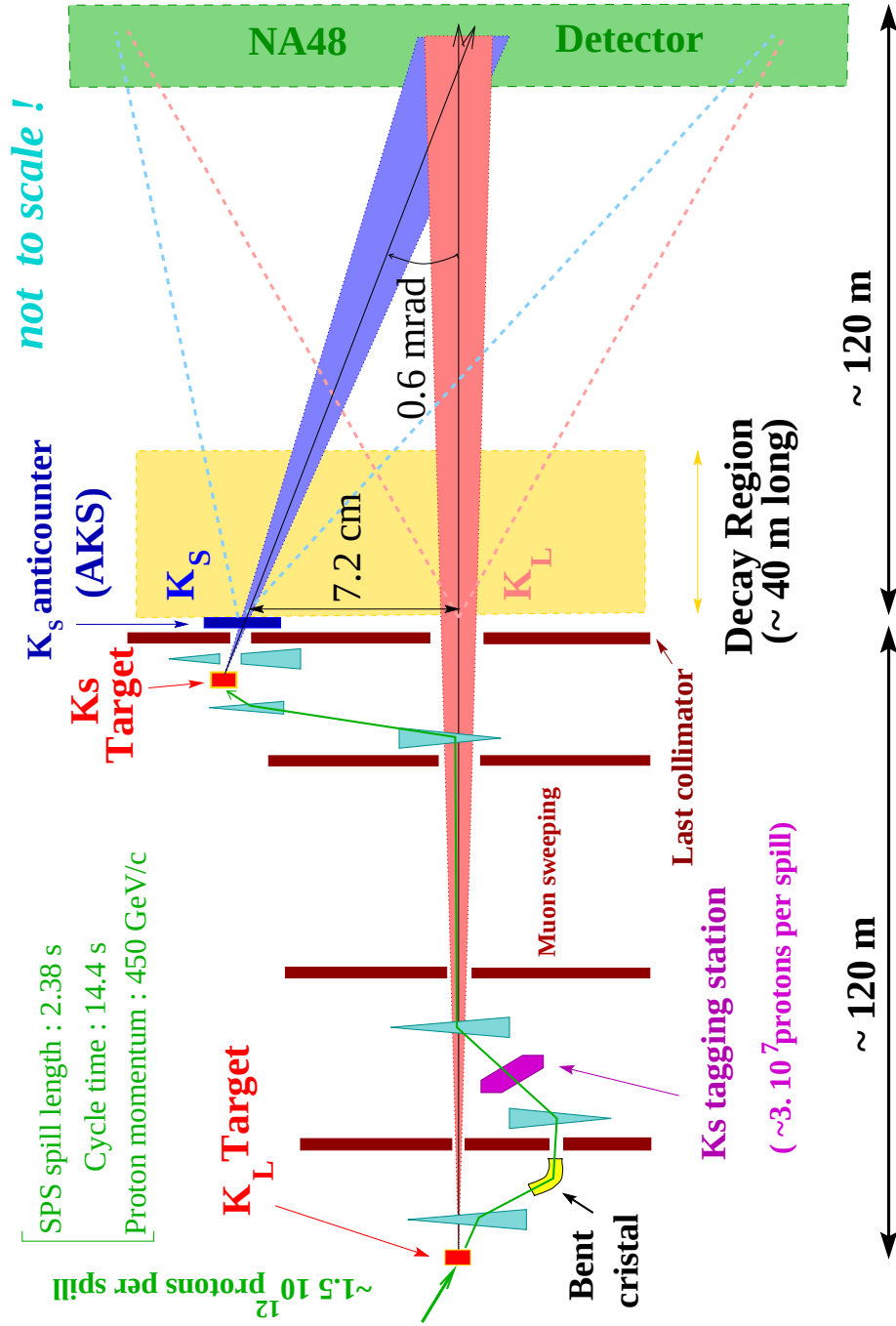


Figure 2.1: The NA48 experimental setup: the two simultaneous and almost collinear kaon beamlines converge in the same center at the central detector longitudinal position.

To achieve a statistical error on $\mathcal{R} \sim 5 \cdot 10^{-4}$ a large number of decays is needed. The experiment is capable of standing very high rates, ~ 1 MHz of instantaneous particle flux, in order to take data with an intense KL beam. A very fast trigger electronics and read-out system are mandatory.

The sensitivity of the measurement to the detection efficiency variations with the time, and the rate are also minimized. Indeed, the detector was designed to have zero dead-time and 100% efficient trigger and read-out. Unfortunately, due to high rate photon conversion on the beam pipe, the read-out of the drift chambers electronics suffers from a dead-time of about 25%; however this is almost the same for K_S and K_L decays.

The detection efficiency, and acceptance, at a given energy and position, are very similar for K_S and K_L decay products. The two beams are separated by ~ 6 cm at the end of the collimators, hence they are quasi-collinear.

The longitudinal distributions of the decay vertices are very different for K_S and K_L decays. The distribution for K_L decays is almost flat, because of the long lifetime. Only K_L decays occurring in a fiducial region also populated by K_S decays are considered. In the calculation of the double ratio, K_L events are weighted with a proper function of the kaon lifetime, to make the K_L and K_S vertex distributions similar.

A system of scintillator counters, with a lead converter, is used to veto the events, in order to precisely define the upstream edge of the fiducial volume, on the KS beam line. This is necessary because of the rapidly falling exponential decay vertex distribution.

The background is very different in each of the four modes: while it is almost negligible in the case of K_S decays, it is larger than the signal, by some order of magnitude, in the case of K_L decays. Therefore the experiment is designed to have a background rejection factor of about 10^{-5} , which is achieved by the very high energy and position resolutions of the calorimeter and the magnetic spectrometer, and by very efficient veto counters.

2.2 The Kaon beams and associated detectors

The NA48 neutral beam [20] are produced from the primary 450 GeV protons delivered by the CERN-Super-Proton-Synchrotron (SPS), whose complex is shown

in figure 2.2. The devised beam system is shown in figure 2.1 and in the more detailed figure 2.3.

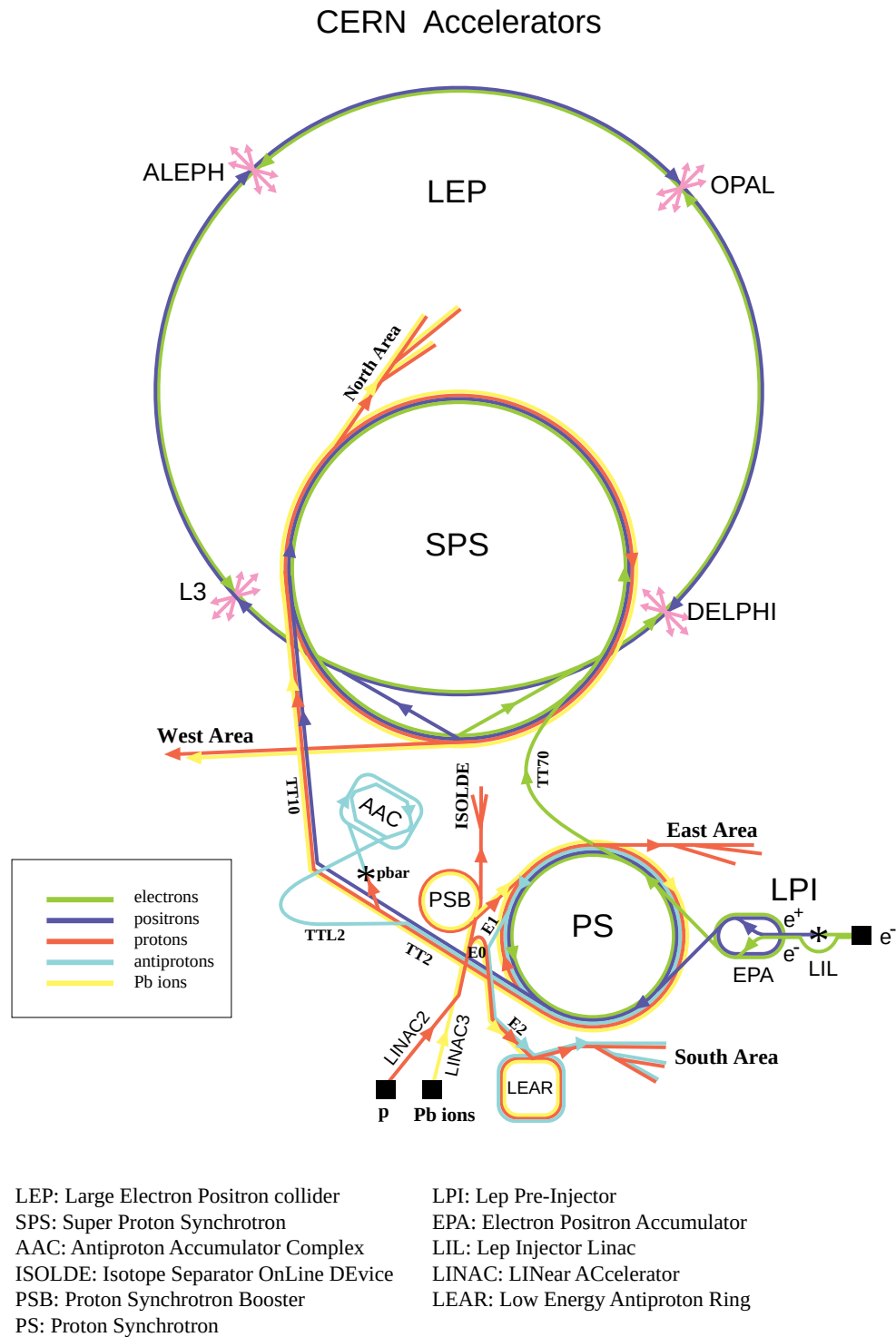


Figure 2.2: The accelerators complex at CERN. The NA48 experiment is located in the North Area.

Figure 2.3: Detailed illustration of the NA48 beamlines. Two different production targets are used, located 126 m and 6 m upstream from the beginning of the decay region. This is due to the different mean decay lengths of K_L and K_S (respectively $3.9 \cdot 10^3$ m and 5.9 m at the average momentum of 110 GeV/c). The K_L target which is located 250 m upstream from the central detector, is hit for each SPS extraction burst (2.4 s every 14.4 s), by $\sim 1.5 \cdot 10^{12}$ protons. The protons non interacting into the target impinge on a bent silicon mono-crystal, where a fraction of $\sim 10^{-5}$ undergo channelling, and yields a beam of $\sim 3 \cdot 10^7$ protons. This beam is transported, in the vacuum pipe, to the K_S target.

2.2.1 The primary proton beam

From a duo-plasmatron source, Linac-2 produce protons that are fed into a 750 keV RFQ and 3 Alvarez tanks operating at 200 MHz. Proton pulses are delivered at 50 MeV every 1.2 s, with a length from 10 to 150 ms and an intensity of up to 180 mA.

The PS [100] Booster (PSB), an assembly of four vertically stacked synchrotrons of 50 m diameter, accelerates the linac proton beam up to 1.69 GeV/c. The PSB is able to supply up to $3 \cdot 10^{13}$ protons per pulse (ppp) in 20 bunches at 1 GeV every 1.2 s.

The PS machine accelerates these beams and adapts their longitudinal characteristics to the specific needs of the SPS. Longitudinal emittance is blown-up in a controlled way, using the 200 MHz radio frequency (RF) systems. Bunch lengths and number of bunches are changed with debunching/rebunching techniques. Ultimately protons are bunched at 200 MHz and continuously ejected over 5 turns at 14 GeV/c to SPS.

The SPS [8] is thus filled up with two trains (see figure 2.4) of protons [94] made of ~ 2000 proton bunches each. The bunches are ~ 2 ns wide and exactly 5 ns spaced. The two “trains” are separated by some empty bunches (“holes”), which cover $\sim 10\%$ of the SPS circumference.

Protons are accelerated up to 450 GeV/c, with the 200 MHz RF systems which keep the 5 ns bunch structure; during acceleration the momentum spread $\Delta p/p$ of the protons, around the nominal $p = 450$ GeV/c, is $\lesssim 0.2\%$. Then the RF is switched off, the extraction begins, and the protons start losing their bunched structure.

In 1998, at the very beginning, and at the end of the extraction, two fast extractions were operated. Two bursts of $\sim 2 \cdot 10^{13}$ protons, in ~ 6 ms, were extracted to produce neutrinos for the west area experiments. In between these two extractions, a much slower (~ 2.4 s) spill (later referred to as burst) of protons was operated, to provide protons to the north area experiments.

The protons are removed from the accelerator by controlled excitation of a non-linear betatron (3^{rd} order) resonance of the ring. The growth in amplitude of the betatron oscillation for a particle depends on its momentum. The extraction of protons with increasing $\Delta p/p$ (starting from the lowest $\Delta p/p$ in phase space) is achieved by adjusting the betatron oscillation frequency (later referred to as tune);

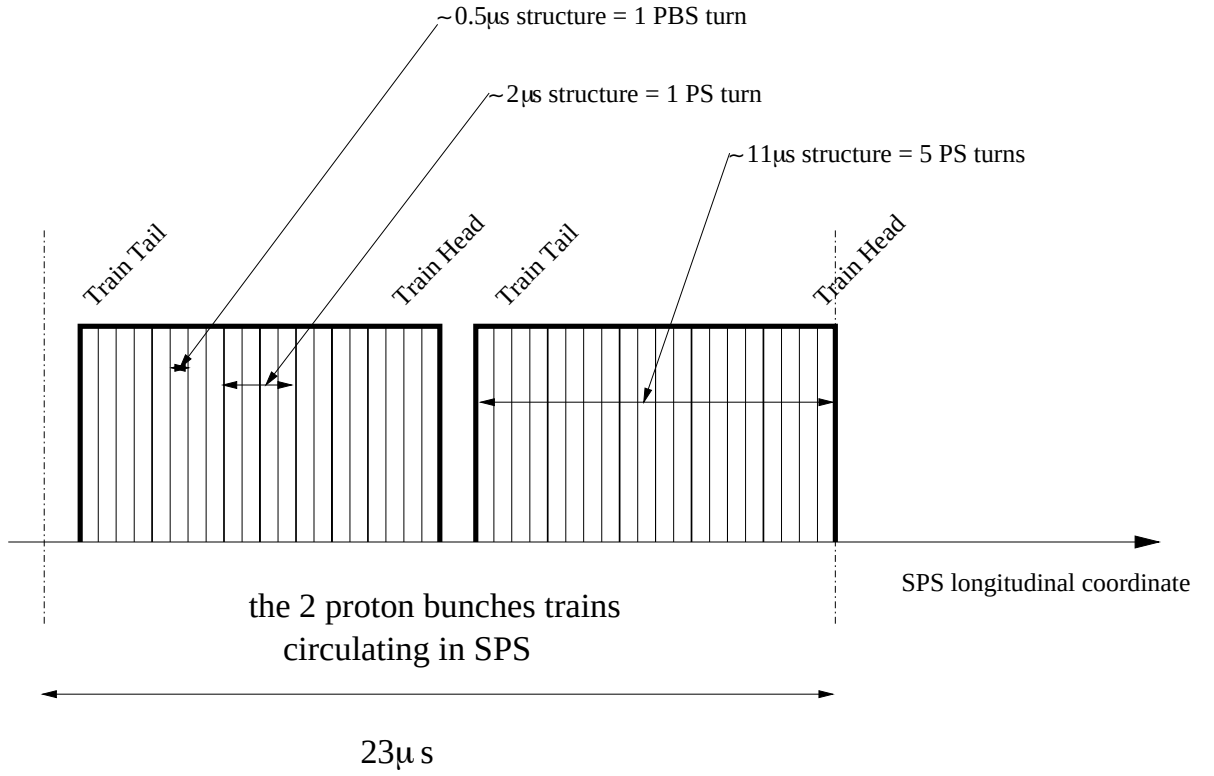


Figure 2.4: *The proton trains circulating in the SPS. Circa 2000 proton bunches are contained in each the train.*

in this way different momentum particles move progressively to resonance. On resonance the enhanced amplitude let the protons cross a septum, be deflected by a magnetic field, and finally be ejected. This kind of extraction is called slow resonant extraction [109], [93].

Part of the extracted protons are transported along the ~ 800 m long beamline, down to the target station T4, which selects the wanted $1.5 \cdot 10^{12}$ protons per burst. The momentum of the extracted protons changes during the extraction, and results in a variation of the beam position.

The optics along the line is adjusted to keep the beam position stable, and to render the rate of the protons constant. The residual variation of the beam momentum and position are responsible of the K_S to K_L ratio changing during the burst. The time structures for these variations are expected at low frequencies (below 500 Hz). These are typical of the current periodic oscillations, and noises, which induce variations in the strength of the magnetic fields along the beam line.

The time structures induced by the SPS injection/extraction scheme are characterized by much higher frequencies (43 kHz, 200 MHz and harmonics).

All this defines the time structure of the burst, which will be studied in Chapter 8.

2.2.2 The K_L beam

The K_L beam is produced by directing the primary proton beam, of $\sim 1.5 \cdot 10^{12}$ protons in 2.4 s onto a cylindrical beryllium target. The target, 2 mm in diameter and 400 mm long, corresponding to $1\lambda_{int}$ for protons, is located 126 m upstream from the last K_L collimator (see figure 2.3).

The neutral K 's are accompanied by an high flux of photons and neutrons. In order to reduce the flux of neutrons, the proton beam is incident on the target at an angle of $\theta = 2.4$ mrad. The flux of neutrons is reduced by a factor of ~ 4 with respect to a $\theta = 0$ mrad production angle, despite a ~ 0.25 reduction factor for the useful K_L .

The K_L beam is collimated in three successive stages by *defining*, *cleaning* and *final* collimators placed respectively 40 m, 100 m and 125 m downstream of the KL target. Figure 2.5 illustrated the three collimator stages. The first collimator defines the beam divergence to be ± 0.15 mrad. The *cleaning* collimator gets rid of the particles scattered or generated in the *defining* collimator's lips; the longitudinal position of those collimators prevent particles from the target to strike the second one. The *final* collimator is located $\sim 3c\tau_s$ downstream from the *cleaning* collimator to let K_S which might be regenerated on its edges to decay before reaching the fiducial volume, which follows immediately downstream.

The resulting neutral beam is propagated downstream in vacuum. A flux of $\sim 2 \cdot 10^7$ K_L crosses per burst the *final* collimator.

2.2.3 The K_S beam

Protons which do not interact in the K_L target ($\sim 40\%$) impinge onto a bent silicon mono-crystal [44] positioned 10 m downstream. A small ($\sim 5 \cdot 10^{-5}$) fraction of them undergoes *channelling*¹ and is redirected towards the K_L beamline. The deflection angle is ~ 9.6 mrad, as illustrated in figure 2.6.

The resulting secondary protons² ($\sim 3 \cdot 10^7$ per burst) are then deflected by a set

¹When positive particles enter crystal within a small *critical* angle to its planes, the collective Coulomb fields can cause them to be *channeled*. If the crystal is mechanically bent, some particles still follow the planes and are thus deflected.

²The out-coming proton beam is sensitive to the angle of incidence onto the crystal and hence to the angle of incidence of the primary protons on the K_L target. Time variations of the K_S to

Figure 2.5: *Illustration of the defining, cleaning and final collimators.*

of magnets and transported (in vacuum) parallel to the **KL** beam to the **KS** target. All the protons being transported to the **KS** target travel through the proton tagging detector which records the time of each proton by an array of scintillators. As will be explained in Section 2.2.4 this detector allows to distinguish decays from the **KS** and **KL** beams.

The K_S beamline is shown in figure 2.7. The **KS** target, identical to the **KL** one, is located 120 m downstream from the **KL** target, and 72 mm above the **KL** beam axis. The vertical displacement is a compromise between the needs to produce two collinear kaon beams, and to have the **KL** beam aperture shielded against secondary particles produced at forward angles in the **KS** target.

The production angle for the **KS** beam is 4.2 mrad, to have momentum spectrum similar to the **KL** beam (see figure 2.8).

The **KS** collimator is such that the **KS** beam converges (with an angle of 0.6 mrad) with the **KL** beam to the center of the detector, ~ 120 m downstream;

The characteristics of the **KL** and **KL** beamlines are summarized in table 2.1.

K_L intensity ratio are primarily caused by this sensitivity on the positioning variations in time of the beam extracted from the SPS. This effect is minimized by a proper tuning of the trimming magnets in the primary proton beamline from the SPS to the **KL** target.

Si cut // to (110) planes
[60 mm x 18 mm x 1.5 mm]

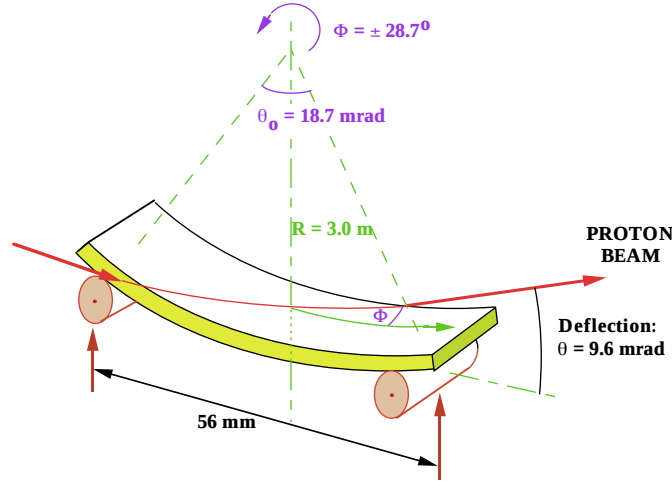


Figure 2.6: An illustration of the bent silicon mono-crystal arrangement, showing the path of the protons. The bending crystal combines the following three features:

- Attenuation of the proton intensity by a fine-tunable factor $\sim 10\%$;
- Selection of small emittance beam, suitable for transport to the K_S target;
- Deflection of this beam in a direction opposite to that of the preceding magnet without canceling its sweeping action on other charge particles (pions and muons).

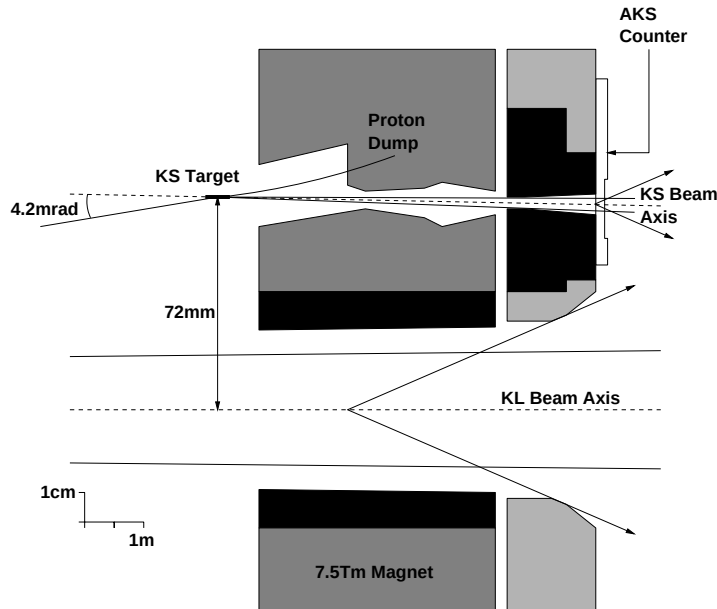


Figure 2.7: Detailed layout of the K_S target station, and beam (vertical cross-section)

The beamlines design fulfills thus the following requests:

- High energy protons are used in order to obtain the required intense kaon fluxes. The K_S to K_L beam intensity ratio is $\sim 5 \cdot 10^{-4}$ in order to collect a similar number of two pion events from K_S and K_L decays.
- The fiducial decay volume is far enough from the K_L target, to let the K_S component in the K_L beam vanish, and close enough to the K_S target, to have a negligible amount of K_L decays in the K_S beam.
- The acceptance for K_S and K_L decay products is very similar; this is why the two beams are designed to have the similar momentum spectrum. Hard kaon momentum spectra are used, to exploit the relativistic lifetime dilatation and shrink the decay solid angle.

2.2.4 The proton tagger

The tagger [17,58] (TAG) is composed of 2 interleaved, orthogonal ladders, each containing 12 narrow foils of NA102A scintillator (see figure 2.9). The width of each foil varies from $200 \mu\text{m}$ to $400 \mu\text{m}$, to follow the beam intensity profile. Each foil sees approximately the same rate ($< 2 \text{ MHz}$) of incident protons. A total foil width of 4 mm (equivalent to $0.01X_0$ radiation lengths) induces no proton losses due to multiple scattering.

To avoid detection inefficiencies, the foils overlap slightly (see figure 2.10). At both ends of the array there are anti-counters to identify halo particles.

The photons from the scintillator are directed to photo-multipliers through an 8 mm air gap and light-guides. The photo-multipliers are read out with a 960 MHz FADC (Fast Analogue to Digital Converter) system which are in practice dead-time free.

A total number of 400 photoelectrons are produced on average per proton hit. The short optical path of the photon to the photo-cathode ($< 2 \text{ cm}$) allows for a time resolution of $\sim 100 \text{ ps}$. Landau tails in the pulse-height distribution are suppressed due to the scattering of δ rays out of the thin foils. This allows for a reduced dynamical range of electronics and, together with the very high readout frequency, for a double pulse separation of 8 ns .

	KL	KS
primary protons per pulse (ppp)	$1.5 \cdot 10^{12}$	$3 \cdot 10^7$
SPS spill time length/cycle time (s)	2.38 / 14.4	
effective spill time length (s)	1.8	1.8
proton momentum (GeV/c)	450	450
length of K^0 beam (m)		
target to final collimator/AKS:	126.00	6.07
target to LKR:	241.10	121.10
production angle of K^0 beam (mrad)	2.4	4.2
angle of convergence to KL (mrad)	0.0	-0.6
angular acceptance (mrad)	± 0.150	± 0.375
beam diameter at LKR (mm)	~ 52	~ 78
useful momentum range (GeV/c)	$70 \div 170$	
useful fiducial volume	$\Delta z_{fiducial} \sim 40 \text{ m}$	

Table 2.1: The nominal design characteristics of the KL and KS beamlines. The beamlines design fulfills thus the following requests:

- The KS to KL beam intensity ratio is $\sim 5 \cdot 10^{-4}$ in order to collect a similar number of two pion events from K_S and K_L decays.
- The fiducial decay volume is far enough from the KL target, to let the K_S component in the KL beam vanish, and close enough to the KS target, to have a negligible amount of K_L decays in the KS beam.
- The KS beam converges with an angle of 0.6 mrad to the KL beam to the center of the detector, $\sim 120 \text{ m}$ downstream; thus the two beams illuminate the same regions of the detector;

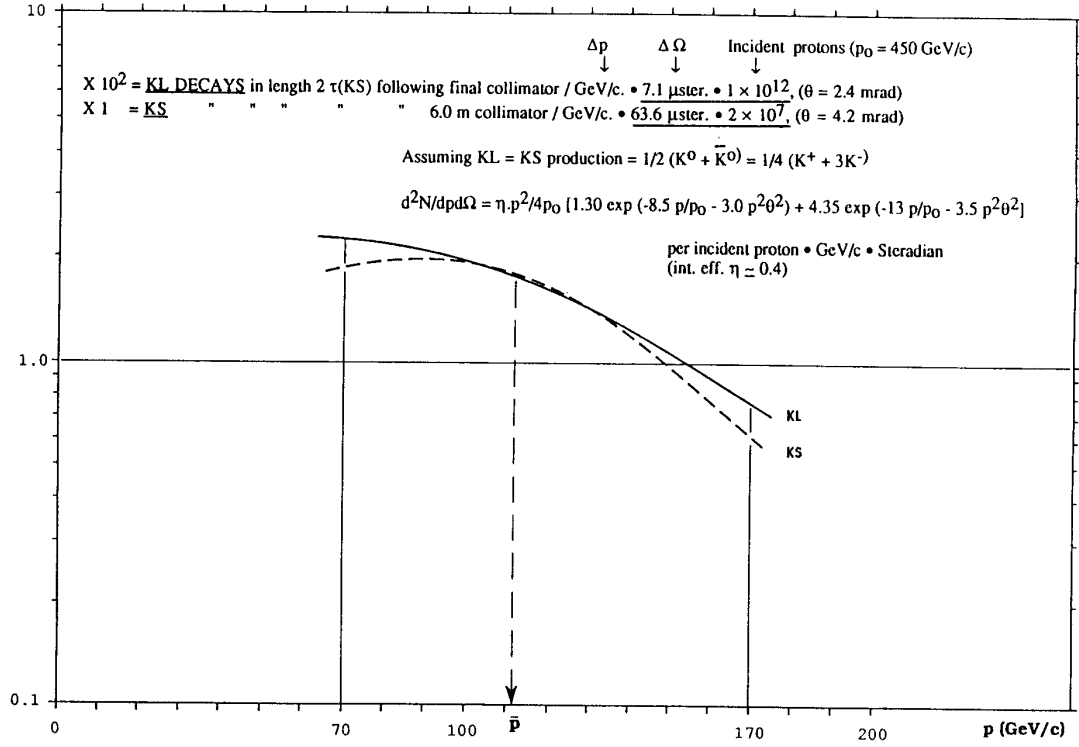


Figure 2.8: The energy spectra of the K_S and K_L decaying within $2 K_S$ lifetimes from the final collimator [12]. Notice the following beam design choices:

- High energy protons are used in order to obtain the required intense kaon fluxes;
- The energy spectra differ by no more than $\pm 10\%$ within the fiducial energy range ($[70, 170]$ GeV); thus the acceptances for K_S and K_L decay products are very similar;
- Hard kaon momentum spectra are used to exploit the relativistic space shrink: a wide region of the decay phase space is thus exploited, despite the ~ 100 m distance between the decay region and the detector.

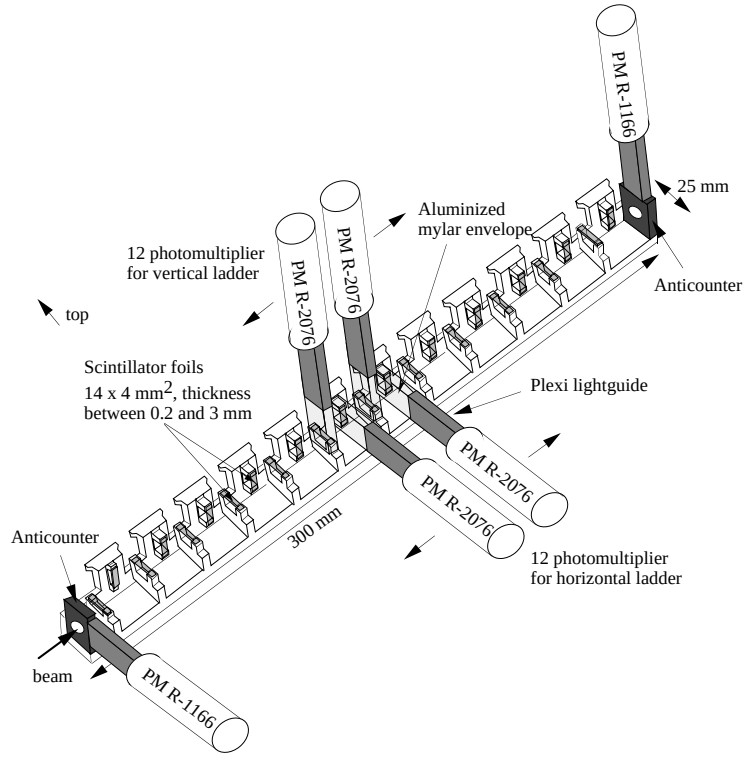


Figure 2.9: *The NA48 tagging station.*

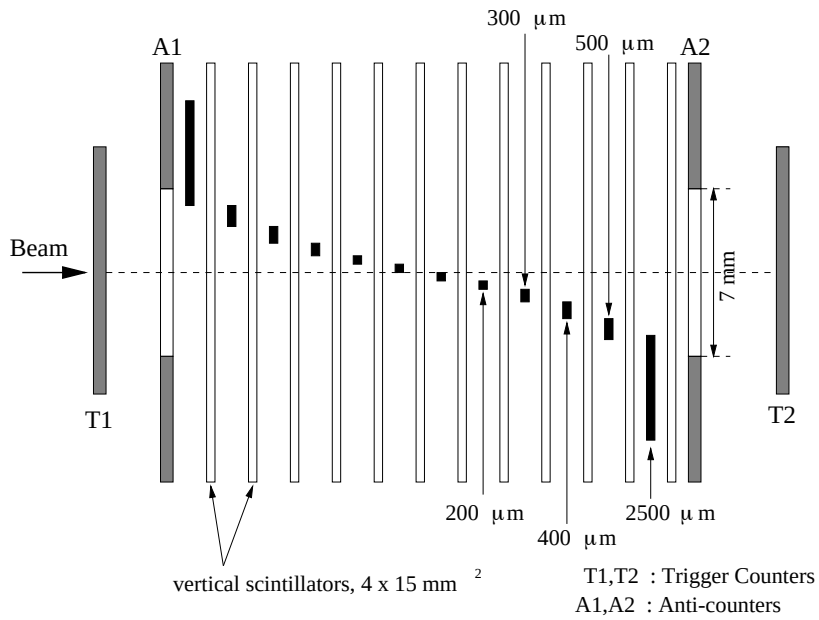


Figure 2.10: *Schematic illustration of the tagger profile.*

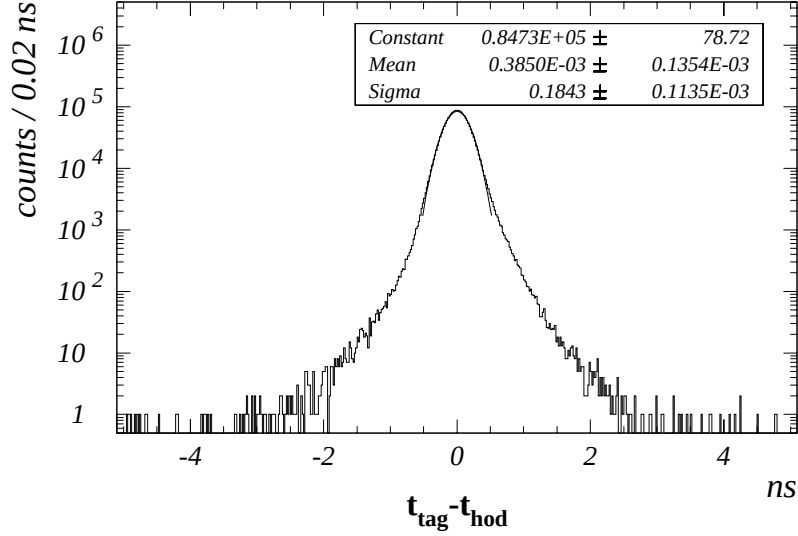


Figure 2.11: Resolution of the time of flight measurement for $\pi^+\pi^-$ events.

The tagger is used to identify the $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ decays. Every K_S event must be produced by a proton, which has crossed the tagger; the event can thus be identified by a time of flight measurement: the time of the event, t_{event} measured in the detector, is compared with the time of the protons (t_{prot}^i $i = 1, \dots, n$), which are measured by the tagger. In the case of a K_S decay there must be a proton such that $t_{event} - t_{prot} = \Delta z/c$, where c is the light speed, and Δz is the distance between the tagger station and the detector.

In practice, the procedure consists in adding the offset $\Delta z/c$ to the proton time, and to look for a coincidence, between the proton and the event, in the time window δt . If no proton is found, then the event is identified as K_L .

The width, δt of the time window is as small as possible³ in order to reduce the probability of random coincidences (later referred to as accidental tagging). The tagger stands instantaneous intensities up to ~ 30 MHz of crossing protons; this results in a probability of $\sim 11\%$ for the accidental tagging, in 4 ns window.

The time of the events is measured, for charged and neutral events, by different detectors, respectively the hodoscope counters and the electromagnetic calorimeter. The time of flight between the tagger and the detector is measured with a resolution

³The measurement of the time of flight has a finite resolution, and tails, which must be considered in the window definition.

of ≈ 180 ps, see figure 2.11.

2.2.5 The K_S anti-counter detector

The K_S anti-counter detector (AKS) consists of a photon converter and 3 scintillator counters (8×4.5 mm transverse size), located at the exit of the KS collimator. A fourth scintillator, with a central hole, acts as a veto for the halo particles. The amplitude, and the time of each signal are recorded.

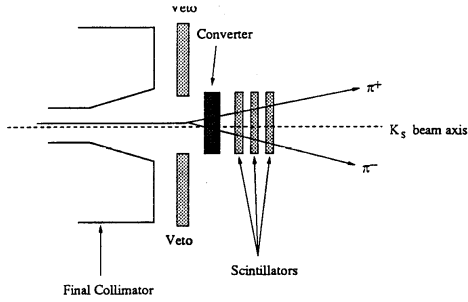


Figure 2.12: Schematic view of the AKS anti-counter.

The converter is made of a 3 mm thick iridium mono-crystal providing 1.79 radiation lengths⁴. The probability of conversion in the crystal is measured to be $(99.964 \pm 0.003)\%$; the efficiency [19] of the central scintillator is measured to be

$(99.97 \pm 0.01)\%$.

The AKS is used to reject (off-line) all the decays $K_S \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$ and $K_S \rightarrow \pi^+ \pi^-$, which is produced upstream of its location, and hence to define very precisely the beginning of the fiducial volume.

Indeed the four events types must be counted in exactly the same fiducial volume. The K_S decays vertex longitudinal position has an exponential distribution, and it is measured with finite resolution. This might cause a migration of events across the upstream boundary of the fiducial region. Conversely K_L decays have an almost flat

⁴The pair production cross section for photons in different materials is normally characterized by the radiation length of the material. The radiation length taken is that of amorphous material, in which no special alignment exists amongst the planes of atoms. However, in crystalline materials, the electric fields experienced by an incident photon are strongly dependent on the direction of the photon with respect to the crystal axis. This leads to a change in the pair production cross section, and the effective radiation length, if the crystal is aligned with the incident beam direction. In the AKS specific case a factor of 2 is achieved in the ratio of radiation length to scattering length with respect to amorphous iridium.

vertex distribution, hence they are not sensitive to resolution effects. The AKS is thus used to veto both charged and neutral K_S decays which occur upstream of its position; this results in a hardware definition of the beginning of the fiducial region.

In addition, the accurately measured position of the AKS counter is used to calibrate the absolute energy scale of the electromagnetic calorimeter, as it will be described later (Section 5.4).

The effective position of the AKS for neutral events is defined inside the converter, at the depth where we obtain 50% of photon conversion probability. In the case of $\pi^+\pi^-$ events the first veto counter defines the beginning of the fiducial region.

2.2.6 The beam intensity monitors

The beam intensities are continuously monitored by the so-called beam counters, later referred to as KL monitor, and the KS monitor (see figure 2.14).

The KL intensity monitor [22] (BCTR or KLM) is placed just before the beam dump. It measures the profile and the intensity of the KL + KS beams. The beam counter consists of two planes (horizontal and vertical) made of 24 scintillating fiber bundles. The active surface of the detector amounts to $\sim 5 \times 5 \text{ cm}^2$ and the measured rate is few MHz. The activity measured in the beam counter is dominated by KL beam.

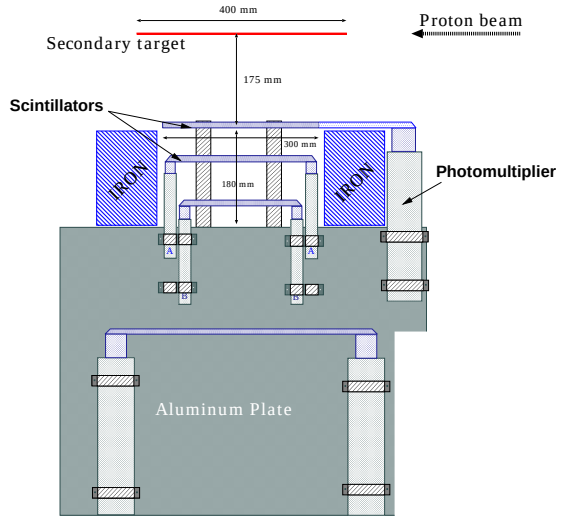


Figure 2.13: Schematic view of the KSM beam monitor.

The KS intensity monitor [21] (KSM) is placed alongside the KS target (see figure 2.13). The KS beam intensity is monitored by counting particles emitted from the KS target perpendicular to the beam direction. It consists of four plastic scintillators arranged parallel to the KS target.

The beam counters are also used to trigger on **random events** (see Section 3.5 on page 71), proportionally to the beam intensities, to study the effects induced by accidental particles in the detector.

2.2.7 The decay region

The decay region (see figure 2.14) begins after the **KS** collimator, 6 m downstream from the target, whose exit coincides longitudinally with the exit of the **KL** final collimator. The K_S beam divergence here is ± 0.375 mrad. The exact origin of the fiducial decay region is defined by the **AKS** anti-counter (see Section 2.2.5) which is crossed by the **KS** beam and is exploited to reject the K_S decays occurring upstream. The decay region is contained in an evacuated (pressure $< 10^{-7}$ bar) tank 89 m in length, with a 0.003 radiation lengths thick polymide (Kevlar) window at the end (see “vacuum tank” in figure 2.14).

The neutral beam continues in a ~ 150 mm diameter tube going through the detector elements to the beam dump. The tube, later referred to as beampipe, is evacuated to avoid particle interactions inducing accidental activity in the detector.

2.2.8 The K_L anti-counter detector

The K_L anti-counter [66] (**AKL**) system consists in seven “rings” of iron and scintillator, which enclose the decay volume, as shown in figures 2.14 and 2.16. The detector covers an acceptance region of ~ 10 mrad (see figure 2.15), which is complementary to the central detector one.

A ring is made of two pockets. A pocket consists in a 3.5 cm thick iron layer, acting as photon converter, followed by a scintillator counters which is readout on both sides. A total of 144 counters are present. The efficiency for a photon detection is ~ 95 %.

The **AKL** anti-counters are used to study the accidental activity, and the background from $K_L \rightarrow 3\pi$.

2.3 The central detector

The NA48 layout is shown in figure 2.16.

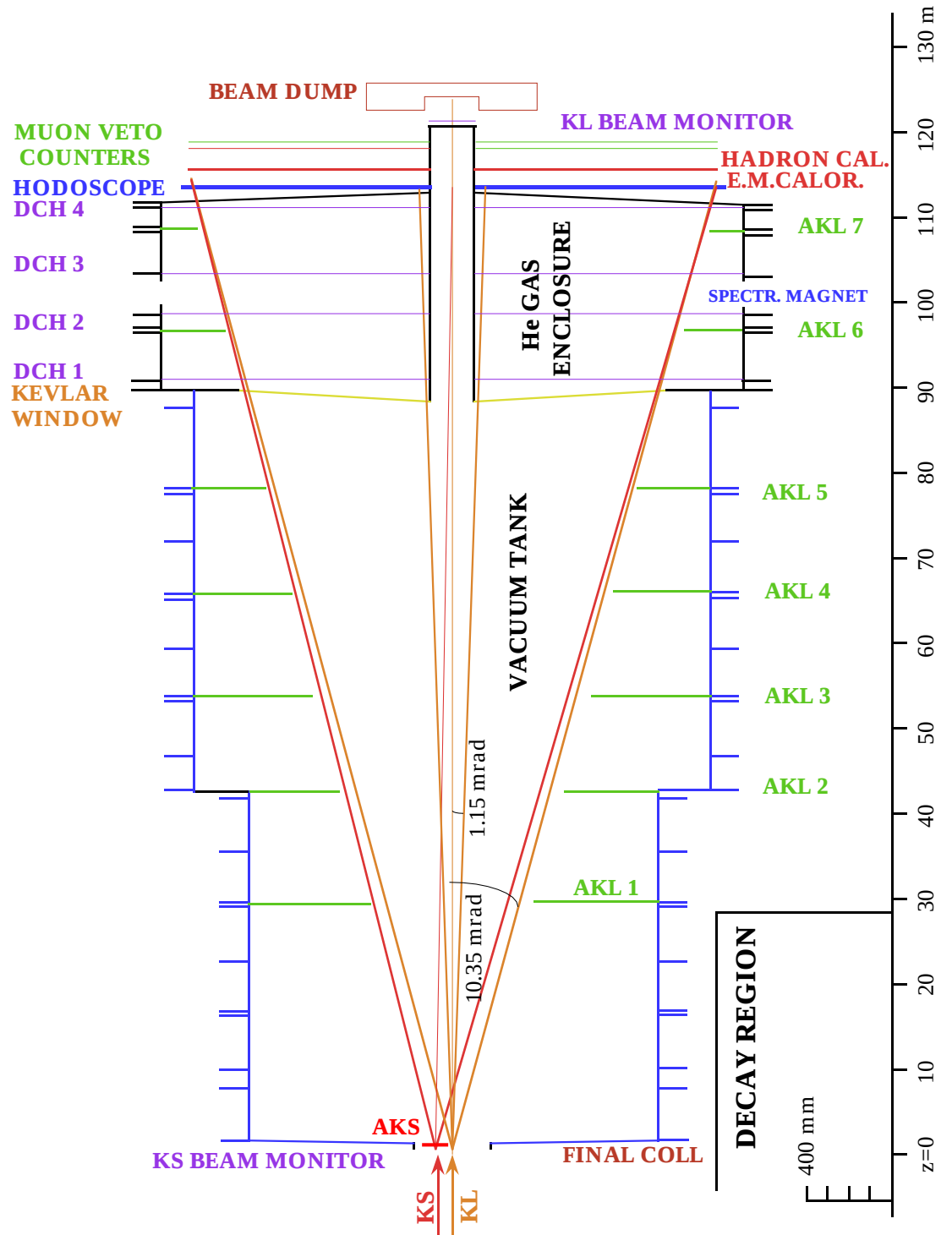


Figure 2.14: Schematic view of the decay and central detector regions.

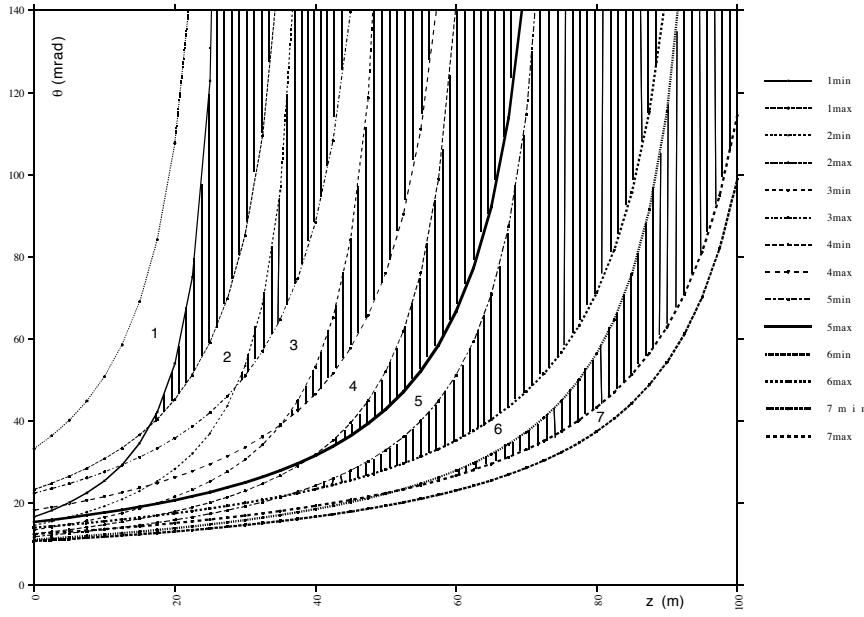


Figure 2.15: *The AKL acceptance coverage.*

2.3.1 The magnetic spectrometer

The magnetic spectrometer is composed by four high resolution wire drift chambers (DCH) and a dipolar magnet located after the first two chambers. It is designed to measure the momenta of the charged tracks, and the position of the decay vertex.

The chambers description: The four drift chamber [14] are illustrated in figure 2.17. They have octagonal shape with a fiducial area of 4.5 m^2 . Each chamber contains 8 planes of grounded sense wires oriented in four different directions (see figure 2.18) orthogonal to the beam axis (referred to as views): 0° (X axis), 90° (Y axis), -45° (U axis), and $+45^\circ$ (V axis). Each view contains two staggered planes of 256 wires to resolve left-right ambiguities (see figure 2.19). It is enclosed between two mylar foils, which bound the geometry of the cell. The hole in the center of the chambers is needed for the location of the beam pipe. It entails a careful construction and positioning of a set of rings on which the central (short) wires of the different planes are soldered. The fine granularity of the wire spacing allows for maximum drift distances of 5 mm which correspond to drift times of the order of $\sim 100 \text{ ns}$.

Each drift chamber is filled with a 50% + 50% Argon–Ethane mixture. Since

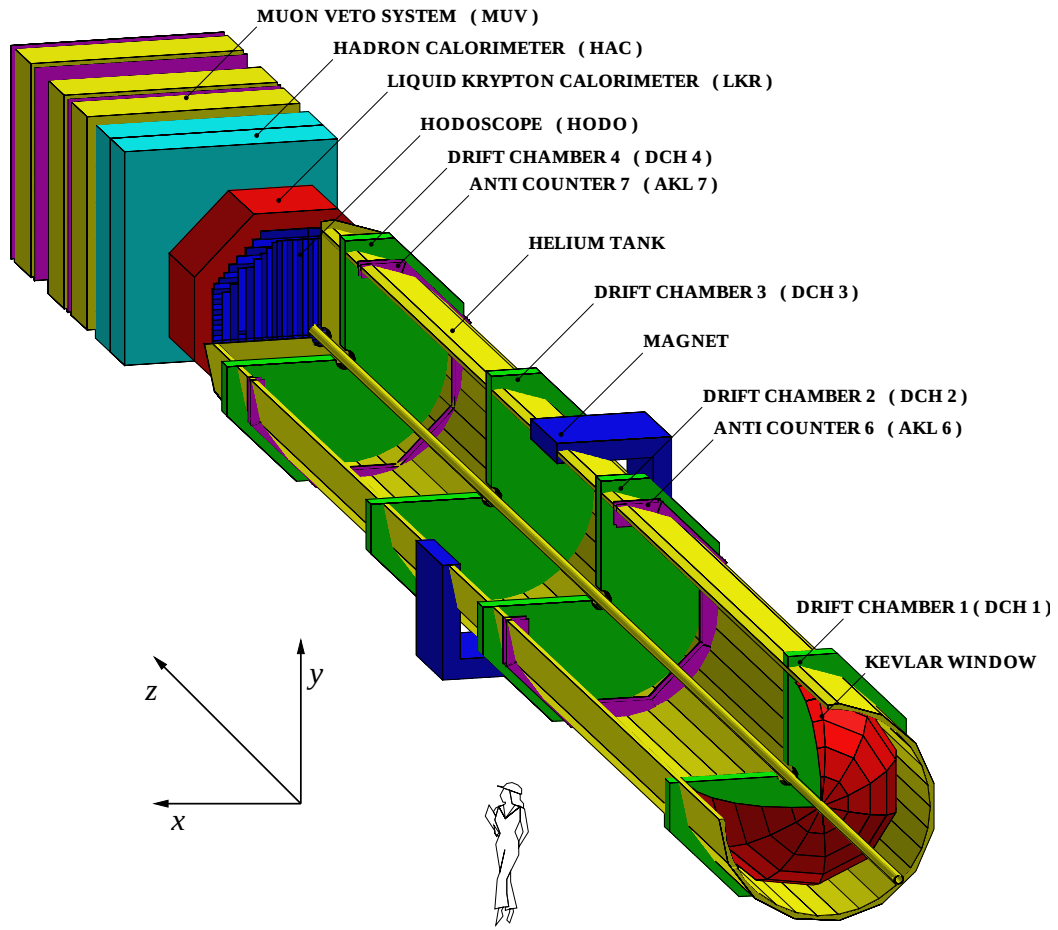


Figure 2.16: The NA48 detector. The detection and measurement of the charged $K_{\pi^+\pi^-}$ decay mode is performed by the magnetic spectrometer, the hodoscope and the muon veto. The neutral decays are detected by an highly performing liquid Krypton electromagnetic calorimeter.

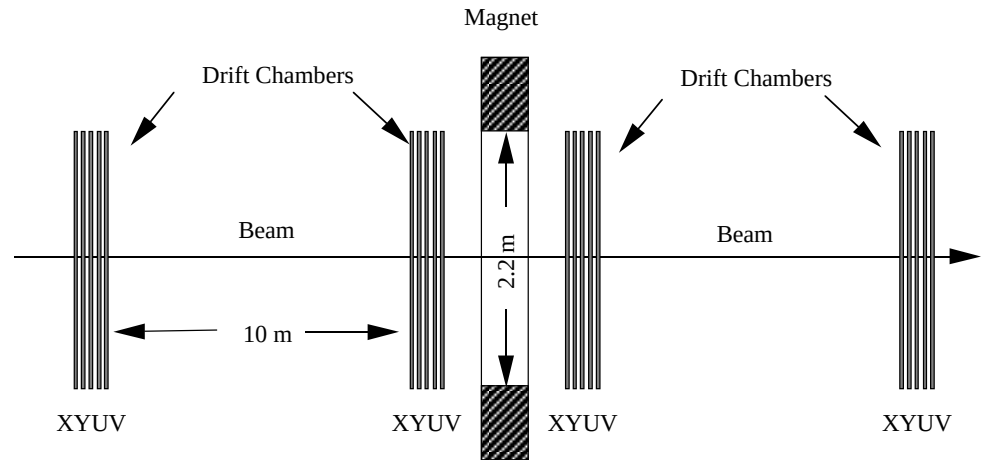


Figure 2.17: Schematic view of the spectrometer.

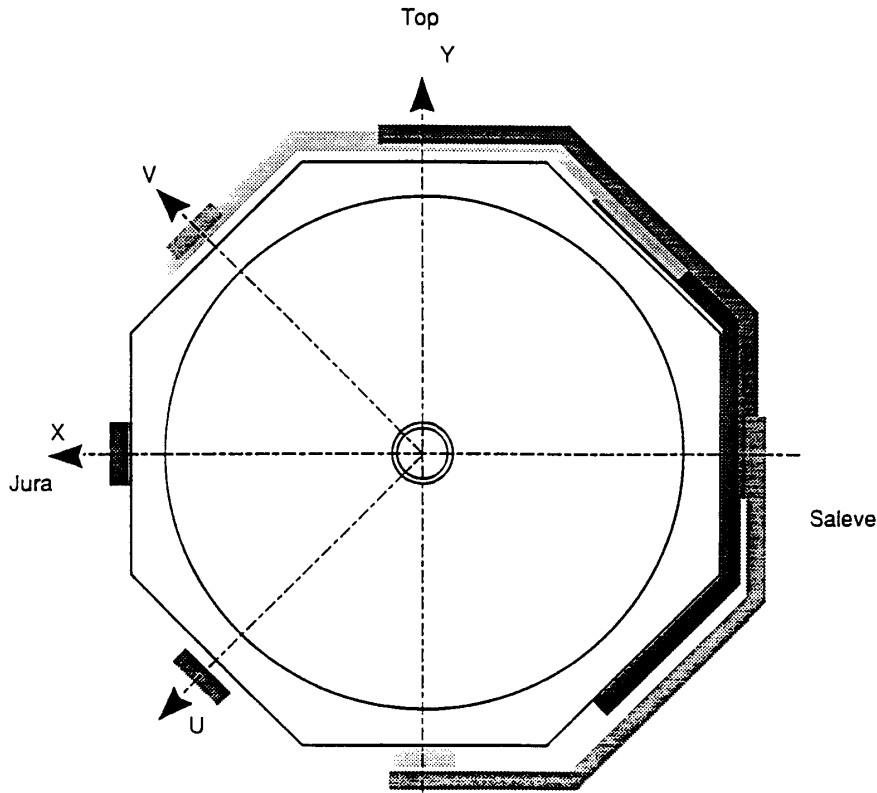


Figure 2.18: *The drift chambers reference system and views.*

the chamber walls cannot stand a large pressure gradient, the detector volume surrounding the chambers is filled with helium, at atmospheric pressure, which minimize multiple scattering effects (see “He gas enclosure” in figure 2.14).

The drift chambers read-out: The signals from the drift chamber wires are amplified and sent to a “TDC card”. There are a total of 28 TDC cards: one for each plane of wires that is read out [9] (in case of chamber 3 only *X* and *Y* views). Each card contains a TDC (Time to Digital Converter) chip, and a FIFO (First In First Out) memory. The TDC cards record which sense wires were hit and the times of these hits. This information is temporarily stored in the FIFO memory before being sent to a “Ring card” which stores this data for $200 \mu\text{s}$. The data stored in the Ring cards can either be read by the Charged Trigger system (see Section 3.1), or sent to the PC Farm, where data for triggered events are combined with the data from other sub-detectors (see Section 3.6).

The time taken to read out data from the Ring cards is proportional to the total number of wire hits. To keep this time low, if a plane has more than 8 wire hits

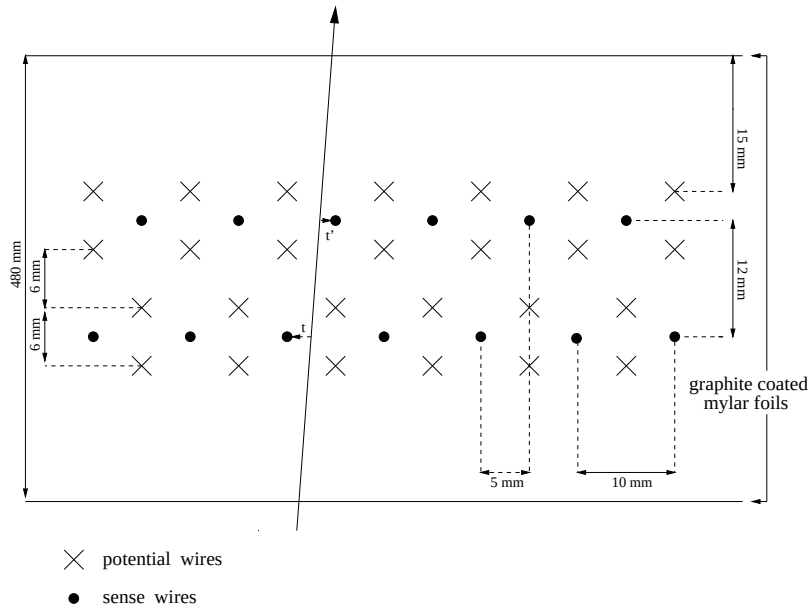


Figure 2.19: *Illustration of wires pattern in a drift chamber cell. The two staggered planes of sense wires compose one view.*

in the previous 100 ns, the FIFO memory on the appropriate TDC card is reset. When a memory reset occurs, the data residing in the FIFO is lost. If this happens, an additional overflow word is added to the data by the TDC card. In principle, events with high wire hit multiplicity are not candidates for $K_{\pi^+\pi^-}$ decays; Thus the loss of these high multiplicity events should not affect the analysis of $\mathcal{R}$. However, in practice, about 25% of $K_{\pi^+\pi^-}$ are influenced by the loss of the data due to the memory reset. These effects are discussed in Section 10.1.

The magnet description: The magnet [64], placed between the 2nd and the 3rd chamber, has an integral of the magnetic field of $\int dz B_y = 0.83 \text{ T m}$, corresponding to $\sim 265 \text{ MeV/c}$ in the transverse momentum for the tracks. The magnet aperture matches the acceptance of the electromagnetic calorimeter.

The fringe field at the DCH2 and DCH3 chambers is smaller than 0.02T. The uniformity of the field in the active region is better than 10%, allowing an easy momentum calculation for the on-line reconstruction.

The performances of the spectrometer: The impact position on a chamber is measured with a precision of $90 \mu\text{m}$ (figure 2.20 shows the illumination of DCH1 by the charged pions.). The transverse geometry of the chambers and their longitudinal distance are known with a relative precision of $2 \cdot 10^{-4}$. The resulting resolution in the

tracks opening angle is very good, and allows to measure, at the level of $\sim 2 \cdot 10^{-4}$ the relative scale between the momentum of the kaon in charged and in neutral decays.

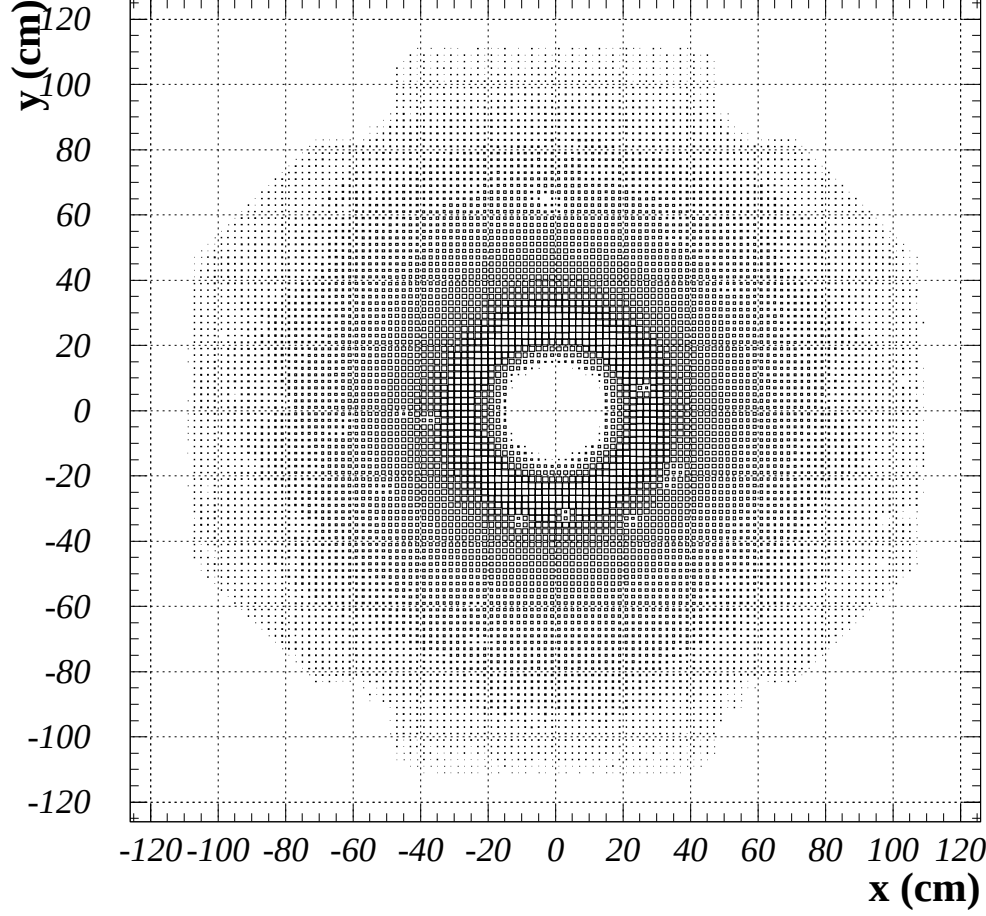


Figure 2.20: *DCH1 illumination by charged pions from the selected $K_{\pi^+\pi^-}$ decays. The low track density spots, the octagonal outern and the circular inner shapes of the distribution are due to the fiducial selections, which will be describes in the next chapter.*

The position of the charged decay vertex is measured with a precision of ~ 500 mm longitudinally, and 2 mm on the transverse plane. Since the beams are vertically separated by $\gtrsim 40$ mm, in the decay region, a clean identification of K_L and K_S decays into $\pi^+\pi^-$ is possible. This information is used as a cross check of the tagging method.

The momentum resolution of the spectrometer is:

$$\frac{\sigma_p}{p} = 0.48\% \oplus 0.009 p_{[\text{GeV}/c]}\% \quad (2.3)$$

The first term is due to multiple scattering effects in helium; the second term is due to the position resolution in the drift chambers. At the average $\pi^\pm$ momentum of 50 GeV/c, the resolution is $\sigma_p/p \approx 0.66\%$, where the two terms in eqn. (2.3) contribute equally.

The resulting resolution on the kaon invariant mass is $\sim 2.5 \text{ MeV}/c^2$; this is shown in figure 2.21.

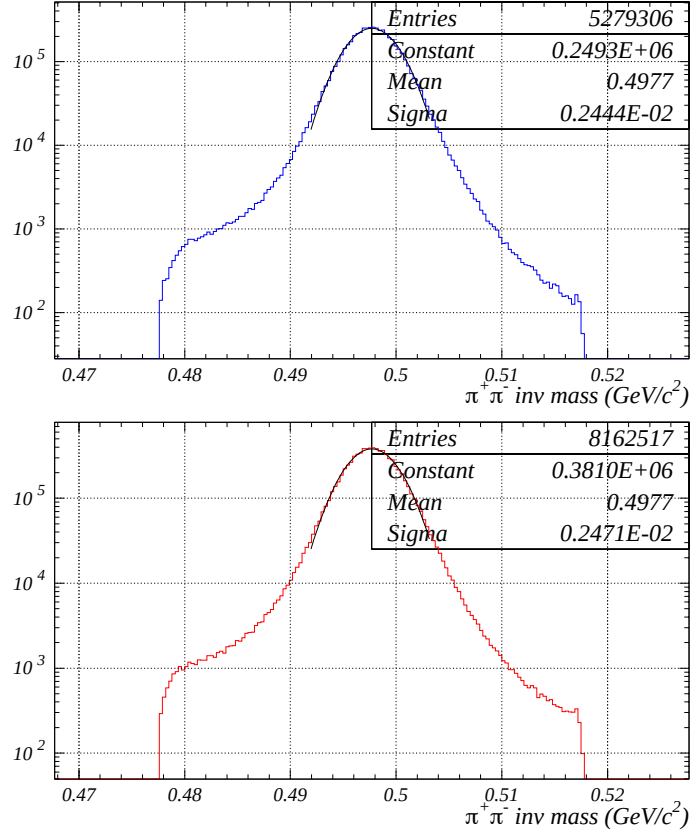


Figure 2.21: $\pi^+\pi^-$ invariant mass for K_S and K_L events.

2.3.2 The charged hodoscope

The charged hodoscope [90] (HODO) is used to provide a fast topological trigger [31,32] for the charged $K_{\pi^+\pi^-}$ events, and to measure their time, both on-line and off-line.

The hodoscope description: The hodoscope (see figure 2.22) consists of a plane of 64 vertical scintillators, followed by a second plane of 64 horizontal scintillators.

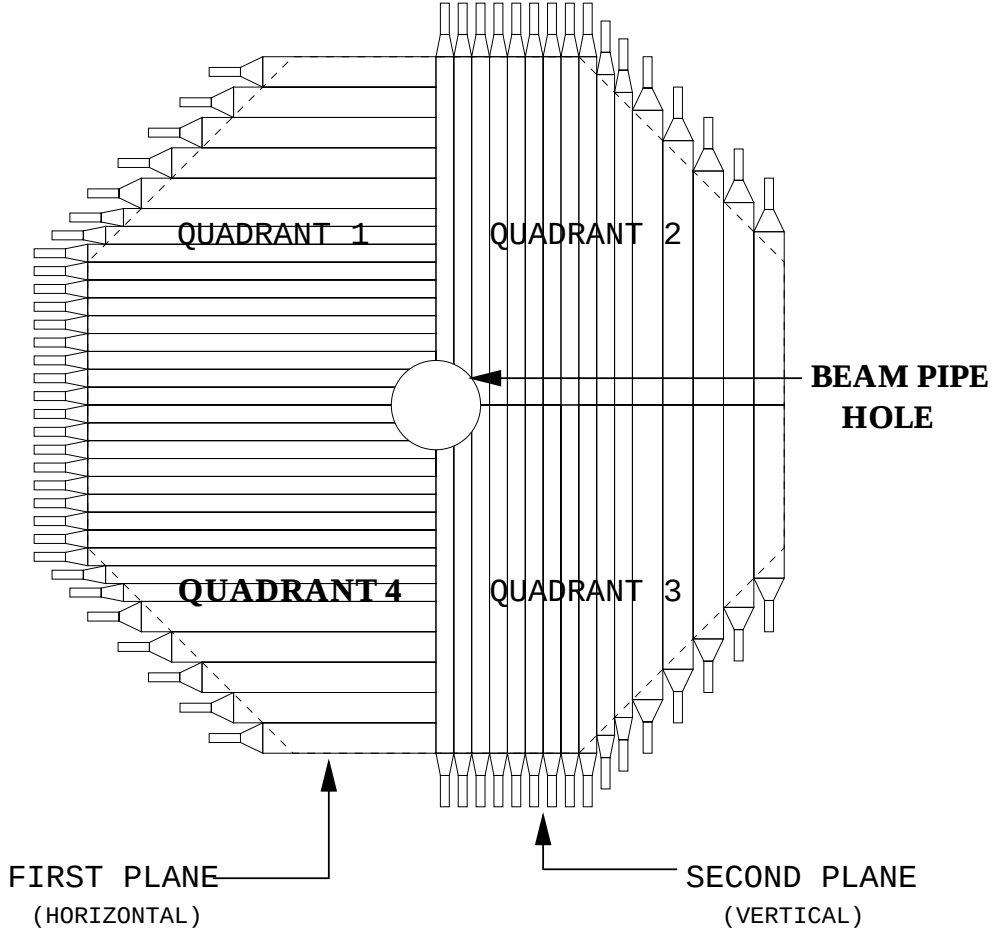


Figure 2.22: *Layout of the charged hodoscope.*

The counters are made of NE110 plastic scintillator, with a high light output. The scintillation light is collected from one edge of the counter through a Plexiglas light guide, with a fish-tail shape, and detected by a XP2262B Philips photo-multiplier.

The distance between the two planes (75 cm), and the position of the second plane with respect to the entrance wall of the electromagnetic calorimeter (80 cm downstream), are chosen to reduce the effects of back-scattering from the calorimeter.

Each plane is divided into four quadrants (later referred to as QV1, ...,4 and QH1, ...,4) of 16 counters. The counter thickness is 2 cm, corresponding to $\sim 0.05 X_0$. The widths are either 6.5 cm, in the region near to the beam pipe, or 9.9 cm. The

lengths vary from 121 cm to 60 cm.

The readout and the “fast logic” electronics: Each analog pulse is fed into a high impedance input of the FADC (Fast Analog to Digital Converter) card. The signals are then individually discriminated and timed within 1 ns. The same discriminators, which work in “burst guard” operation mode, are used to feed the signals to the FTDC (Fast Time to Digital Converter) inputs and to the fast logic electronics.

The discrimination threshold in 1998 was set to 60 mV, as an optimization between the trigger rate requirements and the time resolution needs. The signal given by the coincidence of counters on crossed quadrants, opposite with respect to the beam pipe, is formed to trigger kaon decays into $\pi^+\pi^-$. This signal, referred to as QX, and other fast signals are used in the first level trigger (see Section 3.3.1.1 on page 64).

The readout electronics is hosted in modules called PMB [75] (Pipeline Memory Board), which is illustrated in figure 2.23. In this module the analog signal is shaped, digitized, sampled every 25 ns and read out by 10 bits FADC card. At the same time the discriminated signal triggers a current which ramps between two fixed levels and is sampled at 40 MHz. By fitting the ramp it is possible to reconstruct the time of the hit with very good resolution.

The PMB modules have been specifically designed for the charged hodoscope system, but they are also used for the readout of the AKS, AKL, NHOD, KSM detectors, and of the neutral trigger (NUT) system.

The hodoscope performances [87]: The high granularity design of hodoscope minimizes the effects of the accidental particles, and maximizes both the time measurement resolution, and the detection efficiency.

Four independent time measurements are provided by the hodoscope for each charged decay detected. The consistency among those time measurements guarantees the reduction of non-gaussian tails⁵ within the NA48 experimental requirements.

⁵The most dangerous uncertainties on the event time determination come from the non-gaussian tails in the time distribution. Those tails are mainly due to accidental events, interactions of the decay products in the hodoscope or upstream of it, back scattering from the calorimetric showers.

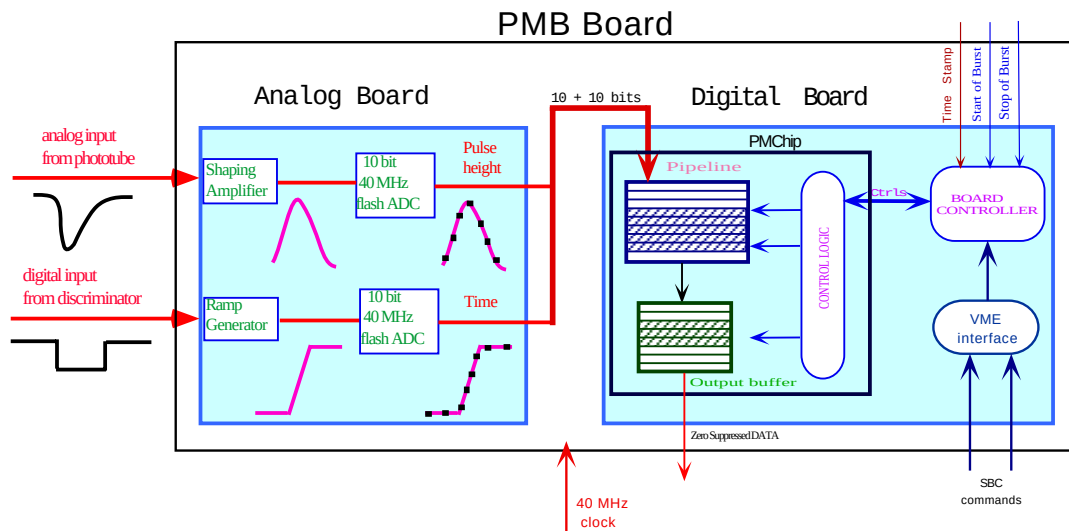


Figure 2.23: Illustration of the PMB boards. The PMB modules have been specifically designed for the charged hodoscope system, but are also used for the readout of the AKS, AKL, NHOD, KSM detectors, and of the Neutral Trigger (NUT) systems.

The dead space between adjacent counters [39] is measured to be less than $200 \mu\text{m}$ (see figures 2.25 and 2.24). An accurate alignment of the detector is ensured in the directions transverse to the beam, both vertically and horizontally, and in the respective positions of the two planes. Care was taken to avoid possible alignment of the dead spaces of the two planes, which would be detrimental for the trigger efficiency. The radius of the central hole, where the beam-pipe sits, is 12.8 cm. This value has been chosen to optimize the geometrical detector efficiency for both kaon beams. The inefficiency of the single counter is typically $\lesssim 10^{-3}$. The resulting geometrical inefficiency in the fiducial volume is measured well below 10^{-4} . The inefficiencies, measured for each of the 8 quadrants with 1997 data, vary between the values of $5 \cdot 10^{-4}$ and $2 \cdot 10^{-3}$ (see figure 2.26).

The time resolution for a single counter, after off-line correction is better than 250 ps. The resulting resolution for the $K_{\pi^+\pi^-}$ event time is ~ 100 ps. A global inefficiency of the order of $2 \cdot 10^{-3}$ is measured for the event time reconstruction. That value accounts for geometrical effects, mechanics problems and readout errors.

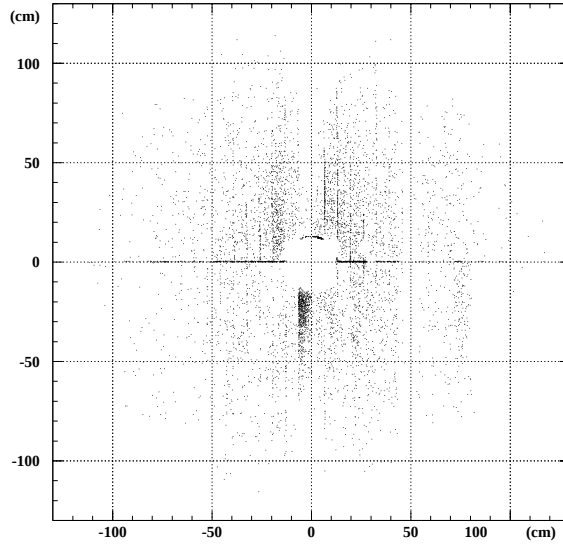


Figure 2.24: The tracks reconstructed by the spectrometer are extrapolated to the vertical plane of the charged hodoscope. The plot shows the position, on the transverse plane, of the tracks which are not detected by any scintillator. The non active space between adjacent counters is clearly visible. It is measured to be $< 200 \mu\text{m}$, resulting in a negligible geometrical inefficiency effect on $\mathcal{R}$. The inefficiency of the read-out electronic chain of the scintillators is also recognizable from the tracks which hit the active region of the scintillators. The overall inefficiency of the 8 charged hodoscope quadrants is shown in figure 2.26. The selected charged events of 1997 (sic) data taking are shown here; the absence of tracks in the vertical column at $x \sim 50 \text{ cm}$ is due to the electromagnetic calorimeter “dead column”, which, in 1997, induced to reject also $\pi^+\pi^-$ events with tracks impinging there. Thus it is feature of the event selection on 1997 data, not related to the charged hodoscope.

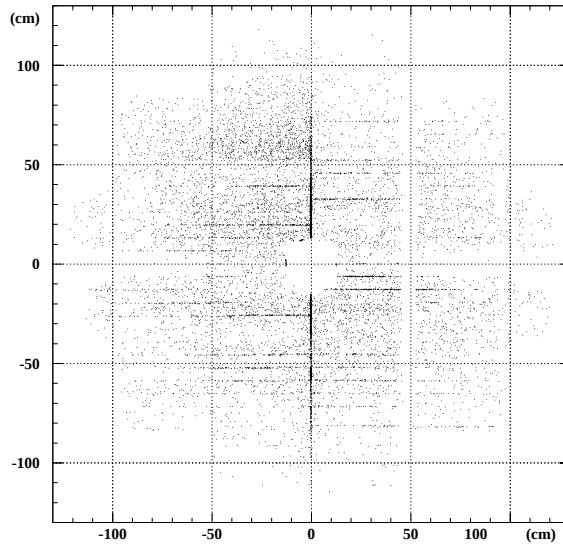


Figure 2.25: The inefficiency of the horizontal charged hodoscope counters. See figure 2.24.

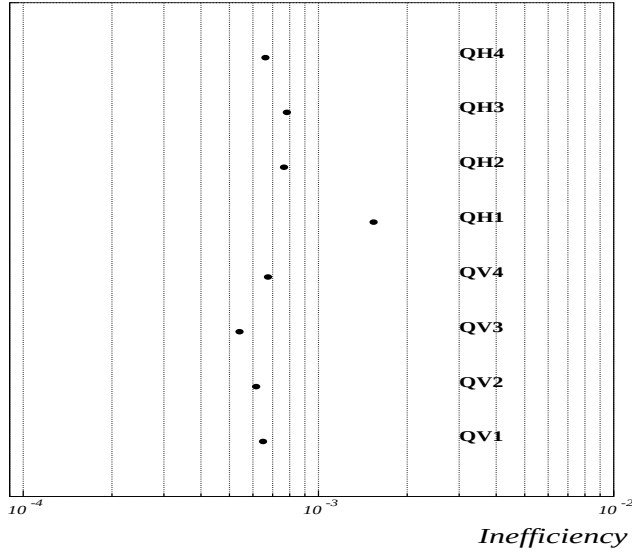


Figure 2.26: The overall inefficiency of the charged hodoscope quadrants, in detecting a crossing track.

2.3.3 The electromagnetic calorimeter

The electromagnetic calorimeter [86, 88] (LKR) of NA48 is a liquid Krypton quasi homogeneous ionization chamber. It is located 80 cm downstream from the charged hodoscope. The calorimeter has been designed specifically to detect the photons from $K_{\pi^0\pi^0}$ events and to measure their energy, position and arrival time.

The calorimeter description: The liquid Krypton is used both as absorber and active medium. The ionization, produced by an electromagnetic shower in the calorimeter, is very well correlated to the energy of the incoming photon or electron.

The calorimeter volume (9 m^3) is divided into 13248 read-out towers, later referred also to as cells, each defined by three Cu–Be–Co $40\text{ }\mu\text{m}$ thick ribbon electrodes, as shown in figures 2.27 and 2.28. The cells are $\sim 2 \times 2\text{ cm}^2$ in cross section, and 127 cm long in the longitudinal direction (equivalent to $27X_0$ and $2\lambda_{int}$ lengths). In the middle of the cells (cathodes) it is placed a collecting anode. The cathodes are connected to ground, while a voltage of 5 kV is applied to the anodes. The ionization current induced on the anode is measured by the electronic chain: actually only the initial current is read out from each cell, in order to achieve a very good time resolution.

To ensure the transverse size of the cells, which must be fixed and known with

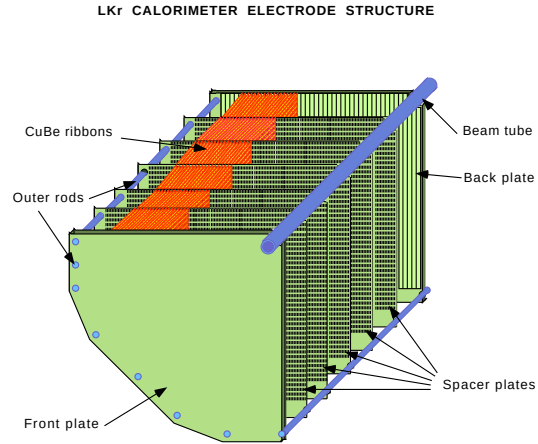


Figure 2.27: *The internal structure of the calorimeter*

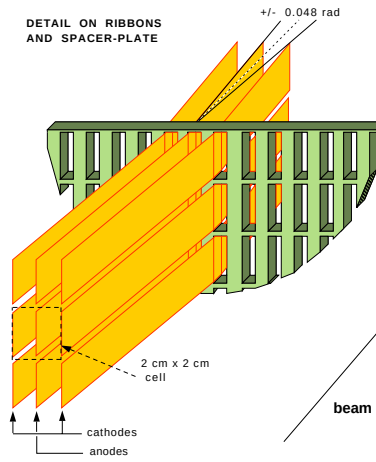


Figure 2.28: *The definition of a tower in the electromagnetic calorimeter.*

Z	36
Density	2.4 g/cm ³
Interaction length	60 cm
Radiation length	4.7 cm
Molière radius	6.1 cm
Boiling point at 1 bar	119.8 K
Radioactivity	500 Bq/cm ³
Electron drift velocity at 5 kV/cm	0.36 cm/ μ s
Dielectric constant	~ 1.7

Table 2.2: *Properties of liquid Krypton (from [88]). The small radiation length allow for very slim showers, both in longitudinal and in transversal directions. High energy electromagnetic showers fully develop within a total length of ~ 125 cm, corresponding to $\sim 1\%$ of the distance between the fiducial region and the calorimeter; the shower transversal area is $\sim 19 \times 19$ cm² corresponding to $\sim 7\%$ the calorimeter surface.*

high precision ($50 \mu\text{m}$)⁶, each of the electrodes is stretched between five accurately machined spacer plates and the front and back plates of the calorimeter. The spacer plates apply an “accordion” (“zig-zag”) geometry to the electrodes which undergo a tension of $2N$. The angle applied to the electrodes by the spacer plates is 48 mrad.

The geometry of the tower is projective: it points towards the average K_S decay position. The overall increment of transversal dimensions of the tower is $\sim 1\%$. The projectivity guarantee the same transversal profile to the showers, provided they are generated by photons from decays in the fiducial region, independently of their longitudinal development. This allows an energy measurement almost unbiased by the shower depth, which strongly depends on energy⁷.

In case the showers develop along the electrodes, the accordion geometry

⁶This in order to keep the constant term of the $\sigma_{E_\gamma}/E_\gamma$ below 0.5% against the strong peaking of the lateral development of the energy deposition

⁷Due to this geometrical feature, given the longitudinal decay vertex position and the center of the shower energy deposition, the measurement of angles between the photons is determined with a reduced contribution from the fluctuation in the longitudinal development of the showers. This is crucial to fix the relative scale for the reconstructed kaon momentum of the $K_{\pi^+\pi^-}$ and $K_{\pi^0\pi^0}$ decays; the relative momentum scale is indeed related to the accuracy in measurement of the angle between charged pions tracks in $\pi^+\pi^-$ decays, and between photons in $\pi^0\pi^0$ decays. Notice that An error of only $2 \cdot 10^{-4}$ in this relative momentum scale induces a systematic error of $5 \sim 10^{-4}$ in $\mathcal{R}$.

minimizes the inefficient ionization, and leads to a smearing of the the non-linearity effects depending on transversal impact point.

The detector is contained in a cryostat, formed by an outer aluminum vessel and an inner steel vessel, which maintains the Krypton at a temperature of 121 K.

The calorimeter read-out: The front-end “cold” electronics is directly mounted on the detector back-plate in order to minimize the noise, and to optimize the timing of signal extraction. It includes a preamplification stage and a calibration system (see figure 2.29). Outside the cryostat, a transceiver drives the output signals to custom readout modules, later referred to as CPD [11] (Calorimeter Pipeline Digitizer). The analog card of the CPD signal generates a shaped pulse with a 70 ns FWHM, which is processed by means of a optimal filtering algorithm to evaluate pulse height and extract energy and time. Asynchronous digital sampling is done every 25 ns by a 10 bit FADC. Since the required dynamic range (3.5 MeV

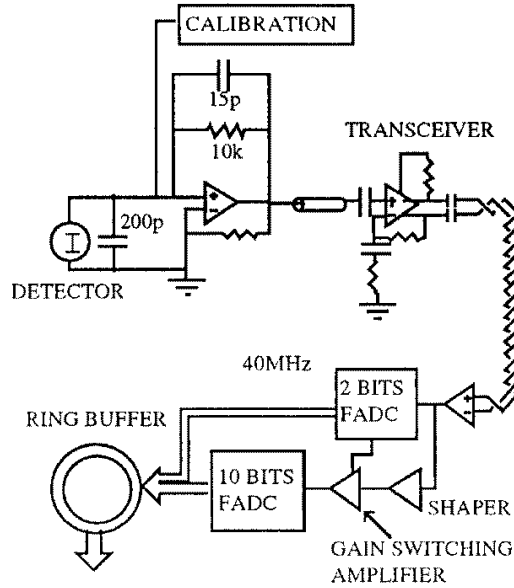


Figure 2.29: Scheme of the electromagnetic calorimeter readout electronics

to 100 GeV) corresponds to 14 bits, the gain of the amplifier is switched among four possible values, depending on the signal amplitude. The selected gain is recorded through 2 additional bits. Analogue summed signals of the calorimeter information are also produced in the CPD’s used by the neutral trigger system.

A dedicated processor, the “data concentrator”, identifies the cells with energies above a predefined threshold, and apply a cluster finding algorithm. Only digitized

information from the cells of these clusters are selected and read out. For a typical photon shower about 100 cells are read out.

The calorimeter performances: The calorimeter copes with an instantaneous rate of ~ 1 MHz; it has no dead-time, and almost full efficiency.

The accuracy in the measurements of the kaon momentum, and decay vertex position⁸ of the neutral events, is crucial to impose exactly the same fiducial volume for the $\pi^+\pi^-$ and the $\pi^0\pi^0$ decays. A good photon energy resolution is required also to keep a low level ($< 0.1\%$) of background⁹ in the reconstructed $K_{\pi^0\pi^0}^L$ sample.

Various methods are exploited to determine the overall energy scale of the LKR, the linearity, the uniformity and the cell-to-cell inter-calibration factors (see Section 5.4.2 on page 112).

The calorimeter linearity is mainly studied using K_{e3} decays, in which the whole electron energy is reconstructed in the calorimeter and can be compared to the momentum measured by the spectrometer to calculate any correction needed.

After calibration factors are applied, the energy resolution was measured to be:

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E_{[\text{GeV}]}}} \oplus \frac{10\%}{E_{[\text{GeV}]}} \oplus 0.5\% \quad (2.4)$$

where the first term relates to the sampling fluctuations, the second to the stochastic fluctuations (electronic noise) and the third to inter-calibration errors, inhomogeneities and energy absorbing material in front of the calorimeter. Figure 2.30 shows the electromagnetic calorimeter energy resolution. The energy resolution at the average energy of 25 GeV is $\sim 1\%$, the three term contributing respectively with 0.7%, 0.4% and 0.5%.

Special “ η runs” were taken in 1998, using the KL beamline to propagate a 75 GeV π^- beam downstream to a 3.5 cm polythene target. The target could be located at two accurately known positions. Charge exchange processes cause π^0 and η particles to be produced in the target; thus 2, 3 or 6 photon events can be used to measure the calibration factors, to cross-check the K_{e3} calibration method, and to measure the non-gaussian tails in the energy measurement.

⁸Given the four photons measured in the calorimeter, the longitudinal vertex position is measured from the energies, and the transversal distances between the photons, assuming their invariant mass to be equal to the kaon mass.

⁹This is mainly due to events from $K_{\pi^0\pi^0\pi^0}$ decays with 2 photons missing detection.

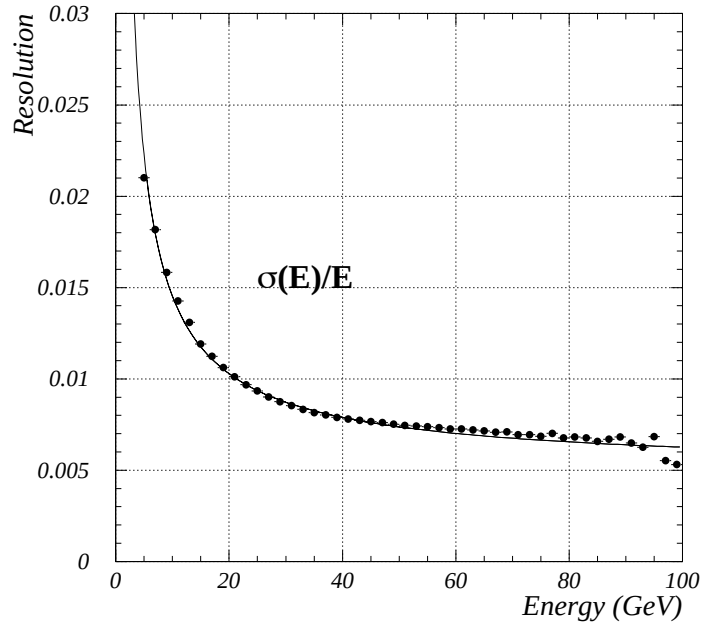


Figure 2.30: *The LKR energy resolution.*

Residual non-linearities are measured at the level of 0.2% in the energy range $[5 \div 100]$ GeV.

The calorimeter geometrical inhomogeneities, and the electromagnetic shower shape, have also been studied with a special “electron run”, by impinging calorimeter with an electron beam, transported through the KL beamline.

After the above corrections are applied, $K_{\pi\pi}^S$ events are used to set the fine overall energy scale. The sharp rise in the reconstructed decay vertex position, created by the AKS anti-counter veto use, is compared to the accurately known geometrical position of the AKS. The energy scale is thus defined with a relative accuracy of $3 \cdot 10^{-3}$.

The position resolution of photon clusters is better than 1.3 mm in the x and y directions for photon energies above 20 GeV. Combining the energy and position measurements, the longitudinal vertex position of the $K_{\pi^0\pi^0}$ decays is reconstructed with resolution of $\sigma_z = 60$ cm.

The transversal geometric scale of the calorimeter is measured with a maximum error of $100 \mu\text{m}/\text{m}$ in x direction and $150 \mu\text{m}/\text{m}$ in y direction.

On average, the angles between photons are measured with a good accuracy of

$2 \cdot 10^{-4}$, similar to the precision attainable in the DCH for the $K_{\pi^+\pi^-}$ decays.

The time resolution a $K_{\pi^0\pi^0}$ decay event is $\sigma_t = 260$ ps, which is crucial for the time of flight measurement, in order to distinguish K_S and K_L events.

During the 1998 run about 50 cells of the calorimeter had either faulty preamplifiers or no voltage applied to the electrodes (they are later referred to as “dead cells”). Events where the shower maximum for a photon is close to a dead cell are rejected.

Figure 2.31 shows the calorimeter illumination by the $\pi^0\pi^0$ photons.

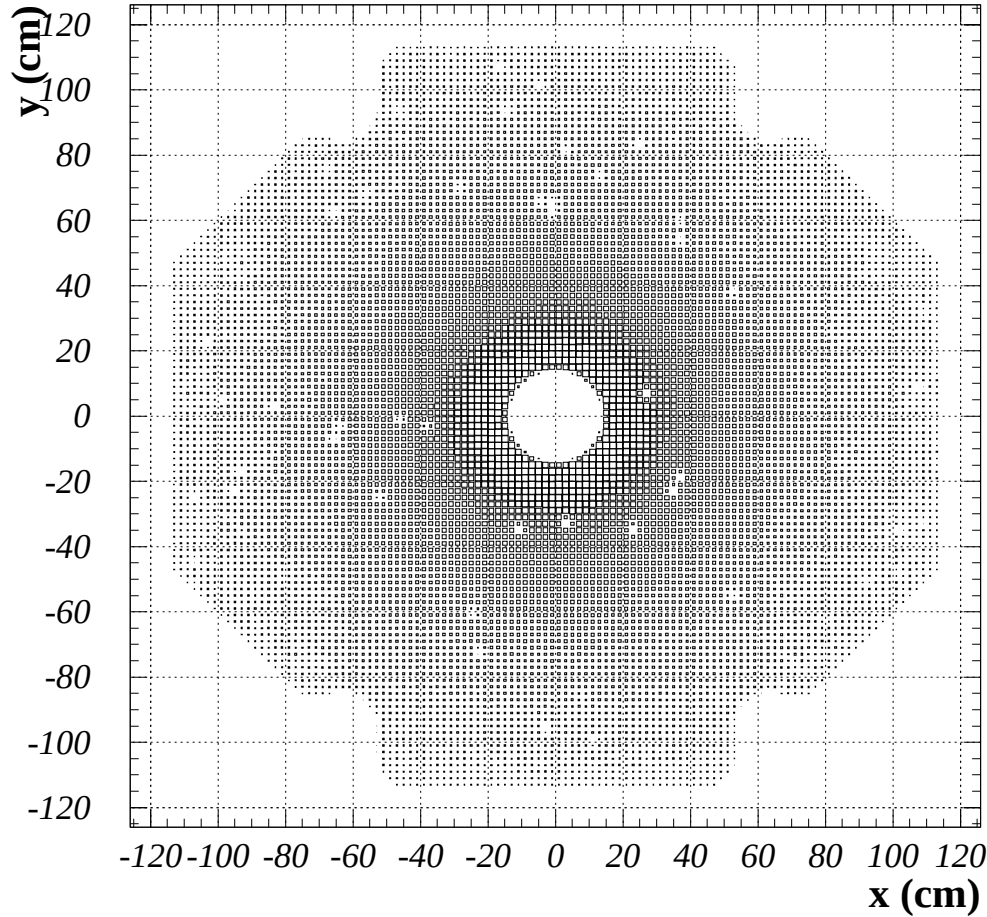


Figure 2.31: Calorimeter illumination by photons from $K_{\pi^0\pi^0}$ decays. The low density spots, the octagonal outer and the circular inner shapes of the distribution are due to the fiducial selections, which will be described in the next chapter.

2.3.4 The neutral hodoscope

The neutral hodoscope [79] (NHOD) is made of 256 bundles of scintillating fibers, each contained in a epoxy-fiberglass tube (7 mm in diameter and 2 m in length). It is immersed in the liquid Krypton volume, at a position corresponding to the average maximum of the electromagnetic shower. The tubes are fixed to the second spacer plate (at a depth of 9.5 radiation lengths) and extend horizontally from the center to the outer edge. The signals are readout by 32 photo-multipliers.

The time of a $K_{\pi^0\pi^0}$ event is measured with a resolution better than 300 ps. This measurement is used to cross check the time measurement by the calorimeter.

The NHOD signals are also used to form an independent “minimum bias” trigger for the neutral events, used to measure the neutral trigger efficiency (see Section 3.3.1.1).

2.3.5 The hadronic calorimeter

A conventional iron-scintillator sandwich calorimeter (HAC), $6.7\lambda_{int}$ thick, follows the LKR detector, to measure the hadronic shower leakage out from the electromagnetic calorimeter. The HAC is composed by two modules (“front” and “back”), each made of 24 scintillator planes which are divided into 44 half-strips per plane and are arranged alternatively along the vertical and horizontal direction (see figure 2.32).

Signals from group of planes are read out by 176 channels. Four CPD’s are used to digitize the signals. The off-line reconstructed energy resolution is $\sigma_{E_{had}}/E_{had} \sim 65\%/\sqrt{E_{[GeV]}}$.

The digitized sum of the signals is sent to the neutral trigger (NUT) to determine the hadronic contribution to the total energy (ETOT), as explained in Section 3.3.1.3.

2.3.6 The muon veto

The muon veto (MUV) consists of three 80 cm ($\sim 5\lambda_{int}$) thick iron walls¹⁰, which act as muon filters, each followed by a plane of scintillator strips. The strips are alternatively vertical and horizontal, partially overlapping, and equipped with

¹⁰Muon loose on average ~ 2.5 GeV when crossing 80 cm of iron due to ionization.

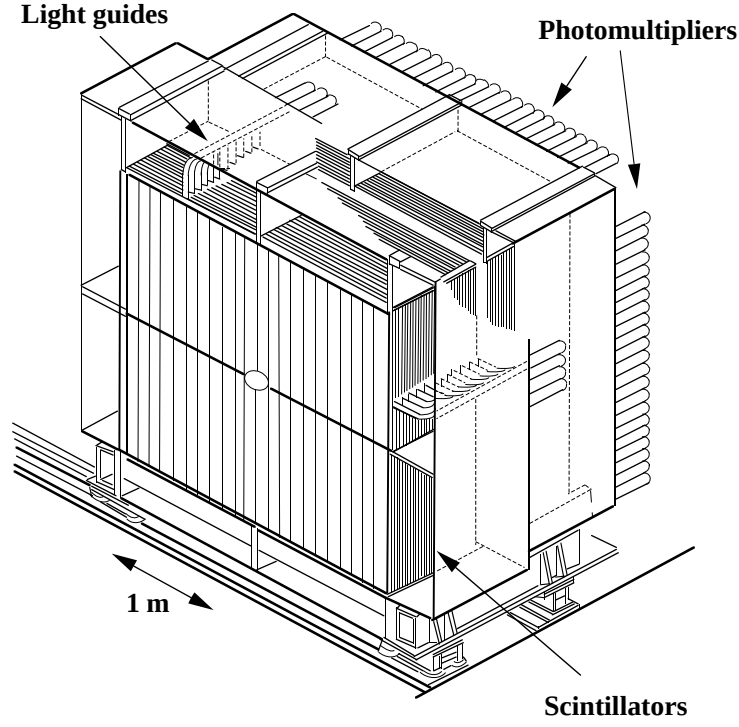


Figure 2.32: *Schematic layout of the hadronic calorimeter.*

photo-multipliers on both sides. The first two planes have 11 strips of scintillator. Plane three has 6 strips of scintillator in the vertical direction.

The time resolution of the MUV was 700 ps during the 1998 run. The inefficiency for $K_{\mu 3}$ rejection is measured to be less than 0.3%.

The probability for a $\pi^\pm$ to be identified as a muon (punch-through), is of the order of $\sim 4\%$. The probability that a $\pi^\pm$ decay on flight is at several percent level.

The muon veto information is used by the off-line analysis to veto $K_{\mu 3}$ events: a $\pi^\pm$ candidate track is rejected in case it match, within a few ns, some hit in the muon veto.

3 Data collection: Trigger and Data Acquisition

Overview

The trigger system of the NA48 experiment consists of two stages which reduce the rate from about 2 million events per burst to about 17.000 events to be read out. A PC Farm collects, from the sub-detectors, the data, which is then reconstructed on-line. The events are filtered and written in several output streams to tape.

3.1 The Trigger System

The experiment relies on a multi level trigger which is capable, in principle, to cope with high rates (MHz) with full efficiency and no dead-time.

The whole NA48 experiment is synchronized by a 40 MHz clock [71], that is, time is defined for all subsystems by a reference clock in units of 25 ns. All data are associated with a time-stamp value, representing the time at which the corresponding decay was detected in some part of the detector. Data from all sub-detectors are continuously digitized and stored in circular memory buffers 200 μ s depth, addressed by a 40 MHz system clock, and referred to also as ring buffers.

Two independent systems are devised to trigger on $K_{\pi^+\pi^-}$ charged and on $K_{\pi^0\pi^0}$ neutral kaon decays (later referred as to Charged Trigger and Neutral Trigger respectively). A third system, the Trigger Supervisor [7] (TS) correlates the former triggers information and produces the final decision to record the data. The trigger system, has then to process, select, and tag the events to be read-out within the 200 μ s data persistence time. A simplified scheme of the trigger system is shown in figure 3.1.

3.2 The Trigger Supervisor

The NA48 Trigger Supervisor [4] (TS) is a fully pipelined 40 MHz digital system which correlates and processes the information from the local trigger sources. It provides the final trigger word, including a time-stamp indicating the event real time, whenever a required condition is fulfilled, and it broadcasts it to all Read Out Controllers (ROCs) within the data persistence onto memory ($\sim 200 \mu$ s). The last stage is de-randomized, in order to guarantee a minimum interval between two

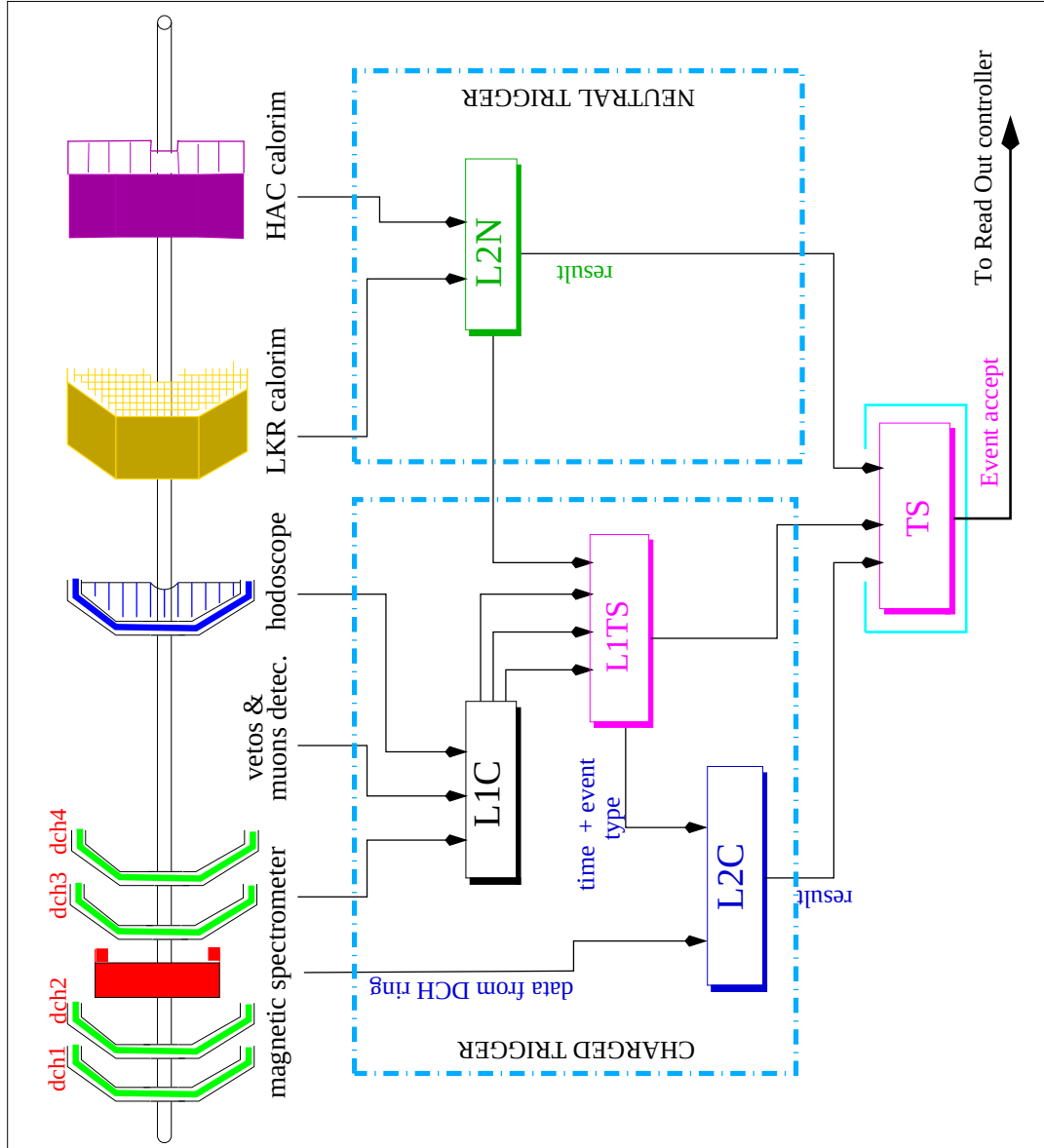


Figure 3.1: Simplified scheme of the trigger system. Two independent systems trigger on $K_{\pi^+\pi^-}$ charged and $K_{\pi^0\pi^0}$ neutral decays (Charged Trigger and Neutral Trigger respectively). A third system (the Trigger Supervisor or TS) correlates the former trigger information and produces the final decision to record the data.

consecutive readout requests. Figure 3.2 shows a block diagram of the TS, indicating its main components.

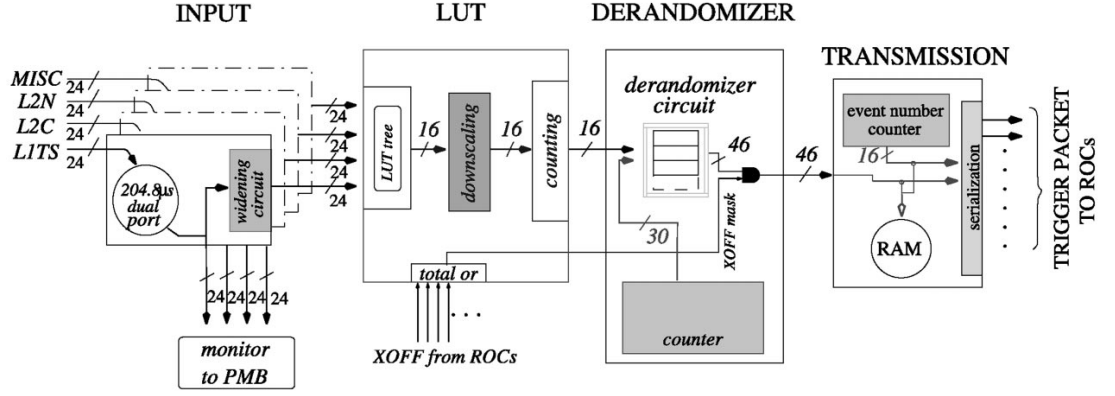


Figure 3.2: A scheme of the trigger supervisor [4]. The TS has been implemented on 8 VME boards, connected by a private bus and monitored by a single board CPU.

3.3 The Charged Trigger system

The Charged Trigger chain is a mixed hardware and software real-time system, partly pipelined.

The chain is composed (see figure 3.1) by a fast first level trigger (L1C), followed by a parallel computing engine (L2C or Massbox). In order to reduce the input rate to L2C below 100 kHz, from the total beam rate of 1 MHz, the first level logic requires loose checks on the topology and the total energy of the event. The checks are based on the signals from the hodoscopes, the first drift chamber, and the calorimeters. This is done inside the fully pipelined Level 1 Trigger Supervisor (L1TS). It continuously receives these signals, performs a time alignment, and produces a 3-bit identification code (later referred to as strobe) to be transferred to the L2C upon finding the checks satisfied. A 30-bit time-stamp is also attached, carrying the event time information.

The L2C (later referred to also as MBOX) is an asynchronous queued system with parallel processing capability. For each L1C trigger, it computes the hit coordinates, the space points and the tracks. It select the events based on the 2-tracks invariant mass, and the measured decay vertex longitudinal position.

3.3.1 The Level 1 Charged trigger

The fast first level (L1C) trigger is based on the signals from the hodoscopes, the calorimeters, and the first drift chamber.

3.3.1.1 The hodoscope topology trigger

The charged hodoscope (see Section 2.3.2) provides various fast signals [31,32] to L1C.

The charged hodoscope is subdivided into quadrants, whose counters signals are combined with logical OR's. Each quadrant includes also the two adjacent counters from the near quadrant, to form an extended quadrant. The QX, given by the coincidence of counters on crossed quadrants, opposite with respect to the beampipe, is formed to trigger kaon decays into $\pi^+\pi^-$. In this way geometrical inefficiencies are avoided in triggering on two body kaon decays, despite the finite size of the beam.

The QX gives also the reference on-line time of the event, i.e. the time-stamp, for the decays of the kaons into $\pi^+\pi^-$. Being the hodoscope counters individually timed, the on-line time resolution of the $\pi^+\pi^-$ trigger signal is only limited by the physical dimensions of the counters. Its value is about 5 ns, which corresponds to the time jitter of the signal. The phase of the QX signal with respect to the 40 MHz clock is also measured in steps of 6.25 ns by a two bit TDC [80]. The fine-time additional information is used by the L2C processors for the fast on-line reconstruction.

The rate of the QX is about 400 kHz at nominal beam intensity, with a reduction of the background by a factor of ~ 2.5 .

Furthermore, the pretrigger provides a dozen of signals, which are used to check the beam rates of events with different topologies. Some signals come from other low-level trigger subsystems, namely the AKL, the NHOD, the MUV, and the neutral hodoscope. The main pre-trigger output signals are:

QOR: total OR of all the charged hodoscope counters;

Q1: "1 *track*" signals in the charged hodoscope;

Q2: "2 *tracks*" signal in the charged hodoscope;

AKL: total OR of the AKL counters;

1 μ : 1 hit in both MUV planes 1 and 2;

2/ μ : 2 hits in either MUV planes 1 or 2, plus 1 hit in the other plane;

T0N: activity in any two quadrants of the Neutral Hodoscope;

The pre-trigger outputs are aligned in time and available after about 200 ns. They are synchronized with a 40 MHz clock, and fed to the Trigger Supervisor where they can be downscaled.

The synchronization is done in a special module [31] (later referred to as Synchronizer¹), which is very efficient (inefficiencies at the level of 10^{-5} have been measured).

The pretrigger signals are also recorded, event by event, by a 40 MHz digital PMB, used as Pattern Unit. Those data are used to measure off-line the efficiency of the trigger. The rates of the pretrigger signals are recorded through end-of-burst scalars.

3.3.1.2 The DCH multiplicity trigger

Every 25 ns the number of hits, integrated in the previous 100 ns, is available for each wire plane of the chambers [10]. The fast signals from the first DCH are combined as follows, and sent to the L1TS:

1TRK: 1 track in the first DCH, i.e. condition is ≤ 2 hits in at least 3 views of DCH1;

2TRK: at least 2 tracks in the first DCH, i.e. condition is ≥ 3 hits in at least 3 views of DCH1;

4TRK: at least 4 tracks in the first DCH, i.e. condition is ≥ 6 hits in at least 3 views of DCH1;

In 1998 the 2TRK was used in coincidence with the QX. It yielded a background reduction of rate by a factor of ~ 1.3 .

3.3.1.3 The ETOT trigger

A further reduction of the background rate (by a factor of ~ 1.6) comes from the coincidence of the QX and the ETOT signal [108], which is an on-line sum of

¹The Synchronizer consists of a cascade of 3 flip-flops. The first flip-flop holds its input signal, which is set equal to 1, until the arrival of the signal to be synchronized, which clocks it. When the signal to be synchronized arrives, the input signal of the first flip-flop is transferred to the input of second one. The 40 MHz clock is used to clock the second and third flip-flops, which make the synchronization.

the energies measured by the two calorimeters. If the energy is above the 35 GeV threshold, the ETOT signal is broadcast from the neutral trigger to the L1TS. ETOT mainly rejects $K_{\mu 3}$ and low energy $\pi^+\pi^-$ events.

3.3.1.4 The Level 1 Trigger Supervisor

Finally the Level 1 Trigger Supervisor (L1TS) combines the QX, the ETOT, and 2TRK, into the $\text{QX} \cdot \text{ETOT} \cdot \text{2TRK}$ coincidence, which is the main trigger request (strobe) to the L2C. Also, L1TS down-scales the single QX and feed it to the L2C, to provide an auxiliary control trigger, to check the ETOT efficiency.

3.3.2 The Level 2 Charged trigger

When the L1TS spots a candidate event, i.e. a set of data detected around a particular time-stamp, it prompts the DCH readout system to send the corresponding data from the Ring Cards to the L2C [1,98] (later referred to also as MBOX). The L2C processes that event (see figure 3.3), and produces an answer, consisting in the time-stamp, and an identification code of the event. The answer is transmitted to the Trigger Supervisor, which eventually decides to readout the corresponding data.

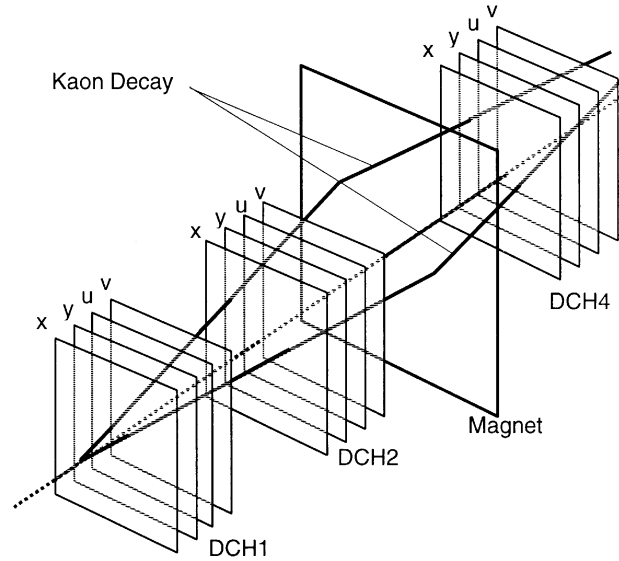


Figure 3.3: A $K_{\pi^+\pi^-}$ and the elements of the spectrometer exploited by the MBOX

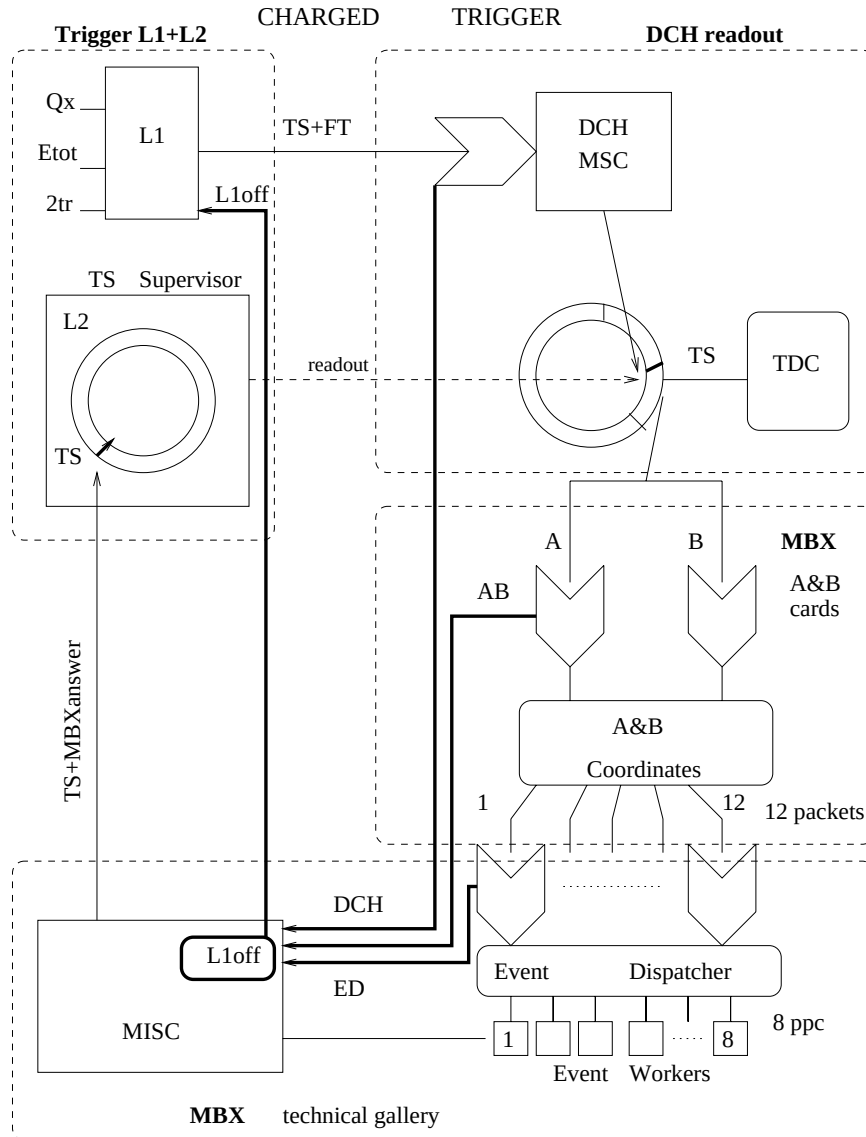


Figure 3.4: Scheme of the MBOX inter-links with the DCH read-out and the Trigger Supervisor

As shown in figure 3.4, the L2C system is made of the following subsystems: the Coordinate Builders (AB cards), the Event Dispatcher (ED), the Event Workers (EWs).

The Coordinate Builders: Each chamber view has its own AB card, which calculates the hit coordinates, by analyzing the the time information of the two planes (namely the A and B planes) of the view, readfrom the DCH Ring Cards. The raw data are fed by the DCH readout system into the input FIFOs of the AB card, and are processed through a 40 MHz pipelined algorithm: all neighboring wire hits are matched and, for each pair of hits, the event time is subtracted from the hit times yielding two drift times. These are then used as indexes in a 2-D Look-Up table to give the corresponding coordinate value.

The event dispatcher: The ED builds the whole event by putting together the coordinate information from the 12 views, and sends them to the first Event Worker (EW), which is available for processing.

The event worker farm: The function of an EW is to receive the 12 coordinate packets of an event, and use them to compute the particle space-points, tracks and magnetic deflections in order to determine whether the event is compatible with a kaon into $\pi^+\pi^-$ decay.

The principle of the algorithm is to assume that the event is a kaon $\pi^+\pi^-$ decay, and compute the corresponding invariant mass; if the calculated mass is not compatible with the neutral kaon mass, the event is tagged as background.

The injected dead-time: The L2C is an asynchronous queued system. Since the statistical distribution of events in time is Poissonian, the queues will fluctuate around an average value, provided that the average processing rate is faster that the event rate. The actual processing latency of an event depends on its intrinsic complexity and on the time lost waiting in queues. Therefore, reducing queues increases the system efficiency.

The chain includes three queues; data word from the DCH Ring Cards are first fed (see figure 3.4) in the DCH Master Service Card (MS Card) trough an input FIFO and from the Master Service Card to the input FIFO of the coordinate builder

cards. Finally, the data computed by the AB Cards are sent to the input FIFO of the L2C Event Dispatcher.

In order to control the queuing levels, the L2C includes an On/Off mechanism: when queues reach a critical level, the L2C asserts an overload L1OFF signal, turning off the L1C; once the queues are absorbed by the system, the L2C releases the L1OFF, allowing the L1C to resume its strobing activity. This mechanism reduces inefficiency by increasing dead-time.

The latency time between two events of the queue in the first queue is sized to allow a complete extraction of the data words ($3.5 \mu\text{s}$) from the DCH Ring Cards and in 1998 was fixed at $6 \mu\text{s}$, and the difference between the On and the Off level was of 6 FIFO slots. This resulted to be the main upper limit for L2C input requests, whose rate could not be more than 200 kHz .

3.4 The Neutral Trigger system

The NA48 neutral trigger [49, 56] is implemented in a 40MHz dead-time free pipeline, using the information of the electromagnetic calorimeter. The total latency of the trigger pipeline is 128 clock cycles corresponding to $3.2 \mu\text{s}$. The trigger reconstructs on-line, every 25 ns, the total energy, the Centre Of Gravity (CoG), the kaon lifetime and the number of peaks in the horizontal and vertical calorimeter projection, and performs a selection on this physical quantities.

In order to calculate these quantities, the calorimeter single-cell information is reduced to two orthogonal views of projective calorimeter information. The data flow in the neutral trigger is shown in figure 3.5. The first step in making the granularity of the calorimeter coarser is to add the calorimeter signals from 16 (2×8) single cells with analogue-sum circuits to form super-cells. The information from a single calorimeter cell is used twice to get two orientations (x- and y-view). This is done in the Calorimeter Pipeline Digitiser (CPD) system [11].

The signal of the super-cell is digitized by a 10-bit 40 MHz FADC, and filtered, to remove super-cells with an energy below a certain threshold. The digital super-cell signals are summed up into 64 vertical and 64 horizontal projections to gain coarser granularity (4 cm wide strips). This digitization and summing into strips is done in the Vienna Filter Module (VFM) system. The SPY system fans out the vertical and horizontal projections to the Pipeline Memory Board (PMB) system and the Peak

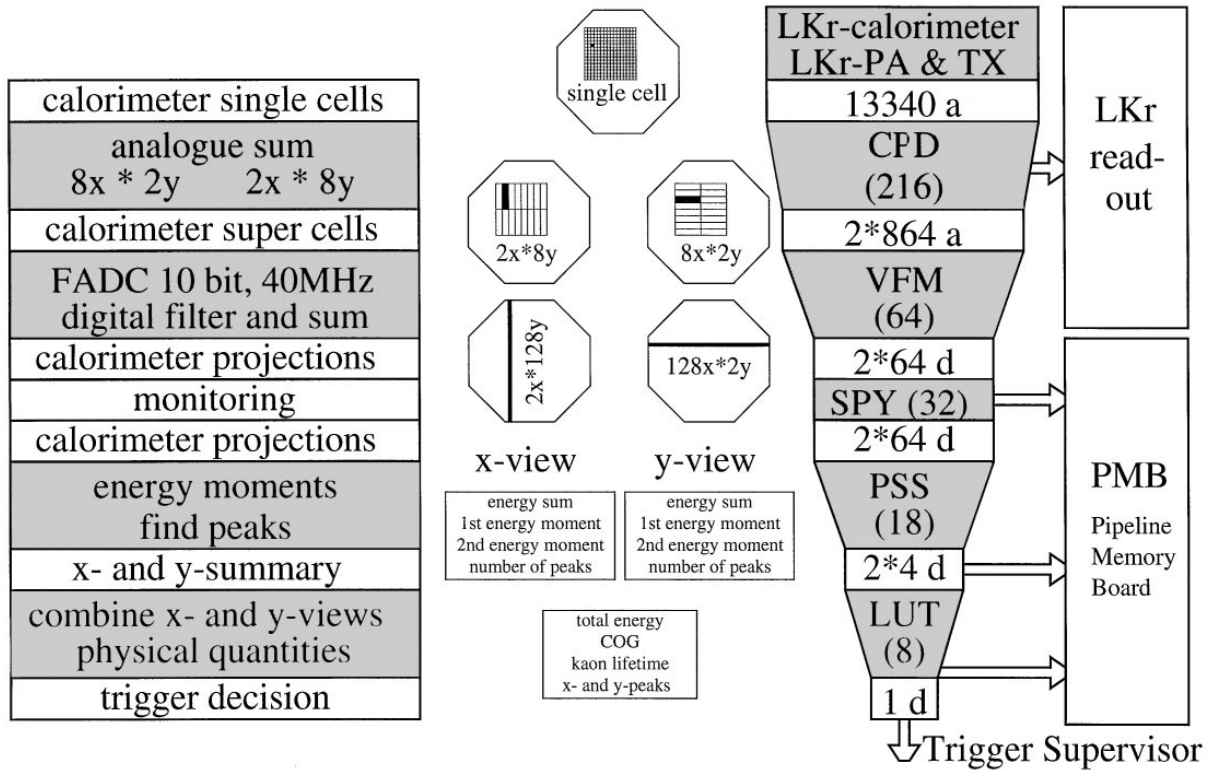


Figure 3.5: The signal flow in the neutral trigger.

Sum System (PSS). In the PSS the total energy deposited in the LKr-calorimeter, the first and second energy moments and the number of peaks seen in the two views are calculated. The peaks are counted in bins of 3.125 ns to identify accidental hits in the calorimeter. In the Look-Up Table (LUT) system these quantities are merged from both views, the physical quantities are calculated and the trigger cuts are applied. For all steps the digital information is stored in the PMB system and recorded with an accepted event. This allows the on-line monitoring of the neutral trigger, and an off-line comparison between the information of the calorimeter readout and the information in the neutral trigger.

In figure 3.6 the event display of a kaon to $\pi^0\pi^0$ event in the electromagnetic calorimeter is shown.

The energy resolution of the trigger has been determined to be 2.7% over the full energy range.

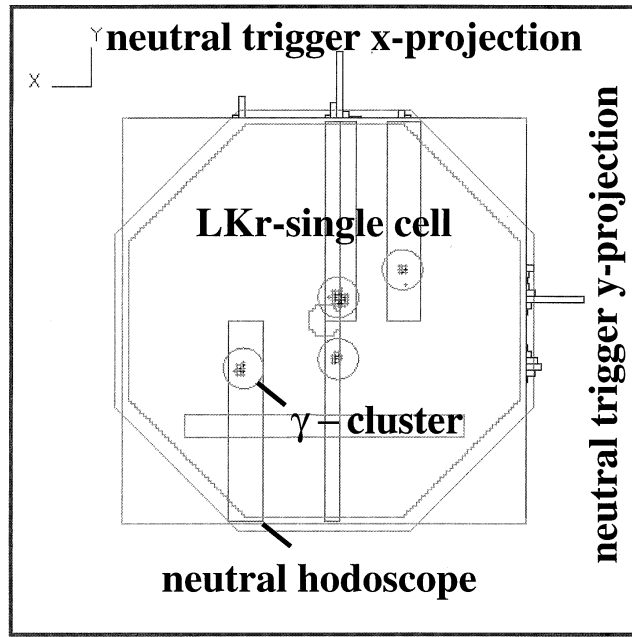


Figure 3.6: $K \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$ decay in the LKR calorimeter.

3.5 The Main Triggers for the 1998 data taking

The Trigger Supervisor collects the above described signals, from the local lower level trigger systems, combines them, and requires the data acquisition.

The trigger configuration for almost the whole 1998 data taking is shown in table 3.1. Those triggers are also referred to as L2 triggers.

$QX \cdot ETOT \cdot 2TRK \cdot MBOX$ $(QX \cdot ETOT + QX/128)/2000$ $QX \cdot ETOT \cdot 2TRK/80$	main $\pi^+ \pi^-$ trigger auxiliary control trigger auxiliary control trigger referred to as L1pp control trigger
L2N T0N/100	main $\pi^0 \pi^0$ trigger auxiliary control trigger
K_S type random K_L type random	special trigger for accidental studies special trigger for accidental studies

Table 3.1: The main triggers for e'/e physics, in almost the whole data 1998 taking.

The special triggers for accidental studies (namely the random triggers), use the the signals of the KLM and KSM monitors, located near the beam dumps: they are downscaed (typically by a factor of 20000) and delayed by $69.3 \mu s$. This provides a

random trigger which is proportional to the intensity of the beams.

The downscaling factors are such that during the spill ~ 10 readouts are triggered by the KLM, and ~ 10 triggered by KSM, later referred respectively as to KL and KS random events or R_L and R_S . The read out performed without zero suppression.

3.6 The Data Acquisition

Figure 3.7 illustrates the NA48 Data Acquisition [110]. If a trigger is issued by the Trigger Supervisor, the sub-detectors send data for that event to the PC farm. The PC farm builds the sub-detector data into complete events, and sends it to the CERN computing center where the data is processed and stored.

3.6.1 Sub-detector Read Out

When a readout request is received by a sub-detector, the event information is selected from the Ring Buffer based on the time stamp information. Information in a $[-400 \div +400]$ ns window around the trigger time-stamp is sent to a dedicated PC (referred to as a sub-detector PC).

3.6.2 The PC Farm

The PC farm consists of 11 sub-detector PCs (SDPCs), 8 event building PCs (EBPCs) and a control PC, each running Linux. The sub-detector PCs store the sub-detector data which has been collected from the ring buffers. The event building PCs rearrange the data and send it to the CERN computing center. The control PC issues instructions to the SDPCs and EBPCs and monitors the PC farm processes. The transfer of information between the PCs is enabled by a fast ethernet switch. Each PC can send, and receive information, to and from the switch at a rate of 200 Mbit/s. During the SPS burst, the SDPCs store the sub-detector data, and at the end of the burst this data is checked and partitioned into eight blocks. Each data block is sent to one of the eight EBPCs. The data on the EBPCs are arranged into complete events: each complete event contains information from each of the sub-detectors. The complete events are then sent, via a 7 km fast ethernet link, to the CERN computing center. The data is fed into a Meiko Computing Surface 2

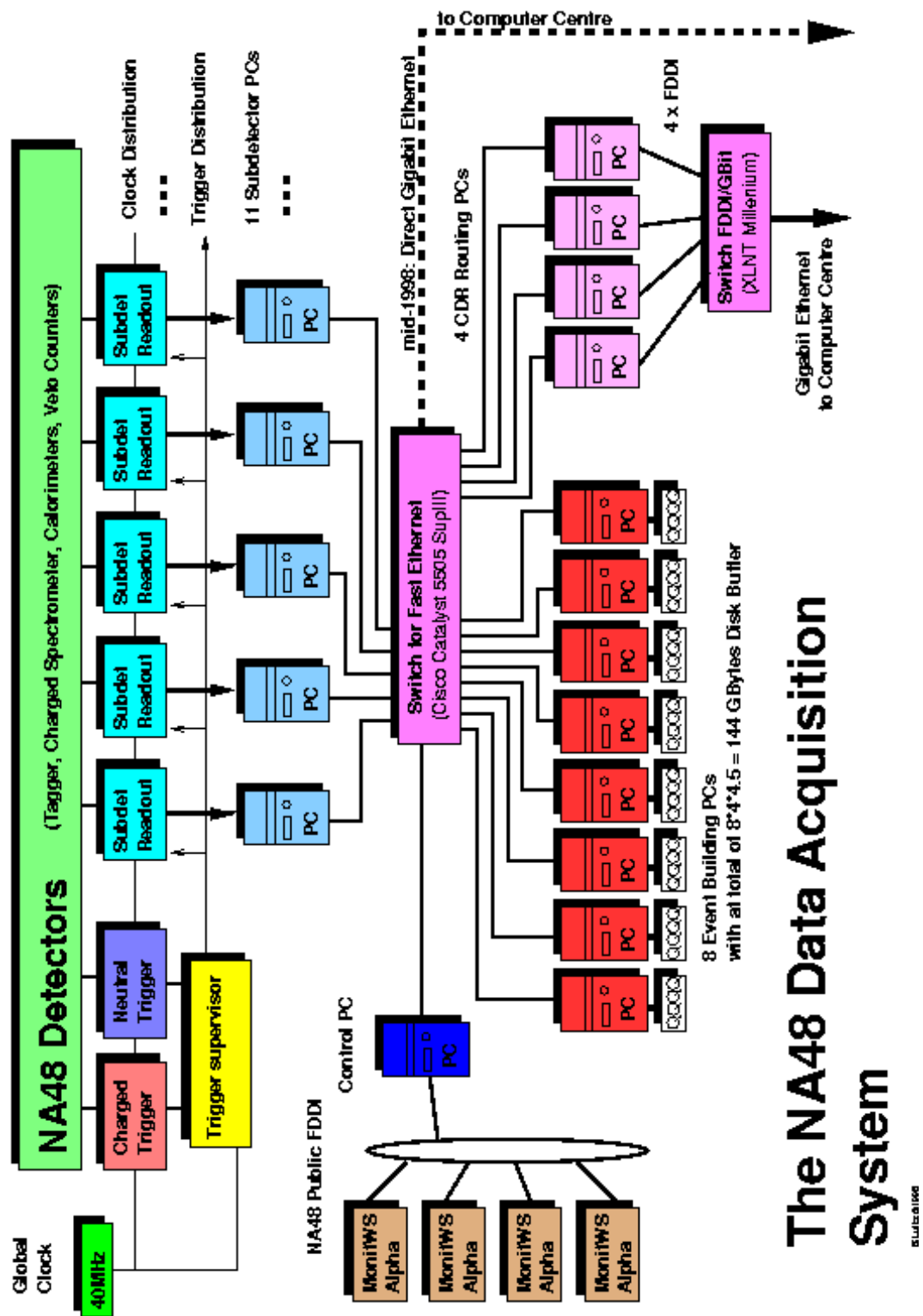


Figure 3.7: The NA48 Data Acquisition system.

parallel processing computer (CS2), where the events are assembled into a burst file.

The final stage of on-line data processing is the reconstruction of the data, and the selection of the reconstructed events by the Level 3 Trigger. The Level 3 Trigger and Real Time Reconstruction (L3/RTR) is implemented entirely in software and run on the CS2 computer. For events with main $\pi^+\pi^-$ or $\pi^0\pi^0$ triggers, the L3/RTR program [52] first executes the LKR and DCH reconstructions, as described in Sections 4.1.1 and 4.1.2, using the best available calibration constants. These events are then filtered by the Neutral or Charged Filter, by very loose cuts. If an event is selected by the Filters, the reconstruction of the data from the other sub-detectors is carried out and the event is saved to tape. A small fraction of the events that do not satisfy the filter conditions are also saved to tape, to check the Filter efficiency.

3.6.3 Data Formats and Reprocessing

The events are saved to tape in two formats: **COmPACT** and **Raw**. The **Raw** data format contains the unreconstructed sub-detector information. The **COmPACT** data format contains a subset of reconstructed quantities, and is used for physics analysis. Due to the large data volume of the NA48 experiment, there is also a **SuperCOmPACT** data format, which contains the selection of the **COmPACT** variables relevant for the measurement of $\mathcal{R}$. The **COmPACT** data set is filtered [84] and those events suitable for the $\mathcal{R}$ analysis are written in **SuperCOmPACT** format.

After the 1998 data-taking period was complete, the **Raw** data set was reprocessed by running the reconstruction program using updated values of the calibration constants. The data used in this thesis is from the re-processing; both **COmPACT** and **SuperCOmPACT** data format are used.

4 Data reduction: Reconstruction and Selection of the events

4.1 Event reconstruction

4.1.1 The $K \rightarrow \pi^+\pi^-$ mode reconstruction

The track reconstruction: The drift chamber reconstruction [34] identifies and measures particle tracks from hits in the drift chambers. It calculates the charge, the momentum, the position and the time crossing of the tracks.

The reconstruction is made in two stages. The first stage uses only the position of the hits to reconstruct the tracks. The second stage uses the drift time information to improve the resolution, and to resolve any left-right ambiguity.

The first step of the reconstruction algorithm is to form *mini-tracks* with the 1st and 2nd the chamber. A mini-track is formed by joining clusters of wire hit in chamber 1 and 2 by a straight line. The mini-tracks must be consistent with the path of a decay product from either the KL or KS beam. The direction of these mini-tracks are used to estimate vertical (y) positions¹ of the track hits in chamber 4. Clusters of wire hit in chamber 4 are grouped into space-points. A space-point is a set of 3 or 4 clusters where the positions on the x and y -view agree with the u and v -view positions. A track is defined when a space-point agrees with an estimated y -positions within 4 cm.

In the second stage reconstruction, the crossing times, measured by the wires, are used. This information is used to gain a better precision for the position of the hits in space. A quality variable is assigned to each track. Tracks are rejected either due to bad quality, or due to inconsistency between the reconstructed space-points and the wire hit information. The track momentum is calculated using the curvature of track trajectory; an accurate map of the magnetic field is accounted. If the closest distance of approach between track pairs is less than 5 cm, then the tracks are defined as coming from a common decay vertex. The position of the vertex is defined as the mid-point between the two tracks at their closest distance of approach.

Each decay vertex with oppositely charged tracks is considered as a candidate for a $K_{\pi^+\pi^-}$ event.

¹There is almost no deflection in this view, due to the magnetic field.

The vertex resolution is typically 50 cm in the longitudinal direction (z), and 2 mm in the transverse directions (x, y). Since the beams are separated by about 6 cm in the decay region, a clean identification of $K_{\pi^+\pi^-}^S$ and $K_{\pi^+\pi^-}^L$ decays is possible (this is referred to as *y-vertex tagging* in the following).

The charged energy measurement: The energy of the kaon for this decay is calculated using the opening angle $\theta_{\pi\pi}$ between the two tracks and the energies of the two tracks, assuming they were charged pions:

$$E_K = \frac{\sqrt{\rho(m_{K^0}^2 - m_{\pi^\pm}^2 \rho)}}{\theta_{\pi\pi}} \quad \text{where} \quad \rho = 2 + \left| \frac{p_+}{p_-} \right| + \left| \frac{p_-}{p_+} \right| \quad (4.1)$$

This measurement of E_K reduces the effects from uncertainties in magnetic field and multiple scattering in the definition of the fiducial energy [81, Appendix A] and in the proper time measurement; it is hence preference to the more usual $E_K = |p_+| + |p_-|$.

The event time measurement: The charged hodoscope is used to define the event time of a $K_{\pi^+\pi^-}$ event [77]. Reconstructed tracks from a common vertex are used to calculate the positions of the charged particle crossing points on the hodoscope. These positions are used to correct the times for the signal propagation in the scintillator.

Among the hits associated to the two tracks, those which are out of time with respect to the average tracks times for more than 6 ns are rejected. The remaining hits are combined to perform a rough time average. Hits that are more than 3σ far from the average are further rejected and the average recalculated. The previous two last step are iterated until all the residual hits are compatible with their average within $3\sigma^2$. If, at least, one hit per track survived, the charged event time is calculated as the average of the hits' time weighted by they average sigmas.

This procedure protects against tails in the single time measurements, mainly due to accidental hits. Events for which the procedure fails are rejected, removing $\sim 0.2\%$ of the signal.

Reconstruction of the muons: The muon veto reconstruction [53] identifies the muons. The regions around the impact points of the reconstructed tracks, projected

²The resolution for the single hit is ~ 200 ps on average

onto the muon veto, are searched for scintillator hits. The track is identified as a muon when a hit is found in both planes 1 and 2. The time of the muon hit is calculated as the average of the two hits, corrected for the propagation time of the photons in the scintillator, and the time for the muon to travel between the scintillator planes.

4.1.2 The $K \rightarrow \pi^0 \pi^0$ mode reconstruction

The photons reconstruction: The LKR reconstruction [103] calculates the energies, positions, times, and sizes of the clusters due to the particle hits in the calorimeter (referred to as a clusters).

The signals from the calorimeter cells are starting point for the reconstruction algorithm. Cells with energies greater than 0.1 GeV are the candidate seed cells for clusters. If a seed cell is higher in energy than the eight surrounding cells, and is greater than a threshold defined by the average energy of the eight surrounding cells ($E_{seed} > 0.18 \text{ GeV} + 1.8 \cdot E_{ave}$), then a cluster is defined.

The next stage of the reconstruction loops over all the clusters. The cluster includes cells up to 11 cm, about the seed cell. If a cell can belong to two or more clusters, the energy of the cell is shared between clusters according to the expected shower profile³. At this stage corrections are made for the energy loss due to the hole for the beam pipe, for residual effects due to the zig-zag structure fo the electrodes, and for the overall energy scale of the calorimeter. The reconstruction algorithm takes into account dead cells within the calorimeter.

The position of a cluster is computed as the barycentre of the energy distribution in a 3×3 box of cells centered on the cluster seed cell⁴. The cluster sizes in the x and y directions are computed using the r.m.s. of the energy distribution in a 5×5 cell box around the seed cell. The time of a cluster is calculated as the energy weighted time average of the cells in 5×5 box centered on the seed cell. Each set of four clusters is considered as a candidate for a $K_{\pi^0 \pi^0}$.

³The shower profile was estimated using a GEANT [33] simulation of showers in the calorimeter. The special “electron runs” (see Section 2.3.3) are also used to measured the showers profile in the electromagnetic calorimeter.

⁴Notice that up to 35% of the energy of a single shower is contained within the seed cell.

The neutral energy and vertex position measurements: Using the position and energy of the clusters, the following quantities are calculated for each $K_{\pi^0\pi^0}$ candidate:

- The kaon energy, which is defined as the sum of the energies of the 4 clusters, is:

$$E_K = \sum_{i=1}^4 E_{\gamma_i} \quad (4.2)$$

The average resolution on E_K is $\sim 0.6\%$;

- The longitudinal position z_{vtx} of the decay vertex, relative to the front entrance of the calorimeter z_{lkr} , is:

$$\Delta z \equiv z_{lkr} - z_{vtx} = \frac{1}{m_K} \sqrt{\sum_{i=1}^4 \sum_{j>i}^4 E_{\gamma_i} E_{\gamma_j} d_{ij}^2}, \quad \text{where} \quad d_{ij}^2 = (x_i - x_j)^2 + (y_i - y_j)^2, \quad (4.3)$$

which is used to reconstruct the decay proper time τ . The resolution on Δz is 50 to 70 cm depending on energy.

For each set of 4 photons, using Δz , the invariant masses (m_{ij} and m_{kl}) of the two photon pairs are computed:

$$m_{ij} = \frac{1}{\Delta z} \sqrt{E_{\gamma_i} E_{\gamma_j} d_{ij}^2}, \quad (4.4)$$

and compared to the π^0 nominal mass. To this purpose, a χ^2 variable is computed as follows:

$$\chi_{\text{reli}}^2 = \left[\frac{(m_{ij} + m_{kl})/2 - m_{\pi^0}}{\sigma_+} \right]^2 + \left[\frac{(m_{ij} - m_{kl})/2}{\sigma_-} \right]^2 \quad (4.5)$$

where $\sigma_{\pm}$ are the resolutions of the invariant mass combinations $(m_{ij} \pm m_{kl})/2$ measured on the data (parameterized as a function of the lowest photon energy). The best pairing of the photons is chosen by taking the pairing with the minimum χ_{reli}^2 . Due to the constraint on m_K , the combinations $(m_{ij} \pm m_{kl})/2$ are to good approximation uncorrelated. Typical values of σ_+ and σ_- are 0.4 and 0.8 MeV/c² (see figure 4.1).

The best pairing combination is used to reject the background, by requiring $\chi_{\text{reli}}^2 < 13.5$.

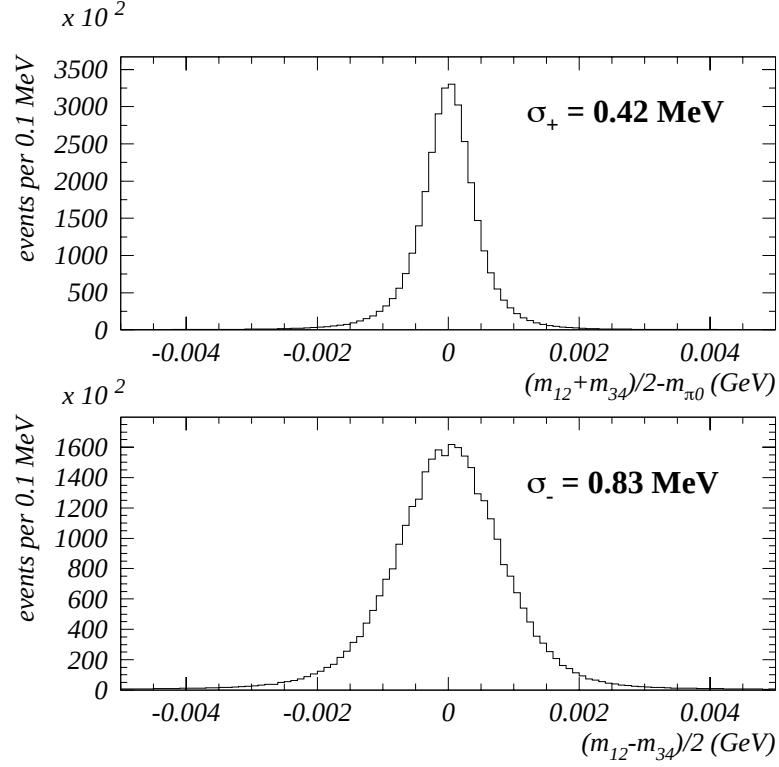


Figure 4.1: The resolution of invariant masses for the selected photon pairs in K_S events. Due to the constraint on m_K , the combinations $(m_{12} \pm m_{34})/2$ (see eqn. 4.5) of the photon pairs in the selected K_S events, are uncorrelated to good approximation.

The event time measurement: The resolution on the time measurement [41] of a single cell is inversely proportional to the energy released in the cell: thus the highest energy cells of the cluster are interesting. For a candidate event only 8 cell times are considered: for each photon, the time of the seed cell, and of the most energetic neighbour cell are chosen. The average of those 8 times is calculated, and the furthest time from the average is rejected, in case it is out with ± 3 ns from the average.

The residual times are combined in an average, weighted with the respective cell resolutions⁵. This time average defines the time of the neutral candidate event.

The above procedure has a negligible ($< 10^{-4}$) inefficiency.

⁵The resolutions are measured on events taken with the *KS-only* mode; they are parametrized as a function of the energy of the shower, separately for the seed and the lateral cells in the cluster.

4.2 Identification of the kaon decays in two pions

4.2.1 Common selections

Trigger dead-time rejection There were two trigger dead-time effects in the 1998 data: the charged trigger dead-time, which comes from both “Massbox dead time” and “QX dead time” (see Chapter 9), and the drift chamber overflow condition (see Chapter 10). Both of these effects prevent charged events from being triggered and reconstructed with full efficiency. In particular, the charged trigger dead-time causes about $\sim 3\%$ of the charged events to be lost. The drift chamber overflow condition occurs with a probability of $\sim 25\%$. But not the whole $\sim 25\%$ results in an effective loss of events: the overflows resulting in an additional inefficiency of the charged trigger are $\sim 9\%$; that is $\sim 9\%$ of the events are not triggered, due to the overflow. The residual $\sim 16\%$ of the overflow probability is correlated to a reconstruction inefficiency of about $\sim 45\%$ (see Chapter 10).

In order to maintain the highest detector efficiency for the final selected events, the requirement that the events used in the analysis do not have overflows within ± 312 ns of the trigger time, is applied. This interval, larger than the sum of the drift and reset time, gets rid of any correlation between overflows and selected events.

In general, if during some interval of time one of the two decay modes could not be recorded, that interval is excluded from the analysis. Thus the selection criteria on overflows, and on charged trigger dead-time, are also applied to the neutral modes. This procedure, which is later referred to as **symmetrization**, is applied whenever possible: it is crucial for the principle of simultaneous data taking to be maintained. It is also useful to avoid indirect biases related to different average beam intensities.

4.2.2 Identification of the $\pi^+\pi^-$ final state

Quality selections: Good $K_{\pi^+\pi^-}$ candidates are first selected using the following criteria:

- The pion momentum is required to be $p_{\pm} < 10$ GeV/c (TRACKS);
- The reconstructed charge of the two tracks must have (VERCDA) opposite sign, and the tracks must be fitted with good χ^2 ;
- The closest distance of approach (CDA) of the two tracks is required to be

< 3 cm. This selection (VERCDA) is effective against bad track association to the hits, and against events with pion decay;

- The center of gravity (CoG) of the event is defined as the momentum-weighted position of the tracks, extrapolated from DCH 1 and 2 to the LKR entrance surface (x_i, y_i) , as follows:

$$\text{CoG} = \frac{\sqrt{\left(\sum_{i=1,2} x_i |p_i|\right)^2 + \left(\sum_{i=1,2} y_i |p_i|\right)^2}}{\sum_{i=1,2} |p_i|} \quad (4.6)$$

The CoG is required to be < 10 cm. This selection (LKRCOG) cleans the sample from kaons scattered in the KS collimator and in the AKS. It also improves the background rejection;

- The time difference between the tracks is required to be < 6 ns in order to reject accidental tracks in the vertex definition (DELTIM);
- The time of the vertex is required to be within ± 20 ns from the center of the trigger time-slice. This selection (t_{vx} selection) avoids to reconstruct events triggered by QX after-pulses (affecting 15% of charged decay events).

Background rejection: To reject the large amount background events with two tracks (mainly from $K_{\mu 3}$, $K_{e 3}$, and $K_{\pi^+\pi^-\pi^0}$ decays of K_L , which have branching ratios up to 200 times larger than $K_{\pi\pi}^L$), the following selections are applied:

- The $\pi^+\pi^-$ invariant mass m_{+-} is required (ULTMAS) to be equal to the kaon mass within 3σ . The resolution $\sigma_{m_{+-}}$ has been parametrized as a function of the energy and is about $\sim 2.5 \text{ MeV}/c^2$ (see figure 2.21);
- The reconstructed kaon transverse momentum is required (ULTPT2) to be equal to zero within the errors. The distance between the target and the spectrometer differs by a factor of 2 for K_S and K_L , which is accounted in the definition of the transverse momentum. In order to have a symmetric selection, for K_S and K_L events, the transverse momentum of the kaon is defined by using the direction connecting the target and the kaon reconstructed position projected at DCH1, as the reference direction for $p_T' = 0$ (see figure 4.2). The distribution of the transverse momentum, defined in this way, is almost

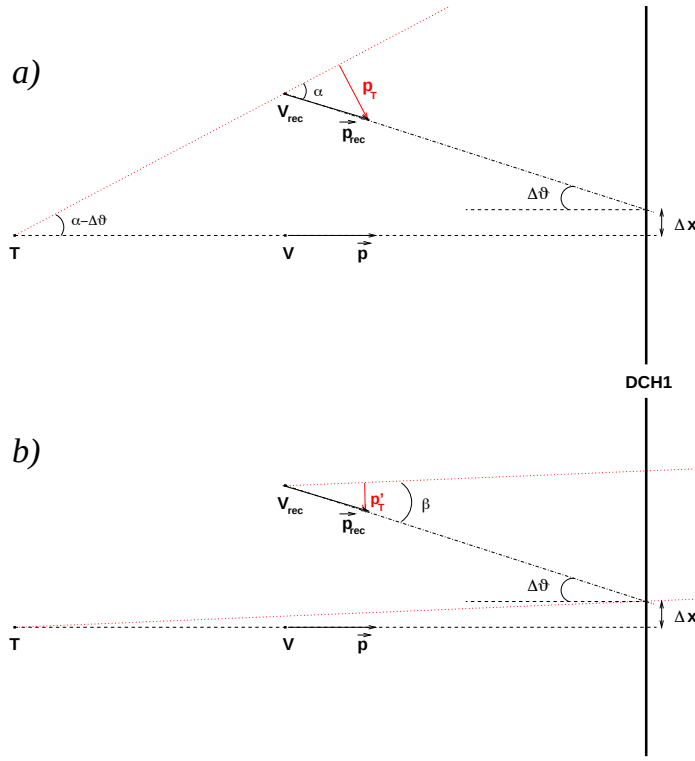


Figure 4.2: Definition of the p_T and p'_T variables, describing the reconstructed kaon transverse momentum. V and P are the true kaon vertex and momentum, V_{rec} and p_{rec} the reconstructed ones (from [59]).

independent on the target position.

Tus the selection $|p'_T| < 0.01414 \text{ GeV}/c$ rejects K_S and K_L good events, with the same probability of $\lesssim 0.1\%$, due to tails in the kinematical variables reconstruction;

- The electrons from K_{e3} are rejected by comparing the track momentum p (expressed in GeV/c) measured by the spectrometer with the track energy E (expressed in GeV) measured by the LKR calorimeter. The requirement $E/p < 0.8$ (KE3) has an efficiency of 95% on true $K_{\pi^+\pi^-}$ events and a rejection factor 500 on K_{e3} decays. In order to make this selection effective, track extrapolations to the LKR surface are required to be within the detector acceptance, and to be at least 2 cm away from the dead cells;
- $K_{\mu 3}$ decays are rejected (KMU3) when one hit in the muon veto, both in space and time (with a selection at $\pm 4 \text{ ns}$), is on the extrapolation of the track. Extrapolated tracks are required to be inside the acceptance of the muon counters. The selection accounts for multiple scattering. The rejection

factor of $K_{\mu 3}$ events is about 500, while several per cent of true $K_{\pi^+\pi^-}$ events are lost due to pion decay;

- The pion momentum asymmetry,

$$\mathcal{A} = \left| \frac{p_+ - p_-}{p_+ + p_-} \right|$$

is used to select symmetric events, i.e. events with small decay angle in the kaon rest frame. The selections (ASYMP) $\mathcal{A} < 0.68$ and $\mathcal{A} < 1.08 - E_K[\text{GeV}]/192$ entirely remove Λ and $\bar{\Lambda}$ semileptonic decays. The selection rejects also events with tracks near the vacuum pipe, which require a precise Monte Carlo modeling. In addition, it helps to minimize the acceptance difference (see [59][Section 5.3]), between K_S and K_L decays.

The Monte Carlo simulation shows that after this selection the residual background is at the level of a few per mill, dominated by K_{e3} and $K_{\mu 3}$ events. The measurement and subtraction of the residual background from the final sample of K_L decays is discussed in the next Chapter 5.

4.2.3 Identification of the $\pi^0\pi^0$ final state

Quality selection: The selection of the $\pi^0\pi^0$ candidates proceeds as follows:

- Photon energy $3 \text{ GeV} < E_\gamma < 100 \text{ GeV}$;
- Distance between the two closest clusters $> 10 \text{ cm}$;
- Clusters must be within the fiducial volume of the calorimeter and at least 2 cm away from any dead cell;
- The difference of any cluster time with the average time of the four clusters must be $< 5 \text{ ns}$;
- The CoG of the event, defined as:

$$\text{CoG} = \frac{\sqrt{\left(\sum_{i=1,4} x_i |E_i|\right)^2 + \left(\sum_{i=1,4} y_i |E_i|\right)^2}}{\sum_{i=1,4} |E_i|} \quad (4.7)$$

must be $< 10 \text{ cm}$. Notice that the selection is the same for the charged events. The bias due to different resolution in the two modes is negligible and is anyway included in the acceptance correction (see Section 5.5).

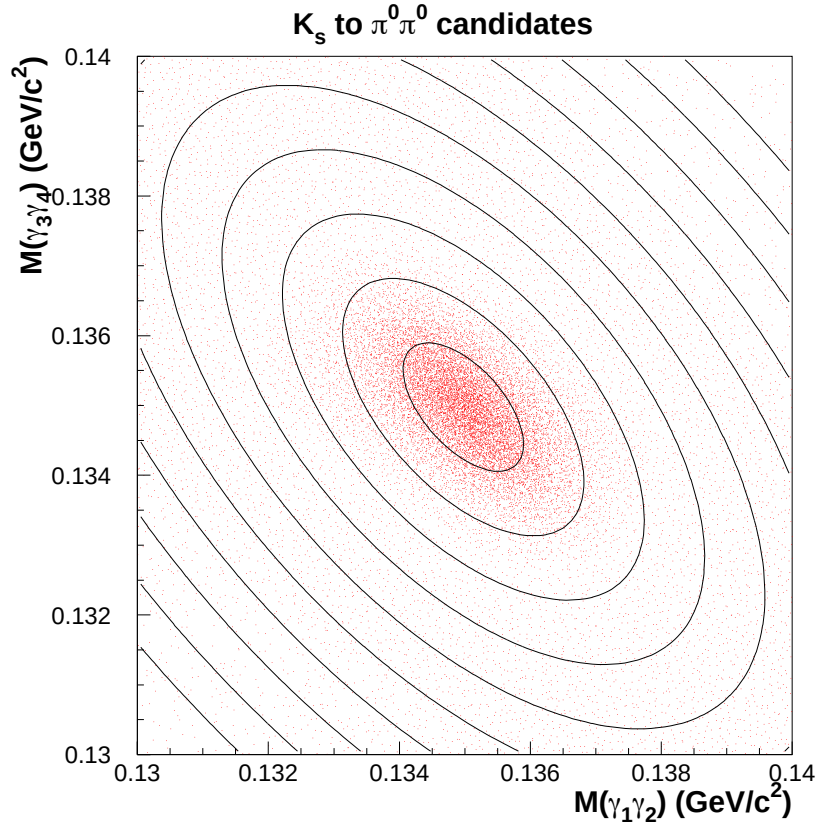


Figure 4.3: The invariant masses ($m_{\gamma_1\gamma_2}$ and $m_{\gamma_3\gamma_4}$) of the selected photon pairs in K_S events.

Background rejection: The following criteria are used to select the true $2\pi^0$ decays, and to reject the $3\pi^0$ decays of K_L ($K_{\pi^0\pi^0\pi^0}$), the main source of background:

- No additional cluster of energy > 1.5 GeV and within ± 3 ns of the candidate event time;
- The best combination of the pairing photon pairs must have a $\chi^2_{\text{reli}} < 13.5$; i.e. the two 2γ invariant masses must agree with the two π^0 hypothesis (see figures 4.3 and 4.1). This requirement removes about 7% of true $K_{\pi^0\pi^0}$ events, because of Dalitz decays, and photon conversions in the Kevlar window or in the spectrometer volume upstream of the magnet (70%); the remaining 30% is due to the electromagnetic calorimeter response, and is dominated by occasional photon nucleon interactions', resulting in smaller reconstructed energy. Both effects are highly symmetric between K_S and K_L events and do not affect the measurement of the double ratio.

Since the surviving $3\pi^0$ events have two undetected clusters in the calorimeter, the total energy is underestimated and consequently the reconstructed vertex is shifted toward the calorimeter (see eqn. 4.3 for Δz). A better rejection of the background is expected by tightening the requirement on the longitudinal position of the decay vertex z_{vtx} , i.e. by moving upstream from the end of the fiducial volume.

The obtained residual background is of about 0.1%. It is measured directly from the data, and subtracted.

4.3 Identification of the K_S and K_L decays

In order to distinguish whether the event came from the KL or KS beamline the tagging procedure is used, which is based on the time of flight (ToF) measurement.

As described in Section 2.2.4, the tagger records the time of all protons going onto the KS beam target. The time of the protons in the tagger (t_{proton}) are compared to the reconstructed event times in the detector (t_{event}). After subtracting the time offset corresponding to the ToF between tagger and the detector, the distribution ($t_{event} - t_{proton}$) for K_S events is centered around 0 (see figure 4.4).

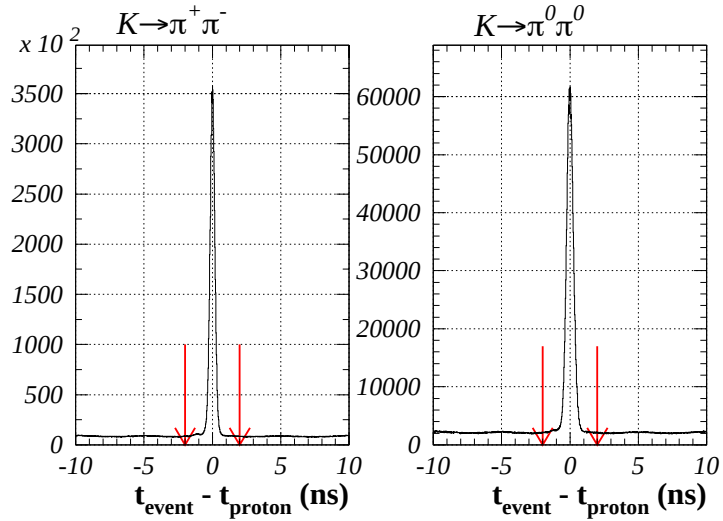


Figure 4.4: Distribution of the minimum difference between tagger and event times for y-vertex tagging selected K_S and K_L charged $K_{\pi^+\pi^-}$ events.

A ± 2 ns window is chosen to identify events as originating by a K_S decay. All decays having a ToF within this window are identified as K_S events; they are usually

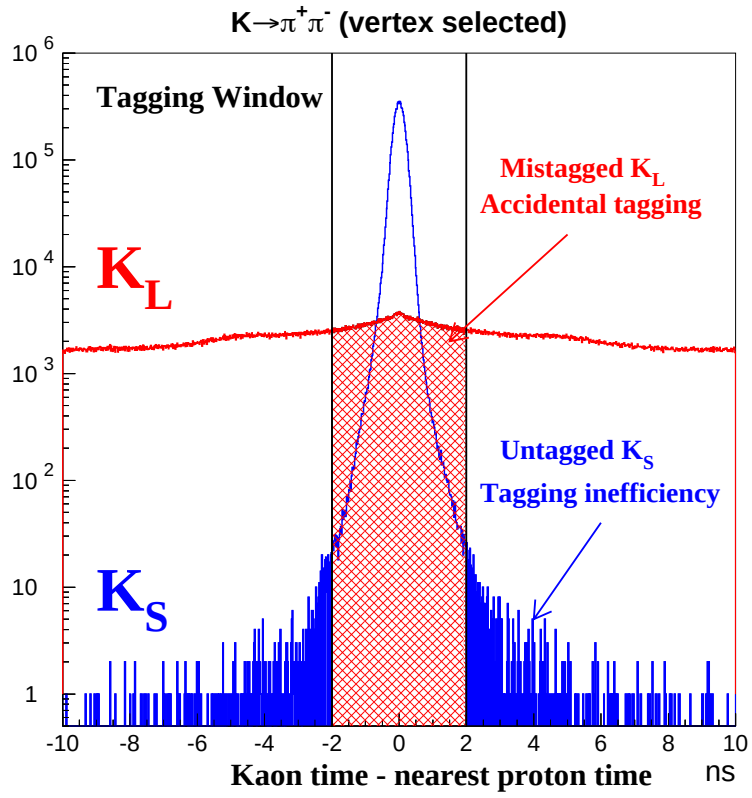


Figure 4.5: Distribution of the minimum difference between tagger and event times for y -vertex tagging selected K_S and K_L charged $K_{\pi^+\pi^-}$ events.

said to be *tagged* as K_S events. All other decays are identified as K_L events.

In the case of charged decays, it is possible to cross check the tagging method by using the reconstructed decay vertex position: the K_L and K_S targets are vertically displaced by ~ 7 cm, and both beams converge at the position of the LKR. The y and z positions of the decay vertex for $K_{\pi^+\pi^-}$ decays are shown in figure 4.6.

The y – z distribution of the vertex allows the decays from the K_L and K_S targets to be unambiguously identified: decays with $y_{vtx} > 4.2 \cdot (1 - z_{vtx}/z_{lkr})$ are from the K_S target, the others are from the K_L target.

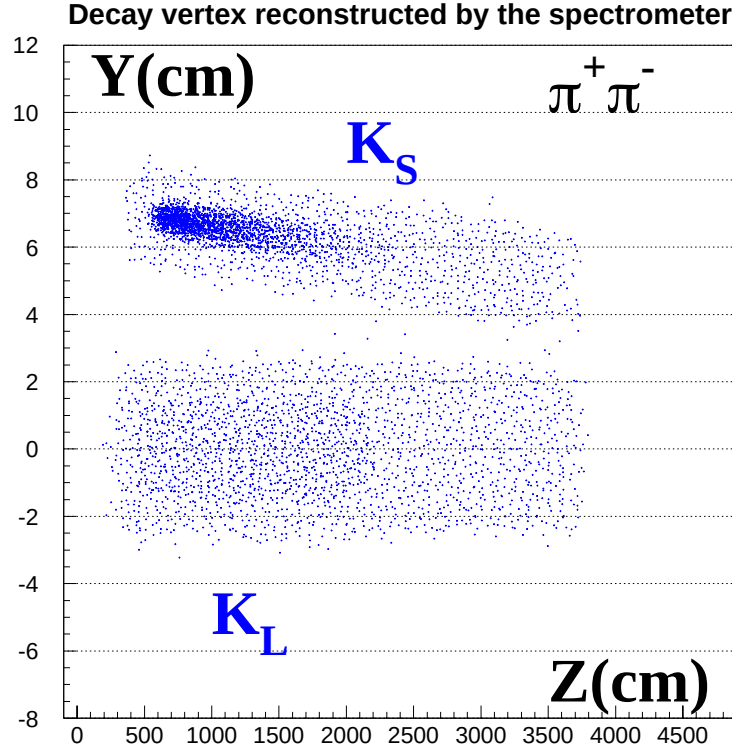


Figure 4.6: The decay vertex of selected K_S and K_L charged $K_{\pi^+\pi^-}$ events, reconstructed by the spectrometer.

Figure 4.7 shows the ToF for $K_{\pi^+\pi^-}^L$ and $K_{\pi^+\pi^-}^S$ events versus the vertex position reconstructed by the spectrometer. It can be seen that the tagging method based on the ToF measurement can lead to misidentify events (see figure 4.5); those events are referred to as mistagged events.

- When K_S events are mistagged as K_L , the effect is referred to as tagging inefficiency. As shown in figure 4.5, very few $K_{\pi^+\pi^-}^S$ events are out with the ± 2 ns tagging window, i.e. the tagging inefficiency is very small ($\alpha_{SL} \lesssim 2 \cdot 10^{-4}$).

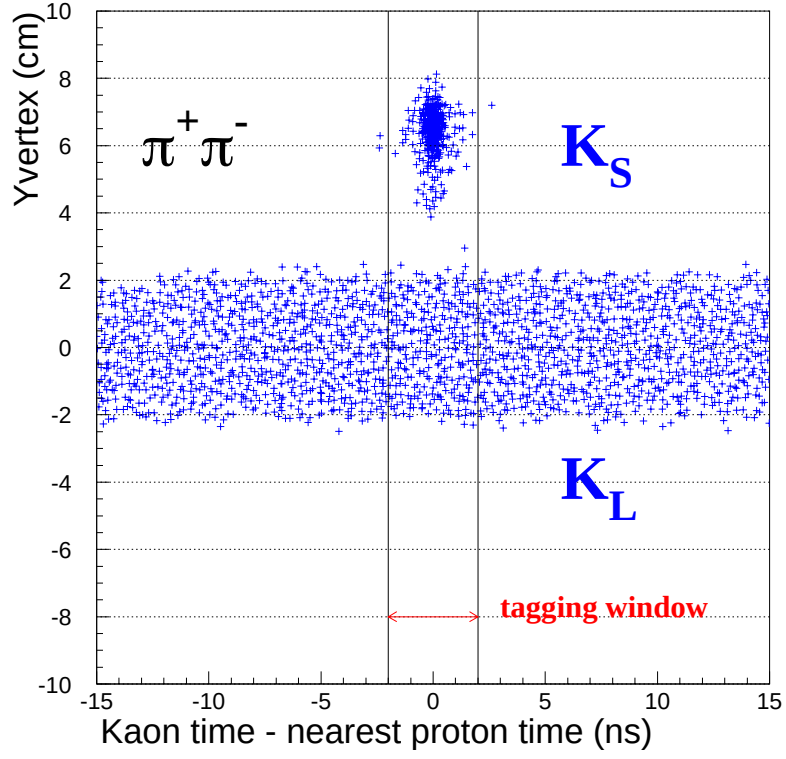


Figure 4.7: The vertical position of the decay vertex for selected K_S and K_L charged $K_{\pi^+\pi^-}$ events, is shown versus the minimum difference between tagger and event times.

Notice that the events with no time reconstructed, due to inefficiencies in charged hodoscope or electromagnetic calorimeter time measurement, are rejected (see Sections 4.1.1 and 4.1.2). These losses are measured to affect K_S and K_L events with the same probability. On the other hand, tagging inefficiencies, are due mostly to tagger inefficiency in the reconstruction of the proton time; in other words, the residual non gaussian tails in the resolution of the event time by charged hodoscope and electromagnetic calorimeter, have negligible effects on the time of flight measurement.

- When K_L decays are mistagged as K_S decays the effect is called accidental tagging or tagging dilution. The accidental tagging probability α_{LS} is measured as the ratio of the number of events tagged as K_S from the KL beam, and the total the number of events from the KL beam. The probability α_{LS} is $\sim 11\%$.

In case of the neutral modes, the mistagging probabilities α_{LS} and α_{SL} cannot be measured directly: the differences, respectively $\Delta\alpha_{LS}$ and $\Delta\alpha_{SL}$ of those mistagging parameters for neutral and charged events are measured, and added to the α_{LS} and α_{SL} parameters measured for charged events.

Those two mistagging corrections are crucial in the measurement of $\mathcal{R}$, which results to be much sensitive to the paramteres $\Delta\alpha_{LS}$ and $\Delta\alpha_{SL}$. The more $\Delta\alpha_{LS}$ and $\Delta\alpha_{SL}$ are close to zero, the less those corrections influence the result due to cancellation in the double ratio. Many efforts has been made in order to render the mistagging probabilities equal in the two modes, and to measure them with the best accuracy.

4.4 Selection of the kaon energy range and the fiducial decay volume

The fiducial range in kaon energy and decay region used to count events is $70 \text{ GeV} < E_K < 170 \text{ GeV}$ and $0\tau_S < \tau < 3.5\tau_S$, where the τ proper time is used to determine the longitudinal position of the decay vertex ($\tau \equiv \frac{(z_{vtx} - z_{aks})m_K}{p_K}$) and $\tau = 0$ is defined at the position of the AKS counter.

4.4.1 The fiducial energy range

In order to avoid biasing effects due to different energy distributions for K_S and K_L decays, the fiducial energy range ($[70 \div 170]$ GeV) is chosen where the differences between the energy spectra of the KS and KL beams are contained within $\pm 10\%$. The analysis is performed in 20 independent bins of energy, to avoid any residual effect due to the different shape of the spectra.

4.4.2 The fiducial decay volume

The length of the fiducial decay region is a compromise between the need of rejecting background (in the K_L mode) and collecting high-statistic samples.

In the case of K_L decays, the proper time selection is applied on the reconstructed τ , while for K_S the selection at $\tau = 0$ is applied using the AKS system to veto events occurring upstream: no activity in the AKS is required within ± 3 ns of the event time. The nominal $\tau = 0$ position for $K_{\pi^0\pi^0}$ and $K_{\pi^+\pi^-}$ modes, differs by 21.0 ± 0.5 mm, that is the width of the AKS scintillators. This is to take into account the fact that the AKS do not detect neutral decays occurring inside the scintillators.

The veto efficiency of the AKS is 0.9964 ± 0.0003 (0.9923 ± 0.0010) for neutral (charged) decays and leads to a negligible effect on the measurement of $\mathcal{R}$.

4.4.3 The proper time weighting

The distributions of the longitudinal vertex position are very different for K_S and K_L events because of the lifetime ratio $\tau_L/\tau_S = 579.6$. To reduce the effects of the acceptance difference, the two distributions are equalized (see 4.8) by weighting the K_L events with the following function of the of the reconstructed decay proper time τ :

$$w(t) = e^{-\tau\left(\frac{1}{\tau_S} - \frac{1}{\tau_L}\right)} \quad (4.8)$$

modified, as a second approximation, to take into account the residual pure K_S and K_L interference in the KL beam.

The weighting procedure reduce the sensitivity of the measurement to the accuracy of the Monte Carlo simulation of the experiment, reducing the systematic

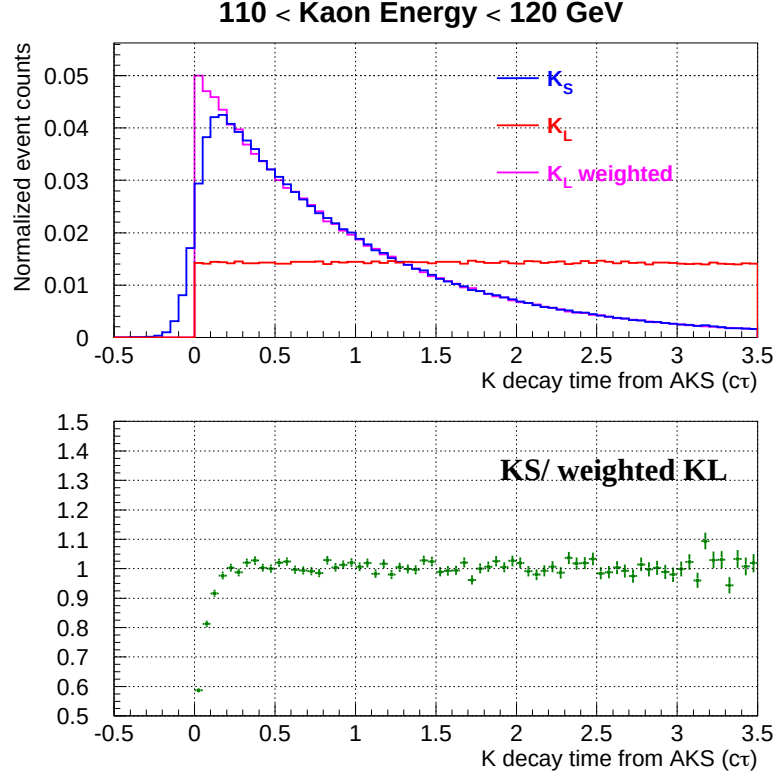


Figure 4.8: The decay vertex of K_S , K_L and weighted K_L , selected in the energy interval $[110 \div 120]$ GeV as a function of the reconstructed proper time τ (top figure). The different behaviour of the K_S and K_L distributions near $\tau = 0$ is due to the difference in definition of the beginning of the fiducial volume: for K_S events the selection at $\tau = 0$ is applied using the AKS system to veto decays occurring upstream; for K_L events the selection $\tau = 0$ is performed using the reconstructed τ variable. The ratio of the K_S and the weighted K_L distributions is shown in the bottom figure.

error. The residual acceptance difference, after weighting, is about 0.1%, thus it can be evaluated with a large relative error.

The weighting method minimizes all the effects related to the geometry, like the detector efficiencies, and considerably reduces the effects of the neutral background, due to the shift on the z_{vtx} position for the $3\pi^0$ events. The statistical power of the K_L samples is reduced by $\sim 40\%$.

4.5 The final event samples

The number of events obtained after reconstruction, identification, and selection is shown in table 4.1; the energy distribution is shown in figure 4.9.

Decay mode	number of events	
	Unweighted	Weighted
$K_L \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$	1001443	283825
$K_S \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$	1918801	
$K_L \rightarrow \pi^+ \pi^-$	4334563	1222422
$K_S \rightarrow \pi^+ \pi^-$	8043669	

Table 4.1: *The four statistical samples of the selected events. The K_L weighting method minimizes all the effects related to the geometry and to the background. The drawback is the statistical power of the K_L samples reduced by a factor of 0.4.*

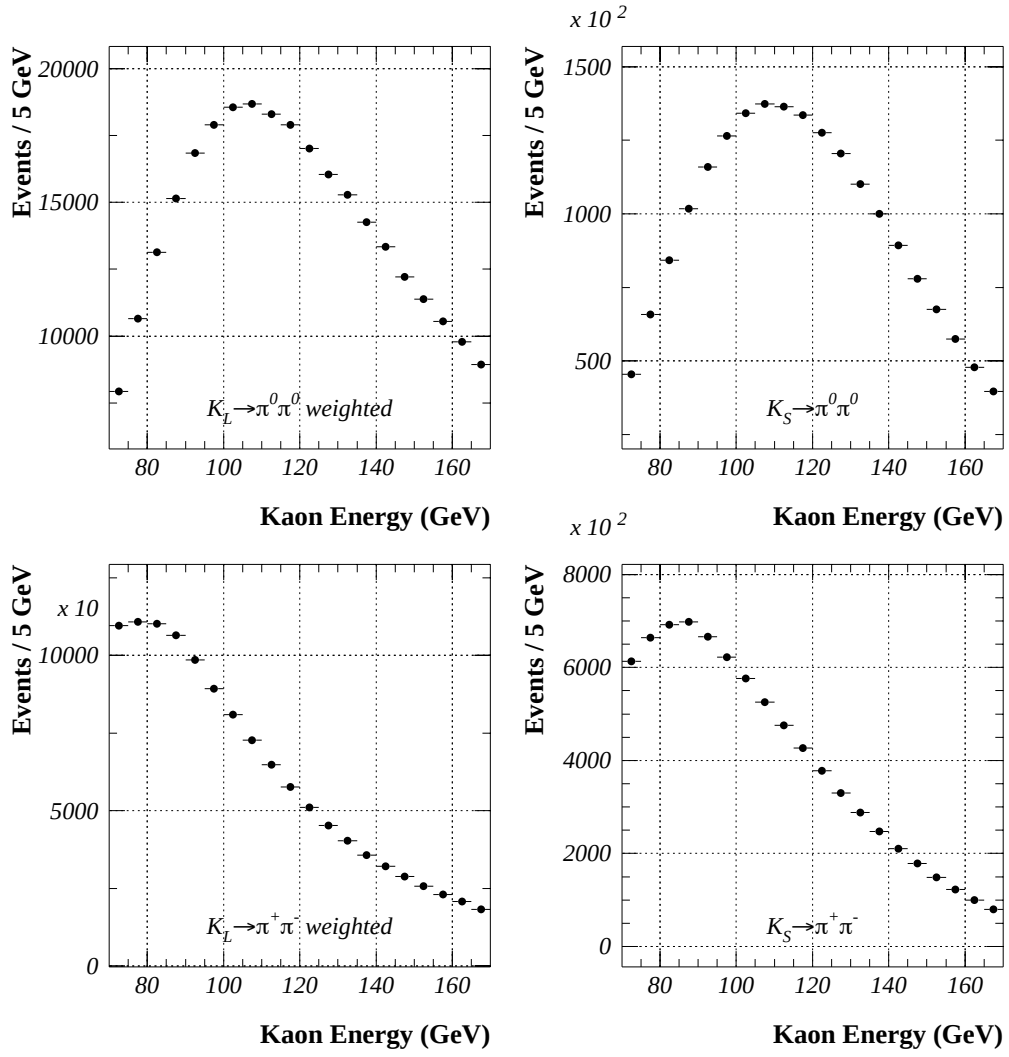


Figure 4.9: The four statistical samples of the selected events as a function of the kaon energy.

5 The measurement of $\mathcal{R}$ and systematic uncertainties

Overview

Once the final sample is selected, second order corrections are applied to the four numbers, to take into account:

- Trigger and reconstruction inefficiencies;
- Event losses caused by beam related activity;
- Background;
- Mistagging caused by tagging accidentals and inefficiencies;
- Definition of the fiducial ranges of energy and decay volume;
- Acceptance correction due to of detector and selection;

Those subjects will be discussed in the following chapters, in connection with the rate effects on the measurement of the double ratio $\mathcal{R}$, which is the argument of this thesis.

This chapter describes how the analysis addresses to the various matters, and summarizes the results that the above corrections yield on the double ratio. In order to be insensitive to the difference of the kaon momentum distribution, of about 10% in the range $[70 \div 170]$ GeV, the computation of $\mathcal{R}$ is done in 20 energy bins. The number of K_S and weighted K_L candidates are corrected for the mistagging effects as described below. Corrections for trigger efficiency, background subtraction, and residual K_S/K_L acceptance difference are applied separately in each energy bin.

Performing the analysis in 20 kaon energy bins is equivalent to making 20 independent measurements of the double ratio, $\mathcal{R}$. To calculate the global value of $\mathcal{R}$ an unbiased logarithmic estimator is used, known as the $\log(\mathcal{R})$ estimator.

5.1 Trigger, reconstruction and accidental effects

The trigger system, and the reconstruction methods used, are affected by geometrical and rate dependent effects. The geometrical effects are induced by the reconstruction algorithms, and by low-efficiency regions in the detectors. This matter is still being studied, however small bias in the measurement of $\mathcal{R}$ is expected from those effects. For instance, the overall $\pi^+\pi^-$ reconstruction efficiency has been

found to be the same for K_S and K_L decays using a Monte Carlo computation which includes the measured efficiencies of each drift chamber wire.

On the contrary, the potential biases on $\mathcal{R}$, due to effects of rate, are not small. Dead-time and inefficiencies of the trigger system [40,50], and reconstruction, are deeply correlated through the effects of accidental particles. For instance, the overflow condition affects both the on-line and off-line reconstruction efficiencies. The matter is complicated by the different on-line and off-line implemented algorithms. Furthermore, the rate induced effects have impact on many other aspects of the measurement.

The detailed measurement of the trigger and reconstruction effects are described in the following chapters.

5.2 Mistagging effects

The number of selected events has to be corrected for the K_S - K_L misidentification probabilities, namely the accidental tagging (α_{LS}) and tagging inefficiency (α_{SL}).

Given the mistagging probabilities, α_{LS} and α_{SL} , it is possible to relate the numbers of tagged events (indicated as N in the following) to the actual numbers of true events ($\mathcal{N}$) from the KL and KS beamlines.

Let us define:

- $N_{L(S)_{tag}}^{N(C)}$ the measured number of events, tagged as $K_L(K_S)$, by the tagger, and treated consequently in the analysis; i.e. K_L events are weighted with the proper time τ and the beginning of the decay region ($\tau > 0$) is defined with the measured τ ; K_S events are not weighted and the selection $\tau > 0$ is devised by the AKS veto (see Section 4.2);
- $N_{L(S)_{mis}}^{N(C)}$ as the number of events tagged as $K_L(K_S)$, but treated while being analyzed, as if they were tagged as $K_S(K_L)$, for what concerns the weight and the definition of the decay region;
- $\mathcal{N}_{L(S)}^{N(C)}$ the number of true events, unweighted;
- $\mathcal{N}_{L(S)}^{N(C)w}$ the number of true events, weighted;
- $\mathcal{N}_{L(S)_{mis}}^{N(C)}$ the number of true “mistagged” events, i.e. the $K_L(K_S)$ events, treated as if they were $K_S(K_L)$ for what concerns the weight and the definition of the decay region;

- The differences between neutral and charged quantities are referred to with a Δ in front; e.g. the difference of the accidental tagging probability is defined as $\Delta\alpha_{LS} \equiv \alpha_{LS}^N - \alpha_{LS}^C$, and the difference of the tagging inefficiency is defined as $\Delta\alpha_{SL} \equiv \alpha_{SL}^N - \alpha_{SL}^C$.

Then the relation holds:

$$\begin{cases} N_{L_{tag}^w} &= \mathcal{N}_L^w(1 - \alpha_{LS}) + \alpha_{SL}\mathcal{N}_{S_{mis}} \\ N_{S_{tag}} &= \mathcal{N}_S(1 - \alpha_{SL}) + \alpha_{LS}\mathcal{N}_{L_{mis}} \\ N_{L_{mis}} &= \mathcal{N}_{L_{mis}}(1 - \alpha_{LS}) + \alpha_{SL}\mathcal{N}_S \\ N_{S_{mis}} &= \mathcal{N}_{S_{mis}}(1 - \alpha_{SL}) + \alpha_{LS}\mathcal{N}_L \end{cases} \quad (5.1)$$

These relations can be inverted to get the correction formulae:

$$\begin{aligned} \mathcal{N}_L^w &= \frac{(1 - \alpha_{SL})N_{L_{tag}^w} - \alpha_{SL}N_{S_{mis}}}{1 - \alpha_{SL} - \alpha_{LS}} \\ \mathcal{N}_S &= \frac{(1 - \alpha_{LS})N_{S_{tag}} - \alpha_{LS}N_{L_{mis}}}{1 - \alpha_{SL} - \alpha_{LS}} \end{aligned} \quad (5.2)$$

Those numbers of true events are then used to measure the double ratio $\mathcal{R}$. This results in a “second order” correction to $\mathcal{R}$. At this stage, the values of α_{LS} and α_{SL} are used, which are measured with the charged events, exploiting the *y*-vertex *tagging*. The measured values are: $\alpha_{LS} = 0.11059 \pm 0.00014$ and $\alpha_{SL} = 0.00019 \pm 0.00001$, which results in a correction to $\mathcal{R}$ of:

$$\Delta\mathcal{R} = 77.7 \cdot 10^{-4}$$

with negligible error.

The correction is understood as follows; assuming that α_{LS} is the same for charged and neutral events, and assuming that α_{SL} is negligible, the bias on $\mathcal{R}$ is parametrized as:

$$\begin{aligned} \mathcal{R}_{measured} &= \frac{N_{L_{tag}}^N N_{S_{tag}}^C}{N_{L_{tag}}^C N_{S_{tag}}^N} = \frac{\mathcal{N}_L^N(1 - \alpha_{LS}^N) + \alpha_{SL}^N \mathcal{N}_{S_{mis}}^N}{\mathcal{N}_L^C(1 - \alpha_{LS}^C) + \alpha_{SL}^C \mathcal{N}_{S_{mis}}^C} \cdot \frac{\mathcal{N}_S^C(1 - \alpha_{SL}^C) + \alpha_{LS}^C \mathcal{N}_{L_{mis}}^C}{\mathcal{N}_S^N(1 - \alpha_{SL}^N) + \alpha_{LS}^N \mathcal{N}_{L_{mis}}^N} \sim \\ &\mathcal{R}_{true} \frac{1 - \alpha_{LS}^N}{1 - \alpha_{LS}^C} \cdot \frac{1 + \alpha_{LS}^C \mathcal{N}_{L_{mis}}^C / \mathcal{N}_S^C}{1 + \alpha_{LS}^N \mathcal{N}_{L_{mis}}^N / \mathcal{N}_S^N} \sim \mathcal{R}_{true} [1 + \alpha_{LS} (\frac{\mathcal{N}_{L_{mis}}^C}{\mathcal{N}_S^C} - \frac{\mathcal{N}_{L_{mis}}^N}{\mathcal{N}_S^N})] \end{aligned} \quad (5.3)$$

which yields:

$$\Delta\mathcal{R} \approx \alpha_{LS} \cdot \Delta(\frac{\mathcal{N}_{L_{mis}}}{\mathcal{N}_S}) \quad (5.4)$$

where $\Delta(\frac{\mathcal{N}_{L_{mis}}}{\mathcal{N}_S})$ does not vanish, because of the different acceptances [59] for charged and neutral events. The accuracy of this correction depends on the accuracy to which α_{LS} is known, since the ratio $\Delta(\frac{\mathcal{N}_{L_{mis}}}{\mathcal{N}_S})$ is measured with large statistics.

5.2.1 Mistagging differences between charged and neutral modes

In a second stage the differences $\Delta\alpha_{LS}$ and $\Delta\alpha_{SL}$ are evaluated, and a “third order” correction is applied to $\mathcal{R}$, as shown in the following.

Without simplifying assumptions, the bias on $\mathcal{R}$ measured reads:

$$\begin{aligned}\mathcal{R}_{measured} &= \frac{\mathcal{N}_{L_{tag}}^N \mathcal{N}_{S_{tag}}^C}{\mathcal{N}_{L_{tag}}^C \mathcal{N}_{S_{tag}}^N} = \frac{\mathcal{N}_{L^w}^N (1 - \alpha_{LS}^N) + \alpha_{SL}^N \mathcal{N}_{S_{mis}}^N}{\mathcal{N}_{L^w}^C (1 - \alpha_{LS}^C) + \alpha_{SL}^C \mathcal{N}_{S_{mis}}^C} \cdot \frac{\mathcal{N}_S^C (1 - \alpha_{SL}^C) + \alpha_{LS}^C \mathcal{N}_{L_{mis}}^C}{\mathcal{N}_S^N (1 - \alpha_{SL}^N) + \alpha_{LS}^N \mathcal{N}_{L_{mis}}^N} = \\ &= \mathcal{R}_{true} \frac{1 - \alpha_{LS}^N + \alpha_{SL}^N \mathcal{N}_{S_{mis}}^N / \mathcal{N}_{L^w}^N}{1 - \alpha_{LS}^C + \alpha_{SL}^C \mathcal{N}_{S_{mis}}^C / \mathcal{N}_{L^w}^C} \cdot \frac{1 - \alpha_{SL}^C + \alpha_{LS}^C \mathcal{N}_{L_{mis}}^C / \mathcal{N}_S^C}{1 - \alpha_{SL}^N + \alpha_{LS}^N \mathcal{N}_{L_{mis}}^N / \mathcal{N}_S^N} \quad (5.5)\end{aligned}$$

By calculating its Taylor series to first order, around 0 for the α_{LS} and α_{SL} terms, and around 1 for the $\mathcal{R}$ terms, the above expression leads, to the following relationship between the deviations of $\mathcal{R}_{measured}$ and $\mathcal{R}_{true}$ from 1:

$$\begin{aligned}\delta\mathcal{R}_{true} &\approx \left[1 + \alpha_{LS} \mathcal{N}_L^C / \mathcal{N}_S^C \right] \delta\mathcal{R}_{measured} + \\ &\quad \left[\frac{1 + \mathcal{N}_{S_{mis}}^C / \mathcal{N}_S^C (1 + \alpha_{LS} \mathcal{N}_L^C / \mathcal{N}_S^C)}{\mathcal{N}_{L^w}^C / \mathcal{N}_S^C (1 - \alpha_{LS})} \right] \Delta\alpha_{SL} - \left[\frac{1 + \mathcal{N}_L^C / \mathcal{N}_S^C}{1 - \alpha_{LS}} \right] \Delta\alpha_{LS} \quad (5.6)\end{aligned}$$

Considering the values:

$$\begin{cases} \mathcal{N}_L^C / \mathcal{N}_S^C \approx 0.526 \\ \mathcal{N}_{L^w}^C / \mathcal{N}_L^C \approx 1/3.5 \\ \mathcal{N}_{S_{mis}}^C / \mathcal{N}_S^C \approx 0.532 \end{cases}, \quad (5.7)$$

expr. (5.6) reads:

$$(1 - \mathcal{R}_{true}) = 1.058 (1 - \mathcal{R}_{measured}) + 6.15 \Delta\alpha_{SL} - 1.73 \Delta\alpha_{LS} \quad (5.8)$$

Notice that:

- Eqn. (5.8) points to a “dilution” effect on $\mathcal{R}$, at the level of 6%, due to mistagging, in the case $\mathcal{R}$ differs from 1 and no correction is applied;

- The coefficients between the differences in mistagging probabilities and $\Delta\mathcal{R}$, fix the needed level of systematic uncertainties on the knowledge of $\Delta\alpha_{SL}$ and $\Delta\alpha_{LS}$;
- The K_L weighting procedure enhances the coefficient in front of $\Delta\alpha_{SL}$ from 3.50 to 6.15.

Different detectors are used to determine the event time of the charged and the neutral decays: the LKR for the $\pi^0\pi^0$ decays and the charged hodoscope for the $\pi^+\pi^-$ decays. The amount of accidental tagging and tagging inefficiency can thus be different.

If there were no modulations of the beam rate, both mistagging effects would be equal for the charged and the neutral events: a flat time distribution of the protons flux makes α_{LS} independent of the resolution of the event time measurement¹, which is different for the charged and the neutral events. On the other hand, in the ± 2 ns window, α_{SL} is dominated [77] by the tagger inefficiency² which is independent of the kaon decay mode.

Thus the values of α_{LS} and α_{SL} may be different for charged and neutral decays, only due to rate effects. If the instantaneous rate seen by the charged and the neutral events is not the same because of trigger effects (for instance, different dead times), the effective rates of accidental protons and the effective tagger inefficiencies might turn out to be different. Furthermore, modulations of accidental proton rate can introduce dependence of α_{LS} from the event time resolution.

The more the rate effects are equal, in charged and neutral events, the less the mistagging correction affects the result, due to the cancellation in the double ratio. To have the best symmetrical treatment of the data, we have to ensure that:

- The selections which might affect the rate, like overflows and trigger dead-time rejection, are applied, both for neutral and for charged decay events;
- The ToF method is used to identify both neutral and charged K_S events; the *y-vertex tagging* is used only to measure the mistagging probabilities in the charged case;

¹The convolution of a flat and a gaussian distribution still results in a flat distribution with the same level.

²The event time resolution is < 250 ps for both charged and neutral modes, and its the tails yield negligible contribution to α_{SL}

- The measurement of mistagging effects is performed with the maximum allowed accuracy;

Rate effects are deeply related to the time structures of the primary proton flux, this subject will be presented in Chapter 8.

5.2.2 Measurement of $\Delta\alpha_{LS}$

The tagging dilution α_{LS} is essentially the probability for a K_L decay to have at least one proton hit in the tagger, inside the tagging window $[-2, +2]$ ns about the event time. The value of α_{LS} is therefore a function of the rate of the protons in the tagger. The actual rate of the protons can be measured using the protons seen in the sidebands of the tagging distribution.

Figure 5.1 show the difference between the event time and all protons in the tagger, for events identified as K_L by the tagging procedure. The instantaneous rate of the protons has a 200 MHz structure which is a relic of the RF frequency of the SPS accelerator (this matters will be studied in detail in Chapter 8). As the tagging window $[-2, +2]$ ns is centered on a peak of this structure, the measurement of β_{LS} also uses windows of $[-2, +2]$ ns centered on the structure.

Let us use the following notation (see figure 5.2, and [41, 45]):

- α • The probability of finding at least one proton within the $[-2, +2]$ ns tagging window about the event time (later referred to as central tagging window) is referred to as α (e.g. α_{LS}). They can be thought as in-time coincidences between the event and the proton in the tagger;
- β • The probability of finding at least one proton in a sideband tagging window of $[-2, +2]$ ns, centered on the maxima of the 200 MHz beam modulation, is referred to as β . In particular, sideband probabilities for true K_L events are labelled β_{LS} , for true K_L events tagged as K_L by the tagger method the probabilities are labelled β_{tag} , and for true K_L events mistagged as K_S are labelled β_{mis} . They can be thought as delayed coincidences between the event and the protons in the tagger. To calculate the average value of the β quantities, the windows centered at -30, -25, -20, and -15 ns from the event time are used. The other windows are not used as they are either too close to the edge of the tagger readout window, or too close to 0.

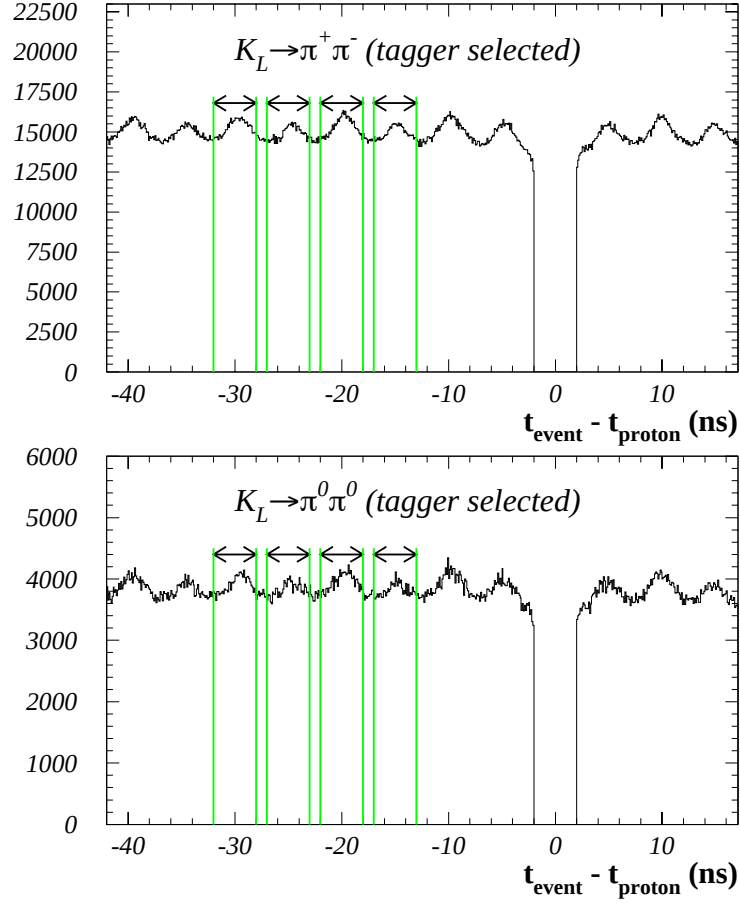


Figure 5.1: The difference between the time of the event and of each proton detected by the tagger, for neutral and charged decays identified as K_L decays by the tagger. The rate of protons shows modulation, which is a relic of the RF frequency of the SPS accelerator. This will be studied in detail in Chapter 8

W • The difference between probabilities in the central and in the sideband windows are referred to as W , e.g. $W_{LS} \equiv \alpha_{LS} - \beta_{LS}$. W measures the correlation between the probability of finding a proton in-time with the event and the probability of a delayed coincidence. Notice that, using the relation

$$\beta_{LS} = \alpha_{LS}\beta_{mis} + (1 - \alpha_{LS})\beta_{tag}$$

one can write:

$$W_{LS} = (1 + \beta_{tag} - \beta_{mis})\alpha_{LS} - \beta_{tag} \quad (5.9)$$

Δ • Neutral quantities minus charged quantities have a Δ in front, as usual; for example $\Delta\beta_{tag} \equiv \beta_{tag}^N - \beta_{tag}^C$.

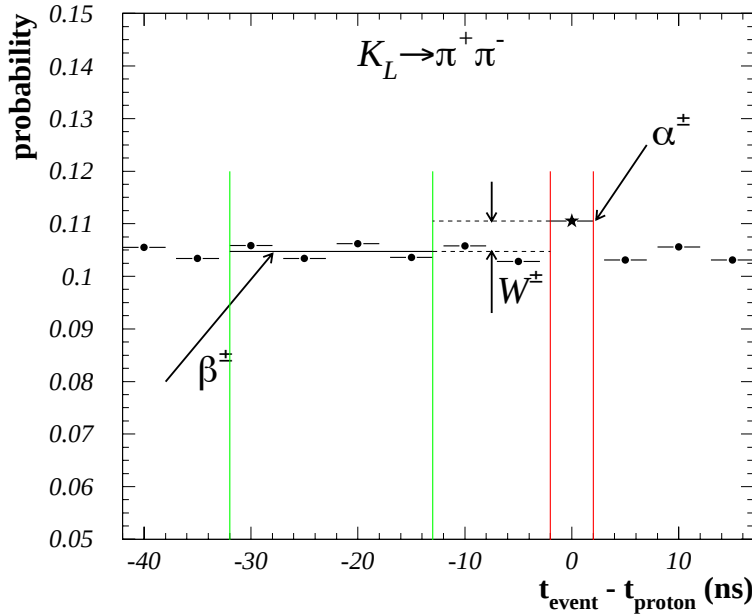


Figure 5.2: The tagging parameters illustrated I. The probability of finding at least one proton in a 4 ns window is shown on the vertical axis.

By using the y -vertex tagging, all the α^C , β^C and W^C quantities are measured. On the contrary, the only relevant quantity that can be obtained from the $K_{\pi^0\pi^0}$ neutral mode events is the average sideband probability³ β_{tag}^N .

³The contribution from true K_S mistagged as K_L is very small

Figure 5.3 shows the probabilities β_{tag} , and β_{LS} to have at least one proton in the various $[-2, +2]$ ns windows for K_L events, tagged respectively by the tagger and by the y -vertex tagging. The average values of β_{tag} , for the chosen time windows, are:

$$\beta_{tag}^C = (0.10477 \pm 0.00009), \quad \text{and} \quad \beta_{tag}^N = (0.10525 \pm 0.00018)$$

which yields a difference of

$$\Delta\beta_{tag} = 0.00047 \pm 0.00020$$

Figure 5.4 shows the probability β_{tag} for charged and neutral events.

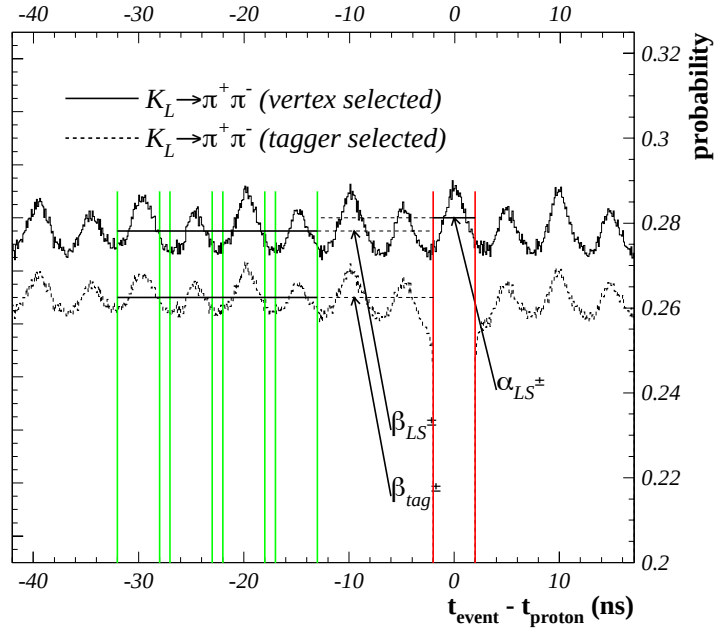


Figure 5.3: The tagging parameters illustrated II. The probability of finding at least one proton in a 100 ps window is shown on the vertical axis.

The simplest method to measure the relation of β_{tag} with α_{LS} is to measure the two probabilities for the neutral mode, by means of the K_L into $3\pi^0$ decays ($K_{\pi^0\pi^0\pi^0}$). By using the W quantities and the above relation (5.9), the neutral to charged difference in accidental tagging is given by:

$$\Delta\alpha_{LS} = \alpha_{LS}^N - \alpha_{LS}^C = \frac{\Delta\beta_{tag} + \Delta W_{LS} + (\Delta\beta_{mis} - \Delta\beta_{tag})\alpha_{LS}^N}{1 + \beta_{tag}^C - \beta_{mis}^C} \equiv \Delta\beta_{tag} + \overline{\Delta W_{LS}} \quad (5.10)$$

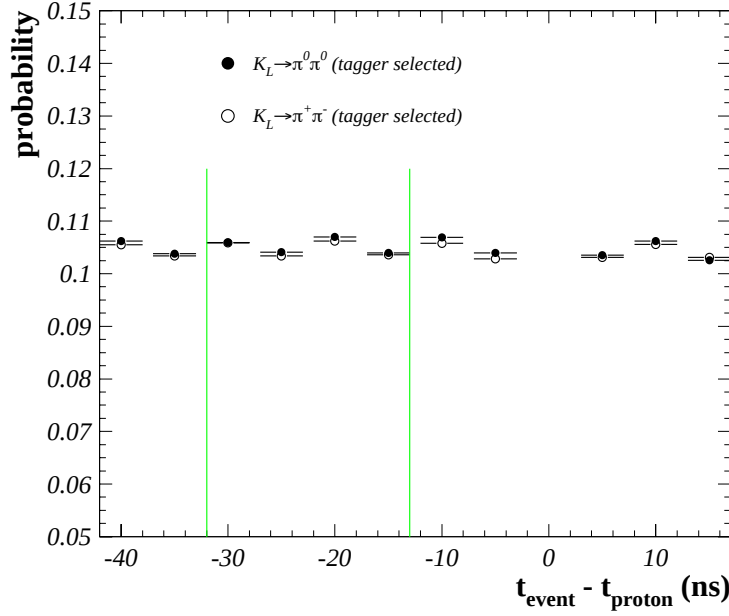


Figure 5.4: The probability β_{tag} for charged and neutral events. The probability of finding at least one proton in a 4 ns window is shown on the vertical axis.

where $\Delta\beta_{tag}$ is measured using $K_{\pi^+\pi^-}$ and $K_{\pi^0\pi^0}$, while α_{LS}^N , ΔW_{LS} , and $\Delta\beta_{mis}$ are measured using $K_{\pi^+\pi^-}$ and $K_{\pi^0\pi^0\pi^0}$.

It is found [45]: $\overline{\Delta W_{LS}} = (1.3 \pm 1.8) \cdot 10^{-4}$, which leads to a difference in accidental tagging of: $\Delta\alpha_{LS} = (6.0 \pm 2.7) \cdot 10^{-4}$. Finally the effect of mistagging yield a “third order” correction to $\mathcal{R}$ of:

$$\Delta\mathcal{R} = (11.8 \pm 5.3) \cdot 10^{-4}$$

5.2.3 Measurement of $\Delta\alpha_{SL}$

Two methods [78] are used to measure $\Delta\alpha_{SL}$; the first is a direct measurement of α_{SL}^N , that identifies K_S to $\pi^0\pi^0$ decay by a method other than the tagger, the second is a measurement of $\Delta\alpha_{SL}$ by looking at events where both the LKR and the HODO make the event time measurement.

Three different data sets have been studied to estimate a value for $\Delta\alpha_{SL}$:

- i) *KS-only runs*: All decays in this case are from the KS beamline, allowing a direct measurement of both α_{SL}^C and α_{SL}^N . The difference is $\Delta\alpha_{SL} = (-0.11 \pm 0.49) \cdot 10^{-4}$;

ii) **Photon conversions:** Photons from both $K_S \rightarrow 2\pi^0 \rightarrow 4\gamma$ and $K_S \rightarrow 3\pi^0 \rightarrow 6\gamma$ may convert into a e^+e^- pair when crossing material of the detector. Most photon conversions take place at the Kevlar Window. In this cases the event time is reconstructed by both the HODO and the LKR. It is estimated that $\Delta\alpha_{SL} < 1 \cdot 10^{-4}$.

ii') **π^0 Dalitz decays:** Electron tracks from π^0 Dalitz decays are used to reconstruct the position of the decay vertex $K_S \rightarrow \pi^0\pi^0 \rightarrow 3\gamma e^+e^-$. The vertical (y) position of the decay vertex is used to separate K_L from K_S decays. The measurement is limited by poor statistics, and yields $\Delta\alpha_{SL} = (3.0^{+5.0}_{-2.5}) \cdot 10^{-4}$.

These measurements are consistent with the value of $\Delta\alpha_{SL} = 0$, i.e. the tagging inefficiencies in both the charged and neutral decays mode are small and equal. No correction on $\mathcal{R}$ is thus applied. The error of the measurement is estimated to be $0.5 \cdot 10^{-4}$. Recalling expr. (5.8), this converts into a uncertainty on $\mathcal{R}$ of:

$$\Delta\mathcal{R} = 3 \cdot 10^{-4}$$

5.3 Background subtraction

5.3.1 Charged background subtraction

The background contamination in the $K_L \rightarrow \pi^+\pi^-$ sample is expected to come from K_{e3} and $K_{\mu3}$ decays. Two samples of K_L events with a well identified electron or muon are selected. The K_{e3} events are identified by applying all the criteria used for the charged selection, excluding the invariant mass, the transverse momentum, and the E/p requirements, and asking for $E/p > 0.9$, to tag the electrons. Likewise the $K_{\mu3}$ events are identified by releasing the μ rejection, and, instead, by requiring the coincidence in time within $\pm 2\text{ns}$ between the event and the muon. The K_L weighting is applied to the K_{e3} and the $K_{\mu3}$ events.

For each of the four samples of K_L , K_S , K_{e3} , and $K_{\mu3}$ events, the distribution of the transverse momentum $p_T'^2$ versus the invariant mass M_{+-} is used to measure the amount of background contamination in the K_L sample. Three regions are selected on the plane $(M_{+-}, p_T'^2)$: one signal region (SR) and two control regions (CR1, CR2) as shown in figure 5.6. Let $L_{1(2)}$, $S_{1(2)}$, $E_{1(2)}$, and $M_{1(2)}$ be the number of events in

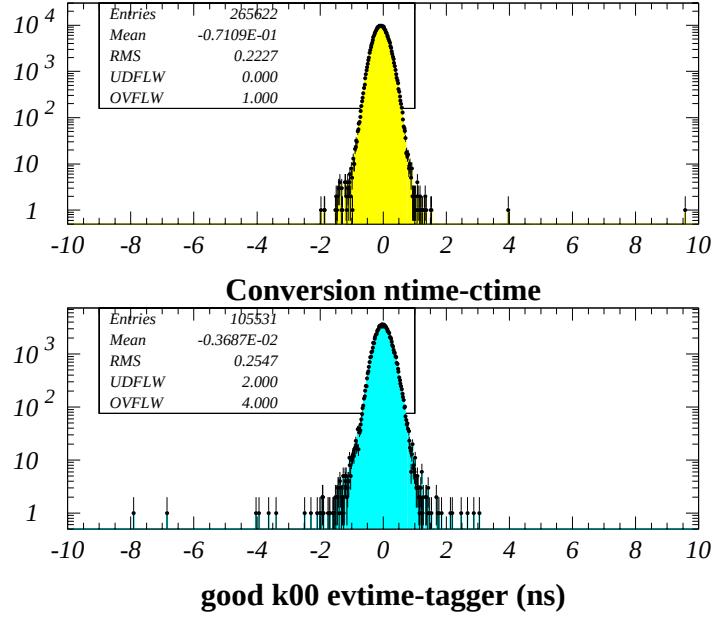


Figure 5.5: Comparison of the tagging inefficiency for neutral and charged events. The event time for events with photon conversions is measured both with charged hodoscope and electromagnetic calorimeter (top figure). This allows a direct comparison of the reconstruction efficiency between the charged and the neutral time, hence a measurement of $\Delta\alpha_{SL}$. Bottom figure shows the difference between the event time and the time of the nearest proton, reconstructed in the tagger, for $K_{\pi^0\pi^0}$ events in *KS-only* beam mode. This allows a direct measurement of the tagging inefficiency α_{SL}^N .

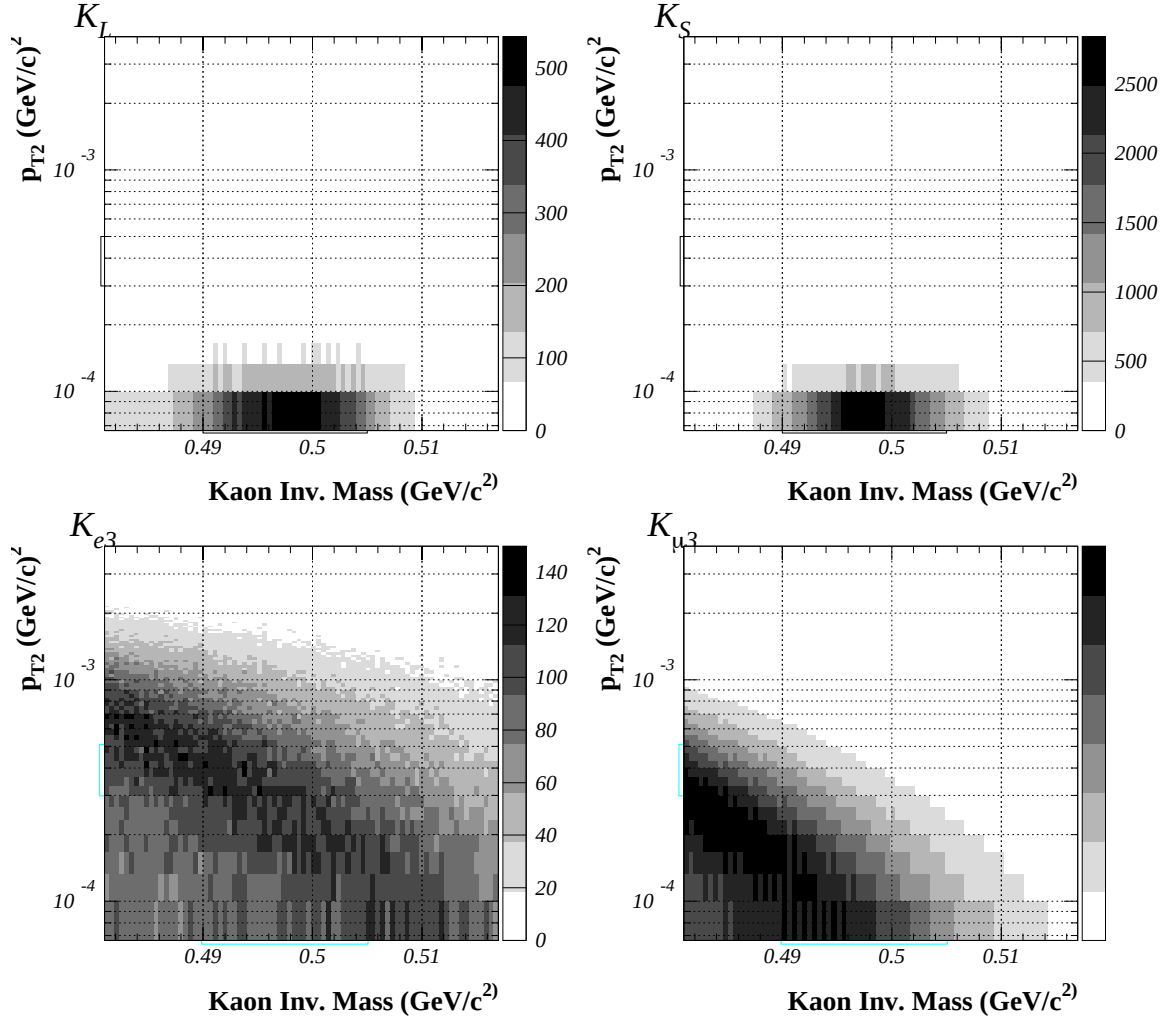


Figure 5.6: Distribution of the transverse momentum $p_T'^2$ versus the invariant mass M_{+-} for the four event samples used in charged background analysis. The signal and control regions are also shown.

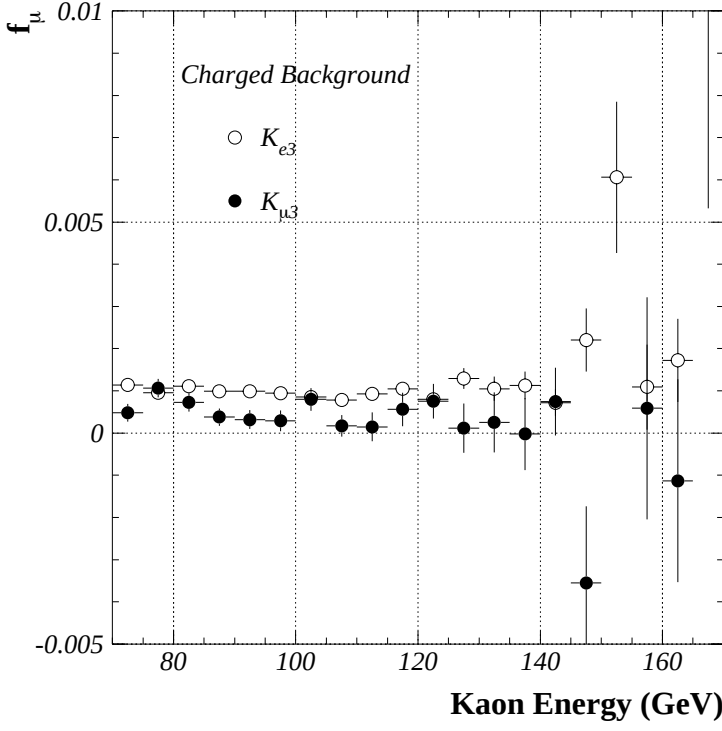


Figure 5.7: The measured fraction of $K_{\mu 3}$ and $K_{e 3}$ events to be subtracted from K_L charged events.

the CR1(CR2), respectively in the K_L , K_S , $K_{e 3}$, and $K_{\mu 3}$ samples. The number of K_L events in the control regions must be the sum of three contributions:

$$L_i = f_{signal}S_i + f_e E_i + f_\mu M_i \quad (5.11)$$

where the index $i = 1, 2$ relates respectively to CR1 and CR2; the three parameters f_{signal} , f_e , and f_μ represent the fractional contributions to the number of events in control regions, respectively from the signal, and from the $K_{e 3}$, and $K_{\mu 3}$ background. The signal contribution f_{signal} is measured by means of the K_S event sample, which is normalized in such a way that the same number of K_S and K_L events are counted in the region: $(p_T'^2 < 5 \cdot 10^{-5} \text{ (GeV/c)}^2, |M_{+-} - M_K| < 2.5 \text{ MeV/c}^2)$ The f_e , and f_μ parameters are obtained by inverting equations (5.11):

$$\begin{cases} f_\mu = \frac{E_2(L_1 - f_{signal}S_1) - E_1(L_2 - f_{signal}S_2)}{M_1E_2 - E_1M_2} \\ f_e = \frac{M_1(L_2 - f_{signal}S_2) - M_2(L_1 - f_{signal}S_1)}{M_1E_2 - E_1M_2} \end{cases} \quad (5.12)$$

The background turns out to be $(10 \pm 2.2) \cdot 10^{-4}$ on average in the full energy range, dominated by the K_{e3} events. The background subtraction is performed for each energy bin, and the final correction on $\mathcal{R}$ becomes:

$$\Delta\mathcal{R} = (9.9 \pm 2.9) \cdot 10^{-4}$$

5.3.2 Regenerated K_S in the K_L beam

If the selection $p'_T < 0.01414 \text{ MeV}/c$ is released, genuine $\pi^+\pi^-$ events are observed in the sample of the charged events, with values of p'_T much larger than $0.01414 \text{ MeV}/c$. These events are identified [35] as K_S decays, due to regeneration on the cleaning and the final collimators of the K_L beam⁴.

Due to the cut on p'_T , applied to the $\pi^+\pi^-$ candidate events, the regenerated events are not included in the final $\pi^+\pi^-$ event sample. However, no similar cut can be defined for the $\pi^0\pi^0$ events. Therefore a small fraction of the final sample of neutral $K_{\pi^0\pi^0}^L$ events are due to regenerated kaons. This fraction is estimated with the charged $K_{\pi^+\pi^-}^L$ decays. An additional cut is applied, in this analysis, to the $\pi^+\pi^-$ selection, rejecting events with additional activity in the LKR. Indeed, the same is done in the $\pi^0\pi^0$ selection, to reject the background.

The fraction of regenerated events in the $\pi^0\pi^0$ sample is estimated to be $(10.0 \pm 3.0) \cdot 10^{-4}$, and yields a correction to $\mathcal{R}$ of:

$$\Delta\mathcal{R} = -(10.0 \pm 3.0) \cdot 10^{-4}$$

Since large statistics is required by this method, the correction is not made in each kaon energy bin.

5.3.3 Neutral background subtraction

For each kaon energy bin, the contamination of $K_L \rightarrow 3\pi^0$ events in the neutral sample is measured on the data [59], by looking at the distribution of the χ_{reli}^2 variable (see figure 5.8):

⁴A backward extrapolation is made at the longitudinal position of the final and the cleaning collimators, in order to calculate the radial positions of the kaon producing these events in the K_L beam. They are distributed around $r = 2.8 \text{ cm}$ at the final collimator and $r = 1.8 \text{ cm}$ at the cleaning collimator, which agree with the respective actual radii of the two collimators. The reconstructed lifetime of these events is $\sim 1\tau_S$.

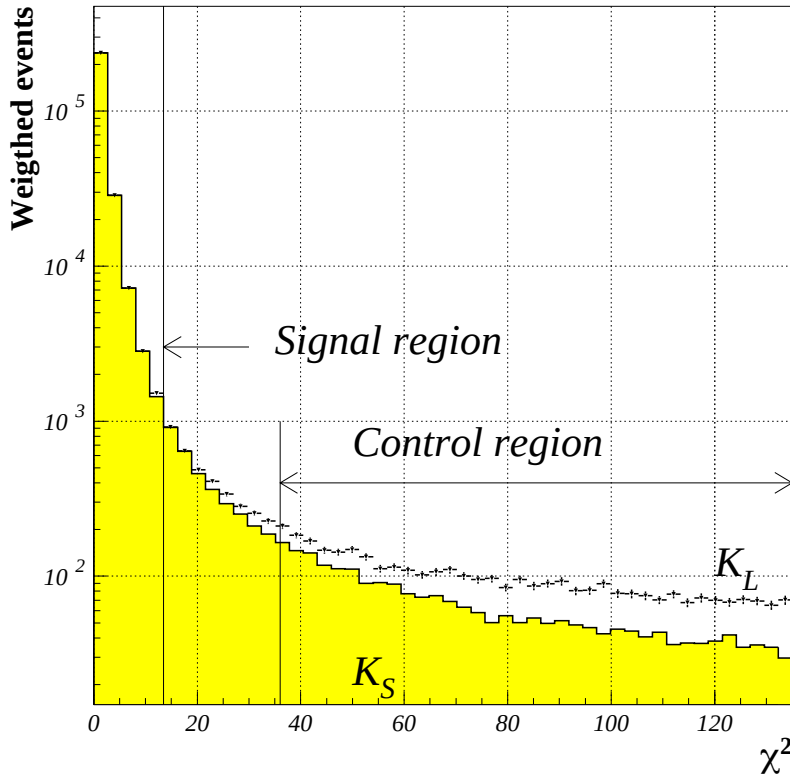


Figure 5.8: The distribution of the R_{elli} variable for K_S and K_L weighted events. The residual background in K_L events is measured in the control region, by means of the selected K_S events.

- The range $36 < \chi_{\text{relli}}^2 < 135$ is selected as control region (CR), independent of the signal region, $\chi_{\text{relli}}^2 < 13.5$.
- The amount of signal in the CR, due to misreconstruction, is estimated by means of the selected $K_S \rightarrow 2\pi^0$ events. The K_S distribution is corrected for mistagging, and it is normalized to the K_L 's by using the events with small $\chi_{\text{relli}}^2 < 2.7$, where the contamination is negligible;
- The difference between the K_L and K_S events in the CR results in a nearly flat distribution: this is extrapolated backward, linearly, to measure the background level in the signal region.
- A factor of 1.2 ± 0.2 , calculated via Monte Carlo, is applied to the result, to account for the uncertainty in the shape of the background χ_{relli}^2 distribution.

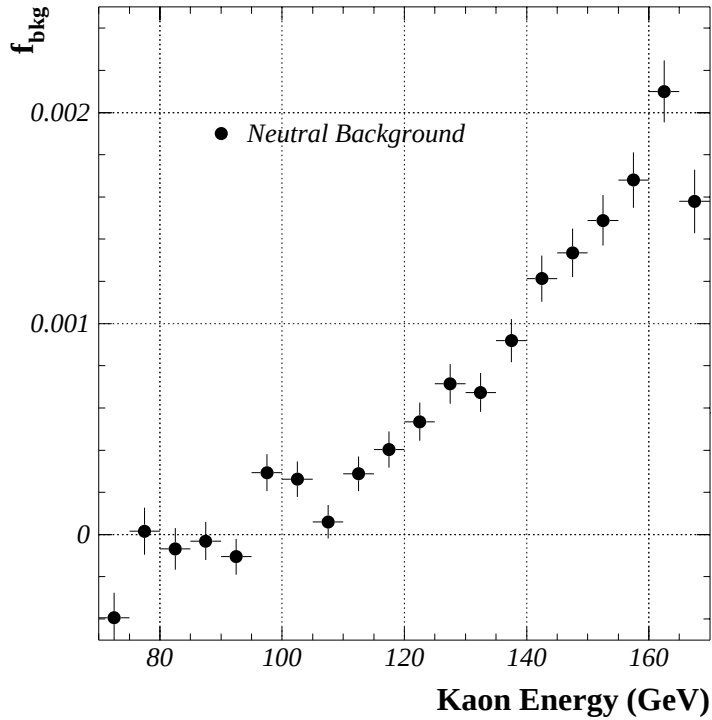


Figure 5.9: The measured level of $3\pi^0$ background in the final K_L sample, as a function of the kaon energy.

The fraction of background events is shown in figure 5.9 as a function of the kaon energy. The background, measured in each energy bin, is subtracted from the $K_L \rightarrow \pi^0\pi^0$ sample. The average over the whole energy spectrum is $(5.8 \pm 1.0) \cdot 10^{-4}$, where the error is dominated by the uncertainty on the extrapolation factor. The correction on $\mathcal{R}$ is:

$$\Delta\mathcal{R} = (-4.7 \pm 0.9) \cdot 10^{-4}$$

5.4 Absolute energy scale and Transverse geometry scale

The kaon energy and the position of the decay vertex are measured, for neutral and charged events, by means of different detectors. Therefore an error on the absolute energy scale of the electromagnetic calorimeter or on the the knowledge of the geometry of the drift chambers, might result in different fiducial energy, and volume regions, for the two cases.

5.4.1 The energy scale for the charged mode

For the charged decays the vertex is measured from the reconstructed tracks, and it is completely determined by the detector geometry. The accurate knowledge of the drift chambers geometry is necessary because it fixes the energy scale: since the kaon energy is measured using expr. (4.1), only the $\pi^+\pi^-$ opening angle $\theta_{\pi\pi}$, and the momentum ratio of the two pions, are needed. The accuracy in the measurement of the opening angle depends on knowledge of the ratio of the transverse to the longitudinal geometry scale of the drift chambers. The ratio of the pion momenta depends only slightly on the knowledge of the magnetic field; which is anyway accurately mapped, and used in the reconstruction, to measure the pion momenta.

The transverse geometry of the drift chambers is measured with precision machines, as well as the longitudinal distances. The geometry of the drift chambers is also calibrated using special data sets, taken with the spectrometer magnet turned off.

The reconstructed position of the beginning of the fiducial decay volume is compared with the actual one by fitting the AKS position. This is also useful to study the non gaussian-tails in the vertex reconstruction. Figure 5.10 shows the distribution of the reconstructed decay vertex in K_S events for $\pi^+\pi^-$ and $\pi^0\pi^0$ modes.

The correction [51] to the double ratio $\mathcal{R}$ due to the residual effect of the charged energy scale is:

$$\Delta\mathcal{R} = (+2 \pm 2) \cdot 10^{-4}$$

5.4.2 The energy scale for the neutral modes

The measurements of the kaon energy, the decay vertex, and the proper time of the neutral mode rely on the measurement of the photon energies and positions in the calorimeter.

The calorimeter performances are studied, and adjusted, using the $\pi^0\pi^0$ events, K_{e3} decays, where the electron energy measured in the calorimeter can be compared to the momentum measured in the spectrometer, and the special η run data (see Chapter 2).

The $K_{\pi^0\pi^0}^S$ events are used to set the overall energy and distance scales. The energy scale is adjusted in such a way that, the sharp rise of the reconstructed decay vertex position, matches the known geometrical position of the AKS anti-counter

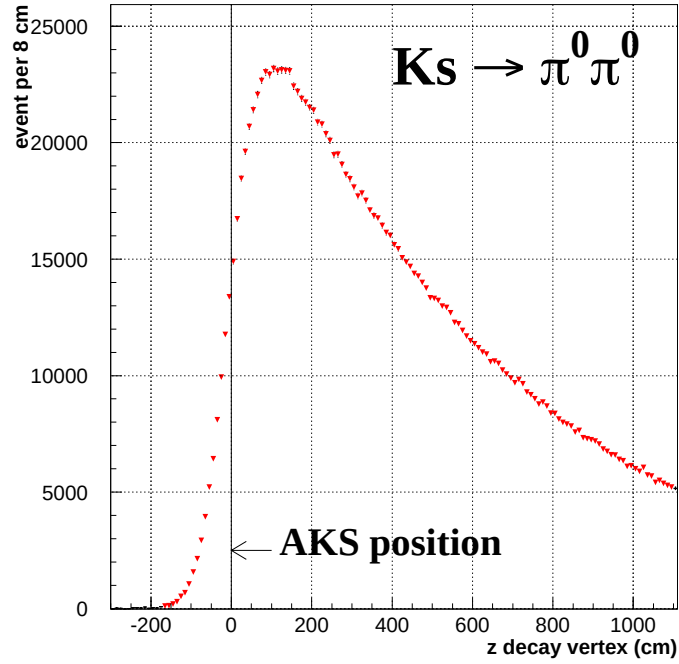
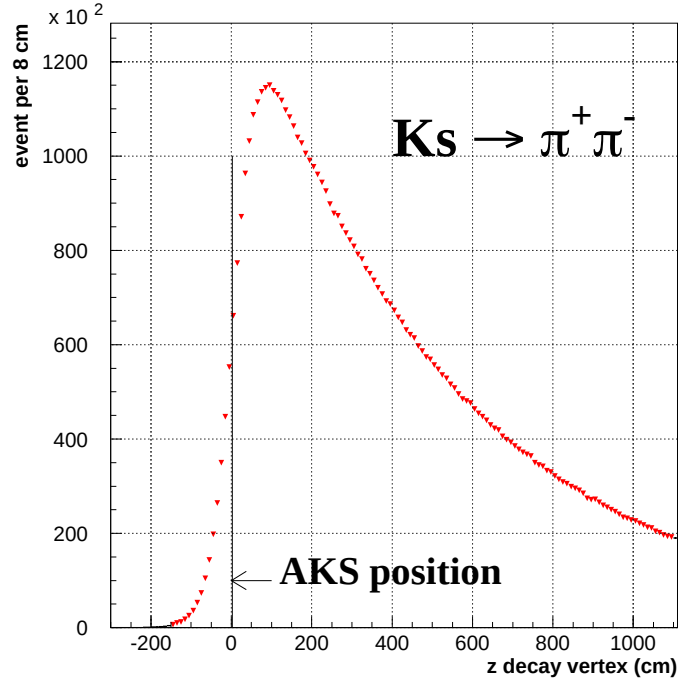


Figure 5.10: Distribution of the reconstructed decay vertex in K_S events for $\pi^+ \pi^-$ and $\pi^0 \pi^0$ modes. The sharp rise of the reconstructed decay vertex position is devised by the AKS veto.

(see figure 5.10). The energy scale is stable within $\pm 3 \cdot 10^{-4}$ during the entire run. In order to account for non-Gaussian tails in the energy resolution, a Monte Carlo is used to fit the shape of the vertex position distribution. This measurement of the energy scale is also checked using the data from the η run (see figure 5.11). Further cross-check is done using Dalitz decays and comparing the neutral vertex position with the vertex reconstructed using the charged tracks. The accuracy of the energy scale setting is estimated to $\pm 3 \cdot 10^{-4}$ which leads to an uncertainty of $\Delta\mathcal{R} = \pm 3 \cdot 10^{-4}$ on the double ratio.

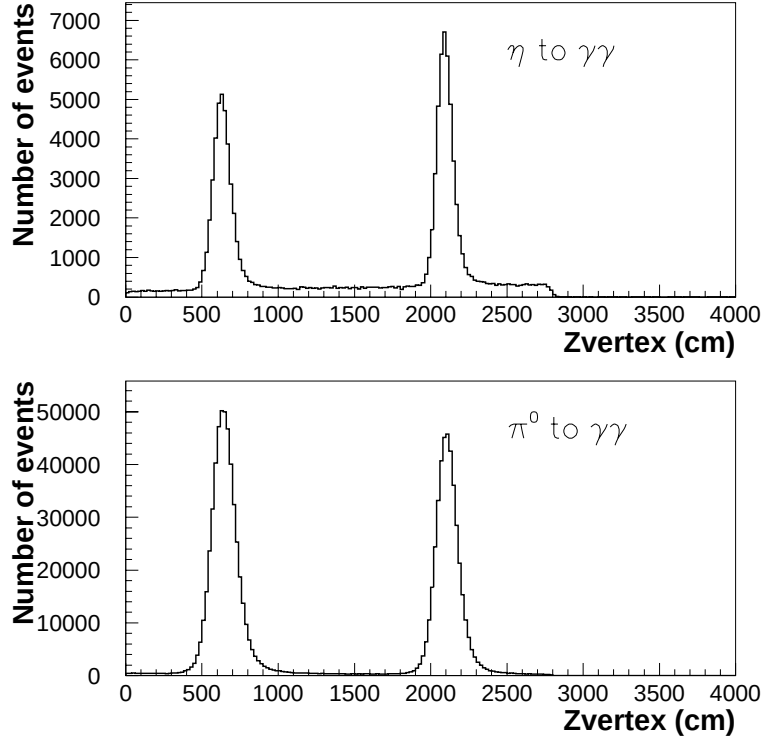


Figure 5.11: The reconstructed positions of the targets in the η runs. This measurement provides a cross-check for the energy scale measurement.

The above procedure assumes that the transverse size of the calorimeter is known. This is checked by means of K_{e3} decays comparing the reconstructed cluster position with the electron track impact point extrapolated to the calorimeter. The comparison is performed with an accuracy of $300 \mu\text{m}/\text{m}$ on the transverse scale, which leads to an uncertainty on the double ratio of $\Delta\mathcal{R} = \pm 3 \cdot 10^{-4}$.

Additional uncertainties come from non-uniformity and non-linearity of the calorimeter response. The uniformity of the calorimeter response over its surface is

checked, and optimized, using K_{e3} decays and π^0 decays from the η runs. Residual non-uniformities in the calorimeter response over large distances are at the level of $\approx 10^{-3}$ and the corresponding systematic uncertainty on the double ratio is $\Delta\mathcal{R} = \pm 3 \cdot 10^{-4}$.

The calorimeter energy non-linearity is studied using K_{e3} events (see figure 5.12), K_S and K_L decays into $\pi^0\pi^0$, and π^0 and η decays from the η runs. Non linearities are found to be at the level of 0.2% in the energy response between 5 and 100 GeV with a possible energy offset of ± 20 MeV. These effects are taken as systematic uncertainties and lead to an error on the double ratio of $\Delta\mathcal{R} = \pm 5 \cdot 10^{-4}$.

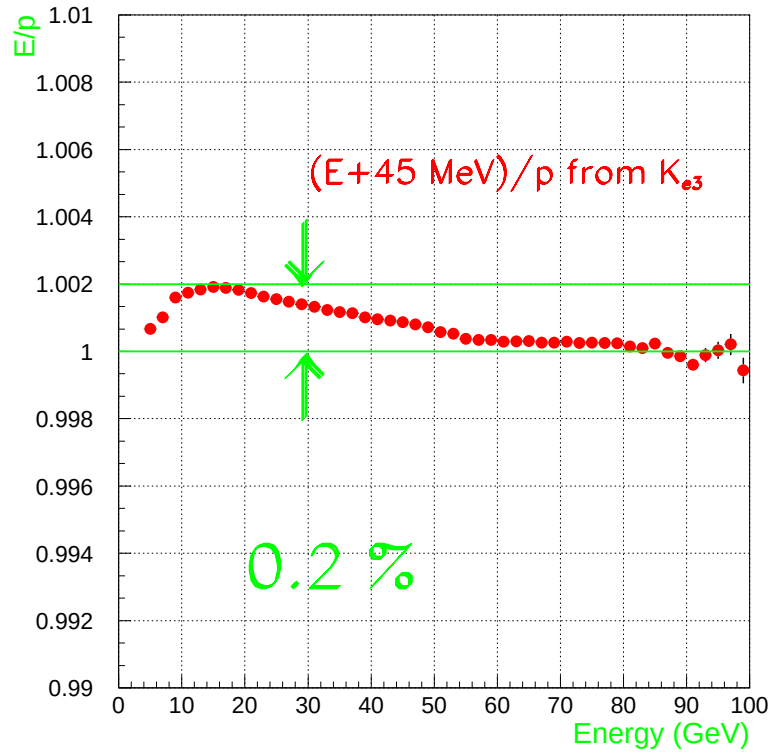


Figure 5.12: *The residual non-linearity in the electromagnetic calorimeter, studied using K_{e3} events.*

Other uncertainties, in the photon energy reconstruction (energy sharing between clusters, and space charge effect), and residual effects due to the difference between the photon direction and the projectivity direction of the calorimeter, are estimated to be $\pm 3 \cdot 10^{-4}$ on the double ratio.

Adding the errors together in quadrature, the total systematic uncertainty [107]

on the double ratio, due to the measurement of photon energies and positions, is:

$$\Delta\mathcal{R} = \pm 7 \cdot 10^{-4}$$

5.5 Detector and selections acceptances

The K_S and K_L acceptances are made very similar, in both neutral and charged modes, by using the technique of weighting the K_L events according to their proper time, so that the effective longitudinal vertex distributions are similar. The weighting factor, shown in expr. (4.8), must include small contributions from interference [63], and from K_S decays in the K_L beam; both of them are significant only for kaon energies above 140 GeV.

Residual acceptance differences are expected [59, 60], because of the different geometry of the K_L and K_S beamlines. Additionally, some of the selections may not affect symmetrically K_L and K_S decays.

The final acceptance correction is studied with a full simulation of the beams and the detector, which includes:

- The geometrical description of the beam lines (including K_S halo from scattering in the collimator and in the AKS);
- The detailed detector geometry. The inefficiencies of the single wires in the chambers are included, as well as the electromagnetic calorimeter dead cells;
- The particles scattering on the wires or other material in the chambers;
- The secondary interactions upstream the LKR (as multiple scattering, nuclear interactions, gamma conversions) and the pion decay;
- The reconstruction of charged tracks and LKR clusters.

Tails of the E/p distribution are not simulated, because the distribution of E/p is intrinsically equal for K_S and K_L , and does not affect $\mathcal{R}$. The tagger, the AKS, and the trigger systems are not simulated: they induce corrections to $\mathcal{R}$ which are accurately calculated using the data directly. The effects of rate and accidental activity are also measured using the data directly.

The Monte Carlo event sample is five times larger than the data. The measured acceptances [61,104] are respectively $\sim 54\%$ and $\sim 25\%$ for charge and neutral modes. In both cases, the difference between K_S and K_L is at the level of few permille. The acceptance correction is evaluated and applied in each energy bin. The average correction over the kaon energies in the fiducial energy interval, is:

$$\Delta\mathcal{R} = (27 \pm 8) \cdot 10^{-4}$$

Almost half the uncertainty ($6.5 \cdot 10^{-4}$) has statistical origin. The main sources of systematic error ($5 \cdot 10^{-4}$) depend on the knowledge of the positions and divergences of the beams [59].

Conclusions

The analysis strategy is outlined in this chapter, and some of the measured corrections to $\mathcal{R}$ are described.

One most important rate effect, namely the mistagging related correction, is described in some detail. This effect is deeply connected to the time structure of the beam intensity, which is studied in Chapter 8. The other effects of rate were skipped here, and are studied in the following part of the thesis.

The corrections to $\mathcal{R}$ which are not related to the rate were described in this chapter, and are summarized in table 5.1.

In Chapter 13 the summary of all the corrections, and the final result with the 1998 data will be discussed.

	correction	uncertainty
	$\times 10^{-4}$	
Charged Background	+9.9	± 2.9
Beam Scattering	-10.0	± 3.0
Neutral Background	-4.7	± 0.9
Charged Energy and Geometry Scale	+2.0	± 2.0
Neutral Energy and Geometry Scale	-	± 7.0
Acceptance	+27.0	± 8.0

Table 5.1: *The rate independent corrections and uncertainties to $\mathcal{R}$. In order to be insensitive to the difference in the beam momentum spectra, the range used ($[70 - 170]$ GeV) in kaon energy is divided in 20 bins. The double ratio $\mathcal{R}$ is computed in each bin and the various corrections are applied separately bin per bin.*

6 A study of the rate effects on the ϵ'/ϵ measurement

Overview

An overview is presented in this chapter on the rate effects in NA48. The high rate experienced by the detector might bias the double ratio $\mathcal{R}$ in different ways:

- An important fraction of the trigger, reconstruction, and selection inefficiencies are expected to be dependent on the rate, due to accidental particles in the beams. This chapter is devoted to introducing this problem, and the methods used to solve it.
- The mistagging probabilities are proportional to the primary proton intensity; they are studied in Chapter 5, and their relation to the time structures of the beams are investigated in Chapter 8.

Particles produced by the primary protons interacting in the target and by random decays of the K in the beam, can be detected together with a two body K decay. This coincidence might result in a loss of the kaon decay, depending on the separation in time, and in space, of the two events. Accidental particles might affect the trigger efficiency, generate the overflow condition, and bias the event reconstruction and selection. Extra activity in the detector worsens the resolution of the measured kinematical variables, and might cause migrations of events over the selection acceptance boundaries, resulting in losses or gains of $K_{\pi\pi}$ events.

A priori the effect is different for $K_{\pi^+\pi^-}$ and $K_{\pi^0\pi^0}$ decays. However these final states, both from K_S and K_L decays, are recorded simultaneously, thus any accidental effects should cancel, to first order, since the two beams are exposed to the same accidentals. Various methods are envisaged to check this cancellation effect. They are introduced in this chapter, and applied in the following.

6.1 Addressing the problem of rate effects

Let us consider the following definitions and notation:

- $\mathcal{R}_{true}$ is the true double ratio, and $\mathcal{R}_{measured}$ is the measured double ratio;

- T is the time of the data taking (e.g. the whole 1998 data taking period of ~ 120 days, or the burst time duration of ~ 2.38 s);
- $I_L(t)$ and $I_S(t)$ are the instantaneous rates at time t : $\frac{dn_L}{dt}(t)$ and $\frac{dn_S}{dt}(t)$ respectively for K_L and K_S decays;
- $\Lambda_{S,L}^{N,C}(t)$ is the total probability of losing a $K_{\pi\pi}$ at a time t due to accidental effects in the detector. It takes into account the probability that an event is gained, which is smaller than the probability that an event is lost. The term $\Lambda_{S,L}^{N,C}(t)$ may be different for charged and neutral decays on for $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events;
- C accounts for factors which are not related to beam intensities and accidental effects (e.g. acceptances);
- given a function $f(t)$ which varies with time t , the notation $\langle f \rangle \equiv 1/T \int_T f(t) dt$ is used. The function $f(t)$ can be written as $f(t) \equiv \langle f \rangle (1 + \eta_f(t))$, where the time varying fraction of $f(t)$ is written explicitly. Notice that $\langle \eta_f \rangle = 0$ and that $\langle \eta_f^2 \rangle = \sigma_f^2 / \langle f \rangle^2$ is the relative variance of $f(t)$.

The bias on the measurement of $\mathcal{R}$ due to accidentals can be parametrized as follows:

$$\mathcal{R}_{measured} = \mathcal{R}_{true} \cdot C \cdot \frac{1/T \cdot \int_T (1 - \Lambda_L^N(t)) I_L(t) dt}{1/T \cdot \int_T (1 - \Lambda_S^N(t)) I_S(t) dt} \cdot \frac{1/T \cdot \int_T (1 - \Lambda_S^C(t)) I_S(t) dt}{1/T \cdot \int_T (1 - \Lambda_L^C(t)) I_L(t) dt} \quad (6.1)$$

or

$$\mathcal{R}_{measured} = \mathcal{R}_{true} \cdot C \cdot \frac{1 - \frac{\langle \Lambda_L^N I_L \rangle}{\langle I_L \rangle}}{1 - \frac{\langle \Lambda_S^N I_S \rangle}{\langle I_S \rangle}} \cdot \frac{1 - \frac{\langle \Lambda_S^C I_S \rangle}{\langle I_S \rangle}}{1 - \frac{\langle \Lambda_L^C I_L \rangle}{\langle I_L \rangle}} \quad (6.2)$$

Writing:

$$\begin{cases} I_S(t) \equiv \langle I_S \rangle \cdot (1 + \eta_S(t)) \\ I_L(t) \equiv \langle I_L \rangle \cdot (1 + \eta_L(t)) \\ \Lambda_{S,L}^{N,C}(t) \equiv \lambda_{S,L}^{N,C} \cdot (1 + \eta_\Lambda(t)) \end{cases} \quad (6.3)$$

eqn. (6.1) can be written as:

$$\Delta\mathcal{R}/\mathcal{R} = 1 - \frac{1 - \lambda_L^N (1 + \langle \eta_A \eta_L \rangle)}{1 - \lambda_S^N (1 + \langle \eta_A \eta_S \rangle)} \cdot \frac{1 - \lambda_S^C (1 + \langle \eta_A \eta_S \rangle)}{1 - \lambda_L^C (1 + \langle \eta_A \eta_L \rangle)} \quad (6.4)$$

6.1.1 Accidental effects which depend on the rate

From the hypothesis *that the accidental related losses are proportional to the counting rates in the detector and hence to the beam¹ intensity*, I_A , one writes:

$$\Lambda_{S,L}^{N,C}(t) = \kappa_{S,L}^{N,C} \cdot I_A(t) \quad (6.5)$$

where the intensity dependence I_A and the detector (trigger, reconstruction and selection) effects $\lambda_{S,L}^{N,C}$ are separated. These two terms can be written as the sum of a constant and a time dependent part with zero time average:

$$I_A(t) \equiv \langle I_A \rangle \cdot (1 + \eta_A(t)) \quad (6.6)$$

and

$$\Lambda_{S,L}^{N,C}(t) \equiv \lambda_{S,L}^{N,C} \cdot (1 + \eta_A(t)) \quad (6.7)$$

where $I_A(t)$ and $\Lambda_{S,L}^{N,C}(t)$ have the same time dependence, due to eqn. (6.5), and the factor $\lambda_{S,L}^{N,C} \equiv \kappa_{S,L}^{N,C} \langle I_A \rangle$ is the time average for the loss probability in the four $K_{\pi\pi}$ modes.

Then eqn. (6.4) becomes:

$$\Delta\mathcal{R}/\mathcal{R} = 1 - \frac{1 - \lambda_L^N (1 + \langle \eta_A \eta_L \rangle)}{1 - \lambda_S^N (1 + \langle \eta_A \eta_S \rangle)} \cdot \frac{1 - \lambda_S^C (1 + \langle \eta_A \eta_S \rangle)}{1 - \lambda_L^C (1 + \langle \eta_A \eta_L \rangle)} \quad (6.8)$$

$$\sim \left((\lambda^N - \lambda^C) \langle \eta_A (\eta_S - \eta_L) \rangle \right) + \left(\delta\lambda^N - \delta\lambda^C \right) \quad (6.9)$$

where $\delta\lambda \equiv \lambda_S - \lambda_L$. In case of *equal fractional losses for K_S and K_L events*:

$$\lambda_L = \lambda_S \quad (6.10)$$

so that eqn. (6.8) can be approximated to first order in λ by:

$$\Delta\mathcal{R}/\mathcal{R}|_{intensity} \equiv (\lambda^N - \lambda^C) \langle \eta_A (\eta_S - \eta_L) \rangle \quad (6.11)$$

¹It will be shown in Chapter 7 that the main source of accidentals is the KL beam, hence $I_A \sim I_L$

which will be referred to as the *intensity dependent bias* induced by the accidentals on $\mathcal{R}$. The condition $\Delta\mathcal{R} = 0$ of no accidental effect on $\mathcal{R}$ is fulfilled if at least one of the following conditions is achieved:

- i) The fraction of losses for $K_{\pi^+\pi^-}$ decays balance that for $K_{\pi^0\pi^0}$ decays, i.e. $\lambda^N = \lambda^C$
- ii) I_S and I_L are varying arbitrarily but I_A is constant, i.e. $\eta_A = 0$
- iii) I_A is varying arbitrarily but the ratio I_S/I_L is constant, i.e. $\eta_S = \eta_L$

The first condition (later referred to as $\mathcal{N}/\mathcal{C}$ balance) is a priori the most demanding. Concerning the second condition, the fraction of accidentals generated in the KS beam is negligible (see Section 7.3) and so the approximation $I_A \sim I_L$ holds. Thus the condition is also unfulfilled due to time variations of the KL beam which are not negligible. The third condition represents the basic principle of the experiment: if the two beams were 100% correlated the accidental activity would have no effect on $\mathcal{R}$.

Therefore it is mandatory to measure the **auto-correlation** $\langle \eta_L^2 \rangle$ and $\langle \eta_S^2 \rangle$ (later referred to also as **beam fluctuation terms**) and the **cross-correlation** $\langle \eta_S \eta_L \rangle$ of the beam intensities. This subject will be introduced in the next sections and fully covered in Chapter 8.2. The **auto-correlation** of the beam intensities will be found to be at the level of $\langle \eta_L^2 \rangle \sim \langle \eta_S^2 \rangle \sim 0.25$, which points to huge ($\sim 50\%$) r.m.s. values for I_S and I_L . But the difference between **auto-correlation** and **cross-correlation** namely $\langle \eta_L \eta_L - \eta_S \eta_L \rangle$, and $\langle \eta_S \eta_S - \eta_S \eta_L \rangle$, will be measured to be very small: ≈ -0.006 , and ≈ 0.018 respectively. This points to a $\lesssim 10\%$ r.m.s. for the ratio I_S/I_L , and implies that the term $\langle \eta_A(\eta_S - \eta_L) \rangle$ in eqn. (6.11) is very small. Therefore the third condition is not violated.

It is worth noticing that the more the KS and KL beam intensities are correlated in time, the smaller any bias on $\mathcal{R}$ is, due to the variations of detection inefficiencies with time². To this point notice that distinct and conspicuous time structures for KS and KL can couple with any kind of inefficiency variation with time, resulting in a average unequal inefficiency for K_S and K_L events.

Various methods of evaluating the term $(\lambda^N - \lambda^C)$ in eqn. (6.11) are introduced in the next sections. In Chapter 12 a conservative upper limit of this term will be

²from this point of view the effect of the accidentals is just a special case

found at the level of few percent. The limit for the bias on $\mathcal{R}$ is set:

$$\Delta\mathcal{R}/\mathcal{R}|_{intensity} \equiv (\lambda^N - \lambda^C) \langle \eta_A(\eta_S - \eta_L) \rangle \lesssim 2 \cdot 10^{-4} \quad (6.12)$$

6.1.2 Accidental effects which depend on the geometry

The condition $\lambda_L = \lambda_S$ might be violated. For instance, an accidental particle could have different effects on K_S and K_L events, depending on the different beam geometries. This induces a different bias on $\mathcal{R}$ than the one previously discussed (see eqn. 6.11). Then an additional accidental related bias has to be considered, due to $\delta\lambda \equiv \lambda_S - \lambda_L \neq 0$ not vanishing:

$$\Delta\mathcal{R}/\mathcal{R}|_{geometry} \equiv \delta\lambda^N - \delta\lambda^C \quad (6.13)$$

The method to measure this effect is introduced in the next sections. In Chapter 12 the bias on $\mathcal{R}$ is set to :

$$\Delta\mathcal{R}/\mathcal{R}|_{geometry} \equiv \delta\lambda^N - \delta\lambda^C \sim (4 \pm 4) \cdot 10^{-4} \quad (6.14)$$

6.1.3 Accidental in-time effects

The particles produced by the same proton interaction as the $K_{\pi\pi}$ (later referred to as in time) are not accounted for in the above approach. They are particularly dangerous because they might affect the K_S and K_L decays to different extent. The subject is treated in Chapter 11.

6.2 The experimental methods

Unfortunately there is not a direct, straightforward recipe for the correction to $\mathcal{R}$. Many partial results are found with different methods, which are outlined in this section, and applied in the following chapters.

6.2.1 Accidental effects analyzed with the extra-activity method

The finite duration of electronic signals (detector memory time) is the main cause for its sensitivity to the accidental activity. This can lead to loss of events

through trigger inefficiencies and dead time, overflow appearance, biases in the reconstruction, and the worsening of resolutions (e.g. tails in time measurements).

Any accidental activity which affects the $K_{\pi\pi}$ event detection and selection, leaves a trace in the sidebands of the read-out time windows. Therefore the analysis of the average level of activity (later referred to as extra-activity) in the read-out time windows, for the different sub-detectors, allows the singling out of those effects. In other words the rate dependent losses affect the effective beam intensity which is seen by the selected events (instantaneous intensity). The amount of extra-activity observed around the time of the events is an estimate of the beam instantaneous intensity and therefore it is used to estimate the level of the losses.

Different indicators for the extra-activity in the sidebands of the read-out time windows are used. The use of distinct indicators for the accidental activity related to KS and KL beams is crucial. In the case of KS beam activity, the hits in the tagger, in the KS monitor and in the anti-KS detector are studied, while the tracks, the space points and the overflows in the drift chambers, the energy clusters in the electromagnetic calorimeter, and the hits in the anti-KL detector and in the muon veto are used to measure the KL beam accidentals.

The indicators should have the following characteristics in order not to introduce biases:

- i) The efficiency of detection for the accidentals should be the same for the four $K_{\pi\pi}$ modes;
- ii) The measurement of the time of the accidentals should be allowed with an accuracy sufficient to single out the detector activity related to the $K_{\pi\pi}$;
- iii) The loss probability should not be directly correlated to the loss of the event;

Only the last condition is critical. Let us take, for instance, the out-of-time tracks detected by the spectrometer as indicator of accidental activity. The tracks are correlated to the presence of overflows, hence they do not measure the intensity of the beam in an unbiased way. In general, if the activity detected by an indicator can directly cause some losses, then the indicator is biased. Detectors which are not in the central detector (e.g. the tagger and the anti-KL detector, which are not used in the trigger, nor in the reconstruction) have good chance to be unbiased. Nevertheless, detectors included in the central detector can also measure

the extra-activity, provided the sidebands are sufficiently far from the event time, so as not to be directly affected by the losses.

Let us assume we are using an unbiased indicator (e.g the tagger), and count, for each selected event, the number m of hits (e.g. reconstructed protons in the tagger) in some selected sideband of the read-out time window (see illustration in figure 6.1).

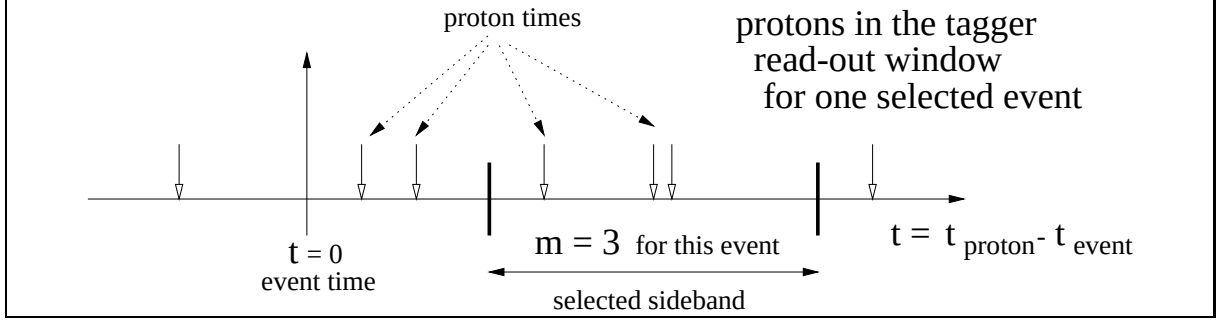


Figure 6.1: Illustration of the (extra-activity) hits counting which is done event by event over some selected region of the read-out window. This region is also referred to as a sideband due to the fact that usually it has to be chosen far from the event time. Only out-of-time hits should be counted, to avoid correlations with the event induced hits.

Let us consider $\frac{dn}{dm}$, the distribution of the selected events as a function of the number of hits m for recorded in each event (see illustration in figure 6.2).

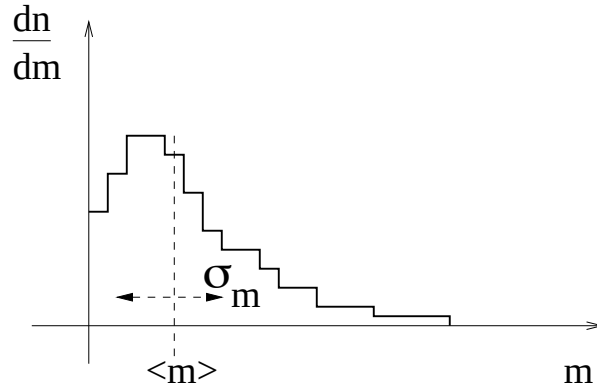


Figure 6.2: The extra-activity hits are counted event by event for the selected $K_{\pi\pi}$ decays. The distribution of the events as a function of the number of hits counted gives useful information to study the intensity variations in time. In particular the average $\langle m \rangle$ and the variance σ_m of the number of hits measured on different samples of detected events allow the measurements of the KS and KL beams fluctuation and correlation terms.

Given $I_K(t)$, the probability of having a $K_{\pi\pi}$ decay (in one of the four modes) at time t ; $1 - \Lambda_K(t)$, the probability of triggering and selecting the event; and $m(t)$, the

number of hits in the sideband, then the average number $\langle m \rangle$ of hits in the sideband can be written as:

$$\langle m \rangle_K = \frac{1/T \cdot \int_T m(t) (1 - \Lambda_K(t)) I_K(t) dt}{1/T \cdot \int_T (1 - \Lambda_K(t)) I_K(t) dt} = M/N \quad (6.15)$$

where M is the total number of hits counted on the whole data sample consisting of N events. The notation $\langle \dots \rangle_K$ is to make evident that the average is measured by sampling m with triggered and selected $K_{\pi\pi}$ events, and the symbol K stays for S or L. Eqn. (6.15) can be written as:

$$\langle m \rangle_K = \frac{\langle m(1 - \Lambda_K)I_K \rangle}{\langle (1 - \Lambda_K)I_K \rangle} = \frac{\langle mI_K \rangle}{\langle I_K \rangle} \cdot \frac{1 - \frac{\langle m\Lambda_K I_K \rangle}{\langle mI_K \rangle}}{1 - \frac{\langle \Lambda_K I_K \rangle}{\langle I_K \rangle}} \quad (6.16)$$

With the usual notation, i.e. extracting the time varying fractions:

$$\begin{cases} m(t) \equiv \langle m \rangle_0 (1 + \eta_m(t)) \\ I_K(t) \equiv \langle I_K \rangle (1 + \eta_K(t)) \\ \Lambda(t) \equiv \lambda (1 + \eta_\Lambda(t)) \end{cases} \quad (6.17)$$

one writes:

$$\langle m \rangle_K = \langle m \rangle_0 \cdot \langle (1 + \eta_m)(1 + \eta_K) \rangle \cdot \frac{1 - \lambda \frac{\langle (1 + \eta_m)(1 + \eta_\Lambda)(1 + \eta_K) \rangle}{\langle (1 + \eta_m)(1 + \eta_K) \rangle}}{1 - \lambda \langle (1 + \eta_\Lambda)(1 + \eta_K) \rangle} \quad (6.18)$$

which, to first order in λ , and to second order in η , justify:

$$\langle m \rangle_K = \langle m \rangle_0 \cdot \langle 1 + \eta_m \eta_K \rangle \cdot \{1 - \lambda \langle \eta_m \eta_\Lambda \rangle\} \quad (6.19)$$

where the term η_m represents the time variations of the **KL(KS)** beam, relative to the average intensity $\langle m \rangle_0$, respectively for a **KL(KS)** beam intensity indicator. Notice that the term $\langle m \rangle_0$ is the plain average value of m . This could be measured by sampling the number m of hits in the sideband at a fixed time intervals, or by sampling m with randomly triggered events. It is different from $\langle m \rangle_K$ because the latter is measured by sampling m with triggered and selected events. The factor $\langle 1 + \eta_m \eta_K \rangle \cdot \{1 - \lambda \langle \eta_m \eta_\Lambda \rangle\}$ accounts for the difference:

- The term $\langle 1 + \eta_m \eta_K \rangle$ is the enhancement factor due to the sampling by triggered events. It quantitatively expresses the fact that the trigger selects higher intensities. The term $\langle \eta_m \eta_K \rangle$ represents a beam fluctuation term, which is of the order of 0.25.
- The term $\{1 - \lambda \langle \eta_m \eta_\Lambda \rangle\}$ is the quantitative expression for the drop in the average extra-activity level due to the losses. Notice that the usual assumption is that the losses depend linearly on the intensity, which leads to the relation $\eta_\Lambda(t) = \eta_A(t)$, where $\eta_A(t)$ are the relative time variations of the flux of the accidentals. Notice also that it will be found that $\eta_A \sim \eta_L$.

6.2.1.1 Measurement of the beam intensity fluctuations

The beam fluctuation terms are extracted from the relative square variance $\frac{\sigma_m^2}{\langle m \rangle^2}|_K$ of the m distribution, measured for triggered and selected events. The term $\langle m^2 \rangle_K$ is written as:

$$\langle m^2 \rangle_K = \frac{\langle m^2 (1 - \Lambda_K) I_K \rangle}{\langle (1 - \Lambda_K) I_K \rangle} = \frac{\langle m^2 I_K \rangle}{\langle I_K \rangle} \cdot \frac{1 - \frac{\langle m^2 \Lambda_K I_K \rangle}{\langle m^2 I_K \rangle}}{1 - \frac{\langle \Lambda_K I_K \rangle}{\langle I_K \rangle}} \quad (6.20)$$

and approximated with:

$$\langle m^2 \rangle_K = \langle m \rangle_0^2 \cdot \langle 1 + 2 \eta_m \eta_K + \eta_m^2 \rangle \cdot \{1 - 2 \lambda \langle \eta_m \eta_\Lambda \rangle\} \quad (6.21)$$

Then for the relative square variance:

$$\frac{\sigma_m^2}{\langle m \rangle^2}|_K = \frac{\langle m^2 \rangle_K}{\langle m \rangle_K^2} - 1 \sim \langle \eta_m^2 \rangle \quad (6.22)$$

In case of a KL(KS) beam intensity indicator being used, the value of $\langle \eta_L^2 \rangle$ ($\langle \eta_S^2 \rangle$) is measured. Of course the expression for $\frac{\sigma_m^2}{\langle m \rangle^2}|_K$ does not account for the Poisson statistics of m , which in case of small $\langle m \rangle$ values will dominate. Thus in Chapter 8 the value of $\langle \eta_m^2 \rangle$ will be extracted by the measured variance using:

$$\langle \eta_m^2 \rangle = \frac{\sigma_m^2}{\langle m \rangle^2}|_{measured} - \frac{\sigma_m^2}{\langle m \rangle^2}|_{poisson} = \frac{\sigma_m^2}{\langle m \rangle^2}|_{measured} - \frac{1}{\langle m \rangle} \quad (6.23)$$

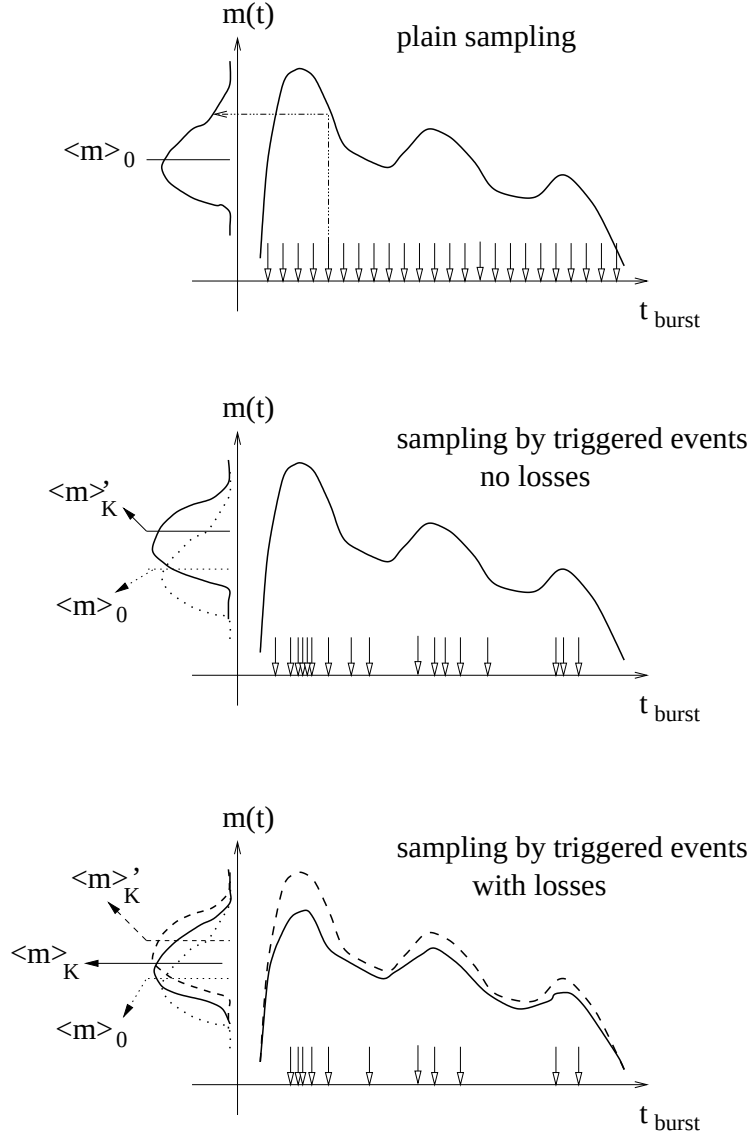


Figure 6.3: Illustration of the three terms in eqn. 6.18. The term $\langle m \rangle_0$ is the plain average value of the number of hits per event m ; this could be measured by sampling m with events triggered at a fixed time intervals (or by sampling m with purely randomly triggered events). The term $\langle 1 + \eta_m \eta_K \rangle$ is the enhancement factor (represented as the shift $\langle m \rangle_0 \rightarrow \langle m \rangle'_K$) due to the sampling by triggered events: the trigger selects naturally higher intensities. The term $\{1 - \lambda \langle \eta_m \eta_\Lambda \rangle\}$ is the reduction factor (represented as the shift $\langle m \rangle'_K \rightarrow \langle m \rangle_K$) in the average extra-activity level due to the losses. The rate dependent losses of events have the tendency to cut off the highest intensities, because there the detectors suffer the highest inefficiencies.

6.2.1.2 Measurement of the intensity correlation of the beams

The ratio of the measurements of $\langle m \rangle_S$ and $\langle m \rangle_L$ respectively with the selected K_S and K_L events can be written as:

$$\frac{\langle m \rangle_S}{\langle m \rangle_L} = \frac{\langle 1 + \eta_m \eta_S \rangle}{\langle 1 + \eta_m \eta_L \rangle} \cdot \frac{1 - \lambda_S \langle \eta_m \eta_{\Lambda_S} \rangle}{1 - \lambda_L \langle \eta_m \eta_{\Lambda_L} \rangle} \quad (6.24)$$

If the assumption that $\Lambda_L = \Lambda_S$, that is the difference in geometric accidental losses for $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ is negligible (which will be shown in Chapter 12), then the expr. (6.24) is approximated by:

$$\frac{\langle m \rangle_S}{\langle m \rangle_L} \sim 1 + \langle \eta_m \eta_S - \eta_m \eta_L \rangle \quad (6.25)$$

which leads to a measurement of the differences between the **auto-correlation** and **cross-correlation**

$$\langle \eta_L \eta_L - \eta_S \eta_L \rangle \sim -0.006 \quad (6.26)$$

$$\langle \eta_S \eta_S - \eta_S \eta_L \rangle \sim +0.018 \quad (6.27)$$

respectively using a **KL** beam intensity indicator (e.g. the anti-KL detector) or a **KS** beam intensity (e.g. the tagger).

As was introduced in Section 6.1.1 on page 122, this measurement is an important step towards the measurement of the bias on $\mathcal{R}$ due to accidental effects (see eqn. 6.11). In particular, different methods will take advantage of the measured limits on the relative correlation difference:

$$\left| \frac{\langle \eta_L \eta_L - \eta_L \eta_S \rangle}{\langle \eta_L \eta_L \rangle} \right| \sim \left| \frac{\langle \eta_L \eta_L - \eta_L \eta_S \rangle}{\langle \eta_L \eta_S \rangle} \right| \sim 0.025 \quad (6.28)$$

$$\left| \frac{\langle \eta_L \eta_L - \eta_L \eta_S \rangle}{\langle 1 + \eta_L \eta_L \rangle} \right| \sim \left| \frac{\langle \eta_L \eta_L - \eta_L \eta_S \rangle}{\langle 1 + \eta_L \eta_S \rangle} \right| \sim 0.005 \quad (6.29)$$

6.2.1.3 Measurement of the differential losses for neutral and charged decays

The ratio of the measurements of $\langle m \rangle_N$ and $\langle m \rangle_C$ respectively with the selected $K_{\pi^0\pi^0}$ and $K_{\pi^+\pi^-}$ events of a given kaon type (K_S for instance) can be written as:

$$\frac{\langle m \rangle_N}{\langle m \rangle_C} = \frac{\langle 1 + \eta_m \eta_N \rangle}{\langle 1 + \eta_m \eta_C \rangle} \cdot \frac{1 - \lambda^N \langle \eta_m \eta_{\Lambda^N} \rangle}{1 - \lambda^C \langle \eta_m \eta_{\Lambda^C} \rangle} \quad (6.30)$$

where the term $\frac{\langle 1 + \eta_m \eta_N \rangle}{\langle 1 + \eta_m \eta_C \rangle}$ vanish due to the fact that the flux of kaons is the same.

In principle one can measure the difference between $\frac{\langle m \rangle_N}{\langle m \rangle_C}$ measured with a **KS** and a **KL** indicator obtaining:

$$\frac{\langle m \rangle_N}{\langle m \rangle_C} \Big|_S - \frac{\langle m \rangle_N}{\langle m \rangle_C} \Big|_L = \frac{1 - \lambda^N \langle \eta_{\Lambda^N} (\eta_S - \eta_L) \rangle}{1 - \lambda^C \langle \eta_{\Lambda^C} (\eta_S - \eta_L) \rangle} \quad (6.31)$$

which gives directly the bias on $\mathcal{R}$ due to intensity accidental effects, see eqn. (6.8). The availability of non biased **KS** and a **KL** indicators is mandatory in this case. The tagger is found to be almost unbiased, while the AKL will turn out to have some amount of bias. Then the relation (6.31) cannot be fully exploited and only limits on the difference $\lambda_N - \lambda_C$ can be estimated from the extra-activity method. Taking the expression:

$$\frac{\langle m \rangle_N}{\langle m \rangle_C} = \frac{1 - \lambda^N \langle \eta_m \eta_{\Lambda^N} \rangle}{1 - \lambda^C \langle \eta_m \eta_{\Lambda^C} \rangle} \quad (6.32)$$

as an upper limit on the accidental neutral to charged differential effect of the losses on intensity $\frac{1 - \lambda^N \langle \eta_m \eta_A \rangle}{1 - \lambda^C \langle \eta_m \eta_A \rangle} = 1 - (\lambda^N - \lambda^C) \cdot \langle \eta_m \eta_A \rangle$ and using the independently measured value of $\langle \eta_m \eta_A \rangle \sim 0.25$, one can limit the value of $\lambda^N - \lambda^C$ to the level of a few percent. Given the very small decorrelation of the beams (see eqn. 6.26) this is enough to limit (see eqn. 6.11) the bias on $\mathcal{R}$ to:

$$\Delta \mathcal{R} / \mathcal{R} |_{intensity} = \left| (\lambda_N - \lambda_C) \langle \eta_L \eta_S \rangle \cdot \frac{\langle \eta_L \eta_L - \eta_L \eta_S \rangle}{\langle \eta_L \eta_S \rangle} \right| \lesssim 0.006 \cdot 0.025 \sim 1.5 \cdot 10^{-4} \quad (6.33)$$

6.2.2 Accidental effects analyzed with the beam counters

Much information is available from the KLM, QX, KSM and AKS detector counts:

- i) The total counts are recorded for each burst;
- ii) The counters are sampled at fixed times (sampling rate ~ 100 Hz);
- iii) The incremental read-out of the scalars between successive Level-2 triggers is available for each trigger.

6.2.2.1 Measurement of the beam intensity fluctuations

Given the beam intensity $I(t)$, with average value $\langle I \rangle = 1/T \int_T I(t) dt$, the fluctuations of the intensity around $\langle I \rangle$ can be measured with delayed coincidences. In case the flux is not constant (i.e. pure poissonian with a fixed average rate) with time then the coincidence rate is enhanced by the presence of time structures. In general, the more important the fluctuations, the higher inefficiencies and dead time in the experiment.

The measured single counts and delayed coincidences (S and C respectively) from a beam counter in a burst (see figure 6.4) can be written as:

$$S = c \cdot \int_T dt I(t) \quad (6.34)$$

$$C = c^2 \cdot \int_T dt I(t) \int_{\delta t}^{\delta t + \Delta t} d\tau I(t + \tau) \quad (6.35)$$

where c is a normalization factor, δt the delay of the coincidence and Δt the coincidence width. Given the approximation $I(t + \tau) \sim I(t)$, and the usual notation $I(t) \equiv \langle I \rangle (1 + \eta(t))$, then the ratio:

$$\frac{C}{S^2 \cdot \Delta t} \sim 1 + \langle \eta^2 \rangle \quad (6.36)$$

allows us to estimate the beam fluctuations $\langle \eta^2 \rangle$. The quantity $\frac{T_{eff}}{T} \equiv \frac{S^2 \cdot \Delta t}{C}$ is usually referred to as **effective burst length**.

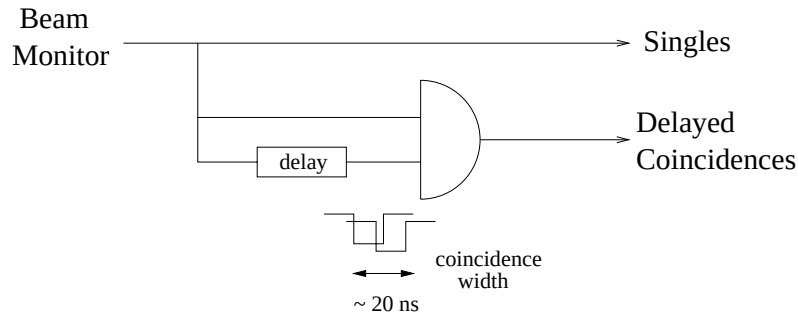


Figure 6.4: Illustration of a setup for the effective burst length measurement.

This method differs from the extra-activity method (see Section 6.2.1.1 on page 127) in the timing resolution. While the former is sensitive only to slow time variations (cutoff frequency $\sim \frac{1}{\langle \Delta t_i \rangle}$) the latter covers a wider range of frequencies.

6.2.2.2 Measurement of the intensity correlation of the beams

The beam counters are exploited to measure the intensity correlation of the beams. In particular the samplings (ii) and (iii) (see Section 6.2.2 on page 130) are used.

Given the KS and KL beam monitor counts N_s^i and N_L^i sampled n times (in a burst) with the possibly variable sampling intervals Δt_i , the auto-correlation and cross-correlation can be written as:

$$\frac{\langle I_L^2 \rangle}{\langle I_L \rangle^2} = \frac{\sum_{i=1}^n (N_L^i)^2 \Delta t_i}{(\sum_{i=1}^n N_L^i \Delta t_i)^2} \quad (6.37)$$

$$\frac{\langle I_s^2 \rangle}{\langle I_s \rangle^2} = \frac{\sum_{i=1}^n (N_s^i)^2 \Delta t_i}{(\sum_{i=1}^n N_s^i \Delta t_i)^2} \quad (6.38)$$

$$\text{and } \frac{\langle I_s I_L \rangle}{\langle I_s \rangle \cdot \langle I_L \rangle} = \frac{\sum_{i=1}^n N_s^i N_L^i \Delta t_i}{(\sum_{i=1}^n N_s^i \Delta t_i) \cdot (\sum_{i=1}^n N_L^i \Delta t_i)} \quad (6.39)$$

where in case (ii) the sampling interval is constant $\Delta t_i \sim 10$ ms, while in case (iii) it is variable. In particular, the latter is the distance between two successive triggers, which in the case of the triggers used for this study is $\langle \Delta t_i \rangle \gtrsim 1$ ms (see Chapter 8).

This method differs from the extra-activity method (see Section 6.2.2.2) in the timing resolution. While the former is sensitive only to slow time variations (cutoff frequency $\nu_{cutoff} \sim \frac{1}{\langle \Delta t_i \rangle} \sim 1$ kHz) the latter covers a wider range of frequencies (up to $\nu_{cutoff} \sim 10$ MHz). Thus comparing the two methods allows us to understand whether the small amount of beam intensity decorrelation is caused by high or low frequency structures of the beams.

In Chapter 8 the result will be found to be:

$$\langle \eta_L \eta_L - \eta_s \eta_L \rangle = \frac{\langle I_L^2 \rangle}{\langle I_L \rangle^2} - \frac{\langle I_s I_L \rangle}{\langle I_s \rangle \cdot \langle I_L \rangle} \sim +0.005 \quad (6.40)$$

6.2.3 Accidental effects analyzed with special beam conditions

In Chapter 7 it will be shown that the sources of the accidental effects are found in the KL beam line rather than in the KS beam. The ratio of the amount of accidental activity induced by the two beams is $KS : KL \lesssim 2 : 100$.

Thus one may switch the KL beam off and measure the residual event losses on $K_{\pi\pi}^S$ events. In particular by this method the difference of the losses for neutral and charged events is obtained.

The numbers of neutral and charged $K_{\pi\pi}^S$ events in *KS-only* beam mode can be written as:

$$\overline{N}_S^N = C^N \cdot \langle \overline{I} \rangle \quad \text{and} \quad \overline{N}_S^C = C^C \cdot \langle \overline{I} \rangle \quad (6.41)$$

where $\overline{I}$ is the kaon flux in the *KS-only* beam mode, and the factors C^C and C^N account for the different acceptances and inefficiencies which are in principle not dependent on accidental effects. On the other hand, the numbers of neutral and charged $K_{\pi\pi}^S$ events collected in *KS+KL* beam mode are:

$$N_S^N = C^N \cdot \langle I \rangle (1 - \lambda^N \langle 1 + \eta_{\Lambda^N} \eta_S \rangle) \quad (6.42)$$

$$N_S^C = C^C \cdot \langle I \rangle (1 - \lambda^C \langle 1 + \eta_{\Lambda^C} \eta_S \rangle) \quad (6.43)$$

where the kaon flux I is of course different from $\overline{I}$, while the coefficients C^C and C^N are the same. Assuming the losses are linearly proportional to the KL intensity, then the differential losses can be measured by the double ratio:

$$1 - \frac{N_S^N / N_S^C}{\overline{N}_S^N / \overline{N}_S^C} \sim (\lambda^N - \lambda^C) \langle 1 + \eta_L \eta_S \rangle \quad (6.44)$$

This will be measured in Chapter 12 to be $\lesssim 0.01$. Considering the measurement of the beam correlation on eqn. (6.28) one gets a limit on $\Delta\mathcal{R}/\mathcal{R}|_{intensity}$:

$$\Delta\mathcal{R}/\mathcal{R}|_{intensity} = \left| (\lambda^N - \lambda^C) \langle 1 + \eta_L \eta_S \rangle \cdot \frac{\langle \eta_L \eta_L - \eta_L \eta_S \rangle}{\langle 1 + \eta_L \eta_S \rangle} \right| \lesssim 0.01 \cdot 0.005 = 0.5 \cdot 10^{-4} \quad (6.45)$$

6.2.4 Accidental effects analyzed with the random events

The accidental effects can be studied also with **random events** (see Section 3.5). These events are triggered at random but in proportion to the intensity of the beams. The delay of the triggers is needed to decorrelate the detector activity induced by the selected $K_{\pi\pi}$ events from the activity read-out in the **random events**. Due to the SPS 3^{rd} order resonance extraction mode, protons reach the extraction position in the SPS ring with the very same phase space conditions only every three SPS revolutions, i.e. $69 \mu s$. Given this amount of delay the intensity conditions recorded within the **random events** represent as faithfully as possible the intensity conditions of the $K_{\pi\pi}$ events³, but without being directly correlated to them.

³Just $69 \mu s$ at the beginning of the burst are not reproduced.

These events can be used to measure the accidental effects on $\mathcal{R}$ with two methods. The **overlay method** will be introduced in Section 6.2.5, while their use in the extra-activity method is described in the following.

6.2.4.1 Measurement of the losses with the random events

In principle, the **random events** do not experience losses due to any effects. Then if one compares the extra-activity level in the sidebands for **random** and selected $K_{\pi\pi}$ events, the difference is an estimate of the rate dependent losses of $K_{\pi\pi}$ events.

By inspection of eqn. (6.18) in the case of **random events**, one recognizes that the losses term falls out:

$$\langle m \rangle_R = \langle m \rangle_0 \cdot \langle 1 + \eta_m \eta_R \rangle \quad (6.46)$$

The residual term should be the equal to $\langle m \rangle_0 \cdot \langle 1 + \eta_m \eta_K \rangle$, that is the corresponding term in expr. (6.18) if **random events** represent properly the intensity conditions of the $K_{\pi\pi}$ events, i.e. if $\eta_R = \eta_K$.

Then by taking the ratio of expr. (6.18) and expr. (6.46) measured, for instance, respectively on K_S events and R_S events, one gets:

$$\frac{\langle m \rangle_S}{\langle m \rangle_{R_S}} = 1 - \lambda_S \langle \eta_m \eta_{\Lambda_S} \rangle \quad (6.47)$$

This method leads to the estimation of the single contributions by the four modes to the correction $\Delta\mathcal{R}/\mathcal{R}$. Of course this method relies on having good quality **random events**, which unfortunately was not completely achieved during the 1998 data taking.

6.2.5 Accidental effects analyzed with the overlay method

A different method of measuring the rate of losses also takes advantage of the **random events**. If they are triggered at a rate proportional to the beam intensities then they represent the accidental activity in the detector as it is seen by the $K_{\pi\pi}$ events.

6.2.5.1 Data overlays

The whole sample of the filtered neutral decay events and a fraction (30%) of the filtered charged decays were linearly **overlayed** with the **random events** collected in

1998. Given a triggered kaon decay, a properly chosen **random event** was overlayed in the following way. For each detector, the signals read-out for the **original**, and the **random event** were linearly summed channel by channel. The outcome was fed into the reconstruction software, and the sample of the **overlayed events** was obtained.

The **overlayed events** follow the standard analysis, and the verdict of the reconstruction and selection chain for the **original event**, is compared with the verdict for the **overlayed event**. By counting, for each mode, the losses (i.e. when the original event was accepted and the overlayed event rejected) and the gains (original rejected and overlayed accepted), the bias due to accidental effects can be estimated. Notice that the gains are caused by the migrations of events across the selection acceptance boundaries, which is a consequence of the worsened resolution for the measurement of the kinematical variables due to the presence of accidental activity. The global effect is a net loss of events⁴.

Let n_{orig} be the number of original events which pass the selection before the overlay, n_{common} the number of events which pass the selection both before and after the overlay, and n_{loss} and n_{gain} the numbers of lost and gained events respectively. Then n_{orig} can be written as $n_{common} + n_{loss}$, and the number of events which pass the selections after the overlay is $n_{common} + n_{gain}$. The difference between these two numbers, normalized to n_{orig} , gives the overall loss probability:

$$\Lambda \equiv \frac{n_{loss} - n_{gain}}{n_{orig}} \gtrsim 0 \quad (6.48)$$

If K_L proper time weighting is to be accounted for, then $n_{common} + n_{loss}$ is substituted by $\sum_i (w_i)_{common} + \sum_i (w_i)_{loss}$, and $n_{common} + n_{gain}$ becomes $\sum_i (w'_i)_{common} + \sum_i (w'_i)_{gain}$. This accounts for the possibility that an event, whose weight is w_i before the overlay, might have a different weight w'_i after the overlay. The overall loss probability becomes:

$$\Lambda \equiv \frac{\sum_i (w_i)_{loss} - \sum_i (w'_i)_{gain} - \sum_i (w'_i - w_i)_{common}}{\sum_i (w_i)_{orig}} \gtrsim 0 \quad (6.49)$$

where the term $\sum_i (w'_i - w_i)_{common}$ is referred to as weight shift.

The accidental effects on trigger, tagging, and event time reconstruction are not included in the procedure. Different methods are discussed in Chapters 9 and 5 which allow us to measure the overall trigger, tagging, and time reconstruction

⁴There is not a “detailed balance” between losses and gains; this is the non trivial part of the study.

inefficiencies, including the accidental effects. Thus the overlay procedure accounts for the accidental effects only on reconstruction and selection. Moreover the procedure does not account for any in-time accidental effects, which are by definition correlated with the original event and cannot be introduced by overlaying random events, even if the latter were perfectly synchronized with the original event.

In principle, both the intensity and the geometric biases (see eqn. 6.11 and 6.13) can be estimated with the overlay method. Let us consider one decay mode, e.g. a K_L neutral $K_{\pi^0\pi^0}$ decay. Let $\overline{\Lambda}_L^N(t')$ be the probability of losing⁵ an overlayed event at a time t' , due to the effects induced by the extra-activity recorded by the random event. On assuming that the losses are proportional to the detector activity, and this is proportional to the (KL) beam intensity, one can write:

$$\overline{\Lambda}_L^N(t') \equiv \overline{\kappa}_L^N \cdot I_A(t') \equiv \overline{\kappa}_L^N \cdot \langle I_A \rangle (1 + \eta_A(t')) \equiv \overline{\lambda}_L^N \cdot (1 + \eta_A(t')) \quad (6.50)$$

Then the number of original events that are reconstructed and selected reads:

$$1/T \cdot \int_T (1 - \Lambda_L^N(t)) I_L(t) dt \equiv \langle I_L \rangle \cdot (1 - \lambda_L^N(1 + \langle \eta_A \eta_L \rangle)) \quad (6.51)$$

and the number of reconstructed and selected overlayed events is written as:

$$1/T \cdot \int_T dt (1 - \Lambda_L^N(t)) (1 - \overline{\Lambda}_L^N(t')) I_L(t) \quad (6.52)$$

Then the expression:

$$\langle I_L \rangle \cdot \{1 - \lambda_L^N(1 + \langle \eta_A \eta_L \rangle) + \overline{\lambda}_L^N(1 + \overline{\langle \eta_A \eta_L \rangle})\} + \langle \Lambda \overline{\Lambda} I \rangle \quad (6.53)$$

is a good approximation of eqn. 6.52 *provided that, for every original event, a random event can be found such that $t = t'$* . The difference⁶ between eqn. (6.52) and eqn. (6.51) normalized to eqn. (6.51) (like in eqn. 6.48) yields the losses for the $K_{\pi^0\pi^0}^L$ decay mode:

$$\overline{\lambda}_L^N(1 + \overline{\langle \eta_A \eta_L \rangle}) \quad (6.54)$$

The double ratio of the terms like (6.52) for the four modes yields an estimate for the accidental bias on $\mathcal{R}$.

Unfortunately there are many conditions which must be respected for this estimate to be reliable:

⁵Notice that gains from here on are included in $\overline{\Lambda}_L^N(t')$

⁶Notice that the last quadratic term can be dropped in case the losses are small.

- i) In principle, the overlay procedure should overlap each original event with a the random event triggered at the same time in the burst.

However the actual procedure selects the random with the nearest absolute time (i.e. the time in the run and not the time in the burst only) which preceded the original event. This may introduce some amount of bias.

Indeed, concerning eqn. (6.52), the latter procedure results in $\tau \equiv t - t' \neq 0$, where τ is the difference of the time in the burst between the original and the random event. Besides τ is different for each overlayed event: let us say that τ ranges in a interval $\Delta\tau$ about 0. Then the term $\overline{\langle\eta_A\eta_L\rangle}$ has the meaning of a cross-correlation averaged over the range $\Delta\tau$:

$$\overline{\langle\eta_A\eta_L\rangle} \equiv 1/(T \cdot \Delta\tau) \int_T dt \int_{\Delta\tau} d\tau \eta_A(t + \tau) \eta_L(t) \quad (6.55)$$

which is a priori different from the cross-correlation with $\tau = 0$, i.e. the usual:

$$\langle\eta_A\eta_L\rangle \equiv 1/T \int_T dt \eta_A(t) \eta_L(t) \quad (6.56)$$

Thus the term $\overline{\langle\eta_A\eta_L\rangle}$ is a biased estimator of $\langle\eta_A\eta_L\rangle$.

The random rate has to be as high as possible in order to slim the range $\Delta\tau$, at least to the order of 25 ns, which is the time resolution of the trigger. Unfortunately this is far from being true: given 10 randoms per burst the latter criterion results in a $\Delta\tau \sim 2.5s/10 = 0.25s$ and an average $\langle\tau\rangle \sim -0.125s$. This results in overlaying, to the original $K_{\pi\pi}$ events, some accidental activity which is not what they actually see.

- ii) The random triggers must actually provide a faithful picture of the accidental activity seen by the $K_{\pi\pi}$ events. If this were the case then the relation $\overline{\Lambda}_L^N(t') = \Lambda_L^N(t')$ would hold. Otherwise eqn. (6.50) could not be written with the same I_A as in the case of Λ for the $K_{\pi\pi}$ events.
- iii) In case the losses are not small the quadratic term $\langle\Lambda\overline{\Lambda}I\rangle$ would bias the measurement. Care is to be taken due to the high (25%) overflow probability;
- iv) In case the losses are not linearly dependent on the beam intensity, the procedure would be biased. For instance, the noise in the detector is doubled

by the procedure⁷ even though it is independent of the intensity. In general, any not-linear effect lead to a bias when assuming that the difference between the expressions (6.52) and (6.51) represents the losses experienced by the original events.

6.2.5.2 Monte Carlo overlays

In order to escape some of the violated conditions above, another kind of procedure is exploited, which takes advantage of Monte Carlo events. Kaon decays are generated, without simulating any accidental activity in the detector, and are successively overlapped with the real random events.

In this case, the procedure of combining the original decay and random events is different: for every random event a simulated kaon decay is generated, and overlayed to the random⁸ The only condition to be respected is that the random events must cover the same intensity range as the real selected decays, and must have the same intensity distribution.

Of course, Monte Carlo overlay cannot cope with in-time accidental effects either. On the other hand, the procedure still accounts for every inefficiency effect which is generated by the original event itself (e.g. induced overflow, see Chapter 10).

Given the number N of original events, the number of lost events, including also the gains, is written as:

$$N \cdot 1/T \cdot \int_T dt' (1 - \overline{\Lambda}_L^N(t')) I_R(t') \equiv N \cdot (1 - \langle \overline{\Lambda}_L^N I_R \rangle) = N \cdot (1 - \langle I_R \rangle \cdot \overline{\Lambda}_L^N \langle 1 + \eta_A \eta_R \rangle) \quad (6.57)$$

where the intensity $I_R(t')$, and the time dependent loss $\overline{\Lambda}_L^N(t')$, relate to the random event.

The double ratio of these factors (eqn. 6.57) for the four modes allows us to measure both the intensity, and the geometrical accidental biases on $\mathcal{R}$. The former needs both the conditions $\langle \eta_A \eta_R \rangle = \langle \eta_A \eta_K \rangle$ and $\langle I_R \rangle = \langle I_K \rangle$ to be verified. The latter requires that $\langle \overline{\Lambda} \rangle$, sampled with by the randoms, is the same as $\langle \Lambda \rangle$ (which becomes $\langle I_R \rangle = \langle I_K \rangle$, in case the losses depend linearly on the intensity).

⁷The noise is recorded both in the random and in the original event

⁸this is exactly the opposite than what was done with data: in that case for every selected kaon decay a random was chosen to be overlapped.

Conclusions

This chapter introduces the effects of the accidental particles on $\mathcal{R}$, which might be biased either due to intensity effects, or due to geometrical effects. These are caused by the coincidence of two concurring effects:

- i) The probability to lose a charged or a neutral kaon decays is different;
- ii) The probability for a K_S or a K_L decay to be close in time (space) to some accidental activity in the detector, and to be rejected due to the presence of that activity, is different;

The first effect (i) might be a priori huge. However one can select the events in order to reduce as much as possible the difference in loss probability. For instance, this is the reason for the symmetrization of the charged trigger dead time (see Section 9). The second effect (ii) deals with the correlations in time (space) between the K_S or K_L events and the beam of the accidental particles, which is almost the KL beam. Any decorrelation in time (space) of the beams might couple with the first effect and result in the so-called intensity (geometrical) bias on $\mathcal{R}$ related to the accidentals.

Another effect which might bias $\mathcal{R}$ is accidental tagging, which is strongly rate dependent. This was introduced in Chapter 5. The extent of the mistagging effects is deeply related to the time structure of the beam, which will be investigated in Chapter 8. This kind of rate effect is also related to the above mentioned accidental effects: any loss of charged (neutral) events, induced by the accidental activity, results in a reduction of the average intensity experienced by the charged (neutral) events. And any difference of the average intensity between charged and neutral events results in a difference of accidental tagging probability.

7 A tentative phenomenology of the accidentals

Overview

In this chapter the accidental activity produced by the two beams is studied.

7.1 The counting rate of the detectors

Table 7.1 shows the **KL** and **KS** beam properties, and expected flux compositions. Most of the background activity that illuminates the detector is expected from both leptonic and hadronic K_L and Λ decay products, which might also develop showers along the beam line. The **KS** beam contributes mostly with Λ decays and showers from the collimator region.

Neutral kaons are accompanied by a strong contamination mainly from photons and neutrons. They are dangerous as they might interact with the beam pipe materials and produce electromagnetic or hadronic showers whose debris illuminate the detector¹.

The muons from the target, residual after the swapping magnets, are in principle less dangerous. For instance, as they just result in single tracks, the spectrometer reconstruction can cope with their presence.

Table 7.2 summarizes the rates measured in the sub-detectors, as counts per pulse (referred to as **cpp**; notice that one pulse corresponds to 1.8s of effective time), taken with different beam conditions (i.e. $L+S$, L -only and S -only). Using these measurements, the contributions from different sources to the total rates are singled out as follows:

$$\begin{aligned} \text{cpp}_{KL} &= \text{cpp}_{L+S} - \text{cpp}_{S\text{-only}} \\ \text{cpp}_{BKG} &= \text{cpp}_{L\text{-only}} + \text{cpp}_{S\text{-only}} - \text{cpp}_{L+S} \\ \text{cpp}_{KS} &= \text{cpp}_{L+S} - \text{cpp}_{L\text{-only}} \end{aligned} \tag{7.1}$$

Here, cpp_{KL} is the rate produced by the decays along **KL** beam downstream

¹Neutrons are responsible for the need of a beam pipe along the helium region: if neutrons were crossing that region without a vacuum beam pipe they would interact with helium producing a huge amount of accidental activity in the detector [30]. On the other hand, in the residual gas along the decay region, neutrons interact mimicking a K decay with only a negligible probability $< 10^{-8}$ [42]

	KL	KS
primary protons per pulse (ppp)	$1.5 \cdot 10^{12}$	$3 \cdot 10^7$
SPS spill time length/cycle time (s)	2.38 / 14.4	
effective spill time length (s)	1.8	1.8
length of K^0 beam (m)		
target to final collimator/AKS:	126.00	6.07
target to LKR:	241.10	121.10
production angle of K^0 beam (mrad)	2.4	4.2
angle of convergence to KL (mrad)	0.0	-0.6
angular acceptance (mrad)	± 0.150	± 0.375
beam diameter at LKR (mm)	~ 52	~ 78
useful momentum range (GeV/c)	$70 \div 170$	
average kaon momentum (GeV/c)	110	
useful fiducial length for decays	$\Delta l = 3.5\lambda_S$ $\approx \Delta l \sim 40 \text{ m}$	
particle flux per pulse at production (in the angular beam acceptance):		
K^0	$2 \cdot 10^7$	$2 \cdot 10^2$
Λ	$1 \cdot 10^8$	$2 \cdot 10^2$
n	$2 \cdot 10^8$	$1 \cdot 10^3$
γ	$2 \cdot 10^9$	$2 \cdot 10^4$
decays per pulse between coll. and detector:		
K^0	$1.5 \cdot 10^6$	$2 \cdot 10^2$
Λ	$2 \cdot 10^7$	$4 \cdot 10^1$
particle flux per pulse through beam pipe:		
K^0	$2 \cdot 10^7$	$2 \cdot 10^2 K_L$
Λ	$5 \cdot 10^7$	$1.5 \cdot 10^2$
n	$2 \cdot 10^8$	$1 \cdot 10^3$
γ	$2 \cdot 10^9$	$2 \cdot 10^4$
muon flux per pulse through the detector	$4.5 \cdot 10^5$	$< 10^3$
useful $K_{\pi\pi}$ decays per pulse	$1.3 \cdot 10^2$	$1.5 \cdot 10^2$

Table 7.1: Nominal design characteristics of the beams. The particle fluxes are estimated with Monte Carlo and normalized to the observed rates of K^0 decays and muons accepted by NA48. The bulk of the accidental particles which cross the detector come from K_L and Λ decays along the beam line.

from TAX17, plus the neutral hadrons originating in the **KL** target region; this contribution is later referred to as *KL*. The rate cpp_{BKG} estimates the contributions (later referred to as *BKG*) from the proton dump in TAX17, plus muons from the **KL** target region; for what concerns time structures and intensity variations, this kind of accidental activity is also related to the **KL** beam activity. Finally, cpp_{KS} measures the rate produced only in the **KS** beam (later referred to as *KS*), including accidentals originating along the proton transport beam line, downstream of TAX17.

The main facts to be noticed are:

- The rate of the accidentals from the **KL** and **KS** beams are described respectively as the combinations of the rates $\text{cpp}_{AL} \equiv \text{cpp}_{KL} + \text{cpp}_{BKG}$ and $\text{cpp}_{AS} \equiv \text{cpp}_{KS}$. The ratio of the **KS** and **KL** beam rates is $\text{cpp}_{AS}/\text{cpp}_{AL} \approx 5 \cdot 10^{-2}$. This is three orders of magnitude bigger than the ratio $\text{ppp}_{KS}/\text{ppp}_{KL} \sim 2 \cdot 10^{-5}$ of the protons per pulse (referred to as **ppp**) on **KS** to **KL** targets.

This fact can be explained by the differences between the two beams lines (length, collimators, dumps, and sweeping magnet) and the resulting difference in the nature of their accidentals originating there.

- The **overflow** rate in the DCH measures the rate of high-multiplicity events; they almost are showers produced in interactions with the collimators or with the detector (beam pipe, Kevlar windows, DCH supports, the magnet, and the AKL iron layers). A fraction of 20% of the total comes from the **KS** beam.
- The *BKG* contribution to the rates is large both in the core of the detector (see table 7.2, the difference between the “ ≥ 1 TRK” and “ ≥ 2 TRK” rates at DCH1) and in the peripheral region (see the AKL rates). This kind of low-multiplicity accidentals are mostly due to muons (see μ rates), which explains the negligible rate of **overflow** in the *BKG* component compared to the *KL* and *KS* rates.
- The rates of the triggered and selected $\pi^+\pi^-$ and $\pi^0\pi^0$ events are at the level of 100 events per pulse.

From table 7.2, the rate of charged particles is at the level of ~ 1 MHz (including high multiplicity events with a rate of ~ 400 kHz). Neutral particles also have ~ 1 MHz rates.

counts per pulse (cpp)	<i>KL</i>	<i>BKG</i>	<i>KS</i>	TOTAL	
protons to KL target	1.5	-	-	1.5	$\times 10^{12}$
protons to KS target	-	-	3.0	3.0	$\times 10^7$
KSM	< 0.01	0.1	1.9	2.0	$\times 10^5$
AKS (higher threshold)	-	-	4.7	4.7	$\times 10^4$
AKS (lower threshold)	-	-	<i>x.x</i>	<i>x.x</i>	$\times 10^4$
AKL TOTAL OR	1.3	4.1	0.5	5.9	$\times 10^6$
AKL 1 OR	0.28	1.14	0.24	1.66	$\times 10^6$
AKL 2 OR	0.30	0.66	0.14	1.10	$\times 10^6$
AKL 3 OR	0.27	1.13	0.09	1.49	$\times 10^6$
AKL 4 OR	0.28	1.05	0.07	1.40	$\times 10^6$
AKL 5 OR	0.35	1.32	0.08	1.75	$\times 10^6$
AKL 6 OR	0.31	0.36	0.04	0.71	$\times 10^6$
AKL 7 OR	0.37	0.19	0.04	0.60	$\times 10^6$
AKL TOTAL AND	0.5	1.4	0.05	2.0	$\times 10^6$
NHOD	1.4	-	0.01	1.4	$\times 10^5$
DCH1	9.0	8.0	0.7	18.0	$\times 10^5$
DCH4	10.0	5.0	0.5	16.0	$\times 10^5$
≥ 1 TRK @ DCH1	6.6	6.5	1.0	14.1	$\times 10^5$
≥ 2 TRK @ DCH1	5.6	1.6	0.5	7.7	$\times 10^5$
≥ 4 TRK @ DCH1	2.5	0.5	0.35	3.3	$\times 10^5$
OVFL @ DCH1	0.7	< 0.01	0.15	0.85	$\times 10^5$
QOR	1.5	0.7	0.10	2.3	$\times 10^6$
QVQH	1.1	0.3	0.05	1.5	$\times 10^6$
QX	7.2	0.15	0.35	7.7	$\times 10^5$
QOR μ (μ)	2.6	1.8	< 0.01	4.4	$\times 10^5$
QX μ ($K_{\mu 3}$)	1.9	0.1	< 0.01	2.0	$\times 10^5$
Q2 μ AKL ($K_{\mu 3}$)	1.5	0.02	< 0.01	1.5	$\times 10^5$
Q2 μ AKL ($K_{e3}, K_{\pi^+\pi^-}$)	3.4	0.01	0.15	3.6	$\times 10^5$
μ	4.9	3.9	-	8.8	$\times 10^5$
2μ	0.5	0.06	< 0.01	0.6	$\times 10^5$
HAK 1	5.0	3.3	0.05	8.4	$\times 10^5$
HAC X	3.1	< 0.01	0.05	3.2	$\times 10^5$
BCTR	1.1	-	-	1.1	$\times 10^7$

Table 7.2: Measured rates [43] from *KS* (downstream of TAX17), *KL* (neutral hadrons from KL target and downstream of TAX17) and *BKG* (muons from KL target station and proton dump background). Due to the presence of a KL dump in *KS-only* mode one should consider also the residual ($\sim 10^{-3}$) fraction of KL beam which outcomes from that dump. This is accounted for in *BKG* and subtracted in *KL*.

7.2 What do accidentals look like ?

A sampling of the accidental activity in the detector (later referred to as **uncorrelated**) is obtained by triggering the DAQ of the experiment at random, but proportionally to the intensity of the beams (see the **random events** in Section 3.5).

Random events are used here to investigate:

- How the extra activity looks in the detector (the space and time occupancy for random and selected events is compared);
- What kind of physical events are observed in the read-out windows;
- The fraction of **uncorrelated** accidental activity coming from **KS** beam.

Notice that the QX and beam monitors rates recorded in random and selected events are in agreement within 10%. This level of agreement between the intensity measured in random and selected events is sufficient for the studies presented in this chapter, but not for the studies presented in next chapters. It will be shown that, unfortunately, some bad features in the random data taking were present, which resulted in random events seeing, on average, smaller intensities than selected events.

Physical particles are very rarely recorded in **random events**; most of the events record just the noise of the detector.

Let us define the following:

- An accidental cluster in the electromagnetic calorimeter, is an event with ≥ 1 energy clusters within a 6 ns time window. The time of the LKR cluster is the average of the times of the those clusters.
- An accidental track in the spectrometer, is an event with ≥ 1 tracks within a 6 ns. The time of the accidental track is the average of the track times.

The probability of finding at least one accidental track or cluster is $\sim 2 \cdot 10^{-4}$ per ns.

Figure 7.1 shows the total energy for the accidental cluster and track events. The distributions for selected $K \rightarrow \pi\pi$ decays are also shown. The accidental events are almost all low energy. The energy distribution for accidentals in the LKR shows a peak at ~ 0.6 GeV due to mip particles (muons).

Figure 7.2 shows the square of the radial distributions, in the transverse plane, of the accidental tracks and clusters. The distribution of the selected $K \rightarrow \pi\pi$ decays are also shown. The distribution of tracks and clusters in accidental events are similar. This not true for the selected $K_{\pi\pi}$ events, and is probably due to the same origin of the accidental tracks and clusters.

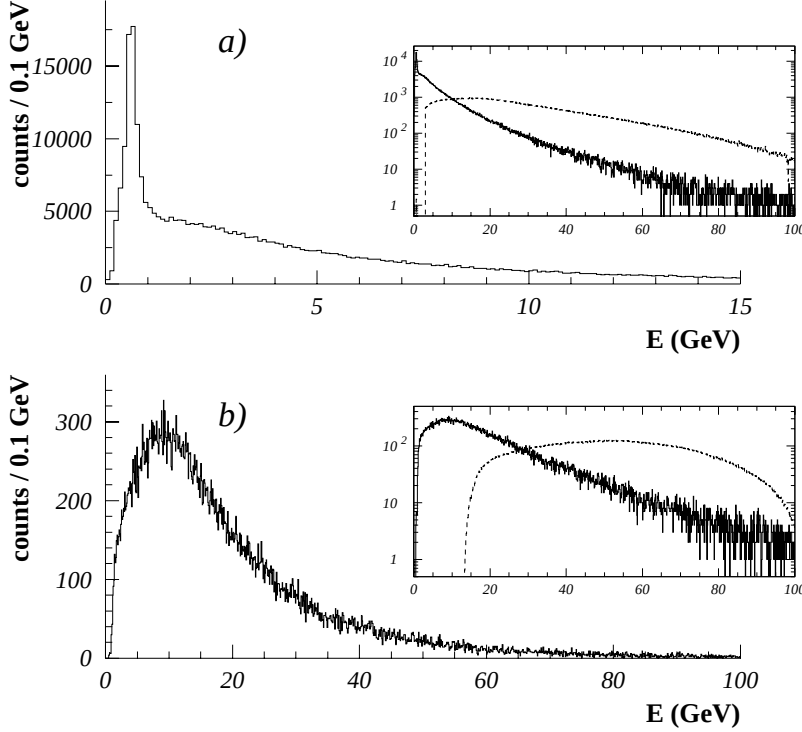


Figure 7.1: a) the energy of accidental clusters; the inset plot shows also the energy of photon clusters from good $K_{\pi^0\pi^0}$ (dashed line). Figure b) shows the momentum of accidental tracks; the inset plot shows the momentum of charged pions from $K_{\pi^+\pi^-}$ (dashed line).

Figure 7.3 shows the distribution of the accidental vertices reconstructed in random events. The average probability to find a vertex in a random event is $\sim 0.9 \cdot 10^{-4}$ per ns. The bulk of the vertices clearly comes from the KL line. A fraction of $\sim 5\%$ of the vertices results from photon conversions in the Kevlar window, which corresponds to the vertical line in the plot.

To measure the fraction of the accidental events originating in KS beam, coincidences in time between clusters in the detector and protons in the tagger

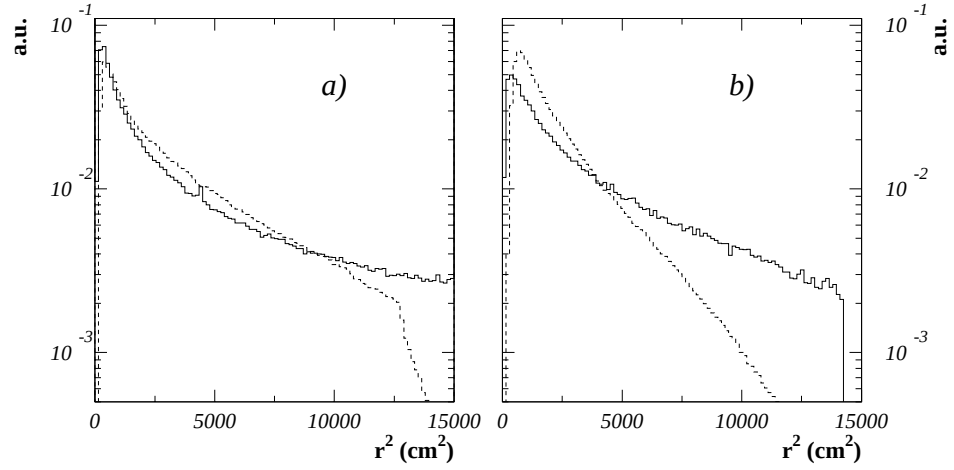


Figure 7.2: The square of the radial distribution of accidental clusters LKR (a) and tracks through DCH1 (b) are shown with solid lines. Dashed lines represent the clusters from good $K_{\pi^0\pi^0}$ events (a) and nd tracks from good $K_{\pi^+\pi^-}$ events (b). The histograms are normalized to the same area.

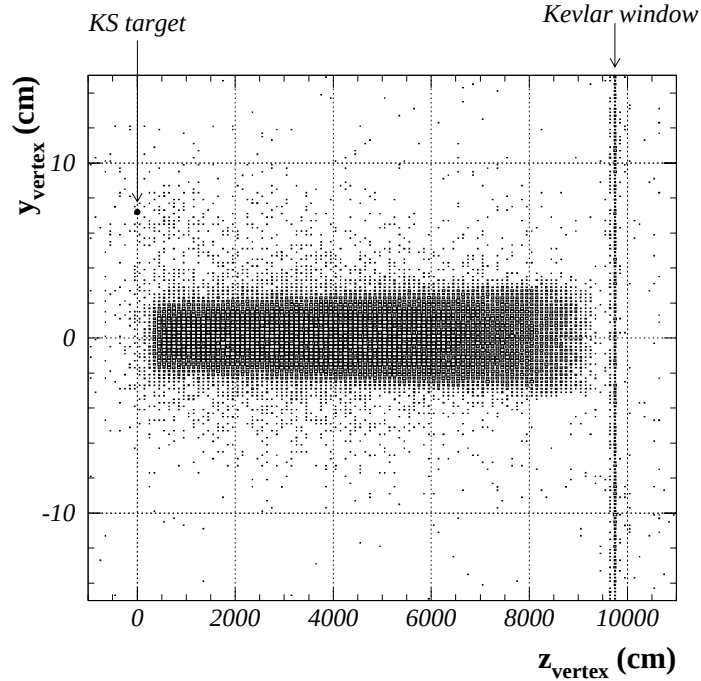


Figure 7.3: The accidental vertices distribution as a function of the vertical position (y) and the longitudinal position (z). Most of the tracks reconstructed are related to one vertex. A fraction of $\sim 5\%$ of the vertex are due to photons conversions in the Kevlar windows, ~ 100 m downstream the final collimator.

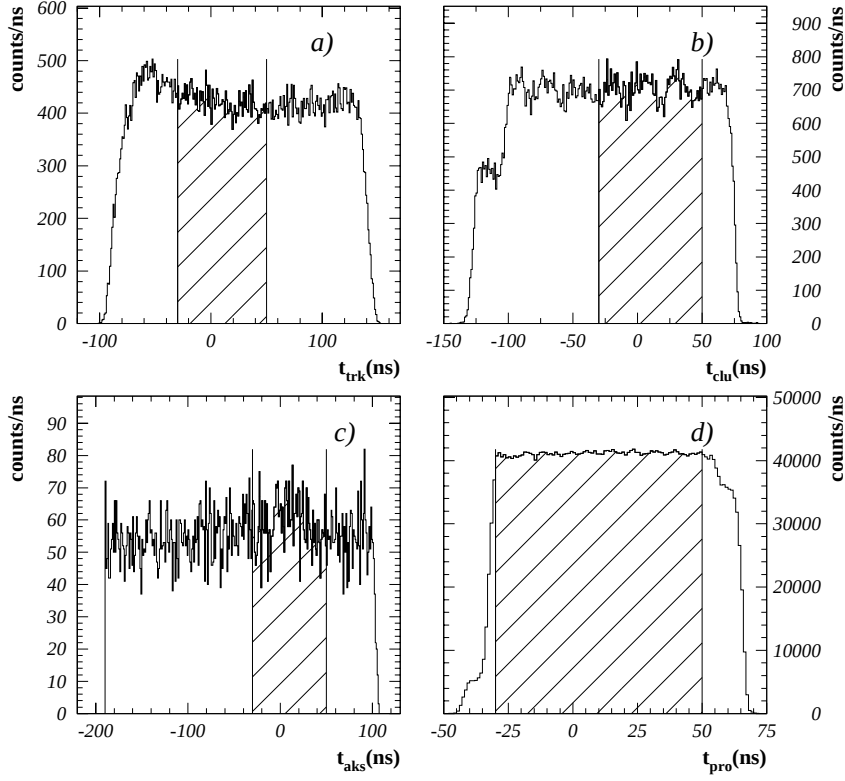


Figure 7.4: The time spectra for tracks (a), clusters (b), hits in AKS (c) and proton hits in TAG (d). The zero time for these random events is the center of the trigger time slot. Notice the different intervals on t axis and the common readout time window mentioned in the analysis (shaded).

are studied.

The hits in the tagger are studied first. Figure 7.5 shows the time difference between two consecutive proton hits detected in the tagger: a Poisson exponential distribution is observed, as expected. The average rate is ~ 27 MHz. Modulations with periods of 5 ns (200 MHz) and 10 ns (100 MHz) are also present. These are the actual beam time structures and will be studied in Chapter 8. In the following analysis, only proton hits separated more than 2 ns from other hits in tagger are considered (to get rid of the fake protons, see figure 7.5). This results in a cutoff at a frequency of $\nu \sim 250$ MHz, which is unimportant here.

Figure 7.4 a,b,c and d, show the time spectra for tracks, energy clusters, AKS hits, and protons respectively for K_S random events. The time distributions are not flat as random distributions ought to be. In this case they are not due to beam structures: to some extent, modulations in track and cluster times are expected as residual dependencies of the reconstructed time from the clock phase. These are removed in the time difference between two hits in the same event.

7.3 The fraction of accidentals from KS beam.

Accidentals coming from the KS beam are first selected with LKR clusters (CLU) due to the good efficiency of this activity indicator for both charged and neutral particles.

First a selection on the energy of the LKR accidental clusters is applied ($E > 1.5$ GeV). This achieves the rejection of mip, that are mostly muons. As discussed in Subsection 7.1 on page 141, muons contribute to the background (BKG) from the KL target station and proton dump.

Requiring a match within ± 2 ns with a proton in the tagger further rejects clusters from the KL beam.

Activity downstream from the KS target is selected looking for coincidences of AKS hits within ± 2 ns from the LKR cluster time. The times of energy clusters (CLU), tracks (TRK), tagger hits (PRO), and AKS hits (AKS) are required to fall inside a common window ($[-30 \div +50]$ ns) with respect to the trigger time, well inside the readout windows of the detectors (see figure 7.4).

Table 7.3 summarises the amount of selected K_S and K_L random events in the time window $[-30 \div 50]$ ns. The effects of applying the standard overflow

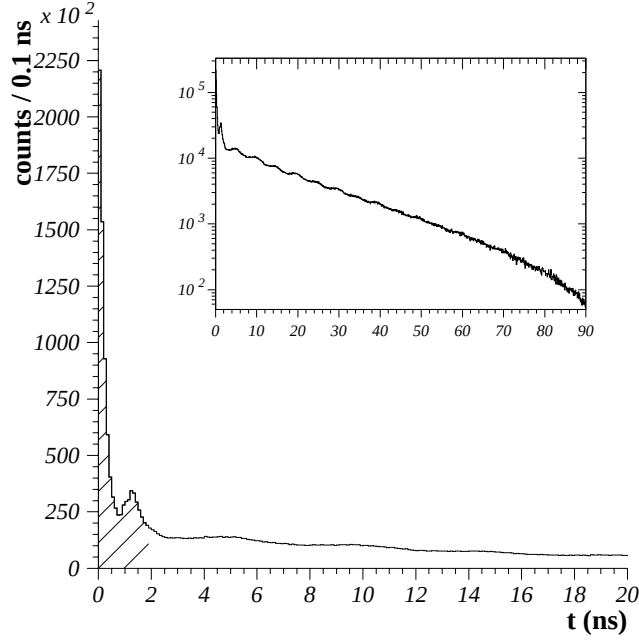


Figure 7.5: The time difference between each proton hit in tagger and the preceding one. The peak at $\Delta t = 0$ ns includes the fake protons reconstructed close to the real one. The peak at $\Delta t = 1.3$ ns is due to halo protons crossing the light-guides of the tagger scintillators. In order to avoid proton double counting, hits within ± 2 ns are counted as single hits. The inset is an enlarged view of the distribution, with the same variables on the horizontal and vertical axes.

rejection (i.e. no OVFL in either DCH1, DCH2 or DCH4 in a time window of $[-312.5 \div 312.5]$ ns) around the accidental time are also shown.

	K_S random events		K_L random events	
	OVFL accepted	OVFL rejected	OVFL accepted	OVFL rejected
all events	1504476	1139240	1792856	1360060
CLU	56372	24998	63184	28175
CLU·PRO	9867	3781	10234	3930
CLU·PRO·AKS	1665	345	1848	375
PRO	3291120	2393966	3685461	2696007
AKS	4720	2312	5265	2548
PRO·AKS	4242	2009	4740	2239

Table 7.3: The amount of all K_S and K_L random in the sample, of LKR accidental clusters in the common time window $[-30 \div 50]$ ns and of their coincidences (within ± 2 ns) with protons (CLU·PRO) and AKS (CLU·PRO·AKS) hits are reported. The number of PRO, AKS hits and PRO·AKS are also reported.

The ratio (see the first column in table 7.3) of the double coincidence CLU·PRO to the triple, CLU·PRO·AKS, is not consistent with the ratio ($\sim 1.5 \cdot 10^{-3}$) between numbers of PRO and PRO·AKS. The latter is, almost², the fraction of protons which interact and result in some activity downstream the KS beam line collimators. The mismatch is understood by considering the rate of protons through TAG (see table 7.3); this points to an average probability of $\alpha \sim 11\%$ to find at least one proton in a 4 ns time window³. The presence of random coincidences (between the 56372 energy clusters and the 3291120 protons), among the 9867 CLU·PRO coincidences, is expected.

At this point, the structures of the beam have to be accounted for. Since the intensities of the beams are not constant in time, the flux of protons shows time modulations and the probability to find any event (either accidental or good, either from KS or from KL beam) is higher on the peaks of those modulations. Thus, the requirement of a coincidence between detected events (energy clusters in the calorimeter) and tagged protons selects higher beam intensities. In other words, the probability (α) to find a proton in the tagger increases in proximity of the event time.

²The K^0 and Λ not interacting in AKS are of course not included.

³Namely this is the accidental tagging probability, which affects also the ϵ'/ϵ analysis.

In case of events originating in the **KS** beam, it is obvious that the probability α_S to find a proton around the time of the event must grow to 1 (with $t \rightarrow 0$, where t is the difference of the accidental event time and the nearest proton time). Less obvious is the behavior when $t \neq 0$. In general, the greater $|t|$ is, the lower $\alpha_S(t)$ is, depending on the structure of the time modulations; i.e. $\alpha_S(t)$ is proportional to the autocorrelation of **KS** beam intensity at time t .

In case of events originating in the **KL** beam, the probability $\alpha_L(t)$ is proportional to the cross-correlation of **KL** and **KS** beam intensities at time t . This does not grow to 1 for $t \rightarrow 0$, but, due to the high degree of correlation of the two simultaneous beams, one expects $\alpha_L(t) \sim \alpha_S(t)$ for $t \neq 0$. In Section 8 on page 157 the relative difference between $\alpha_S(t)$ and $\alpha_L(t)$ is measured to be $\sim 3\%$.

To account for the beam time structures, and in particular for the enhancement of α around the accidental event time, coincidences between clusters and protons (**CLU**·**PRO**) are studied by analyzing the distribution of time differences between all cluster and all proton times. The combination of the all accidental clusters, in the readout time window, with all the protons, in the interval $[-30 \div +50]$ ns is shown in figure 7.6. The distribution is normalized to the number of accidental clusters in the interval $[-30 \div +50]$ ns.

Given the fraction $f_{S(L)}$ of **CLU** originating in **KS** (**KL**) beam and given the average number of protons $\mu_S(t=0)$ in coincidence with a K_S (K_L) accidental **CLU** cluster, in ± 2 ns, then the integral of the peak at $t = 0$ ns over $[-2 \div 2]$ ns is given by:

$$f_S \cdot \mu_S(t=0) + f_L \cdot \mu_L(t=0) \quad (7.2)$$

Where, due to the selection of protons with at least 2 ns time separation with other protons one gets $\mu_S(t=0) = 1$. Notice as well that the statistics of the protons is Poissonian to first approximation so the approximation $\alpha \sim 1 - e^{-\mu}$ holds.

Likewise, the integral of the peak at $t = 10$ ns is given by:

$$f_S \cdot \mu_S(t=10) + f_L \cdot \mu_L(t=10) \quad (7.3)$$

where the assumption is made that:

$$\mu_L(t=0) \sim \mu_L(t=10) \quad (7.4)$$

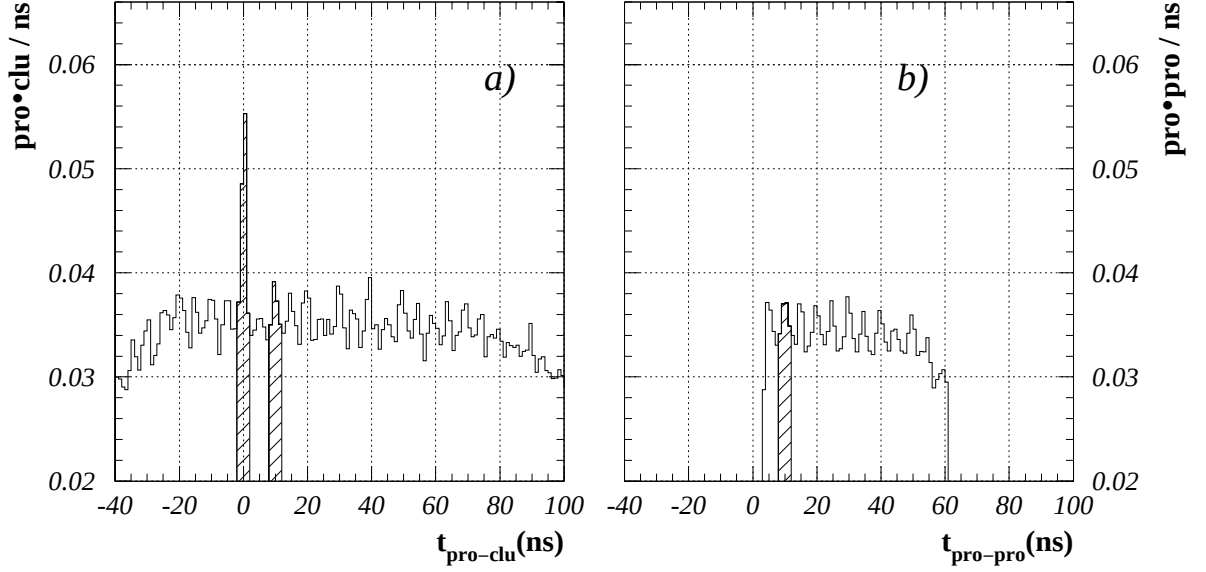


Figure 7.6: The distribution of time differences ($t_{\text{PRO-CLU}}$) between accidental clusters in the readout time window and protons in the interval $[-30 \div 50]$ ns, is shown in figure a). It is normalized to the number CLU in the same interval. Figure b) shows the distribution of time differences ($t_{\text{PRO-PRO}}$) between all protons with $t > 2$ ns in the readout window and the protons in the window $[-2 \div 2]$ ns. The difference of the integrals of a) over $[-2 \div 2]$ ns (shaded) and over $[8 \div 12]$ ns (shaded) gives the fraction of K_S accidentals f_S multiplied by $(1 - \mu_S(t = 10))$ that is the mean number of protons in a 10 ns delayed coincidence, measured in b) as the integral around $[8 \div 12]$ ns. The modulations of period 5 ns (200 MHz) and 10 ns (100 MHz) typical of the time structure of the beams are also noticeable.

Finally, by subtracting eqn. (7.3) from eqn.(7.2) one gets⁴:

$$f_S \cdot (1 - \mu_S(t = 10)) \quad (7.5)$$

The average number of protons $\mu_S(t = 10)$ in a 4 ns window delayed by 10 ns of the protons of 4 ns wide interval centered at $t = 0$, can be measured independently. Table 7.4 shows $\mu_S(t = 10)$, the fraction f_S , and the expected number of CLU for comparison with table 7.3.

		K_S random events		K_L random events	
		OVFL acc.	OVFL rej.	OVFL acc.	OVFL rej.
$\mu_S(t = 10)$	(%)	14.32 ± 0.09	13.73 ± 0.10	13.28 ± 0.09	12.78 ± 0.10
f_S	(%)	3.58 ± 0.29	1.74 ± 0.42	3.15 ± 0.25	1.29 ± 0.37
expected K_S accid.	(evts)	2018 ± 160	434 ± 100	1990 ± 160	363 ± 100

Table 7.4: *The measured average number of proton-proton delayed coincidences $\mu_S(t = 10)$, used to obtain the fraction f_S of CLU accidentals in the beam from Eqn. 7.5. The expected number of CLU from KS accidentals is also shown.*

The expected number of CLU from KS accidentals agrees with the the number of triple coincidences CLU·PRO·AKS(see table 7.3); the small difference ($15 \pm 10\%$ relative difference) may be explained by the neutral hadrons which actually out come from the KS beam line, but are not detected by the AKS⁵. The AKS results are then useful in spotting true accidentals from KS.

The ratio between the intensities of KS and KL beam **uncorrelated** accidentals is then, on average, $\sim 3.5\%$ (1.7%), accepting (rejecting) **overflow**. Using the notation introduced in Chapter 6, this reads:

$$\sim \frac{\langle I_{A_S} \rangle}{\langle I_{A_L} \rangle} \lesssim 3.5\% \text{ (1.7\%)}$$

The $\sim 50\%$ reduction of f_S obtained by applying OVFL rejection is explained by the fact that the OVFL probability is higher ($\sim 80\%$) for accidentals from KS beam with respect to KL's (see table 10.1). Thus, although accidental events from KS

⁴This is also the method one should apply to the selected events, in order to correct for the accidental tagging, in case no charged vertex tagging could be used.

⁵The AKS is highly efficient in detecting both charged particles and photons, but not neutral hadrons.

beam have lower rate than those from **KL** beam, they nevertheless show on average higher multiplicities. This is due to electromagnetic showers originating in the **KS** collimators and in the spectrometer magnet.

It is important that good K_S and K_L events are exposed to the same amount of **KS** accidentals. To this point note that the average number of CLU per event per ns, from **KS** beam, is $(1.38 \pm 0.03) \cdot 10^{-5}$ and $(1.29 \pm 0.03) \cdot 10^{-5}$ respectively measured within K_S and K_L random events ⁶.

The influence of accidental hits from **KS** and **KL** beam on the measurement of $\mathcal{R}$ can be quantified. For instance, the bias on the neutral part ($\mathcal{R}^{00}$) of $\mathcal{R}$ is approximated (see eqns. (6.1) to (6.11)) as:

$$\Delta\mathcal{R}/\mathcal{R} = \kappa_A \langle I_A \rangle \langle \eta_A(\eta_S - \eta_L) \rangle \quad (7.6)$$

The ratio of the biases from **KS** and **KL** accidentals (A_S, A_L) is:

$$\frac{\frac{\Delta\mathcal{R}}{\mathcal{R}}|_{A_S}}{\frac{\Delta\mathcal{R}}{\mathcal{R}}|_{A_L}} = \frac{\kappa_{A_S} \langle I_{A_S} \rangle \langle \eta_{A_S}(\eta_S - \eta_L) \rangle}{\kappa_{A_L} \langle I_{A_L} \rangle \langle \eta_{A_L}(\eta_S - \eta_L) \rangle} \quad (7.7)$$

$$(7.8)$$

Provided κ_{A_S} and κ_{A_L} are of the same order of magnitude, and given the ratio:

$$\frac{\langle \eta_{A_S}(\eta_S - \eta_L) \rangle}{\langle \eta_{A_L}(\eta_S - \eta_L) \rangle} \approx 3$$

(which will be measured in the following chapter) then eqn. (7.7) yields:

$$\frac{\frac{\Delta\mathcal{R}}{\mathcal{R}}|_{A_S}}{\frac{\Delta\mathcal{R}}{\mathcal{R}}|_{A_L}} \lesssim 6\% \quad (7.9)$$

in case overflows are rejected.

Thus, in the following, the accidental activity coming from **KS** beam will be neglected, as it results in a bias on $\mathcal{R}$, which is more than a factor of 10 less than the **KL** accidentals bias.

⁶The $\sim 7\%$ relative difference is due to the bias on the average intensity seen by random events, as noticed at the beginning of the previous section.

Conclusions

Various kinds of accidental activity illuminate the detector. It comes almost completely ($> 96\%$) from the **KL** beam line. The rate of charged particles is ≈ 1 MHz, which includes high multiplicity events (~ 400 kHz). The rate of neutral particles is also ≈ 1 MHz.

The effect of **KS** accidental activity on $\mathcal{R}$ is estimated at least than a factor of 10 less than the effect due to **KL** accidentals.

8 The time structures of the beams

Overview

This chapter is devoted to the study of the variations of the KL and KS beam intensities with time.

An ideal, slow resonant, proton extraction provides a constant particle flux during the time of the burst. In practice, however, it is impossible to produce a burst shape which is perfectly rectangular, without any undesirable transients at both ends and without any modulation of the flux caused, for instance, by power supply ripple and noise. The SPS injection and extraction scheme, and the transport along the beam lines up to the target, cause the presence of various time structures in the particle flux along the burst (see Sections 2.2.1).

In order that the modulations of the burst shape not to have influence on the result, they must be the same for KL and KS beams. Otherwise every variation of the detection inefficiency with time would couple with the variations of the KS to KL intensity ratio I_s/I_L resulting in a bias on $\mathcal{R}$.

Furthermore, the flux should also be as constant as possible to keep stable the measurement of the difference of accidental tagging for charged and neutral events¹. Since it is impossible constant intensities, then it is mandatory to measure the beam variations with time, i.e. the time structure of the beam intensities.

8.1 The instantaneous variations (fluctuations) of the beam intensity

The time dependence of the particle flux (beam intensity) $I(t)$ can be described as:

$$I(t) = I_0 + I_p(t) + I_n(t) \quad (8.1)$$

where I_0 accounts for the constant particles flux, whose statistics is poissonian with constant average; while $I_p(t)$ and $I_n(t)$ are time dependent perturbations to I_0 which account respectively for stochastic noise and periodic intensity variations. In the

¹As described in Chapter 5 $\Delta\beta_{LS}$ is measured in out-of-time sidebands of the tagging windows and extrapolated to the in-time window; the more is constant of the protons flux, the smaller is the uncertainty on the extrapolation

usual notation the intensity is written as $I(t) = \langle I \rangle (1 + \eta(t))$; thus one recognizes that $I_0 \equiv \langle I \rangle$ and $\eta(t) \equiv \frac{I_p(t) + I_n(t)}{I_0}$.

Figure 8.1 illustrate the dependence of the rate of the selected K_S and K_L and of the particles recorded in the AKL readout windows in function of the time in the burst. Only the time variations in a 0.1 s time scale are shown in the plots; but there are variations at several time scales.

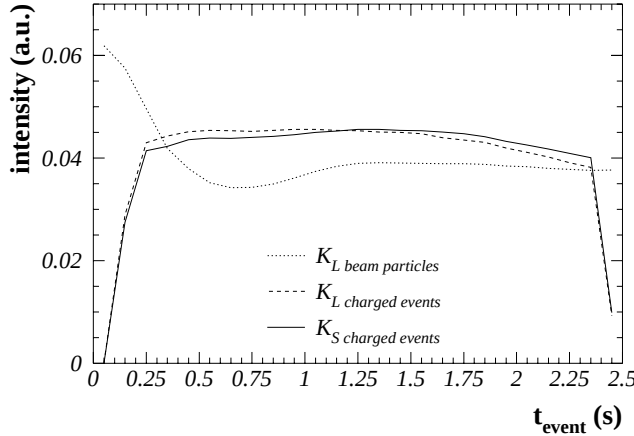


Figure 8.1: The burst intensity dependence with time for selected K_S and K_L events and for particles in the KL beam recorded in the AKL readout window. The plots are normalized to unitary area.

The beginning of the burst ($t_{events} < 150$ ms) is characterized by a high intensity of particles along the beam lines which is associated with a low yield of K_S and K_L selected events. This is partially explained by an intense burst of protons producing, also out of the KL target, a large amount of background particles. The beam intensities also undergo large fluctuations at the beginning of the extraction and the detector suffers not negligible dead time (overflow). It is of great interest to measure the amount of these and of other possible fluctuations.

Different methods have been envisaged in order to quantify the fluctuations of the intensity, measure their frequency spectrum and eventually classify their sources.

8.1.1 The effective spill duration

The beam intensity fluctuations, across the average $\langle I \rangle$, are measured by the square variance relative to $\langle I \rangle$, that is by $\langle \eta^2 \rangle$. In terms of fourier components, the

fluctuation $\langle \eta^2 \rangle$ is the integral of the power spectrum (A.C. power) in the frequency domain, normalized to the square amplitude of the constant term (D.C. power). Notice that usually the **effective spill duration** is defined as the ratio:

$$\frac{T_{eff}}{T} \equiv \frac{\text{D.C. power}}{\text{Total power}} = \frac{1}{1 + \langle \eta^2 \rangle} \quad (8.2)$$

where the total power is the sum of the A.C. power and the D.C. power

In principle the **effective spill duration**, or alike the intensity fluctuations, could be measured by secondary emission monitors (SEM) exposed to the primary protons; the output current can be analyzed an the ratio (8.2) extracted.

During 1997 data taking, the LKR calibrations were performed during the burst, through special events triggered at fixed time intervals. Besides the LKR, other detectors were read-out, e.g. the tagger. The comparison of the extra-activity level sampled by these triggers, with that measures by the selected $K_{\pi\pi}$ events, yielded an estimate for $T_{eff} \sim 1.7$ s (see figure 6.3 on page 128 and [41]).

Alternatively, as described in Section 6.2.2.1, the intensity fluctuations are measured using the beam counters and the extra-activity recorded in the NA48 sub-detectors. It is important to measure separately the fluctuations for the KS and KL beams.

Figure 8.2 shows the measurement of the effective spill duration by the beam monitors counters. The measurement is obtained using the delayed coincidence method, as described in Section 6.2.2.1. For every burst of the 1998 data, the ratio $T_{eff} \equiv \frac{S^2 \cdot \Delta t \cdot T}{C}$ is taken, where S and C are the single and the delayed coincidence counts, Δt is the coincidence width and $T = 2.38$ s is the real spill duration. The resulting average T_{eff} for the KS and KL beam intensities are ~ 1.74 s and ~ 1.80 s respectively. They correspond to fluctuations at the level of $\langle \eta_s^2 \rangle \sim 0.33$ and $\langle \eta_L^2 \rangle \sim 0.38$ respectively. Unfortunately the beam monitor counters suffered various instability problems during the 1998 run and this measurement is not that reliable.

The extra-activity method is exploited to perform a more reliable measurement of the $\langle \eta^2 \rangle$ terms, as explained in Section 6.2.1.1. Given the distribution of the number of hits in some interval of the read-out window, it is shown, in eqn. (6.22), that the variance of the distribution is the fluctuation term $\langle \eta^2 \rangle$. In practice this variance have to be disentangled from the Poisson statistics variance. The less are the hits counted on average, in the selected window, the more the Poisson statistic

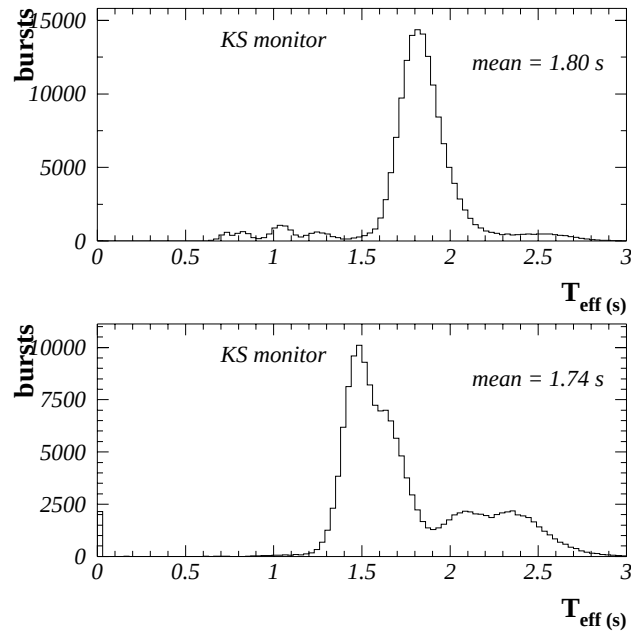


Figure 8.2: The effective burst length measured with the beam counters for every burst during the 1998 data taking. This measurement suffers by some biases due to the bad stability and changing of the working conditions of the counters during the data taking.

fluctuations dominate the overall variance. The TAG and MUV counters are thus exploited for the measurement of the fluctuation terms $\langle\eta_s^2\rangle$ and $\langle\eta_L^2\rangle$. Time windows as large as possible are used, to count hits far from the event time; in particular widths of ~ 60 ns and ~ 100 ns are chosen for the TAG and MUV respectively.

These result in cutoff frequencies of ~ 10 MHz, i.e. the contribution of structure with frequency $\gtrsim 10$ MHz are not included in the measurement.

In table 8.1 the measured fluctuations terms are shown. The relative error is evaluated to be at the level of $\sim 10\%$.

		KS beam (TAG hits)	KL beam (MUV hits)
average number of hits	$\langle m \rangle$	2.3	1.8
fluctuation term	$\langle \eta^2 \rangle$	0.24	0.25

Table 8.1: The KL and KS intensity fluctuation terms (2^{nd} row) $\langle\eta^2\rangle$ measured respectively with the hits in the tagger and in the muon veto counters. These counters are preferable for this kind of measurement because of the need of high hits counting rate. The average number of hits $\langle m \rangle$ is shown on the 2^{st} row. The errors on evaluation of the fluctuation terms are of the order of 10% relative.

Notice that no biases are introduced in first approximation due to the losses.

Notice that fluctuation term at the level of 0.25 indicats r.m.s fluctuations at the level of 50%. One realizes that figure 8.1 is a very smooth representation of the spill structure; at various smaller time scales the structure of the intensity is much complicated. In the following a description of the known structures is presented. There are three distinct time scales: the low frequencies domain ($\nu < 1$ kHz), the intermediate frequencies domain ($1 \text{ kHz} < \nu < 10 \text{ MHz}$) and the high frequency domain ($\nu > 10 \text{ MHz}$). Different tools are used to study these regions in order to understand their contribution to the fluctuations.

8.1.2 The low frequency structures

The intensity variations are determined, at low frequency, by the frequency of the mains power supply (50 Hz and harmonics) and by a band-limited white noise. Both are introduced mainly by the currents fluctuations in the magnets used to

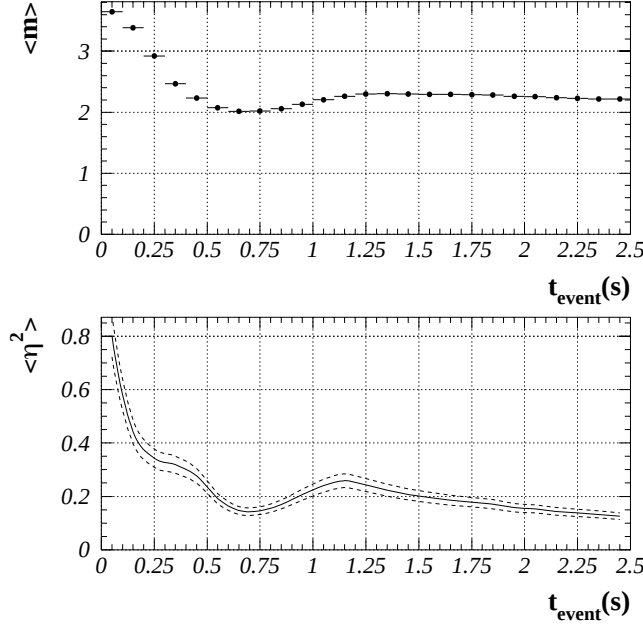


Figure 8.3: The intensity dependence on the time of the event in the burst is shown in figure a). Figure b) shows the fluctuation (i.e. the variance of the intensity relative to the square average intensity) of the beam intensity. The solid line relates to the measured value and the band between the dashed lines refers to the estimated $\pm 10\%$ relative error on the measurement.

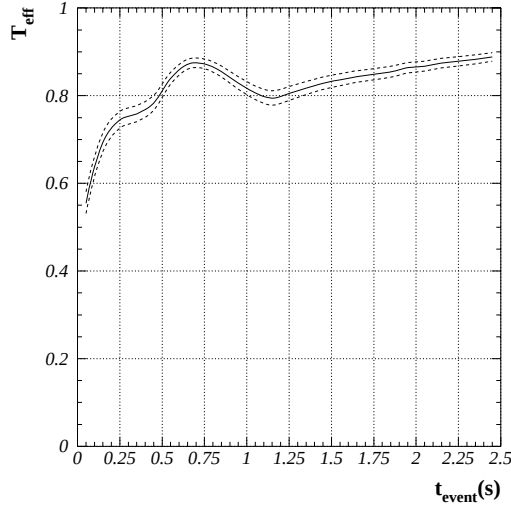


Figure 8.4: The spill efficiency T_{eff}/T as a function of the time of the event in the burst. T_{eff}/T is estimated from the measured fluctuations of the beam through the expression $T_{\text{eff}}/T \equiv \frac{1}{1 + \langle \eta^2 \rangle}$. The dashed lines relates to the error on T_{eff}/T due to the $\pm 10\%$ relative error of the estimate of $\langle \eta^2 \rangle$.

deflect the protons both in the SPS and in their path the targets. The resulting variations are particularly dangerous because they are coupled to the proton beam variations in positions, due to the acromaticity of the optical system for the proton transport. The position of the protons determines the I_S/I_L intensity ratio which eventually is coupled to the accidental particle flux (I_L)

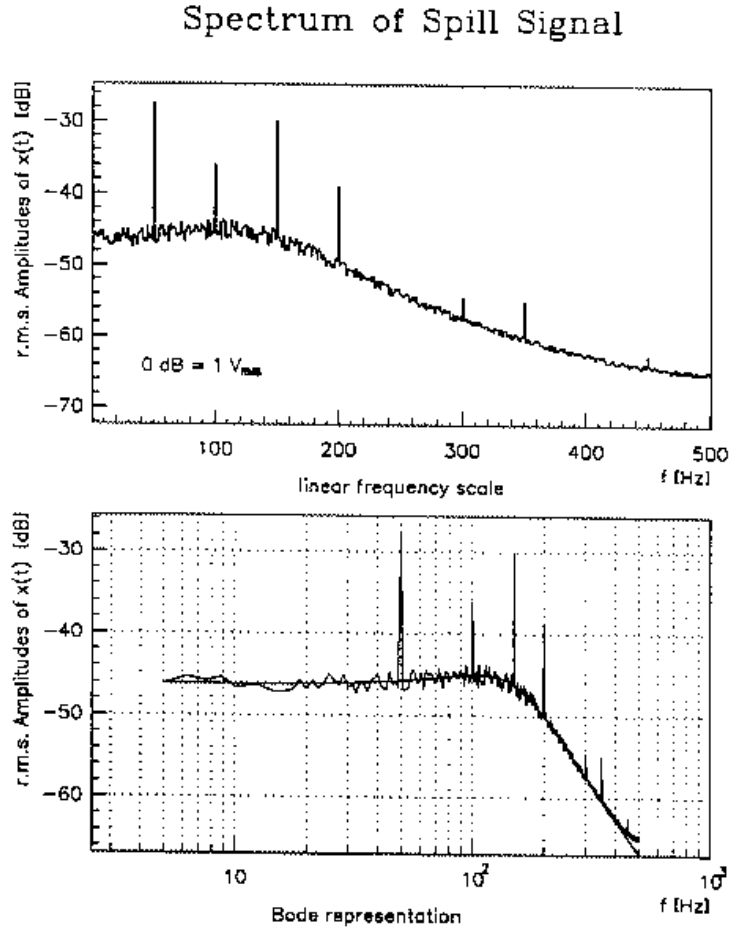


Figure 8.5: *The typical frequency spectrum of burst during the year 1980 (sic).
From the note [67]*

Figure 8.5 shows the typical frequency spectrum for the burst during during the 1980 SPS run (sic). It is taken from a NA31 note [67] addressed to study the low frequency fluctuations of the intensity. The intensity was measured by SEM detectors whose output current was analyzed by Fourier Transform. Notice in the figure 8.5 the presence of both periodic modulations (discrete spectrum) and noise (continuum). The frequency fluctuations in the proton flux are reduced, in NA48,

by means of feed-back systems applied the proton beam transport line.

To study the residual low frequency modulations in NA48 each event records the information of the phase (ϕ_{mains}) of its time with respect to a clock of 50 Hz locked to the phase of the 50 Hz beam power supply. Figure 8.6,a) shows the intensity as measured by the tagger in the sideband. There one can see that the influence of the 50 Hz modulations is reduced and the 100 Hz and 150 Hz are dominating (this is even more clear if a Fourier Transform is performed). Thanks to an improved feed-back system in 1999 those frequency modulation is further reduced.

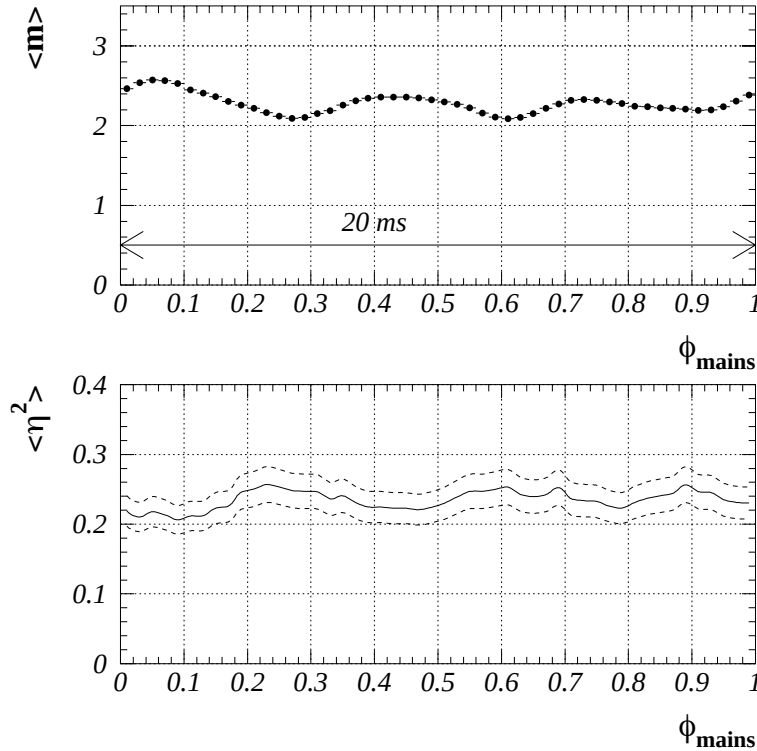


Figure 8.6: The intensity dependence on ϕ_{mains} is shown in figure a). The 50% modulations are observable. The harmonics of frequency 100 Hz and 150 Hz have an higher amplitude due to the filtering performed by a feed-back system. Figure b) shows the fluctuation term $\langle \eta^2 \rangle$ as a function of ϕ_{mains} . The solid line relates to the measured value and the band between the dashed lines refers to the estimated $\pm 10\%$ relative error on the measurement.

Figure 8.6,b) shows the term $\langle \eta^2 \rangle$ as a function of ϕ_{mains} . The dependence of $\langle \eta^2(\phi_{\text{mains}}) \rangle$ on ϕ_{mains} has a maximum amplitude of $\lesssim 0.06$; this points to a contribution of ~ 0.03 (half of the amplitude) from the low frequency periodic

structures to the overall fluctuation term $\langle \eta^2 \rangle \sim 0.25$.

The contribution of the noise is not included, and its evaluation is still under investigation. From the analysis in the note [67] one can derive that the relation between the $\langle \eta^2 \rangle_n$ term due to the noise, and the $\langle \eta^2 \rangle_{pLF}$ term due to the low frequency periodic fluctuations, is:

$$\langle \eta^2 \rangle_n \sim 1.5 \cdot \langle \eta^2 \rangle_{pLF} \quad (8.3)$$

suggesting a contribution of ~ 0.05 to the overall $\langle \eta^2 \rangle$ from the noise. This may be considered an upper limit.

8.1.3 The intermediate frequency structures

The intermediate frequency structures are determined by the processes of injection, acceleration and extraction of the protons through the SPS (see Section 2.2.1 on page 28).

The extraction is illustrated in figure 8.7.

Figure 8.7,a) shows three proton bunches in the phase space defined by the longitudinal position of the protons along the SPS (indicated² as a time t) and the relative difference $\Delta p/p$ between proton momentum and the nominal 450 GeV momentum. When the radio frequency (RF) is switched off protons start to move freely. Their relative motion depends on their $\Delta p/p$ and is described by the relation: $\Delta t/t \approx -1.9 \cdot 10^{-3} \Delta p/p$, i.e. protons with negative $\Delta p/p$ move forward with respect to protons with exactly the nominal momentum. Figure 8.7,b) represents the extraction of protons: during the initial stage, protons in a wide band of momentum are extracted (fast-slow extraction) to be exploited in neutrino production. Thereafter the slow extraction starts and protons in a smaller momentum band are extracted. In this way protons of increasing momentum are progressively extracted. During the first stage more protons are extracted from the head of the two trains than from the tail. This is due to the proton phase space distributions in the bunches which changes along the train. The bunches in the head of the train have to face higher impedances when injected from the PS into the SPS. This results in a broader distribution of the $\Delta p/p$, as depicted in figure 8.7 c).

²The protons take $\sim 23 \mu s$ to complete an SPS circumference, equivalent to a revolution frequency of 43 kHz.

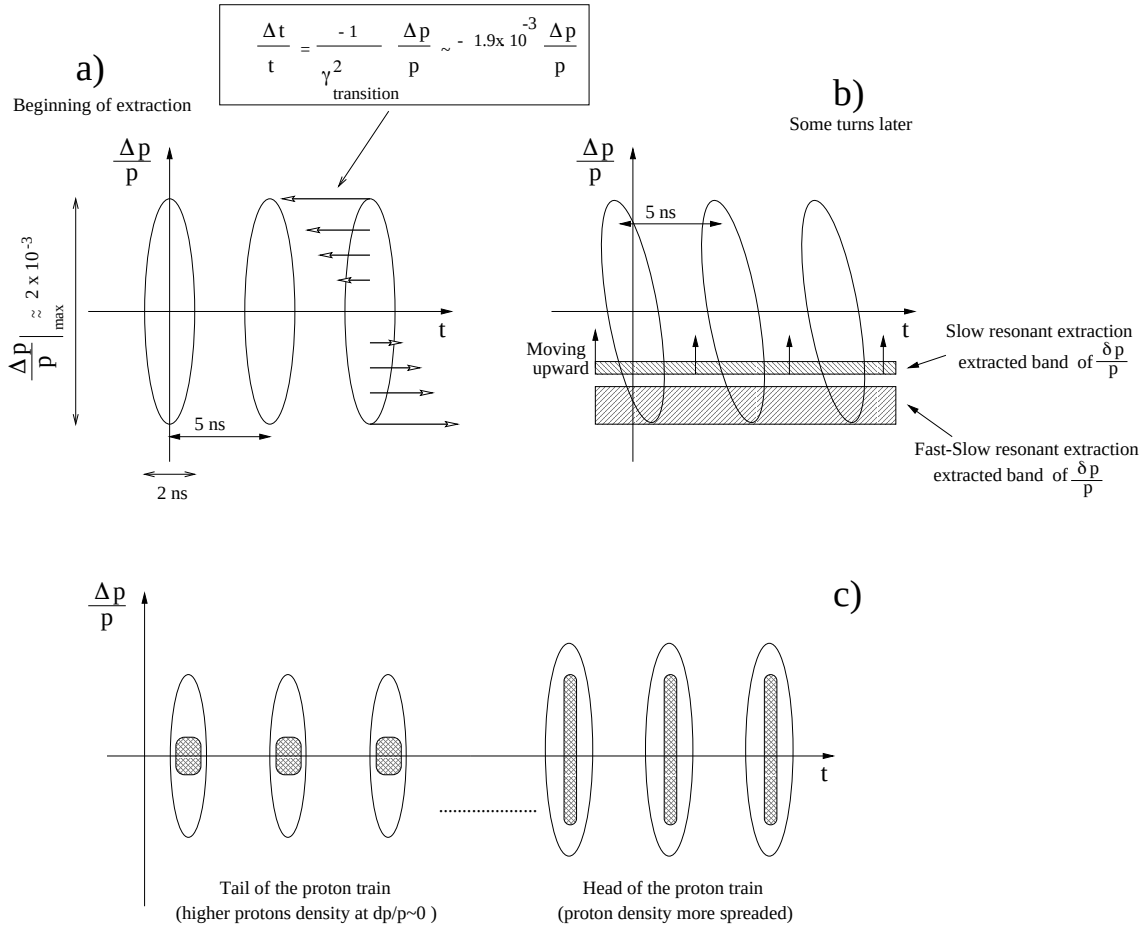


Figure 8.7: The proton extraction represented in phase space. Figure a) shows three proton bunches in the phase space defined by the longitudinal position of the protons t along the SPS (it is represented as a time) and the relative difference $\Delta p/p$ between protons' actual momentum and the nominal 450 GeV momentum. After the radio frequency (RF) is switched off protons start to move freely. Their relative motion depends on their $\Delta p/p$ and is described by the relation: $\Delta t/t \sim -1.9 \cdot 10^{-3} \Delta p/p$, i.e. protons with negative $\Delta p/p$ move forward with respect to protons with exactly the nominal momentum. Drawing b) represents the extraction of protons: during the initial stage, protons in a wide band of momentum are extracted (fast-slow extraction) to be exploited in neutrino production. Thereafter the slow extraction starts and protons in a smaller momentum band are extracted. In this way protons of increasing momentum are moved progressively extracted. During the first stage more protons are extracted from the head of the two trains than from the tail. This is due to the proton distributions in the bunches phase space which changes along the train. The bunches in the head of the train have to face higher impedances when injected from the PS into the SPS. This results in a broader distribution of the $\Delta p/p$, as illustrated in figure c).

In order to observe the intensity variations at this time scale, for each event the phase (ϕ_{SPS}) is recorded with respect to a clock signal whose frequency is the same as the nominal 43 kHz protons' revolution frequency. The clock is synchronized to the protons circulating in the SPS.

Figure 8.8,a) shows the beam intensity measured by the average number of hits in the tagger sideband as a function of the phase ϕ_{SPS} . As usual it results from the average over the whole burst and data taking periods.

The distribution as a function of the phase ϕ_{SPS} can be looked as the distribution of the protons along the SPS circumference. The two trains of bunches and the two holes between them are indicated in the drawing. Notice that the train shape is not flat (to be compared with figure 2.4 on page 29). This is due to the fast-slow initial extraction which induce more protons to be extracted from the head than from the tail of the train. The holes are also not completely lacking in protons. This is due to the fact that the ϕ_{SPS} is locked to a fixed clock frequency, while the protons that are extracted along the burst have a progressively changing momentum and hence velocity. This results in a progressive shift of the observed events with respect to the fixed ϕ_{SPS} phase. Averaging the ϕ_{SPS} distribution over the whole burst length the holes result to be filled with protons, but it is not a real effect.

Figure 8.8,b) shows the term $\langle \eta^2 \rangle$ as a function of ϕ_{SPS} . The dependence of $\langle \eta^2(\phi_{\text{SPS}}) \rangle$ on ϕ_{SPS} has an average amplitude of $\lesssim 0.10$; this points to a contribution of ~ 0.05 from those intermediate frequency structures to the overall fluctuation term $\langle \eta^2 \rangle$.

The correlations between the dependences of the intensity on ϕ_{SPS} and the time of the event in the burst t_{event} is shown in figures 8.9,a) and 8.10. The raise of the intensity in the middle of the burst coincides with the extraction of the protons with $\Delta p/p \gtrsim 0$. These phase space regions are more densely populated for bunches in the tails of the trains, due to the initial fast-slow extraction.

Notice also that the very high intensity at the beginning of the burst is not correlated to the longitudinal position along the SPS.

In figures 8.9,b) and 8.11 the fluctuation are shown as a function of ϕ_{SPS} and t . Notice that the beginning of the burst presents marked fluctuations due to the random differences on the number of protons in the bunches. High fluctuations restart in the middle of the burst in correspondence with the extraction of the $\Delta p/p \sim 0$ protons from the tails of the bunch trains.

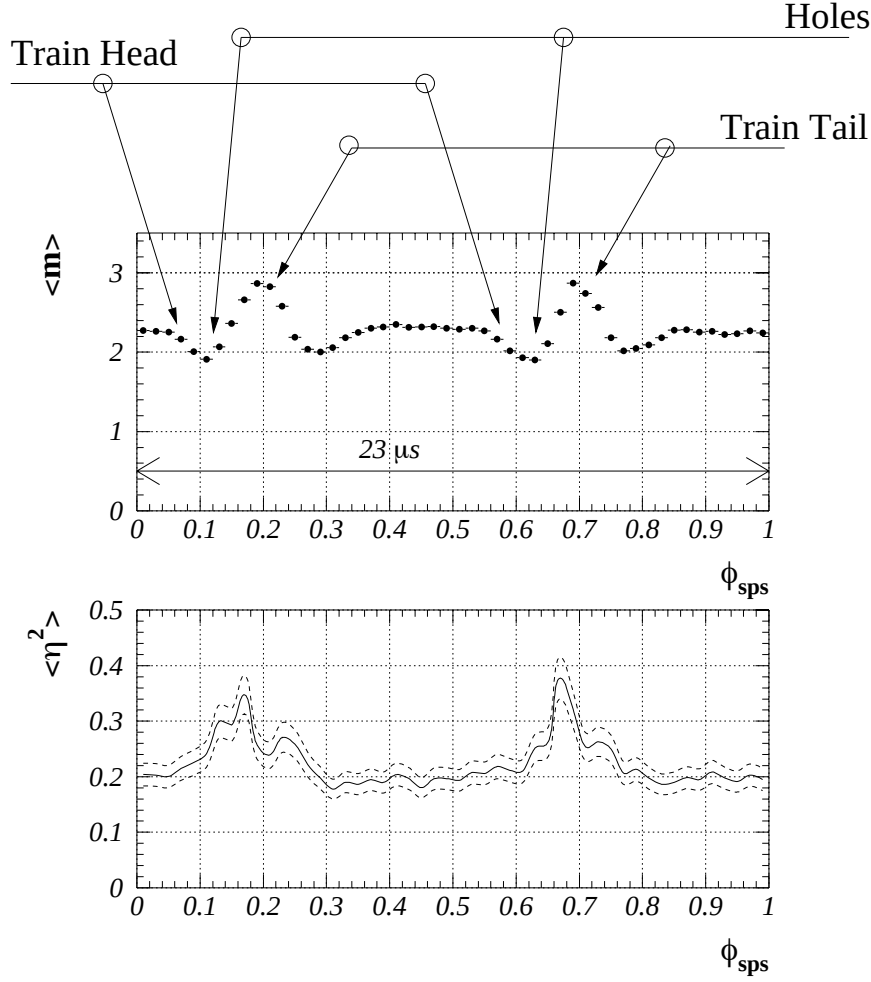


Figure 8.8: The intensity dependence on ϕ_{sps} is shown in figure a). Figure b) shows the fluctuation term $\langle \eta^2 \rangle$ as a function of ϕ_{sps} . The solid line relates to the measured value and the band between the dashed lines refers to the estimated $\pm 10\%$ relative error on the measurement.

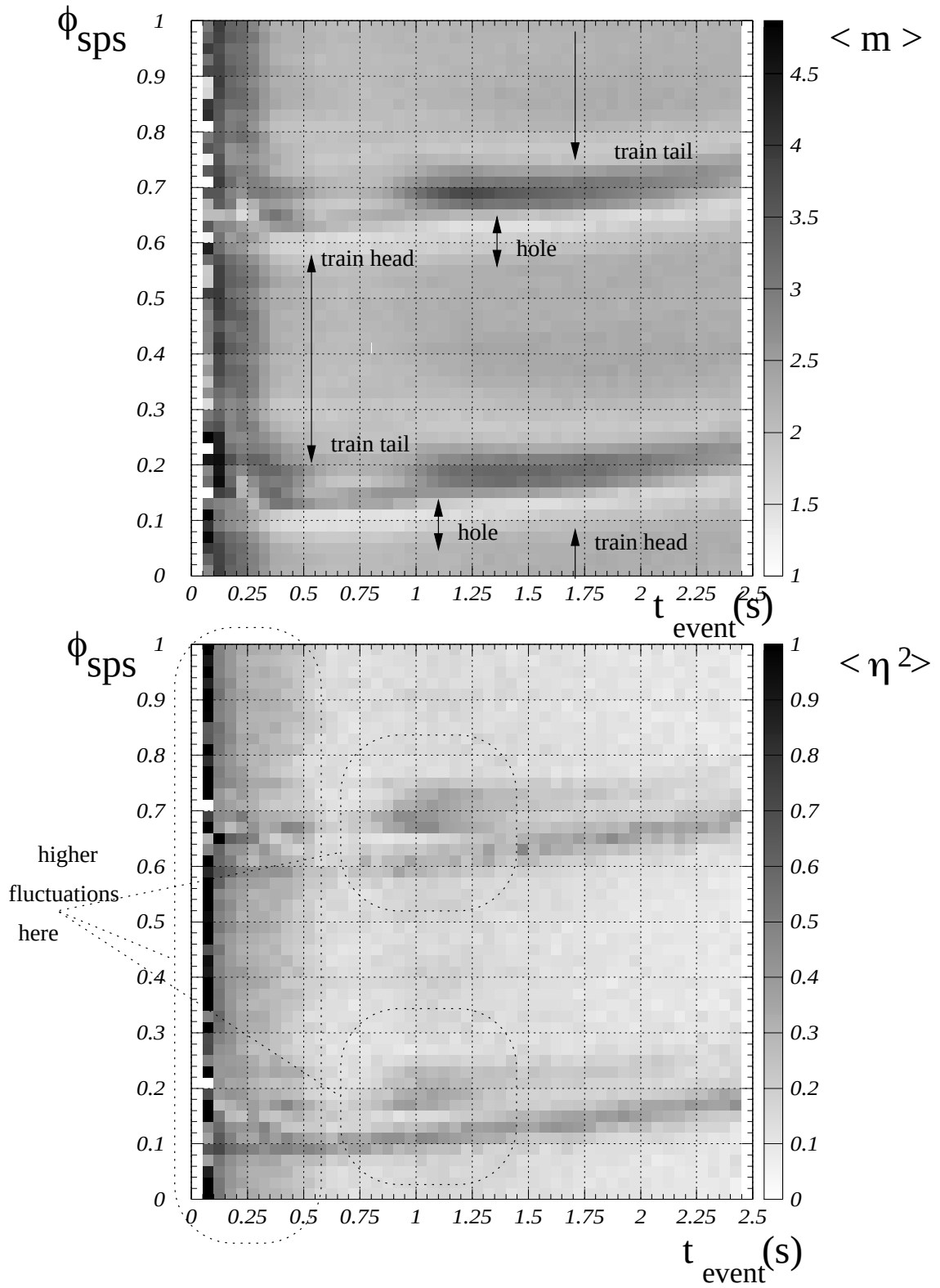


Figure 8.9: The dependence of the intensity on ϕ_{sps} and the time of the event in the burst t_{event} is shown in figure a). Figure b) shows the fluctuation term as a function of ϕ_{sps} and the time of the event in the burst. High fluctuations are present at the beginning of the burst. In middle of the burst the extraction from tail of the bunch trains reawake high fluctuations.

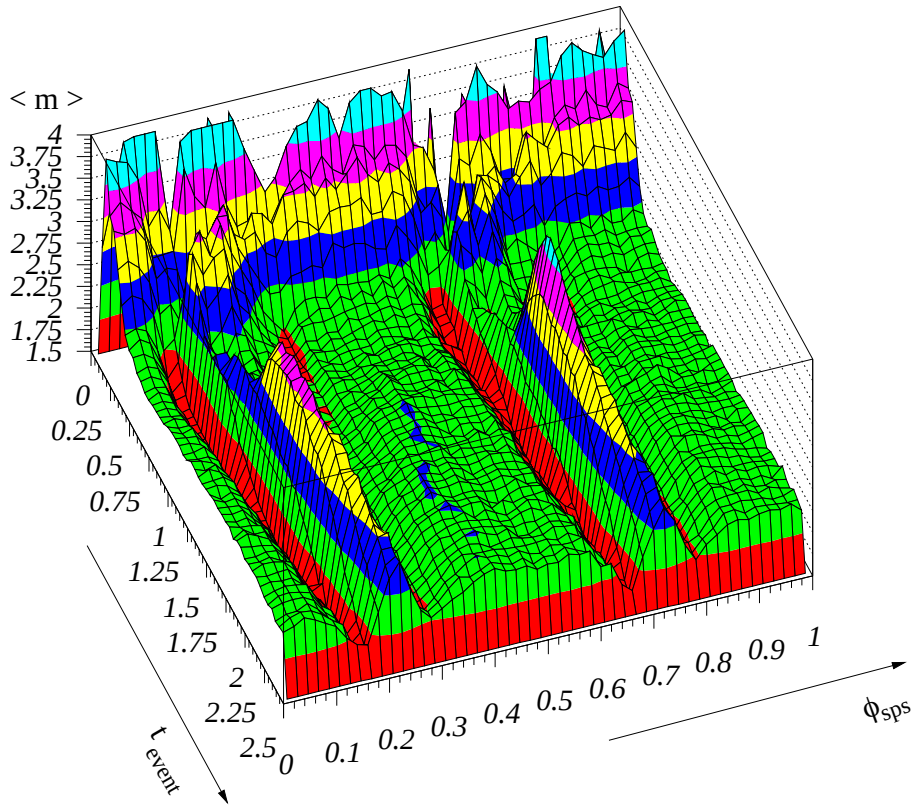


Figure 8.10: The dependence of the intensity on ϕ_{SPS} and the time along the burst t_{event} is shown in figure a).

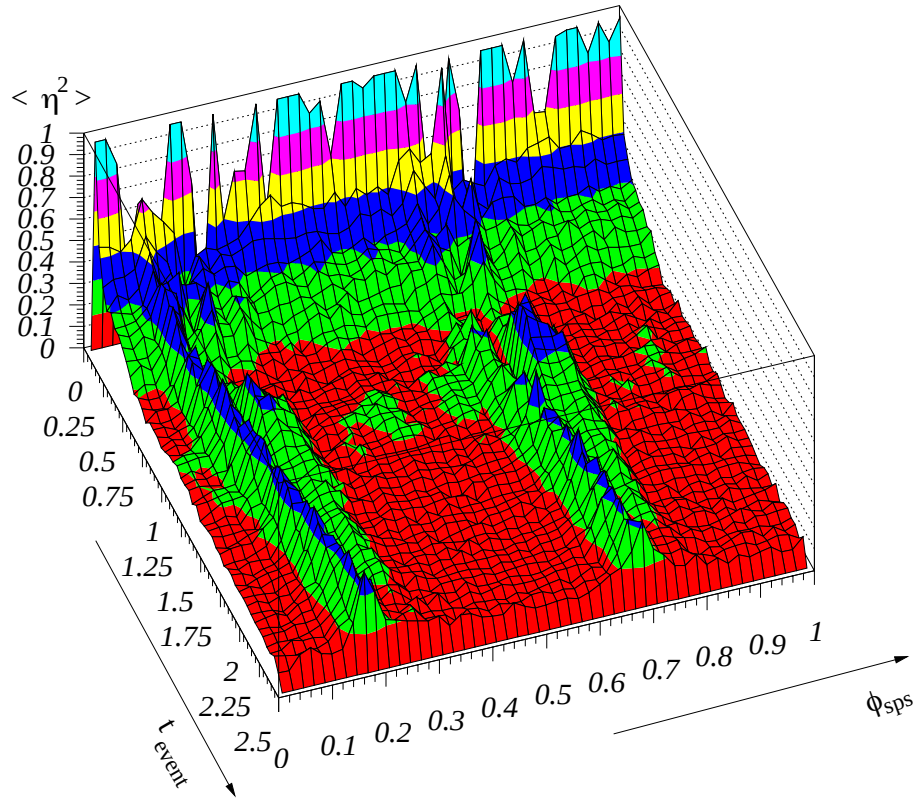


Figure 8.11: The fluctuation term as a function of ϕ_{SPS} and t is shown. High fluctuations are present at the beginning and in the middle of the extraction.

8.1.4 The high frequency structures

When the protons are observed at very small time scale ($\lesssim 100$ ns) they show periodic structure frequencies of 100 MHz and 200 MHz. The tagger (which has very good time resolution, and double pulse resolution < 8 ns) is exploited to detect those structures.

The distance in time between the protons detected in the tagger, and the time of the event ($t = 0$), is shown in figure 8.12. Figure a) relates to the beginning of the burst (time interval $[100 - 150]$ ms) and figure b) relates to the end of the burst (time interval $[2200 - 2250]$ ms). The Fourier Transform of these measured functions are shown respectively in figure 8.13 a) and b).

Notice that at the beginning of the burst the 200 MHz harmonic frequencies are present, while at the end of the burst only the 100 MHz is present.

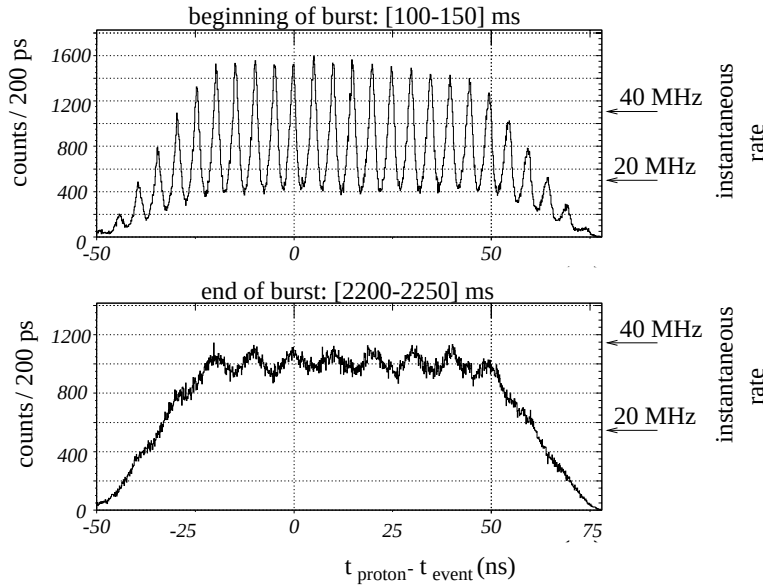


Figure 8.12: The protons detected by the tagger are shown as a function of their time with respect time of the event (that is $t = 0$). Figure a) relates to the time interval $[100 - 150]$ ms in the burst and shows the 200 MHz frequency structure which is present at the beginning of the extraction. Figure b) relates to the time interval $[2200 - 2250]$ ms and shows the 100 MHz which reaches its maximum amplitude at the end of the extraction.

The 200 MHz modulation is easily understood as a residual effect from the proton bunch structure of the SPS (protons are accelerated with 200 MHz radio frequency cavity system which keep the 5 ns bunch structure).

When the radio frequency (RF) is switched off protons start to de-bunch, as

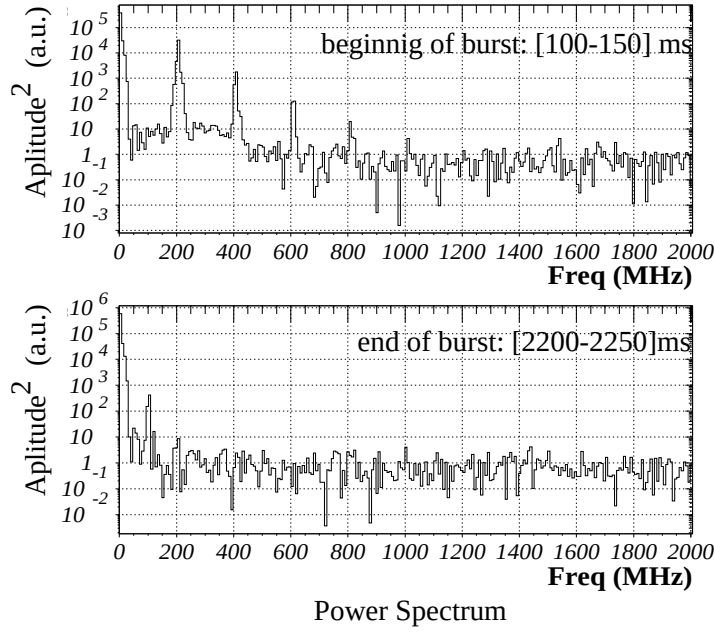


Figure 8.13: The Fourier transform of the proton time distributions at the beginning and end of the burst (see figure 8.12).

illustrated in figure 8.14. Protons with negative $\Delta p/p$ move forward while protons with positive $\Delta p/p$ move backward. Thus the bunches in phase space are stretched. After few ms protons with the lowest $\Delta p/p$ start to overlap the protons with the highest $\Delta p/p$ of the next bunch. The debunching is then observable in the SPS, and is completed after some tens of ms. The strength (i.e. the square amplitude) of the 200 MHz, frequency as a function of the time in the burst, is shown in figure 8.15. The measurement is performed by Fourier Transforming the output current of the Beam Current pick-up of the SPS [23].

The overlap of protons from adjacent bunches within the small extracted band of $\Delta p/p$ takes more time; but after some hundreds of ms the de-bunching is observable also with the extracted protons. The strength of the 200 MHz frequency as a function of the time in the burst is shown in figure 8.16. Here the protons intensity modulation measured by the tagger, as a function of their time, are Fourier Transformed at various instants during the extraction. Notice that after 250 ms the de-bunching is completed.

The short little restart of the 200 MHz after the de-bunching is not completely understood. It is worth noticing that the 200 MHz structure is indeed a 203 MHz

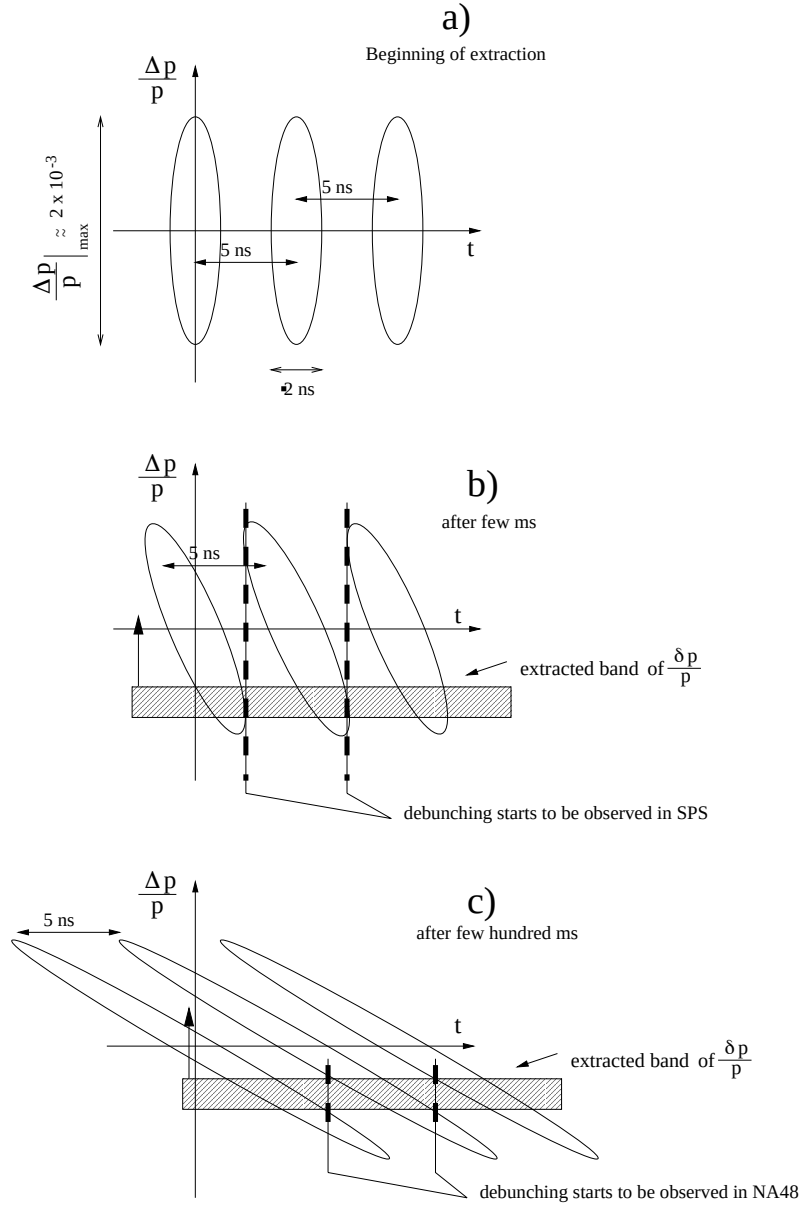


Figure 8.14: Illustration of the de-bunching. Before the beginning of extraction the radio frequency is switched off (a), and protons start to move free. Protons with negative $\Delta p/p$ while protons with positive $\Delta p/p$ move backward. Thus the bunches start to stretch more and more. After few ms protons with the lowest $\Delta p/p$ start to overlap the protons with the highest $\Delta p/p$ of the adjacent bunch (figure b). The debunching is then observable in the SPS. The overlap of protons from adjacent bunches takes more time to be seen by means of the small extracted band of $\Delta p/p$, i.e. from outside the SPS (figure c).

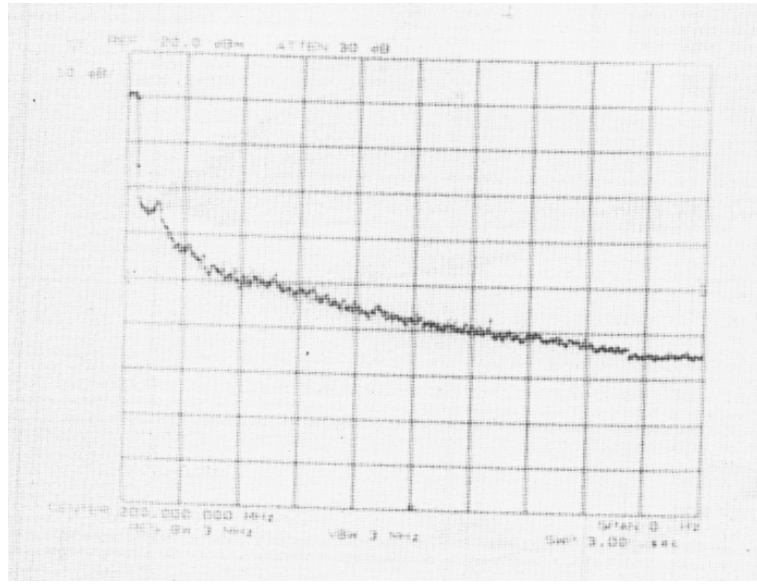


Figure 8.15: The evolution of the amplitude of the 200 MHz structure along the burst. The measurement is performed by fourier transforming the output current of some pick-ups which are sensible to the proton current circulating along the SPS ring. On the horizontal axis the time t in the burst is represented from the beginning of the extraction ($t = 0$ s) beyond the end of the extraction ($t = 3$ s). One horizontal division corresponds to 0.3 s. On the vertical axis the component of the power spectrum at 200 Mhz is shown in logaritmic scale. One vertical division corresponds to 10 dB.

structure, if measured with precision with the protons in the tagger; while the SPS measured frequency is exactly 200 MHz. The reason for this discrepancy is not understood.

Figure 8.16 shows, also, the 100 MHz evolution which increases with the time in the burst. This is understood as the effect of the LEP 100 MHz cavities that are not perfectly dumped during the proton cycle. What is not completely understood is the rise of the 100 MHz frequency, which is visible only with the extracted protons and not with the protons still in the SPS (see figure 8.17, to be compared with figure 8.16).

Considering the overall average contibution of the high frequency periodic fluctuations, their contribution to $\langle \eta^2 \rangle$ if of the order of $\sim 2\%$.

The fluctuations of the number of protons in the bunches can be considered as a kind of noise with typical high frequencies. This contributes to the overall fluctuation term only until the debunching is not completed, i.e. in the first 300 ms of the burst. Those fluctuations are observable in the figures 8.9 and 8.11. Its contribution to $\langle \eta^2 \rangle$ is estimated to be $\sim 2\%$.

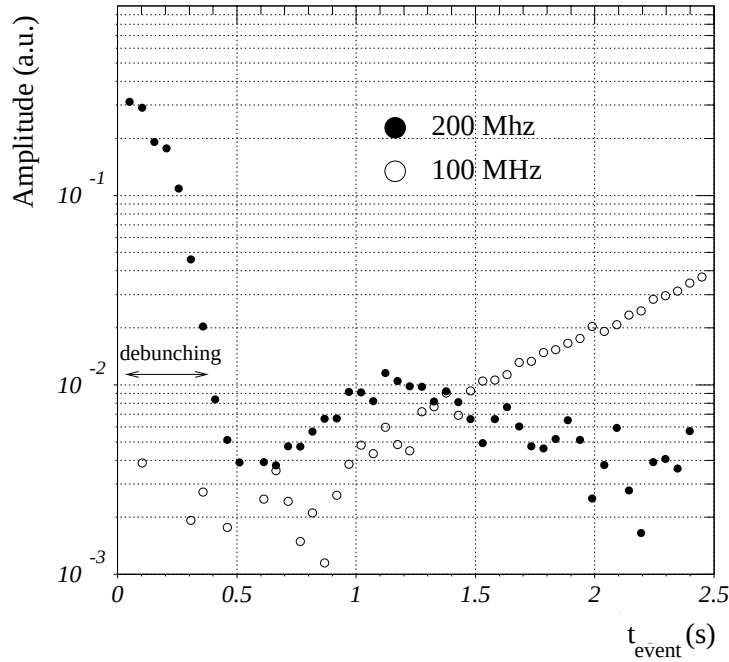


Figure 8.16: The evolution of the amplitude of the 200 MHz and 100 MHz frequency structures along the burst. The evolution of the 200 MHz and 100 MHz frequency structures as they are seen into the SPS is shown respectively in figures 8.15 and 8.17

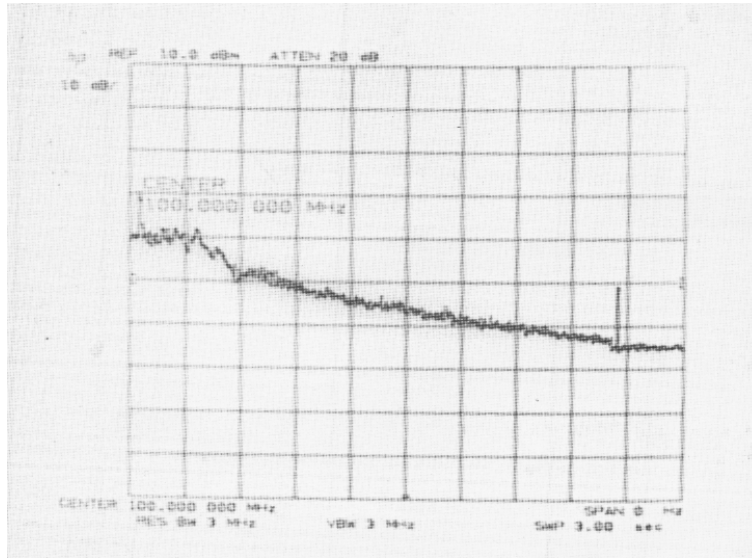


Figure 8.17: The evolution of the amplitude of the 100 MHz structure along the burst. On the horizontal axis the time t in the burst is represented from the beginning of the extraction ($t = 0$ s) beyond the end of the extraction ($t = 3$ s). One horizontal division corresponds to 0.3 s. On the vertical axis the component of the power spectrum at 100 MHz is shown in logarithmic scale. One vertical division corresponds to 10 dB.

8.1.5 The accidental tagging revisited

The intermediate and high frequency fluctuations are responsible for the difference between α_{LS} and β_{LS} .

8.2 The correlations of the K_S and K_L beam intensities

Two different methods are presented to measure the beam correlations.

8.2.1 The measurement of the correlations using the extra-activity indicators

The correlations of the K_S and K_L beam intensities are measured using the selected events, and the accidental hits in the sidebands, which record the intensity of the beams.

In Section 6.2.1.2 the following expression was derived:

$$\langle \eta_m \eta_S - \eta_m \eta_L \rangle \sim \frac{\langle m \rangle_S}{\langle m \rangle_L} - 1 \quad (8.4)$$

which is valid under the assumption that the geometric intensity dependent losses for $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events are the same, i.e. $\lambda_S = \lambda_L$. A K_L beam intensity indicator is needed to measure the intensity in an unbiased way, i.e. a detector whose rate is not directly correlated with the event losses³.

The AKL pockets 2, 3, 4 and 5 are used to measure their out of time hits in the window $20 \text{ ns} < |t_{hits} - t_{event}| < 100 \text{ ns}$ (they are later referred to as AKL). Pocket 1 is not used because it is much exposed to the particle debris from the K_S beam target; pockets 6 and 7 are not used because they are exposed to the particles back scattering from the interactions in the LKR calorimeter. Hits that are within 10 ns are counted only once, in order not to double count the same physical accidental particle which is crossing more than one AKL pocket. The 10 ns binning induces a cutoff to structures with frequencies above $\sim 100 \text{ MHz}$.

Additional indicators to study the K_L beam intensity are exploited:

- the number of space points (SP) reconstructed in the wire chambers in the time window $400 \text{ ns} < |t_{sp.points} - t_{event}| < 600 \text{ ns}$; hits that are within 25 ns are counted only once.

³they are of course correlated indirectly via the lower intensity induced to the losses

- the number of overflows⁴ in any of the wire chambers, in the time window $325 \text{ ns} < |t_{ovfl} - t_{event}| < 600 \text{ ns}$ (OVFL); hits that are within 25 ns are counted only once.

To study the K_S beam intensity, the following indicators are used:

- The number of protons (PRO) in the tagger ladder and in the halo counters (time interval $10 \text{ ns} < |t_{prot} - t_{event}| < 60 \text{ ns}$); hits that are within 4 ns are counted only once.
- The AKS out of time hits (AKS) are also used as K_S beam indicators, despite their low rate. The time interval exploited in this case is $25 \text{ ns} < |t_{ovfl} - t_{event}| < 175 \text{ ns}$.

Table 8.2 shows the average number of hits $\langle m \rangle_s$ and $\langle m \rangle_L$, with the relative difference $\frac{\langle m \rangle_s}{\langle m \rangle_L} - 1$, for charged K_S and K_L events distinguished by y -vertex tagging and selected with $z_{vtx} > 0$.

		KL beam intensity indicators			KS beam intensity indicators	
		AKL	SP	OVFL	PRO	AKS
$\langle m \rangle_s$	10^{-2}	41.48 ± 0.03	32.41 ± 0.02	30.91 ± 0.02	228.50 ± 0.10	0.522 ± 0.003
$\langle m \rangle_L$	10^{-2}	41.25 ± 0.04	32.25 ± 0.03	30.78 ± 0.03	224.45 ± 0.13	0.507 ± 0.003
$\frac{\langle m \rangle_s}{\langle m \rangle_L} - 1$	10^{-2}	0.55 ± 0.11	0.51 ± 0.12	0.40 ± 0.12	1.80 ± 0.07	3.00 ± 0.86

Table 8.2: The KL and KS intensities measured with various intensity indicators.

The difference between the auto-correlation and the cross-correlation parameters is estimated, using AKL and TAG, to be:

$$\langle \eta_L \eta_L - \eta_S \eta_L \rangle \equiv -\langle \eta_L \Delta \eta \rangle = (-0.55 \pm 0.11) \cdot 10^{-2} \quad (8.5)$$

$$\langle \eta_S \eta_S - \eta_S \eta_L \rangle \equiv \langle \eta_S \Delta \eta \rangle = (+1.80 \pm 0.07) \cdot 10^{-2} \quad (8.6)$$

An R.M.S. is obtained for the intensity ratio I_S/I_L of:

$$\frac{\sigma_{\langle \frac{I_S}{I_L} \rangle}}{\langle \frac{I_S}{I_L} \rangle} \sim \sqrt{\langle \Delta \eta^2 \rangle} = \sqrt{\langle \eta_S \Delta \eta \rangle - \langle \eta_L \Delta \eta \rangle} \sim 10\% \quad (8.7)$$

⁴Notice that for each DCH plane only the time of the previous and next overflows closest to the event time are available among the information of COMPACT.

The variations of the average number of hits $\langle m \rangle_S$ and $\langle m \rangle_L$ for K_S , and the unweighted K_L charged events in different time scales, are shown in figure 8.18. In particular the dependences on the time in the burst and in the run are shown in the plot 8.18 a) and b) respectively. The plots 8.18 c) and d) illustrate the variations of $\langle m \rangle_S$ and $\langle m \rangle_L$ with the SPS phase and the phase of the mains, i.e. in the $23 \mu s$ and $40 ms$ time scales.

The variations of the difference $\frac{\langle m \rangle_S}{\langle m \rangle_L} - 1$ is shown in figure 8.19.

The possible biases: The estimate for the $\langle \eta_K \Delta \eta \rangle$ difference rely on the fact that the difference on accidental loss of events due to the different K_S and K_L beam geometry are negligible.

The best proof would be to measure the extra-activity levels on sidebands in **random events** and compare them with the selected events. In practice this cannot be done at the permille level precision due to the problems in the randoms data taking (see Section 12.1.1.6 on page 253).

Some checks are envisaged to establish the precision of the measurement of $\langle \eta_K \Delta \eta \rangle$ (against biases due to the fact that it is measured on selected events):

- a first check is that the difference in the measurement of $\langle m \rangle_S / \langle m \rangle_L - 1$ for unweighted and weighted K_L events is below 0.001;
- the dependence of $\langle m \rangle_S / \langle m \rangle_L - 1$ on the longitudinal coordinate the decay vertex is flat; systematic deviations from flatness in the overall shape can be measured with Kolmogorov criteria within 0.01.
- the distribution of the vertical position at DCH1 $y_{acc.trk}$ of accidental tracks recorded in the event readout window (if any, far more than 20 ns from the event time) is studied. The average number of AKL hits is very similar in shape for K_S and K_L selected events. Selecting the charged events with $y_{acc.trk} < 0$ one should maximize the differential K_S to K_L accidental geometric effects; the measured average values for K_S and K_L events selected that way are the same within 0.005.
- the estimate for $\langle \eta_K \Delta \eta \rangle$ can be done with K_S and K_L neutral events selected with the tagger; it results in agreement with the measurement on charged events (the K_S and K_L are distinguished here with the tagger) within 0.002

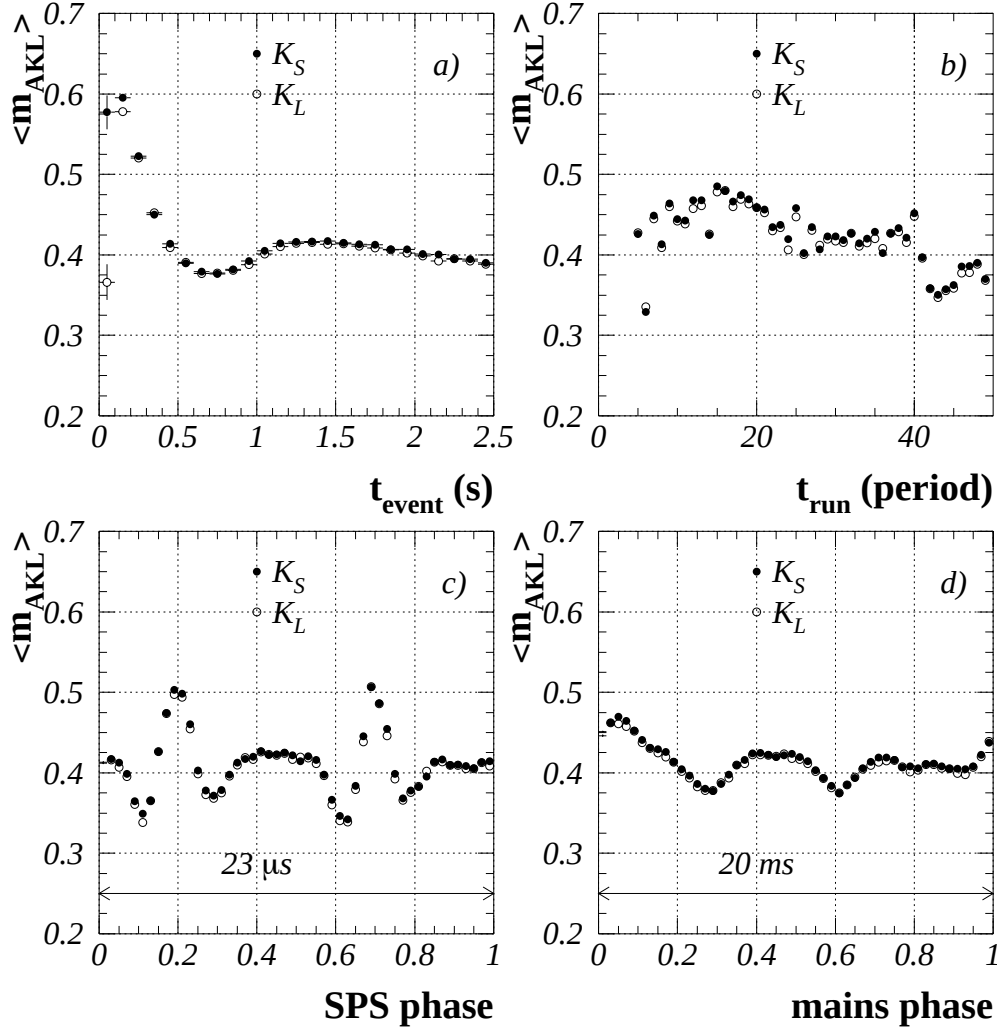


Figure 8.18: The variations of $\langle m \rangle_S$ and $\langle m \rangle_L$ for K_S and unweighted K_L charged events in different time scales are shown. In particular the dependences on the time in the burst and in the run are shown in plots 8.18 a) and b) respectively. Figures 8.18 c) and d) illustrate the variations of $\langle m \rangle_S$ and $\langle m \rangle_L$ with the SPS phase and the phase of the mains, i.e. in the $23 \mu s$ and $40 ms$ time scales.

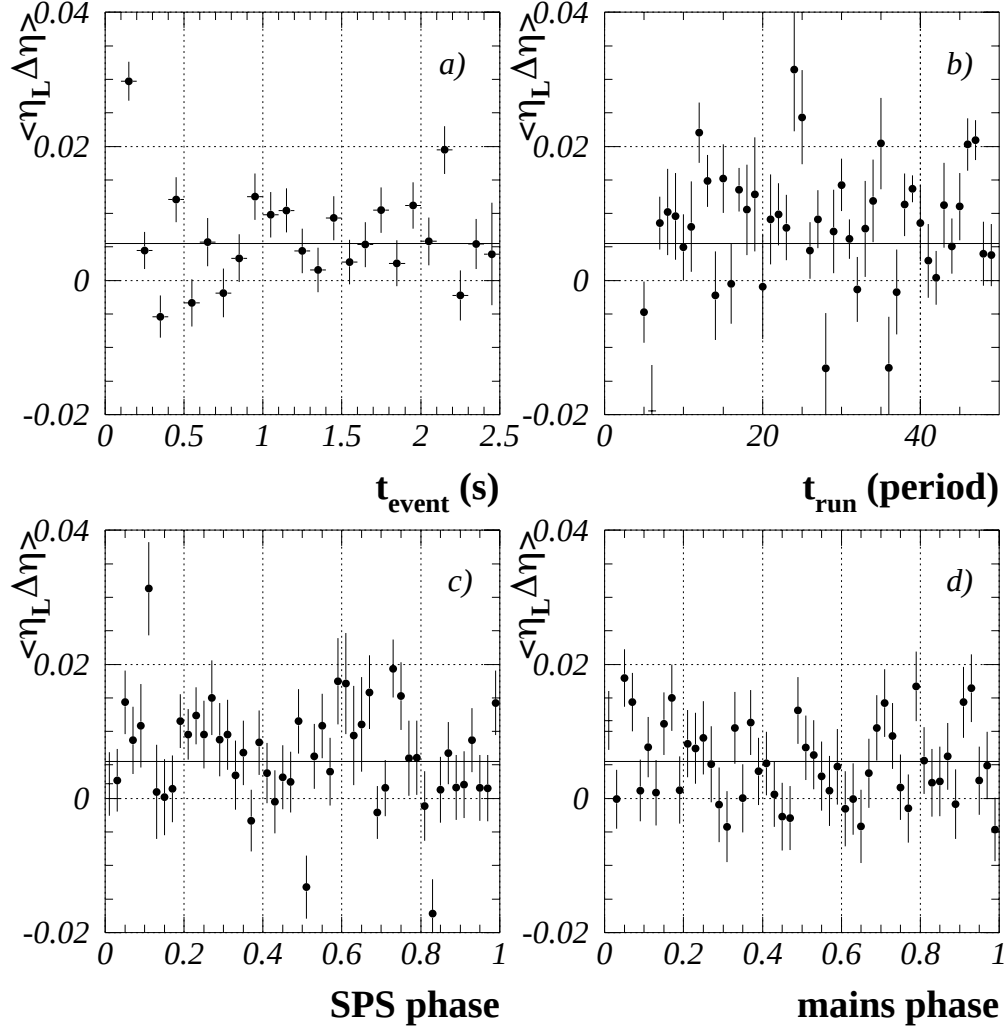


Figure 8.19: The variations of $\frac{\langle m \rangle_S}{\langle m \rangle_L} - 1$ in different time scales are shown. The line drawn for $\frac{\langle m \rangle_S}{\langle m \rangle_L} - 1 = 0.0055$ refers to the ratio of the overall average numbers $\langle m \rangle_S$ and $\langle m \rangle_L$.

Notice that neutral events are biased by some kind of geometric losses which is different than the charged events.

- the accidental geometric losses on events due to reconstruction and selection can be measured with the overlay technique to be less than 0.001. Notice that the accidental geometric losses due to the trigger conditions are less interesting here, as they are directly accounted in the measured correction for the trigger efficiency;
- effects due to some selections on $\langle m \rangle_s / \langle m \rangle_L - 1$ can be estimated releasing the selections and observing that its values is almost unchanged. For instance in case the **overflow** cut on charged events is released (16% of the events are rejected by this selection), the ratio $\langle m \rangle_s / \langle m \rangle_L - 1$ do not change within 0.008;
- one other argument is that, using overlays, the 3% difference between randoms KL and KS is still present in the overlayed events after applying all cuts, so this suggests that a difference in beam intensity will not be washed out by asking for good selected events.
- the AKL and DCH (i.e. SP and OVFL) indicators for KL beam activity are exposed to different kind of activity. The fact that they measure almost the same $\langle \eta_K \Delta \eta \rangle$ enforces the result.

8.2.2 The measurement of the intensity correlations using the beam counters

The beam counters allow measuring the intensity correlation of the beams as described in Section 6.2.2.2 on page 132. In particular the most reliable measurement [2,5] is performed using the incremental read-out of the scalers between successive triggers (see page 130).

Given a couple of counters, respectively exposed to the KS and KL beam, the correlation is measured using eqn. (6.37). Three couples of counters are exploited.

Two different methods are used (see [3] and [6]) which exploit the counts read-out by different triggers. The average of the two values is taken and the semi-difference is used to estimate the systematic errors. In both cases the statistical accuracy is

very high and is not considered. The results are shown in table 8.3.

	couple of counters		couple of counters		couple of counters	
	KLM	KSM	QX	KSM	QX	AKS
$\langle \eta_L \Delta \eta \rangle \quad (10^{-2})$	-2.80 ± 0.20		-0.44 ± 0.30		-0.52 ± 0.12	

Table 8.3: *The correlation of KL and KS intensities measured with various intensity monitors.*

The possible biases: Notice that this method copes with beam time structures only up to a cutoff frequency of ~ 1 kHz. This is probably the origin of the difference between these results and the ones previously shown (see table 8.2). In particular the QX and AKS (or KSM) couple yield a result which are compatible with the previous in absolute value, but have the opposite sign. The KSM and KLM monitors couple yields a high (~ 0.03) decorrelation which need further investigation.

The results of the previous Section are used in the following because they accounts for a wider range of beam structure frequencies.

Conclusions

The protons flow extracted form SPS is not constant in time. The fluctuations of the beam intensity are measured as a function of time in the burst. A value of 0.25 ± 0.03 is found for the variance of the intensity relative to the average intensity. This is equivalent to an r.m.s. at the level of $\sim 50\%$.

Various structures contribute to these huge beam intensity variations. Their contributions estimated contributions are summarized in table 8.4:

The correlations of the intensity variations of the K_S and K_L beams are measured on the taking advantage of the amount of extra-activity recorded in the readout windows for every selected event.

Despite the time variations of the beams intensity are huge, they are measured to be correlated correlated at a level better than 1%. In particular the difference between the KL beam intensity relative variance and the KL – KS beams intensity relative correlation is:

$$\langle \eta_L \eta_L - \eta_S \eta_L \rangle \sim -0.006$$

	contribution to $\langle \eta^2 \rangle$
low frequencies periodic	0.03
low frequencies noise	0.05
intermediate frequencies	0.05
high frequencies periodic	0.02
high frequencies noise	0.02

Table 8.4: *The contribution from the various structures to the beam fluctuations.*

It is still matter of investigation the exact origin of the decorrelation, and in particular which are the frequencies responsible for it. The comparison between the result of Sections 8.2.1 and 8.2.2 seems to indicate that there is not a unique frequency range responsible for the decorrelation.

9 Rate effects on the trigger system

Overview

The chapter is devoted to study the inefficiencies of the trigger for the $K_{\pi^+\pi^-}$ and the $K_{\pi^0\pi^0}$ events. The aim of the study is to distinguish the intrinsic inefficiencies of the trigger, from the inefficiencies caused by the accidental particles close to the $K_{\pi\pi}$ decays.

The knowledge of the causes of losses is crucial to decide how to correct them in the measurement of the double ratio $\mathcal{R}$. For instance, if the condition to loose $K_{\pi^+\pi^-}$ events, is reproduced also in $K_{\pi^0\pi^0}$ neutral events, then those $K_{\pi^0\pi^0}$ neutral events may be rejected off-line, in order to balance the $K_{\pi^+\pi^-}$ lost events; in this case, there would be no need to measure accurately the amount of losses in charged events.

9.1 Charged trigger effects

The two levels trigger (see Section 3.3 on page 63) used for the $K_{\pi^+\pi^-}$ events suffers from various inefficiencies in both levels. In the following analysis all the inefficiencies will be discussed, with special care for those induced by the accidentals. The analysis is focused on the QX signal, and the L2C (Massbox), which are the main components of the charged trigger, and are most sensitive to the accidental activity.

Various sources for the inefficiency, and the dead-time, of the trigger system are singled out, starting from the Massbox dead time. This is a simple example of rate dependent dead-time, which will be discussed in the following chapters.

9.1.1 The main source of dead time in the charged trigger system

The main contribution ($\sim 3\%$ on average) to the charged trigger inefficiency comes from the Massbox dead time (see Section 3.3.2 on page 69 for a detailed description) which is controlled by the L1OFF signal. In order to preserve the data from corruption, the L1OFF device introduces an amount of dead time which varies depending on the instantaneous rate.

For each acquired event, the L1OFF condition is recorded by the Pattern Unit

(see Section 3.3.1.1), Thus the systematics related to the dead-time can be studied, analyzing the samples of the charged minimum bias events (L1pp, see table 3.1), of the **neutral** events, and of the **random** events. These three kind of events are triggered independently of the Massbox, allowing an almost unbiased measurement of the dead-time for the K_S , and the K_L events, and the study of its correlation with the instantaneous intensity.

9.1.1.1 The nature of the Massbox dead time

The average dead time, as a function of the number of QX counts in the burst, is shown in figure 9.1 for all the bursts of the 1998 data taking selected for the epsilon prime analysis.

Figure 9.2 shows the distribution of the QX rates measured for neutral events selected with the standard epsilon prime cuts (see Section 4). The QX rate distribution is shown also for those events with the L1OFF condition set. The ratio of the two distributions gives the dead time with the QX rate¹. The non linear dependence of the dead time as a function of the QX rate can be explained by the proportionality between the duration of the L1OFF signal (referred to as the L1OFF width) and the instantaneous rate. Let I be the instantaneous rate and $\Delta t_{L1OFF} \propto I$ the L1OFF width; then the dead time $\mathcal{D}$ would be proportional to I^2 . A quadratic proportionality is understood within a simple model for the level-1 requests to the Massbox. As introduced in Section 3.3.2, the “bottleneck” of the charged trigger is the input FIFO of the drift chambers Master Service Card. The queue in the FIFO can be modeled as a Markovian Deterministic one server (M|D|1) queue (see [89]) with a fixed service time $\tau = 6 \mu s$. Given the queue input rate I , the average queue length is:

$$\langle \Delta N_{queue} \rangle = \frac{I^2 \tau^2}{2(1 - I\tau)} \quad (9.1)$$

The L1OFF signal width and the dead time $\mathcal{D}$ are hence proportional to I^2 .

In figure 9.3 a) the distribution of $t_{event} - t_{prec.L2}$ is shown for all the events in the sample. Figure 9.3 b) shows the dead time as a function of the time difference

¹The peak at zero in figure 9.2 a) is due some bad working of the QX scales. The QX rate is measured from the ratio of the number of QX counts between each L2 trigger and the preceding one, and the time difference between the two triggers. The closer are the two triggers, the stronger is the bias on the measurement. The range of QX rate > 700 kHz is not reliable due those biases.

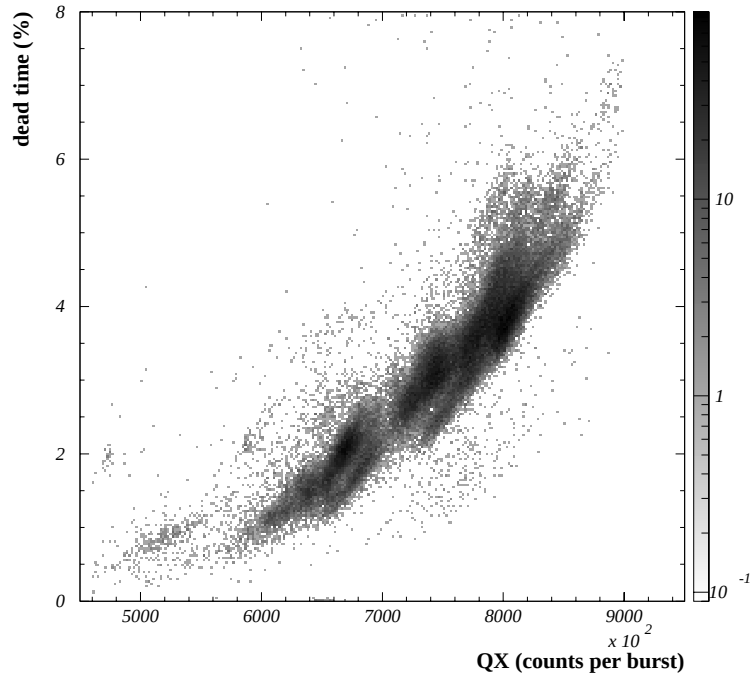


Figure 9.1: The Massbox dead time averaged over the burst duration versus the number of QX counts in the burst. Information are extracted by the Trigger Supervisor scales which are recorded at the end of every burst. In the plot are shown all the 1998 bursts selected for the ϵ'/ϵ analysis.

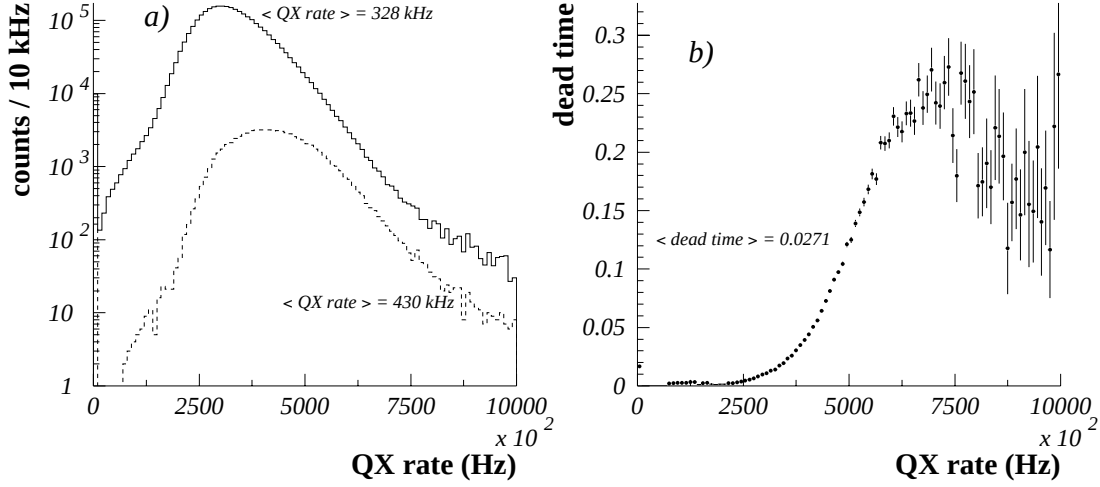


Figure 9.2: The QX rate distribution for the neutral events selected for ϵ'/ϵ analysis is shown in figure a) with solid line; $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events are not separated. The dashed line relates to the QX rate distribution for the subsample of the above neutral events with the condition L1OFF on. The average QX rate is 328 kHz and 430 kHz respectively. In case of neutral events the request of no dead time condition set results on average in a $\sim 2.7\%$ event loss. Figure b) shows the dependence of the Massbox dead time on the QX rate.

$(t_{event} - t_{prec.L2})$ between an event and the previous L2 trigger in case of the neutral events selected for the epsilon prime analysis. No distinction between $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events is made here. Although in an indirect way, the time from the previous event allows to sample the L1OFF signal duration. As one can see it ranges from few μs up to $\sim 150 \mu s$. The main effect is produced by the mentioned queue of the requests to the drift chambers Master Service Card, and it is related to the peak at $\sim 10 \mu s$ (which is referred to as the main time scale $\Delta t_{\mathcal{D}}$ for the Massbox dead time). The time structures of the beam, with frequencies up to $(\Delta t_{\mathcal{D}})^{-1} \sim 1/10 \mu s = 100 \text{ kHz}$, are involved in the time variations of the Massbox dead time.

The peak at $\sim 130 \mu s$ is still being investigated, however it accounts for a small fraction of the inefficiency ($< 10\%$).

Notice that the status of the L1OFF signal is mostly independent of the triggering event. This points to the impossibility for the dead time device to distinguish the $K_{\pi\pi}^S$ decays from the $K_{\pi\pi}^L$ ones; the only differences can thus come from the different intensity experienced by K_S and K_L events.

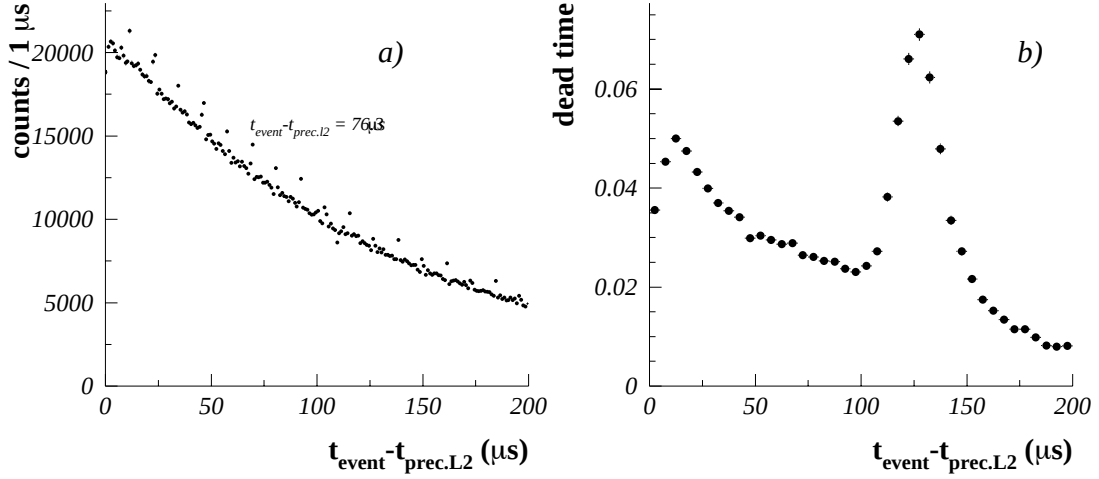


Figure 9.3: The distribution of the time difference ($t_{event} - t_{prec.L2}$) between the selected event and the previous L2 trigger is shown a) for all the neutral events obtained with the standard ϵ'/ϵ selections; $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events are not separated. The time of the event is provided by the Time Stamp of the trigger. The distribution is an exponential with peaks every $\sim 11 \mu s$ which are due to the beam periodic structures. The average time difference $t_{event} - t_{prec.L2}$ is $\sim 76 \mu s$. In figure b) the dead time dependence on $t_{event} - t_{prec.L2}$ is shown. The peak structures at $\sim 10 \mu s$ and $\sim 130 \mu s$ are discussed in the text.

9.1.1.2 The method to measure the dead time and the correction to $\mathcal{R}$

The dead time has a two-fold influence on the double ratio $\mathcal{R}$: it introduces trigger inefficiency and, due to its intensity dependence, it selects $K_{\pi^+\pi^-}^S$ and $K_{\pi^+\pi^-}^L$ events with low intensity. This trigger selection results in a neutral to charged intensity unbalance, which induces a correction to $\mathcal{R}$ through $\Delta\alpha_{LS} \neq 0$.

Following the usual notation, introduced in Chapter 6, the effect on $\mathcal{R}$ due to dead time induced event losses is:

$$\Delta\mathcal{R}/\mathcal{R} = \frac{\Delta\lambda_S^C (1 + \langle\eta_A\eta_S\rangle)}{\Delta\lambda_L^C (1 + \langle\eta_A\eta_L\rangle)} \quad (9.2)$$

which is approximated by:

$$\Delta\mathcal{R}/\mathcal{R} \sim (\Delta\lambda_S^C - \Delta\lambda_L^C) + (\Delta\lambda_S^C \langle\eta_A\eta_S\rangle - \Delta\lambda_L^C \langle\eta_A\eta_L\rangle) \quad (9.3)$$

where $\Delta\lambda$ is the loss per unit intensity due to the dead time inefficiency (i.e. it is the losses' sensitivity to the intensity) and where the hypothesis of linear proportionality between intensity and dead time, is supposed to hold ².

As previously discussed, the mechanism for the dead time generation cannot distinguish between K_S and K_L . Even in case of K_S and K_L events suffering the same dead time ($\Delta\lambda_S^C = \Delta\lambda_L^C \equiv \Delta\lambda^C$) there should be a residual effect $\Delta\mathcal{R}/\mathcal{R}$ on $\mathcal{R}$:

$$\Delta\mathcal{R}/\mathcal{R} = \Delta\lambda^C \langle\eta_A\eta_S - \eta_A\eta_L\rangle \quad (9.4)$$

This means that an effect arises from the fact that the fraction of losses is varying with time and the KL beam intensity is neither constant nor following the KS intensity variations with constant ratio. The difference of the correlation between accidentals intensity and respectively the KS and KL beam intensities $\langle\eta_A\eta_S\rangle \neq \langle\eta_A\eta_L\rangle$ can be compared to the dead time $\mathcal{D}$ which can be written as:

$$\mathcal{D}_{S,L}^{N,R,C_{ctrl}} = \langle\Delta\lambda^C I_{S,L}\rangle / \langle I_{S,L}\rangle = \Delta\lambda_{S,L}^{N,R,C_{ctrl}} \langle 1 + \eta_A\eta_{S,L}\rangle; \quad (9.5)$$

Notice in particular that the difference between $\mathcal{D}_S$ and $\mathcal{D}_L$ is indeed the $\Delta\mathcal{R}/\mathcal{R}$.

Table 9.1 shows $\mathcal{D}$ measured with the samples of **neutral** ($_N$), **random** ($_R$) and **charged control** ($_{C_{ctrl}}$) events.

²The quadratic dependence from the intensity discussed before gives a more reliable model for the losses. In the above expressions it would introduce, in first approximation, a factor of 2 in front of the loss term $\Delta\lambda$ corresponding to a doubled sensitivity of the losses to the intensity.

The separation between K_S and K_L is done by the tagger for the **neutral events** and by the vertex vertical position for the **charged control events**; the **neutral events** are then corrected for accidental tagging³.

	event samples		
	neutral events	random events	charged control events
$\mathcal{D}_S$ (%)	2.75 ± 0.01	2.72 ± 0.02	2.28 ± 0.06
$\mathcal{D}_L$ (%)	2.67 ± 0.02	2.64 ± 0.01	2.29 ± 0.07

Table 9.1: The Massbox dead time $\mathcal{D}$ measured for K_S and K_L decays with neutral, random and charged control event samples. The measurements with neutral events are corrected for accidental tagging as described in footnote^{#3}. The difference $\mathcal{D}_S - \mathcal{D}_L = (8 \pm 2) \cdot 10^{-4}$ measured with neutral, and random events accounts for the effect $\Delta\mathcal{R}/\mathcal{R}$ on $\mathcal{R}$. The measurement with charged control events is probably biased due to correlations of the dead time with other inefficiencies (e.g. trigger, overflow and event reconstruction inefficiencies).

The difference $\mathcal{D}_S - \mathcal{D}_L = (8 \pm 2) \cdot 10^{-4}$ measured with **neutral** and **random** events estimates the effect $\Delta\mathcal{R}/\mathcal{R}$ on $\mathcal{R}$. The relative difference $(\mathcal{D}_S - \mathcal{D}_L)/\mathcal{D} = 3.0 \pm 0.8\%$ is in agreement (see expr. (9.5)) with the relative difference of the beam correlations: $\frac{\langle\eta_A\eta_S\rangle - \langle\eta_A\eta_L\rangle}{1 + \langle\eta_A\eta_L\rangle}$ measured in Section 8.2.1 on page 177.

At the trigger time the status of the L1OFF signal is mostly independent of the selected event. The **neutral events** are not correlated with the charged dead time (the probability for a selected **neutral event** to result in a QX · ETOT · 2TRK request to

³Given two samples of n_S^{tag} and n_L^{tag} respectively $K_{\pi^0\pi^0}^S$ and $K_{\pi^0\pi^0}^L$ tagged neutral events (see also eqn. 5.2), then the corrected amounts of events are:

$$\begin{aligned} n_S &= n_S^{tag} - \frac{\alpha_n}{1 - \alpha_n} n_L^{tag} \\ n_L &= \frac{1}{1 - \alpha_n} n_L^{tag} \end{aligned} \tag{9.6}$$

where α_n is the accidental tagging probability measured with the same sample of events in the side band window (see Section 5.2).

Given the subsets of the inefficient events m_S^{tag} and m_L^{tag} and their proper accidental tagging probability α_m , then the dead time is measured as:

$$\begin{aligned} \mathcal{D}_S &= \frac{m_S^{tag} - \frac{\alpha_m}{1 - \alpha_m} m_L^{tag}}{n_S^{tag} - \frac{\alpha_n}{1 - \alpha_n} n_L^{tag}} \\ \mathcal{D}_L &= \frac{\frac{1}{1 - \alpha_m} m_L^{tag}}{\frac{1}{1 - \alpha_n} n_L^{tag}} \end{aligned} \tag{9.7}$$

the Massbox is $< 10^{-4}$) and the measurement of $\mathcal{D}$ with **neutral events** is unbiased.

On the other hand, the measurement with **charged control events** is likely to be biased due to correlations of the dead time with other rate dependent inefficiencies proper of the charged $K_{\pi^+\pi^-}$ events, in particular with **overflow** and reconstruction inefficiencies.

It follows that the most unbiased way to measure the Massbox dead time is to exploit the **neutral events**. One can choose either to correct $\mathcal{R}$ with the measured dead time inefficiency (see table 9.1), or to get rid of **neutral events** in case they are triggered with the Massbox in L1OFF status (this procedure will be referred to as **symmetrization** in the following). The latter treatment of the dead time is to be preferred because it copes with possible biases in the measurement due to correlation with other inefficiencies proper of the charged events and because it leads to a better **balance of the intensity of the selected neutral and charged events**. Moreover, while the statistical error on $\mathcal{R}$ is not affected by the rejection of the **neutral events** with the L1OFF set, the error on the charged trigger inefficiency is reduced. If the dead-time $\mathcal{D}$ is not included, the charged trigger inefficiency is almost halved, but the number of events in the control sample is the same. This corresponds to an error⁴ on the inefficiency reduced by a factor of $\sqrt{2}$.

9.1.1.3 Intensity effects: the dead time and the accidental tagging difference

The balancing of the intensity is evident for instance in the measurement of the accidental tagging probability. In particular let (α_{LS}^N) and $(\overline{\alpha_{LS}^N})$ be the accidental tagging probabilities measured on the **neutral events**, respectively with and without the Massbox dead-time cut. The difference $\overline{\alpha_{LS}^N} - \alpha_{LS}^N$ is $7.0 \cdot 10^{-4}$, which results in a difference of the accidental tagging probability for **neutral events** and **charged events** changing from $\overline{\Delta\alpha_{LS}} = (12.0 \pm 1.7) \cdot 10^{-4}$ to $\Delta\alpha_{LS} = (5.0 \pm 1.7) \cdot 10^{-4}$.

The $(\overline{\alpha_{LS}^N} - \alpha_{LS}^N)/\alpha_{LS}^N \sim 0.64\%$ relative difference between $\overline{\alpha_{LS}^N}$ and α_{LS}^N can be roughly explained by the simple model previously introduced for the losses. Given the fact that the probability of finding protons in the tagger is a **KS beam intensity**

⁴The error without **symmetrization** is $\sigma_\varepsilon^2 = \varepsilon(1 - \varepsilon)/N$ where N is the number of all the events in the control sample. In case of **symmetrization** the efficiency to be measured is almost halved and its error becomes: $\sigma_\varepsilon^2 \sim \frac{\varepsilon}{2}(1 - \frac{\varepsilon}{2})/N$.

indicator (m_s), and recalling the expr. (6.15) for the intensity measured by some non killing indicator with a selected sample of events, one can write the accidental tagging probability as:

$$\alpha_{LS}^N = \frac{\langle m_s \cdot [1 - \lambda_L(1 + \eta_A)] \cdot I_L \rangle}{\langle [1 - \lambda_L(1 + \eta_A)] \cdot I_L \rangle} \quad (9.8)$$

where α_{LS} is the usual probability of finding a proton in the sideband window when the events of the sample are the neutral selected K_L 's; the term λ_L is the loss per unit of intensity of the events in the sample. In particular let $\overline{\lambda_K}$ and λ_K be the loss sensitivity without and with dead time **symmetrization** respectively, i.e. $\Delta\lambda_K \equiv \overline{\lambda_K} - \lambda_K$.

The expr. (9.8) can be further simplified as:

$$\alpha_{LS}^N \sim \langle m_s \rangle \cdot \langle 1 + \eta_s \eta_K \rangle \cdot [1 - \lambda_K \langle \eta_s \eta_A \rangle] \quad (9.9)$$

taking the difference between α_{LS}^N measured without and with **symmetrization** then:

$$(\overline{\alpha_{LS}^N} - \alpha_{LS}^N)/\alpha_{LS}^N = (\overline{\lambda_K} - \lambda_K) \langle \eta_s \eta_A \rangle = \Delta\lambda_K \langle \eta_s \eta_A \rangle \quad (9.10)$$

which considering eqn.(9.5) yields:

$$(\overline{\alpha_{LS}^N} - \alpha_{LS}^N)/\alpha_{LS}^N = \mathcal{D}_K \cdot \frac{\langle \eta_s \eta_A \rangle}{1 + \langle \eta_s \eta_A \rangle} \quad (9.11)$$

The beam correlation term $\langle \eta_s \eta_A \rangle$, discussed in Chapter 8, is of the order of 25%, and the dead time is $\mathcal{D} \sim 2.5\%$ resulting in $(\overline{\alpha_{LS}^N} - \alpha_{LS}^N)/\alpha_{LS}^N \sim 0.5\%$. A more suited quadratic dependence of the losses from the intensity ($\Lambda \propto I_A^2$) would lead to a factor of 2 in front of the term $\langle \eta_s \eta_A \rangle$ and consequently to $(\overline{\alpha_{LS}^N} - \alpha_{LS}^N)/\alpha_{LS}^N \sim 1.0\%$. These values are in agreement with the measured ones if one considers a $\sim 10\%$ relative error on $\langle \eta_s \eta_A \rangle$.

9.1.1.4 Intensity effects: the dead time in the burst

Figure 9.4 shows the variation of the dead time during the burst for different data sample. The selected events are subdivided into 10 ($\delta t = 0.25$ s wide) time intervals in the burst $t \equiv t_{event}$. The value of the dead time $\mathcal{D}(t, \delta t)$ is relative to the bin centered on t is a time average over the interval δt .

In the previously discussed linear model the dead-time distribution is described as follows (eqn. (9.2) is written with the explicit time dependence of the η terms):

$$\mathcal{D}_K(t, \delta t) = \frac{\langle \Delta\Lambda_K I_K \rangle_{\delta t}(t)}{\langle I_K \rangle_{\delta t}(t)} \quad (9.12)$$

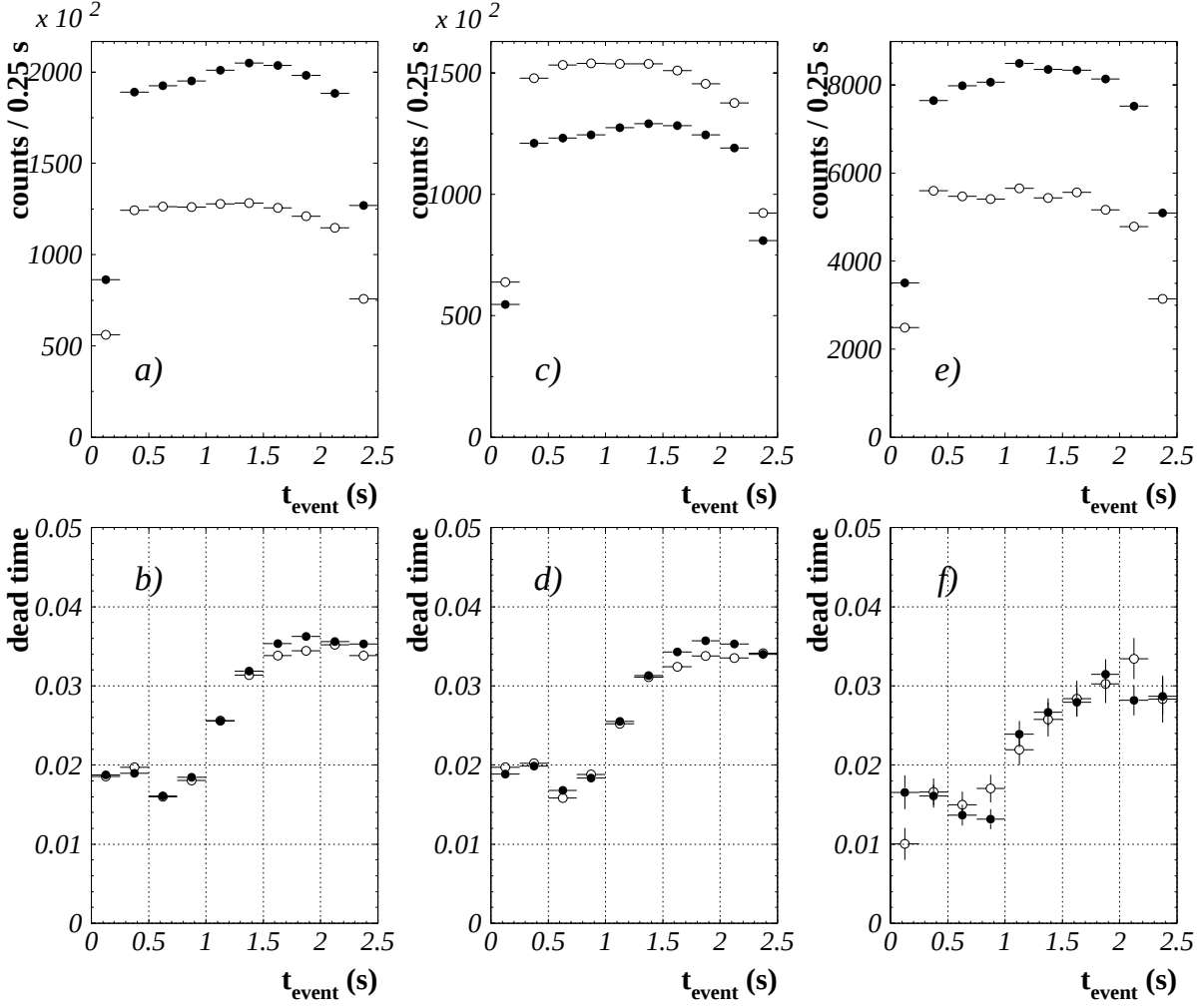


Figure 9.4: The number of $K_{\pi\pi}^S$ (full circle) and $K_{\pi\pi}^L$ (hollow circle) neutral events obtained with the standard epsilon prime selections is shown in a) as a function of the time of the burst t_{event} (notice that in this section the notation $t \equiv t_{\text{event}}$ holds); the number of events, which are tagged as K_S or K_L by the tagger, is already corrected for $L \rightarrow s$ accidental tagging probability (see footnote^{#3}). In figure b) the dead time dependence on the time of the burst is shown for K_S (full circle) and K_L (hollow circle) neutral events (corrected for the $L \rightarrow s$ accidental tagging). Figures c) and d) are the same as a) and b) respectively but are referred to random R_S (full circle) and R_L (hollow circle) events instead of neutral K_S and K_L . Figures e) and f) are the same as a) and b) respectively but are referred to K_S and K_L L1pp control trigger $K_{\pi^+\pi^-}$ events; in this case the events are tagged as K_S or K_L by the vertex vertical position and no accidental tagging correction is needed.

Separating the constant term from the time dependent term in I_K and in $\Delta\Lambda_K$ eqn. (9.12) can be written as:

$$\mathcal{D}_K(t, \delta t) = \Delta\lambda_K \frac{1 + \langle \eta_A + \eta_K + \eta_A\eta_K \rangle_{\delta t}(t)}{\langle 1 + \eta_K \rangle_{\delta t}(t)} \quad (9.13)$$

which is approximated by:

$$\mathcal{D}_K(t, \delta t) = \Delta\lambda_K [1 + \langle \eta_A \rangle_{\delta t}(t) + \langle \eta_A\eta_K \rangle_{\delta t}(t)] \quad (9.14)$$

The term $\langle \eta_A \rangle_{\delta t}(t)$ does not cancel out completely (as it does by definition averaging over the entire data set); only the Fourier components with frequency in the range $\nu_{SPS} \lesssim \nu \lesssim (\delta t)^{-1}$ and with a fixed phase with respect to the extraction spill, will survive.

On the other hand, the Fourier components $\nu \lesssim (\Delta t_{\mathcal{D}})^{-1}$ are present in the term $\langle \eta_A\eta_K \rangle_{\delta t}(t)$ up to the frequency typical of the effect, which is $(\Delta t_{\mathcal{D}})^{-1} \sim 100$ kHz in the case of the dead time. The variations of $\langle \eta_A\eta_K \rangle_{\delta t}(t)$ with the time t in the burst are of course due to the variations of the Fourier spectrum in the burst.

As discussed in Section 2.2, the magnets, which steer the beam from the SPS to the NA48 targets, introduce noise in the time variations of the intensity in the frequency range $\nu \lesssim 400$ Hz. In addition, during the burst, some of the magnet currents are ramped to optimize the beam steering. The slow raise of the dead time during the burst can be qualitatively explained by the increase of the r.m.s. of the low frequency noise. This is accounted for mostly in the term $\langle \eta_A\eta_K \rangle_{\delta t}(t)$ and in the term $\langle \eta_A \rangle_{\delta t}(t)$ for the lowest frequencies.

Notice that the term $\langle \eta_A\eta_K \rangle_{\delta t}(t)$ is expected to dominate upon $\langle \eta_A \rangle_{\delta t}(t)$.

The K_S to K_L dead time difference along the burst is explained with the difference of the correlation term $\langle \eta_A\eta_K \rangle_{\delta t}(t)$ between K_S and K_L events.

9.1.2 Major inefficiency sources in the charged trigger system

The Massbox and the QX signal are responsible for almost half ($\sim 3\%$) of the charged trigger inefficiency. They are expected to be much sensitive to accidentals, and in particular the QX signal plays a key role in influencing that sensitivity. It has, indeed, the double function of providing both the trigger and the fine-time measurement (see Section 3.3.1.1) to the Massbox. The time measurement is crucial for the hits association done in the Look-Up tables of the Massbox, and the QX signal

is responsible of event losses more through bad time measurement than through dead time.

The QX signal is the combination of the outputs of the discriminators working in burst-guard mode, which is described in the trigger Section 3.3.1.1. At the pretrigger output stage the QX is reshaped by an updating discriminator (minimum width ~ 27 ns) and it is feeded into the synchronizer. The synchronizer suffered from very small inefficiency ($< 10^{-5}$) in 1998 and also the dead time introduced by the discriminators is negligible. It is the interaction between the the QX and the synchronizer that produces the inefficiency which is usually referred to as QX dead time. The synchronizer is only sensible to the first edge of the input signals and for each input provide only one output time-slot. This means that in case the QX signal is more than 25 ns (that is, one time-slot) wide then some amount of dead time is introduced by the synchronizer proportionally to the QX signal width.

The width of the QX signal is variable, as one can see from figure 9.5. High multiplicity events, and in particular the high flux (~ 300 kHz) of showers through the charged hodoscope, are expected to yield QX signals wider than the minimum due to the higher amplitude of the signals in the photo-multipliers. The oscillating shape of the photo-multiplier signals (see figure 9.6) explains the peaks in the distribution of the QX width (figure 9.5). The dead time of the system QX-synchronizer is estimated to be equivalent to ~ 20 ns of busy time beyond the ~ 27 ns of the QX minimum width. Given the 450 kHz QX rate (see table 7.2) one expects to loose $\sim 1\%$ of the QX's due to their closeness to other QX's.

Figure 9.7 illustrates a typical pattern for the selected $K_{\pi^+\pi^-}$ event time with respect to the QX time triggered by an earlier accidental event. In particular an averaged probability for the QX signal not to be re-triggered after having been triggered a first time, is roughly sketched. Notice that while the QX busy time varies from few ns up to ~ 100 ns, the dead time probability is very quickly decreasing, i.e. the earlier the accidental QX comes, the more probable is the re-triggering of the good QX.

Only a fraction of the $\sim 1\%$ QX dead time results in an effective loss of events. Let us consider for instance, the case of a $K_{\pi^+\pi^-}$ event whose QX is not formed in the pretrigger due to an accidental QX which is closely preceding the event and is triggering the Massbox. (see figure 9.7) Then in spite of the QX dead time for the $K_{\pi^+\pi^-}$ event, there is some probability for the $K_{\pi^+\pi^-}$ event to be accepted by the

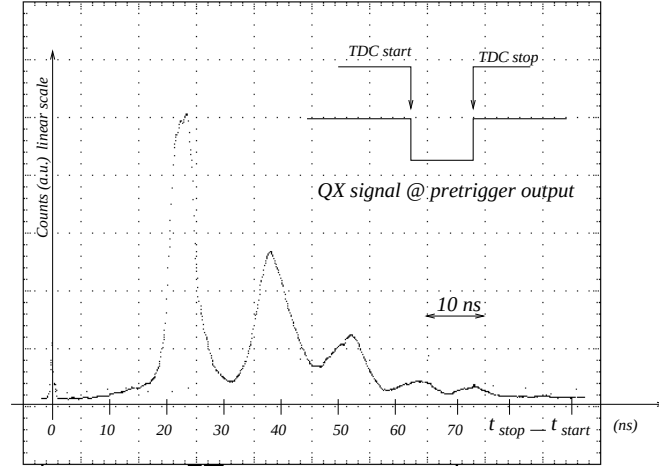


Figure 9.5: The width ($\Delta T_{QX} \equiv t_{stop} - t_{start}$) of the QX signal (at pretrigger output) measured feeding its starting front in the TDC start and its trailing front in the TDC stop. The peaks for $\Delta T_{QX} > 30$ ns are related to the photo-tube signal shape (see figure 9.6)

Massbox. The hits association in the Look-Up tables is made depending on the QX time measurement which relates to the accidental, but the closer the accidental is to the $K_{\pi^+\pi^-}$ event, the more likely the Massbox accepts the trigger as a good one for the $K_{\pi^+\pi^-}$ event.

In the case the time differences between the triggering accidental and the good $K_{\pi^+\pi^-}$ event is $|t_{accidental} - t_{event}| \equiv \Delta t \lesssim 30$ ns the Massbox can accept the events. In case the accidental is too far ($\Delta t \gtrsim 30$ ns) from the $K_{\pi^+\pi^-}$ decay and the QX is still dead, then the inefficiency reaches 100%. Notice that in the following analysis the time (t_{event}) of the $K_{\pi^+\pi^-}$ event is defined as the time of the vertex, that is of the tracks, as measured using the off-line drift chambers reconstruction: $t_{event} \equiv t_{vtx}$. The study of the correlations between the trigger efficiency, and the event time reconstruction by the charged hodoscope, is described in the Section 5.2 about mistagging.

The amount of inefficiency coming from the use of the time information by the Massbox, can be computed from the convolution of the probability, as a function of Δt , for the QX to re-trigger (see figure 9.7), and the Massbox efficiency. The latter is shown in figure 9.8 where the time of the $K_{\pi^+\pi^-}$ event is subtracted from the Fine

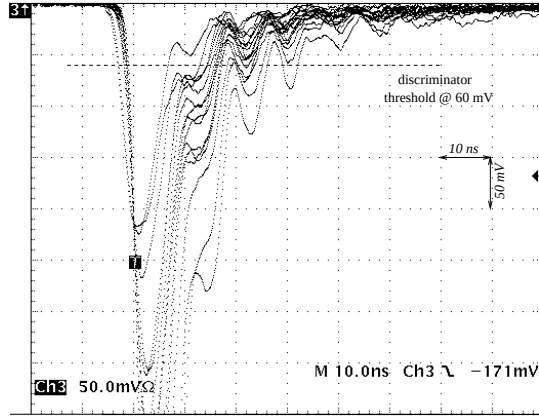
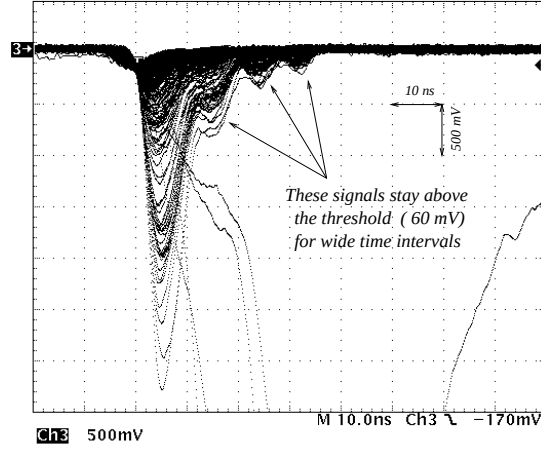


Figure 9.6: The output signals of a photo-tube of the charged hodoscope observed at the oscilloscope for two ranges of signal amplitude (tracks in the bottom figure are recorded with a $\times 10$ zoom factor). Among the recorded tracks many relate to high amplitude signals due to showers through the charged hodoscope. The coincidence of signals of this kind from scintillators in QX configuration might result in a several tens ns QX signal width. The oscillations in the signal amplitude are present also for lower amplitude signals; in case of oscillations near threshold after-pulses are generated.

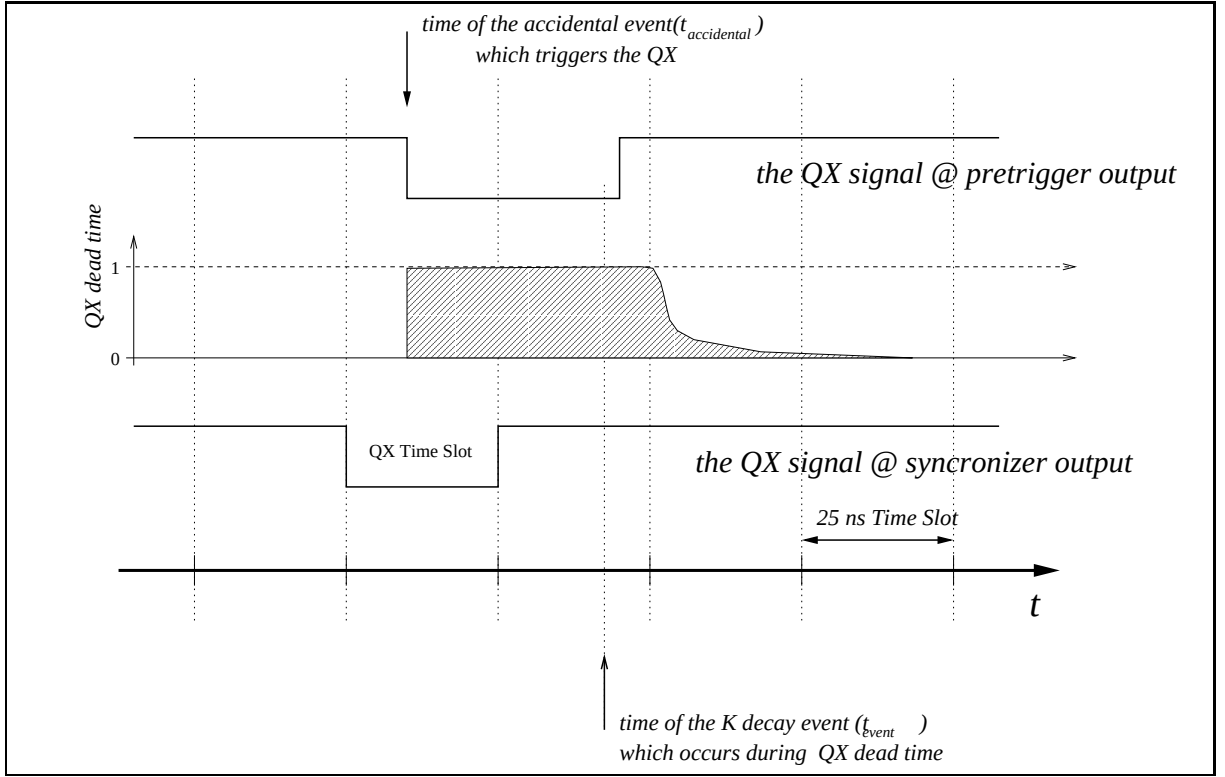


Figure 9.7: The figure shows one possible pattern for the selected $K_{\pi^+\pi^-}$ event time with respect to the QX time triggered by an earlier accidental event. The figure shows a rough draw of the probability for the QX signal not to be re-triggered after being triggered a first time, i.e. the probability for the QX dead time.

Time of the QX found, in the Pattern Unit, nearest to the event. The events in the peak at $t_{QXfine} - t_{event} \sim 0$ correspond to good QX time measurements in absence of accidentals. The events for $t_{QXfine} - t_{event} \lesssim -10$ are due to accidentals preceding closely the $K_{\pi^+\pi^-}$ decay, and resulting in a bad t_{QXfine} time measurement with a Massbox inefficiency. The earlier is the accidental the higher the inefficiency.

The QX signal suffers also from after-pulses (see comment in figure 9.6). In about 15% of the cases a QX is followed by another QX in the second next time-slot. This is an additional possibility for “accidental” QX triggering which is a disturbance mainly for the minimum bias triggers where the Massbox answer is not requested. In case a QX from a genuine $K_{\pi^+\pi^-}$ decay is followed by its after-pulse then the latter can trigger the acquisition for a minimum bias event. Due to its correlation with the first genuine QX, it bias the down-scaling factor of the minimum bias trigger. Moreover the $K_{\pi^+\pi^-}$ decay is recorded, but it is reconstructed at least $\gtrsim 25$ ns away from the trigger time-slot, i.e. in a marginal region of the read-out window where the off-line reconstruction is not optimized.

This is the reason for the introduction of the $\mathbf{t_{vtx}selection}$ (see Section 4.2.2 on page 81), which is envisaged to accept only events whose vertex time is within 20 ns from the middle of the trigger time-slot ⁵.

9.1.2.1 The method to measure the inefficiencies and to account for them in $\mathcal{R}$

The efficiency of the QX, and of the Massbox, can be measured with the sample of events collected by the control trigger $\mathbf{ETOT \cdot 2TRK}$ (also referred to as $\mathbf{L1pp}$, see table 3.1 on page 71), which does not requires neither the QX signal nor the Massbox answer.

Excluding the $\mathbf{t_{vtx}selection}$, whose efficiency is studied as part of the trigger efficiency, all the other selections of the standard epsilon prime analysis are applied. In particular the events with the Massbox dead time bit set or with the **overflow** conditions set are rejected⁶.

The method consists of taking the reconstructed time⁷ t_{vtx} of the selected events

⁵In the case of the main charged ϵ'/ϵ triggers, this rejection overlaps with the tail of QX dead time.

⁶Correlations between trigger efficiency and overflows is studied in Chapter 10

⁷Notice that here $t_{event} \equiv t_{vtx}$

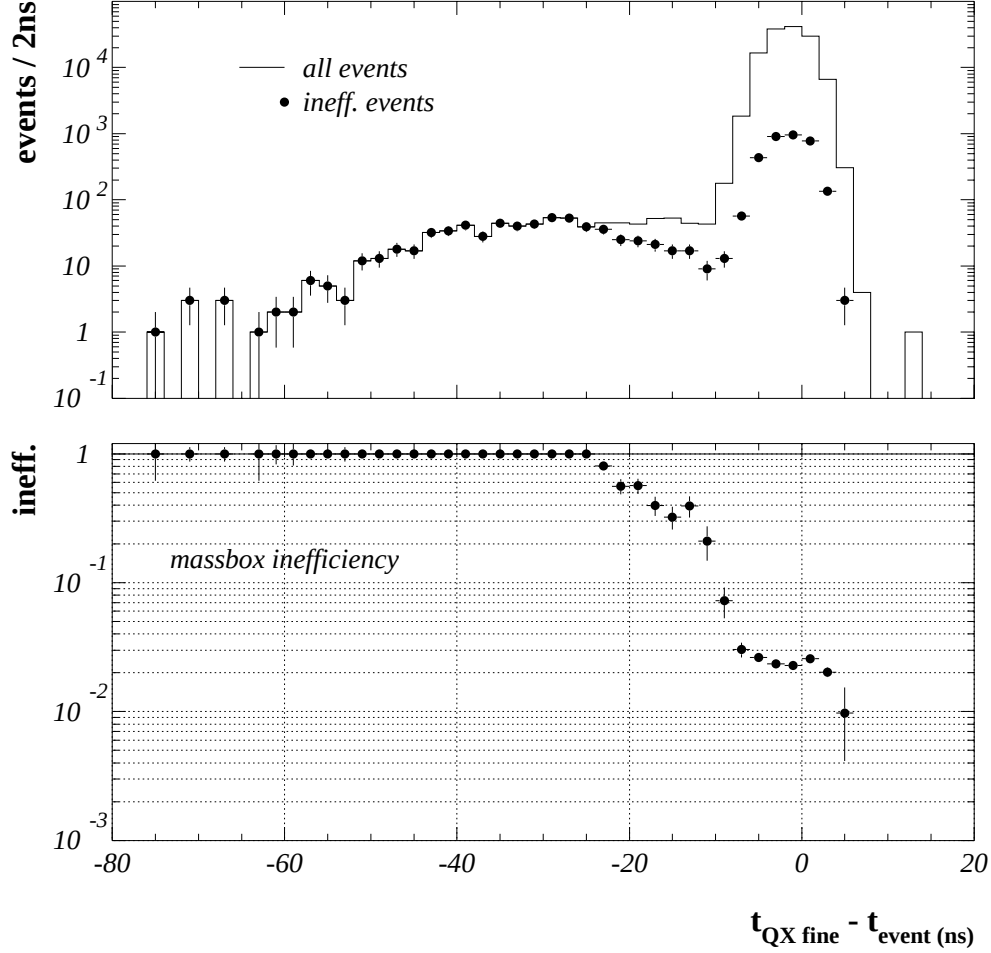


Figure 9.8: The plots share the same horizontal axis, which has been drawn only on the bottom for convenience. Above: the distribution of the difference $t_{QXfine} - t_{event}$ between the time of the event and the Fine Time of the QX found in the Pattern Unit nearest to the event for all the events in the control sample (solid line) and for the inefficient events (full dots). Below: the Massbox inefficiency as a function of $t_{QXfine} - t_{event}$. The events belonging to the peak at $t_{QXfine} - t_{event} \sim 0$ relate to good QX time measurements. The presence of a early accidentals ($t_{QXfine} - t_{event} \lesssim -10$) results in a bad time measurement and hence in Massbox inefficiency. The peak r.m.s. resolutions of the order of $6.25/\sqrt{12}$ ns due to the width of the fine-time time-slot.

as a reference ⁸, defining a vertex time-slot around it, and looking for the nearest QX time-slot and eventually for a Massbox answer. In particular the sample is analyzed subdividing the events into three categories, depending on the positions pattern of the $K_{\pi^+\pi^-}$ vertex time and of the QX time-slot (if any), as described in the following:

case i) the reconstructed time of the vertex, for a $K_{\pi^+\pi^-}$ event, falls in a time-slot where a QX is set or within 20 ns from a QX time-slot (see *case i*) in figure 9.9). In other words the t_{vtx} selection is applied with respect to the QX time-slot. Then the Massbox answer is looked for, in the Pattern Units, in the same time-slot.

Trigger inefficiency ($\sim 2.5 \cdot 10^{-2}$) is due either to pure Massbox inefficiency, or to a bad time measurement due to accidentals very close to the $K_{\pi^+\pi^-}$ event. The latter can be thought as a case of QX dead time, where the time is wrongly measured, i.e. shifted by Δt , where $6.25 \text{ ns} \lesssim \Delta t \lesssim 31.25 \text{ ns}$.

The double ratio $\mathcal{R}$ is corrected for this effect (later referred to as “pure Massbox” efficiency).

case ii) the reconstructed vertex time falls in a time-slot following a QX, and the $K_{\pi^+\pi^-}$ vertex time is more than 20 ns apart from the QX time-slot center (see *case ii*) in figure 9.9).

This sample of events is triggered by an accidental QX which prevents the $K_{\pi^+\pi^-}$ event to re-trigger the QX ⁹. It is a case of QX dead time ($7.5 \text{ ns} \lesssim \Delta t \lesssim 50 \text{ ns}$) where the time is measured so badly for the Massbox, that it does not recognize the $K_{\pi^+\pi^-}$ event; the inefficiency for this pattern of vertex time and QX positions is 100%.

This kind of events accounts for a part of the trigger inefficiency (later referred to as “QX dead time” inefficiency) that can be measured ($\lesssim 4 \cdot 10^{-3}$) and corrected in the double ratio $\mathcal{R}$. Nevertheless, like in the case of the Massbox dead time (see Section 9.1.1.2 on page 192), it is preferable to take into account the “QX dead time” inefficiency in $\mathcal{R}$ through the symmetrization with neutral events.

⁸also for centering the overflow and Massbox dead time cuts

⁹Due to the “bottleneck” the case of two QX in consecutive time-slots it is impossible

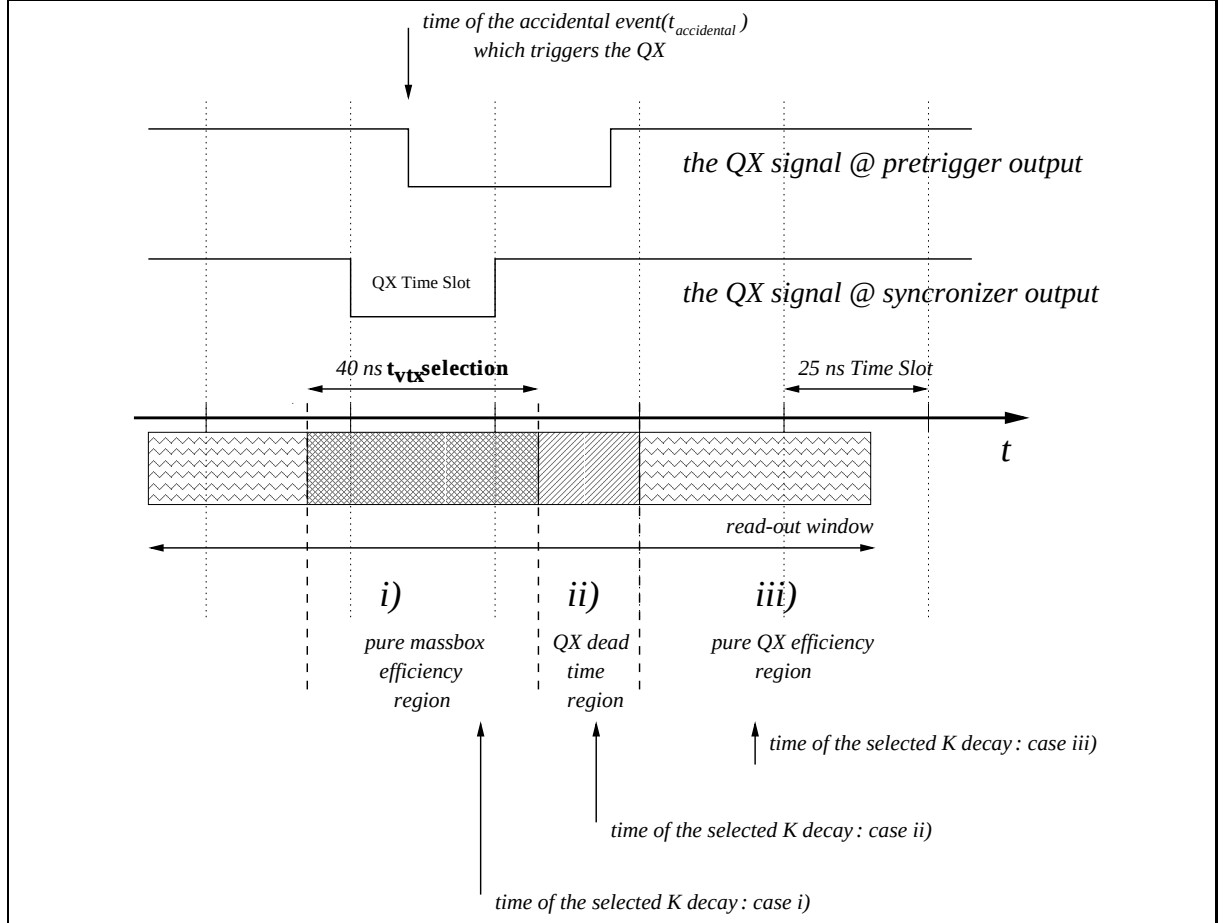


Figure 9.9: The figure shows the three possible patterns for the selected $K_{\pi^+\pi^-}$ event time with respect to the accidental event time and the QX time-slot. They are referred to as cases i), ii) and iii); they are at the origin of the three subsamples which the events of the trigger control sample are subdivided into, as explained in the text.

case iii) the reconstructed $K_{\pi^+\pi^-}$ time of the vertex is far from a QX time-slot by more than one time-slot (see *case iii*) in figure 9.9) or there is no QX at all.

These events take into account the small inefficiency ($\sim 6 \cdot 10^{-4}$) originating from the upper tails ($\Delta t > 25$ ns) of the QX dead time probability, and from pure geometrical QX inefficiency (in the following this is referred to as “pure QX” inefficiency). The pattern of vertex time and QX time does not lead to 100% inefficiency and, since this kind of inefficiency is not reproduced with neutral events, the symmetrization is not possible. The effect should then be measured and corrected in the $\mathcal{R}$.

A correction to the double ratio $\mathcal{R}$, for the inefficiency of the charged trigger, should be applied only to a fraction (“pure Massbox” and “pure QX”) of the measured losses. The residual part (“QX dead time”) is taken into account by symmetrization of the losses with neutral events.

Notice that the method relies on the drift chambers reconstruction because the time of the vertex is needed. The measured trigger inefficiencies are then relative to the reconstruction efficiency, which is supposed to be independent of QX and much higher than the on-line reconstruction’s one, i.e. the Massbox efficiency. The biases that the reconstruction inefficiency might induce in the measurement of the charged trigger inefficiencies, through possible correlations, are expected to be small, and are still under study.

The origins of the inefficiencies will be related, in the following paragraphs, to the accidentals, and to the rate of the beams.

Notice that the time scale in which the accidentals influences the trigger is $-75 \text{ ns} \lesssim t_{\text{accidental}} - t_{\text{event}} \lesssim 50 \text{ ns}$ ¹⁰. Then all the time structures of the beam with frequencies up to ~ 100 MHz are involved in the time variations of these inefficiencies (see Chapter 8).

¹⁰disregarding the overflow influence

9.1.2.2 The “pure Massbox” inefficiency

The previously introduced *case i)* “pure Massbox” accounts for the largest part of the charged trigger inefficiency:

$$\begin{aligned}\mathfrak{A}_S &= (2.27 \pm 0.05)\% \\ \mathfrak{A}_L &= (2.28 \pm 0.06)\% \\ \mathfrak{A}_{L^w} &= (2.29 \pm 0.09)\%\end{aligned}\tag{9.15}$$

for the K_S events, the unweighted and the weighted K_L events respectively¹¹. The measurements in the three samples are compatible within the errors.

Part of the inefficiency is due to the Massbox reconstruction algorithm, and it seems not to be related to accidentals, nor to intensity effects.

Part of the losses are instead due to accidental particles in the detector which result either in a bad measurement of the event fine timing by the fast logic or in some accidental hits in the drift chambers which make the Massbox to reject the event. The former case can be seen as a kind of QX dead time: if the accidental tracks trigger the QX earlier but very close ($\Delta t \lesssim 30$ ns) to the $K_{\pi^+\pi^-}$ event, then the Fine Time is given by the accidental tracks and not to the $K_{\pi^+\pi^-}$ event. In this case the Massbox Look-Up table might fail the hit association¹². This mechanism explains an inefficiency of $\lesssim 0.2\%$ ¹³.

Even in case of correct QX time measurement the Massbox might reject events

¹¹The error for both efficiency $\varepsilon = \frac{\sum_{eff} w}{\sum_{all} w}$ and (inefficiency $\mathfrak{A} \equiv (1 - \varepsilon)$) is estimated with the expression:

$$\sigma_\varepsilon^2 = \frac{1}{N_w} \cdot [(1 - \varepsilon)^2 \varepsilon_w + \varepsilon^2 (1 - \varepsilon_w)]\tag{9.16}$$

where the equivalent number of events is $N_w \equiv \frac{(\sum_{all} w)^2}{\sum_{all} w^2}$ and it is $\varepsilon_w \equiv \frac{\sum_{eff} w^2}{\sum_{all} w^2}$.

In case of constant weights the expr. (9.16) reduces to the variance for unweighted binomial statistic:

$$\sigma_\varepsilon^2 = \frac{1}{N} \cdot (1 - \varepsilon)\varepsilon\tag{9.17}$$

where N is the number of all events.

¹²This kind of inefficiency could be in principle compensated in the double ratio $\mathcal{R}$ with symmetrization with $K_{\pi^0\pi^0}$ neutral events, i.e. neutral events with QX in the neutral trigger could be rejected. But this would be biased due to the presence in $K_{\pi^0\pi^0}$ neutral events of QX generated by the event itself via conversions or backscattering from the LKR

¹³estimated from the 0.6% “QX dead time” inefficiency

either because of a complex hit patterns in the drift chambers or because of accidental hits on the same wires hit by the good $K_{\pi^+\pi^-}$ tracks. In particular late accidental hits overwrite the good hit times in the A Card memory (see description in Section 3.3.2 on page 68) causing wrong hit association by the Massbox.

The effects of accidental tracks on “pure Massbox” control events are shown in figures 9.10 and 9.11. Figure 9.10 shows (solid line) the distribution of the accidental tracks, for all the events in the control sample, as a function of the time difference $t_{extra} - t_{event}$ between the extra track time and the time of the event. The full dots relate to the distribution of the accidental tracks for the inefficient events in the sample. The ratio of the two distributions in figure 9.10 is shown in figure 9.11 which results to be the “pure Massbox” inefficiency as a function of the distance of the accidental tracks from the event $K_{\pi^+\pi^-}$. As one might expect, the presence of an accidental track close to the event ($|t_{extra} - t_{event}| \lesssim 30$ ns) makes the trigger inefficient up to 20%. The dip in the distribution before the $K_{\pi^+\pi^-}$ event time can be explained with a bad measurement of the QX Fine Time and the dip after the event can be explained by overwriting of hits in the Massbox A Card memory because of some late accidental or δ ray generated by the event.

In order to study the dependence of the inefficiency as a function on the intensity, the reconstructed space points in the drift chambers are analyzed. The leftmost figure 9.12 shows the inefficiency dependence as a function of the number of space points¹⁴. In order to obtain figure 9.12, the space points were grouped in bins of 10 ns. The case of 1 space point in abscissa of figure 9.12, corresponds to the case of events with 6 space points belonging to the two $K_{\pi^+\pi^-}$ tracks (i.e. within ~ 10 ns). A number of space points $N_{sp.points}$ implies the presence of at least $N_{sp.points} - 1$ accidental space points in the event.

The figure points to a linear dependence on the intensity¹⁵ of the form: $\epsilon(I) = \epsilon(0) + \kappa I$. The presence of the constant term $\epsilon(0)$ relates to the intensity independent fraction of the inefficiency. Given the average inefficiency $\epsilon \sim 2.28\%$ and the value $\epsilon(0) \sim 1.95\%$ then the fraction of the “pure Massbox” inefficiency

¹⁴Space points have a much higher rate than extra tracks for instance, which makes them preferable in this kind of studies for their lower statistical errors.

¹⁵The space points is intended to be estimator of the intensity: $I \propto (N_{sp.points} - 1)$ where the case of $N_{sp.points} = 1$ is considered as the limit for the intensity: $I \rightarrow 0$

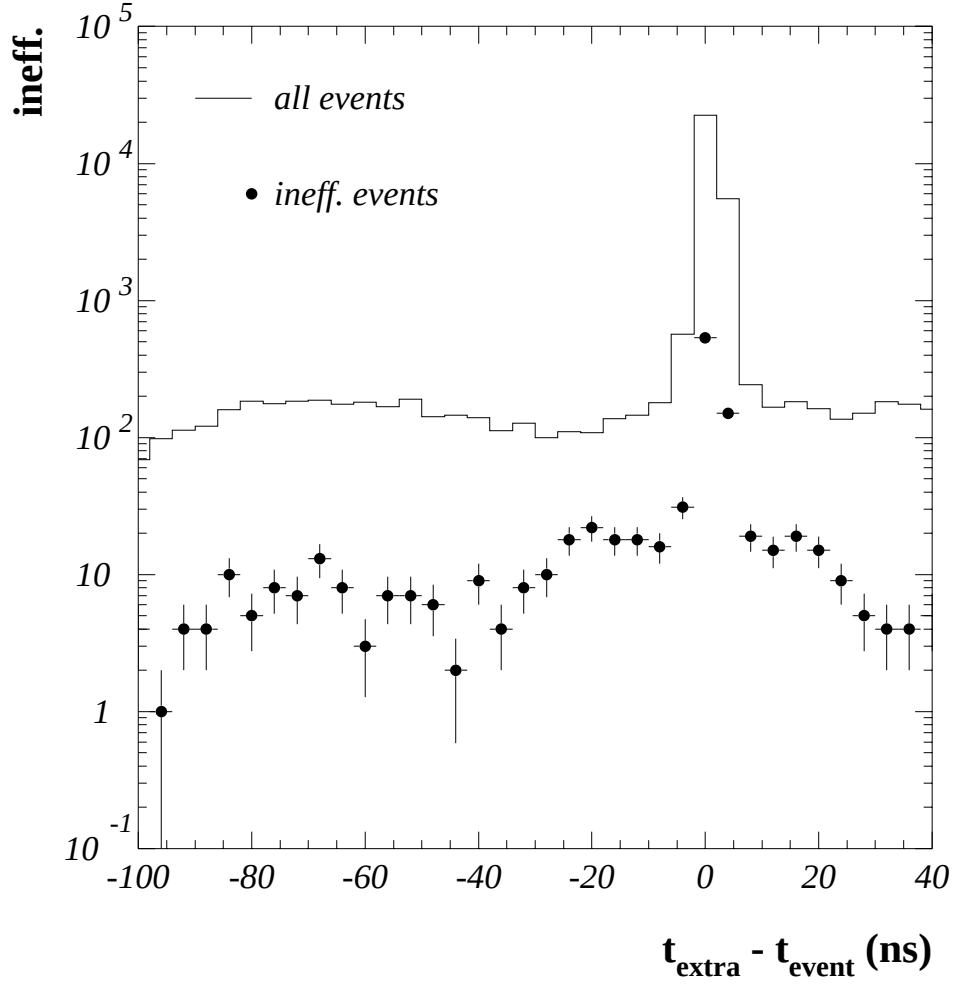


Figure 9.10: The distribution of the accidental tracks for all the “pure Massbox” control events (solid line) and the inefficient events (dashed line) as a function of their time distance from the event $K_{\pi^+\pi^-}$. The ratio of these two distributions is shown in top figure 9.11.

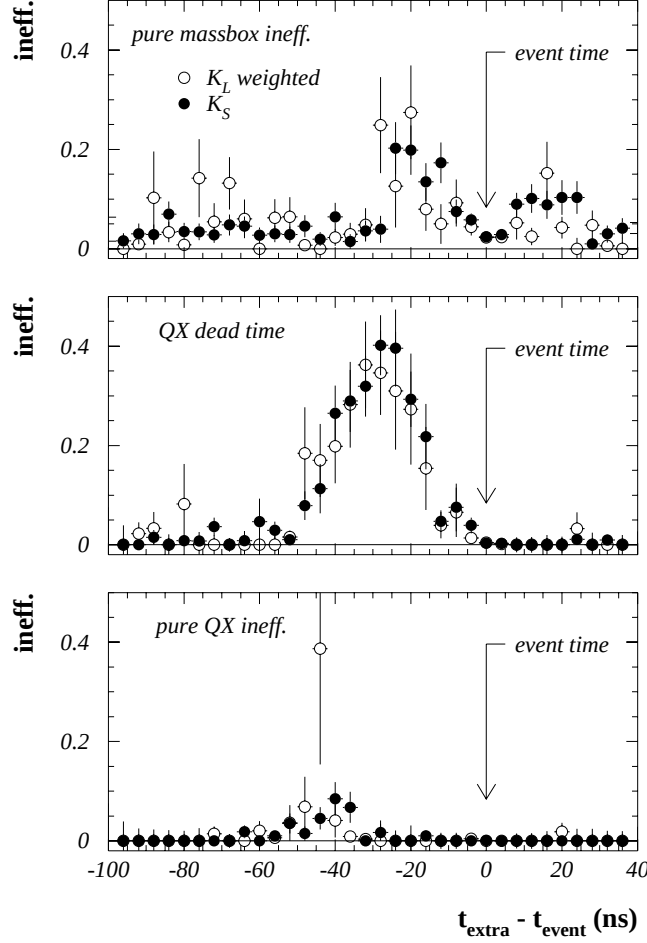


Figure 9.11: The “pure Massbox” inefficiency as a function of the time difference $t_{\text{extra}} - t_{\text{event}}$ between the extra track time and the time of the $K_{\pi^+\pi^-}$ event is shown in the top figure. As noticed here the time of the vertex provides the time if the event, i.e. $t_{\text{event}} \equiv t_{\text{vtx}}$. The full and hollow dots represent $K_{\pi\pi}^S$ and weighted $K_{\pi\pi}^L$ events respectively. The middle and bottom figures show the same distribution relative to the “QX dead time” and “pure QX” inefficiencies respectively. The plots share the same horizontal axis, which has been drawn only on the bottom for convenience.

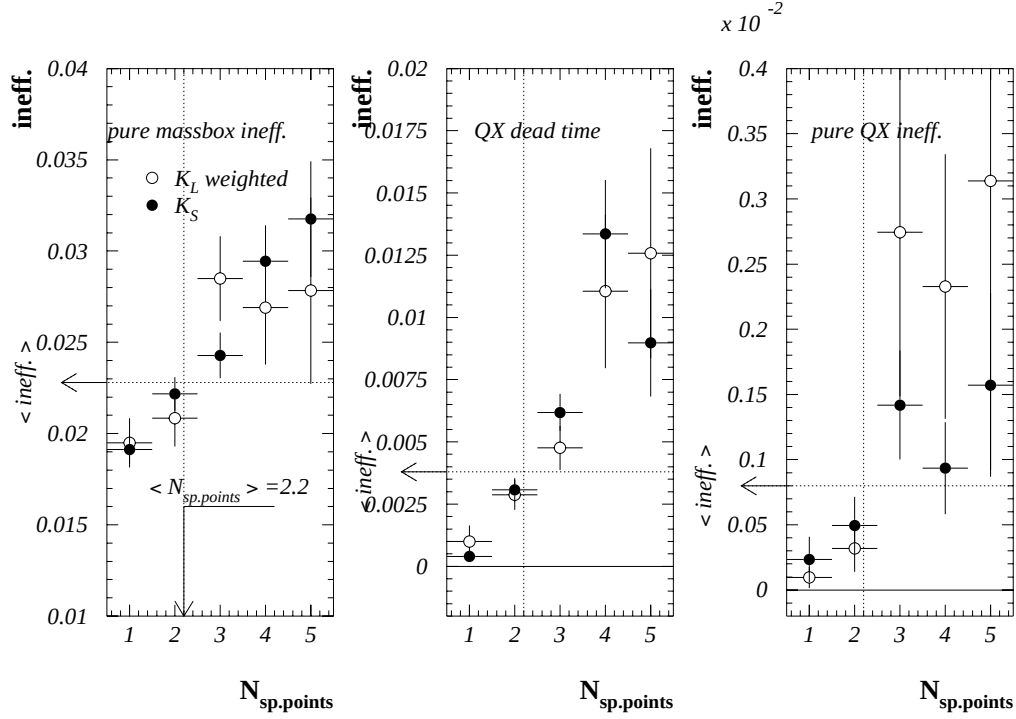


Figure 9.12: The leftmost figure shows the “pure Massbox” inefficiency as a function of the number of space points. A number $N_{sp.points}$ of space points in abscissa corresponds to the presence of at least $N_{sp.points} - 1$ accidental space points in the event, as explained in the text. The middle and the rightmost figures relate to the “QX dead time” and “pure QX” inefficiencies respectively. The full and hollow dots represent $K_{\pi\pi}^S$ and weighted $K_{\pi\pi}^L$ events respectively. The vertical dotted line in the figures is drawn in correspondence of the average number of space points for all the events in the control samples. The horizontal dotted line relates to the average inefficiencies measured in the control samples (see values reported in eqn. (9.15), (9.19) and (9.20)).

which is intensity related is $\frac{\Delta - \Delta(0)}{\Delta} \sim 15\%$, i.e. $\sim 0.3\%$ in absolute value¹⁶.

Notice that the data taken with the *KS-only* beam mode, show a $\sim 0.6\%$ smaller “pure Massbox” inefficiency than data in normal beam conditions: the difference between the two modes is mainly a large reduction of the accidental particle flux. The $\sim 0.6\%$, probably be due to accidental induced inefficiency, is in rough agreement with the above $\sim 0.3\%$ evaluation.

The mechanisms that generate the inefficiencies seem not to be able to distinguish between $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events. In particular for the accidental related part of the inefficiency, the difference between the $K_{\pi\pi}^S$ and the $K_{\pi\pi}^L$ can only arise from S/L different geometrical correlations between accidental and $K_{\pi^+\pi^-}$ tracks or from different beam intensity correlations.

Of course the differential geometrical correlation is reduced by the weighting procedure. On the other hand the compatibility of $\varepsilon_{\setminus L}$ and $\varepsilon_{\setminus L}^w$ points to a very low sensitivity to differential geometric effects. Figure 9.13 shows the distribution of the “pure Massbox” inefficiency for unweighted $K_{\pi\pi}^L$ and weighted $K_{\pi\pi}^L$ events in function of the $K_{\pi^+\pi^-}$ energy. A Kolmogorov test¹⁷ for the comparison between the two distributions test points to a compatibility within $90\%C.L.$ (the probability of having the same shape is $P_{k-test} \sim 99\%$).

In figure 9.14 the distribution of the Massbox inefficiency for the $K_{\pi\pi}^S$ and the

¹⁶Notice that the above $\lesssim 0.2\%$ contribution from the QX dead time is included here

¹⁷The Kolmogorov test is a very powerful statistical test of compatibility between two data distributions (later referred to as $\mathcal{D}_1$ and $\mathcal{D}_2$) as a function of a random variable x . To compare the data samples the maximum distance between the two cumulative distributions ($S_1(x)$, $S_2(x)$) is measured $D_{max} \equiv \max|S_1(x) - S_2(x)|$ over all x . Then a probability $P_{k-test}(D_{max})$ is given as a function of D_{max} set a confidence level (C.L.) for the distributions to be compatible. In particular the distributions are compatible with a $90\%C.L.$ if is it measured $1 - P_{k-test}(D_{max}) < 90\%$. In the case of the histograms compared in this chapter the probability $P_{k-test}(D_{max})$ given by the Kolmogorov distribution function (see [46, 99]) is not used, and the probability distribution functions is obtained with a Montecarlo as follows. The distribution $\mathcal{D}_1$ is used to built a similar distribution $\mathcal{D}'_1$ playing random contents for every bin considering the entries of $\mathcal{D}_1$ ruled by a binomial statistics (in case the histograms are inefficiencies) and taking properly into account the errors and the weights. A D_{max} is obtained. This is repeated for huge amount of times and the distribution of the maximum distances D_{max} yield the searched distribution function which is integrated to measurement the probability function P_{k-test}^1 . Using $\mathcal{D}_2$ the same procedure yields the probability function $P_{k-test}^2(D_{max})$. This is averaged with P_{k-test}^2 to give the final P_{k-test} , which is used as described above.

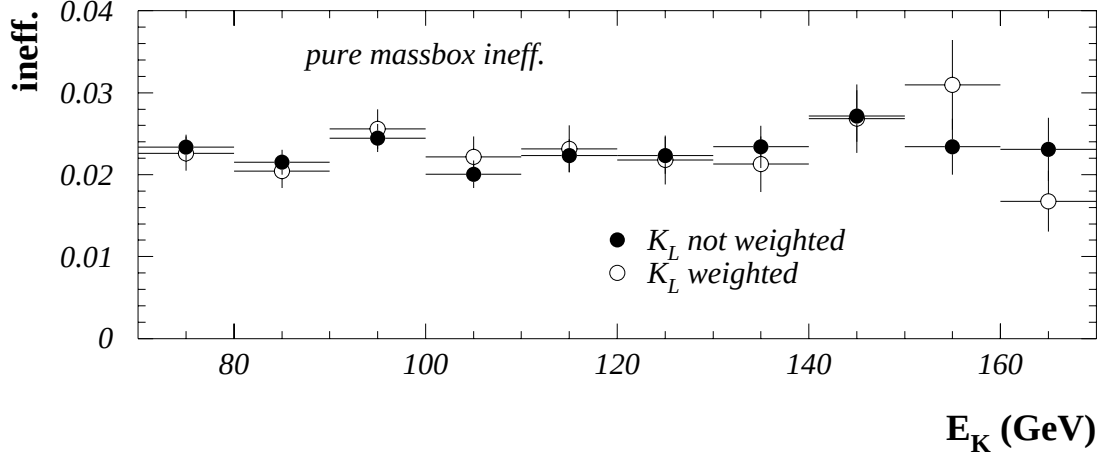


Figure 9.13: The “pure Massbox” inefficiency is shown for unweighted $K_{\pi\pi}^L$ (full dots) and weighted $K_{\pi\pi}^L$ (hollow dots) events as a function of the $K_{\pi^+\pi^-}$ energy. The weighting procedure reduces the differences in the geometrical correlations between accidental and $K_{\pi^+\pi^-}$ tracks. A Kolmogorov test points to a perfect compatibility of the two distributions, fairly within the 90% C.L.

weighted $K_{\pi\pi}^L$ events, as a function of the $K_{\pi^+\pi^-}$ energy, is shown. A Kolmogorov test for the comparison of the two distributions gives a probability of $P_{k-test} = 65\%$ for them to have the same shape, i.e. they are compatible within the 90% C.L.

In conclusion, within the statistical limits of the control sample, there seem not to be differences in energy spectra or geometry¹⁸ for the $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ inefficiencies greater than few units of 10^{-4} .

¹⁸It is possible to limit the effect due to differences in the geometric correlation between accidentals and respectively K_S and K_L selected events. As done in the case of the time variations of the intensity one can measure the spatial correlations:

$$\langle \rho_A \rho_{S,L} \rangle = 1/S \int_S dS \rho_A(r^2) \rho_{S,S}(r^2) \quad (9.18)$$

where ρ relates to the fraction of the accidental flux which depend on r^2 , i.e. one can write $I(r^2) = \langle I \rangle (1 + \rho(r^2))$. Notice that ρ here is equivalent to η in the study of the time dependent intensity correlations.

Once $\langle \rho_A \rho_{S,L} \rangle$ are measured they help in limiting the accidental geometric effect: if the difference $\langle \rho_A \rho_S - \rho_A \rho_L \rangle$ were negligible then there were no accidental geometrical effect on $\mathcal{R}$. In case that difference were not 0 then, given a model for the dependence of the losses on the position of the accidental, the correction on $\mathcal{R}$ could be estimated. An example of this kind of estimation is shown in Section 12.2.2 on page 274

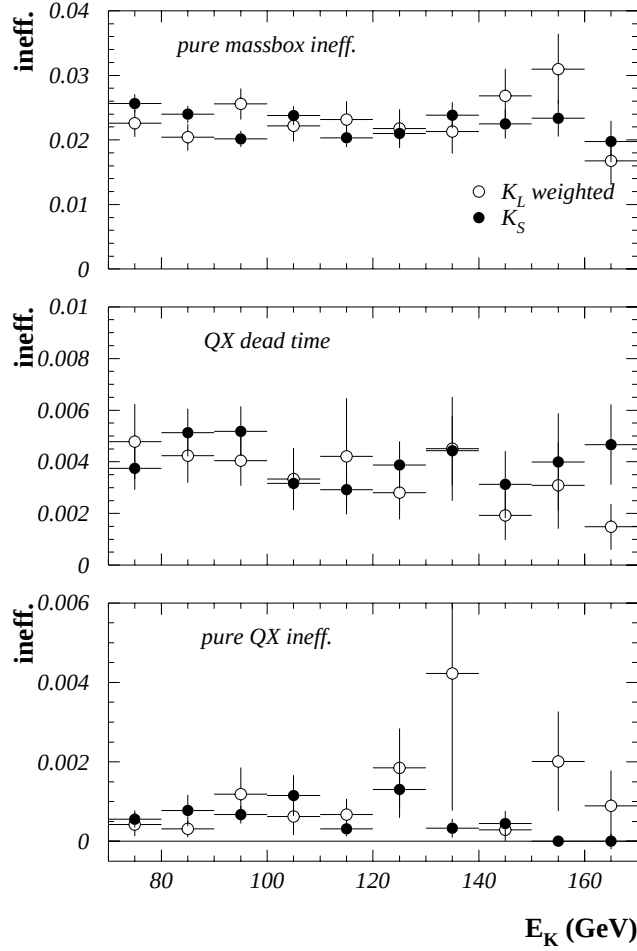


Figure 9.14: The figure on top shows the “pure Massbox” inefficiency for the $K_{\pi\pi}^S$ (full dots) and weighted $K_{\pi\pi}^L$ (hollow dots) events in function of the $K_{\pi+\pi-}$ energy. The middle and bottom figures show the “QX dead time” and “pure QX” inefficiencies respectively. The plots share the same horizontal axis, which has been drawn only on the bottom for convenience. A properly suited Kolmogorov test (see footnote^{#17}) points to a good compatibility of the $K_{\pi\pi}^S$ and weighted $K_{\pi\pi}^L$ distributions, fairly within the 90% C.L. in the all the three cases.

Differences of $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ inefficiencies, due to different intensity correlations, can be observed in the distribution of the inefficiencies as a function of the event time in the burst. Top figure 9.15 shows this dependence of the “pure Massbox” inefficiency $K_{\pi\pi}^S$ and weighted $K_{\pi\pi}^L$ events. As expected, the distributions are almost flat due to the fact that only $\sim 15\%$ of the inefficiency has an accidental intensity dependent origin.

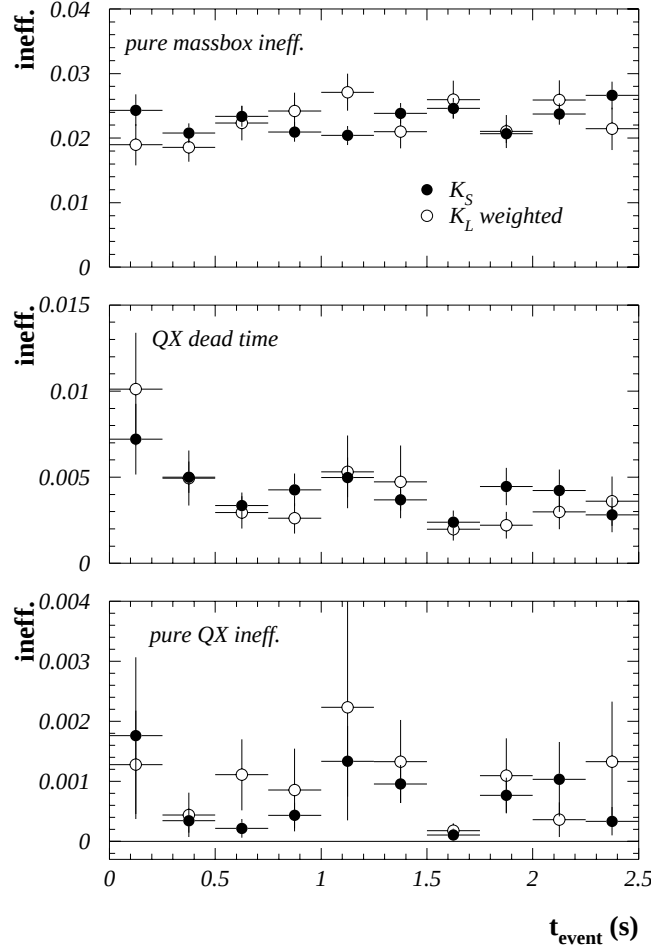


Figure 9.15: The figure on top shows the “pure Massbox” inefficiency for the $K_{\pi\pi}^S$ (full dots) and weighted $K_{\pi\pi}^L$ (hollow dots) events as a function of the event time in the burst. The middle and bottom figures show the “QX dead time” and “pure QX” inefficiencies respectively. The plots share the same horizontal axis, which has been drawn only on the bottom for convenience.

A Kolmogorov test for the comparison between the two distributions gives a probability $P_k = 80\%$ for them to have the same shape, i.e. they are well compatible

within the 90% *C.L.* Within the statistical limits of the control sample there are not differences in the “pure Massbox” inefficiencies for $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events. From the knowledge of the beam correlations difference (at the level of few percent relative difference) one expects that the fraction of the inefficiency with an accidental origin (see Section 9.1.1.2 on page 191) would also give $(\mathfrak{A}_S - \mathfrak{A}_L)/\mathfrak{A} \lesssim 1\%$, which correspond to a difference $\mathfrak{A}_S - \mathfrak{A}_L < 10^{-4}$ and is below our statistical sensitivity.

9.1.2.3 The “QX dead time” inefficiency

The “QX dead time”, previously introduced as *case ii*), accounts for an inefficiency of:

$$\begin{aligned}\mathfrak{A}_S &= (0.39 \pm 0.03)\% \\ \mathfrak{A}_L &= (0.38 \pm 0.04)\% \\ \mathfrak{A}_{L^w} &= (0.37 \pm 0.04)\% \end{aligned} \tag{9.19}$$

for K_S , unweighted and weighted K_L events respectively.

This kind of inefficiency has a clear accidental origin. The middle plot in figure 9.11 shows the very high inefficiency in case of extra tracks in the time interval $-60 \text{ ns} < t_{\text{accidental}} - t_{\text{event}} < -10 \text{ ns}$ before the event. The dependence on the number $N_{\text{sp.points}}$ of space points to a strong dependence on intensity, with a null the constant term $\mathfrak{A}(0) \sim 0$ (see middle plot in figure 9.12).

The middle plot in figure 9.15 shows the dependence of the “QX dead time” inefficiency for $K_{\pi\pi}^S$ and weighted $K_{\pi\pi}^L$ events as a function of the event time (t_{event}) in the burst time scale. The distributions show a strong dependence on the event time which agrees with the accidental origin of the effect. The distributions have a different shape from that related to the Massbox dead time (see figure 9.4). This is understood as the effect of different components of the beam time structure on the inefficiencies: as discussed in Section 9.1.1 on page 185, the Massbox dead time dependence on t_{event} is determined by the beam time structures with frequencies up to $\sim 100 \text{ kHz}$. The “QX dead time” inefficiency suffers the influence of a wider range of frequencies, up to $\sim 100 \text{ MHz}$. This is particularly clear at the beginning of the burst, where the beam fluctuations are very high, and the SPS time structure of $\sim 200 \text{ MHz}$ has a noticeable amplitude (see Chapter 8).

From the beam correlation studies, the difference in inefficiency for the $K_{\pi\pi}^S$ and

the $K_{\pi\pi}^L$ is expected to be of the order of $(\epsilon_s - \epsilon_L) < 10^{-4}$, as it is for the part of the “pure Massbox” inefficiency dependent on the intensity. On the other hand, a Kolmogorov test on the distributions of the middle plot in figure 9.15 gives a probability of $P_k = 70\%$ for them to have the same shape, i.e. allows them to be compatible at $90\% C.L.$

The conditions for the “QX dead time” inefficiency to occur are reproducible in the **neutral events**: this is due to the fact that a QX signal can never be present in two consecutive time-slots. This kind of inefficiency can be symmetrized in an unbiased way with **neutral events**, rejecting those events which have a QX in the time-slot before the trigger’s one: if they were charged $K_{\pi^+\pi^-}$ events they would not be triggered. Like in the case of the Massbox dead time, this is the most preferable way to treat the inefficiency. Indeed it copes both with possible biases in the measurement of the inefficiency made with charged events (e.g. the correlation with reconstruction inefficiency) and with the intensity balancing between **charged** and **neutral events**. It is also convenient from the point of view of the statistical errors, as already pointed out for the case of the Massbox dead time on page 192.

The “QX dead time” inefficiency in **neutral events** is $\sim 0.6\%$. This is explained by an “over-symmetrization” on neutral events: looking at figure 9.9 one recognizes that neutral events are rejected over the whole time-slot next to the QX time-slot, and not only in over the region ii). However this “over-symmetrization” is measured not to introduce biases.

9.1.2.4 The “pure QX” inefficiency

The inefficiency of *case iii*) introduced as “pure QX”, accounts for a small inefficiency:

$$\begin{aligned}\epsilon_s &= (0.07 \pm 0.01)\% \\ \epsilon_L &= (0.08 \pm 0.02)\% \\ \epsilon_{L^w} &= (0.09 \pm 0.03)\% \end{aligned} \tag{9.20}$$

for K_S , unweighted and weighted K_L events respectively.

The inefficient events of this kind are due to the tails of the QX dead time probability (see figure 9.7) in the range $t_{accidental} - t_{event} < -30$ ns: the figure 9.11 shows in the bottom the extra tracks dependence of the inefficiency. The events

which have no QX at all, are another source of inefficient events in this subsample.

The former case, which result in an intensity related inefficiency, is the dominant one. Figure 9.12 at the bottom shows the distribution of the inefficiency as a function of the number $N_{sp.points}$ of the space points in the drift chambers. The intensity related fraction of the inefficiency is estimated to be $> 90\%$. This can also be observed in the bottom figure 9.15 where the variations of the inefficiency as a function of the event time t_{event} in the burst are clear. A Kolmogorov test comparing the distributions of the “QX dead time” (in the middle of figure 9.15) and of the “pure QX” inefficiency (when normalized to the same inefficiency) give a probability of $P_k = 35\%$ for them to have the same shape, i.e. they are compatible within a $90\%C.L.$

Taking into account the previously mentioned results about the beam correlation, the differential $\mathcal{S}/\mathcal{L}$ effect is expected to be very small ($< 10^{-5}$).

9.1.3 Other inefficiency sources in the charged trigger system

The ETOT and 2TRK signals are used both in the trigger request ($QX \cdot ETOT \cdot 2TRK$) to the Massbox, in coincidence with the QX, and as a minimum bias triggers to measurement the QX and Massbox inefficiencies.

The 2TRK signal is a very wide (~ 150 ns) and efficient signal. By means of the same control sample used to measure the “pure ETOT” efficiency, the 2TRK signal is measured to be $> 99.99\%$ efficient, with no possible $\mathcal{S}/\mathcal{L}$ bias greater than $> 10^{-4}$ on the double ratio.

For the ETOT signal things are different. During the 1998 data taking ETOT introduced a $\sim 0.5\%$ inefficiency in the charged trigger because:

- i) Important tails are present in the resolution of the on-line energy measurement of the $K_{\pi^+\pi^-}$ event by the calorimeters. This results in an intrinsic inefficiency in the ETOT signal formation due to the presence of a threshold set at $E_{K_{\pi^+\pi^-}} > 35$ GeV. This inefficiency will be later referred to as “pure ETOT” inefficiency. It is expected to be only dependent on the topology of the selected $K_{\pi^+\pi^-}$ event and not on the rate.
- ii) A “saturation” bug in the ETOT Look-Up tables of the neutral trigger software (see [29]) was responsible for a $\sim \pm 20$ ns r.m.s. jitter of the ETOT signal with a

probability of $\sim 0.3\%$ for a jitter greater than 25 ns. In terms of the 25 ns wide time-slots, the bug was such that the ETOT signal could be found shifted from the $K_{\pi^+\pi^-}$ time-slot by ± 1 or ± 2 time-slots with a probability respectively of $\sim 30\%$ and $\sim 0.3\%$. Since the data taking in 1997, the time jitter forced to a widening, by ± 1 time-slot, of the ETOT signal, before the coincidence $\text{QX} \cdot \text{ETOT}$ is formed. Therefore just the ± 2 time-slots jitter which makes the coincidence $\text{QX} \cdot \text{ETOT}$ by $\sim 0.3\%$ inefficient is left out ¹⁹. This inefficiency will be later referred to as “ $\text{QX} \cdot \text{ETOT}$ coincidence” inefficiency. It is expected to be rate dependent: an accidental, whose energy signal overlaps with the $K_{\pi^+\pi^-}$ event, enhances the probability that the energy seen by the neutral trigger crosses the saturation threshold. Due to the mentioned bug a digitized signal amplitude, higher than the threshold, loses the most significant bit and is seen as a very low energy signal. Hence other time-slots nearby which have an energy just below the saturation threshold, become the energy maxima and result in a shifted ETOT trigger. The higher is the energy of the accidental or of the $K_{\pi^+\pi^-}$ event the more ETOT is shifted.

No unbiased symmetrization with neutral events is envisaged for either of the two inefficiencies, due to their dependence on the $K_{\pi^+\pi^-}$ event topology and energy. The double ratio is corrected for both inefficiencies, which are measured with the same method as the previously described inefficiencies. The measurement of the “pure ETOT” efficiency is done with the control events triggered by the QX, accepted by the Massbox and selected off-line with the standard ϵ'/ϵ criteria. In the selected sample the “pure ETOT” efficient events are those which have some ETOT signal recorded in the Pattern Units within ± 3 time-slots from the trigger. The measurement of the “ $\text{QX} \cdot \text{ETOT}$ coincidence” efficiency requires an ETOT signal within ± 1 time-slot from the trigger in the above control sample, in order to reproduce the ± 1 time-slot widening applied to ETOT before the coincidence with QX. The measurement of the “ $\text{QX} \cdot \text{ETOT}$ coincidence” efficiency can be performed also with the $\text{ETOT} \cdot 2\text{TRK}$ control trigger. In this case the selected events, which have a QX signal within ± 1 time-slot from the ETOT, are accepted as efficient. Table 9.2 shows the measured inefficiencies.

¹⁹The widening by more than 1 time-slot was excluded because in that case the ETOT rate would be increased and it would be useless in coincidence with QX, or even dangerous due possible coincidences with QX after-pulses

	“pure ETOT” inefficiency	“QX · ETOT coincidence” inefficiency
$\mathfrak{A}_S$	$(0.20 \pm 0.02)\%$	$(0.37 \pm 0.03)\%$
$\mathfrak{A}_L$	$(0.17 \pm 0.03)\%$	$(0.32 \pm 0.04)\%$
$\mathfrak{A}_{L^w}$	$(0.14 \pm 0.03)\%$	$(0.31 \pm 0.04)\%$

Table 9.2: The “pure ETOT” and “QX · ETOT coincidence” inefficiencies.

The results for K_S , unweighted and weighted K_L are compatible. Figure 9.16 shows the dependence of the “pure ETOT” (top) and “QX · ETOT coincidence” (bottom) inefficiencies on the off-line reconstructed $K_{\pi^+\pi^-}$ energy ²⁰.

The “pure ETOT” inefficiency shows a systematic tendency to be higher for K_S than for weighted K_L events. This is quantified by the Kolmogorov test, which yields a probability of 2% for them to be compatible and does not allow for their compatibility within the the 90%*C.L.*.

The “QX · ETOT coincidence” inefficiency is bigger for high energy events, as expected. K_S and weighted K_L events are compatible within the 90%*C.L.*

The different origin of the effects are seen in figures 9.17 and 9.18. The former shows the distribution of the “QX · ETOT coincidence” inefficiencies for K_S and weighted K_L events. In case of accidental tracks at more than two time-slots from the event ($|\Delta t| > 50$ ns) the coincidence between ETOT and QX becomes inefficient. No dependence from accidental tracks time is found in case of “pure ETOT”. Figure 9.18 shows the inefficiencies dependence on the number $N_{sp.points}$ of space points in the drift chambers. The “pure ETOT” inefficiency shows little or no dependence from the intensity, while the “QX · ETOT coincidence” losses are estimated to be intensity related at least for a 50% fraction.

9.1.4 Intensity effects: the inefficiencies and the accidental tagging difference

As noticed in Section 9.1.1.3 about the Massbox dead time, the rate dependence of the inefficiency results in a reduction of the (average) intensity of the triggered

²⁰In case of energy bins with 0 inefficient events the plotted error bars represent the upper limit equivalent to 0.38 events, which corresponds to a confidence level of 68%, i.e. to 1σ . Otherwise the errors are measured with the usual expressions given in footnote^{#11}

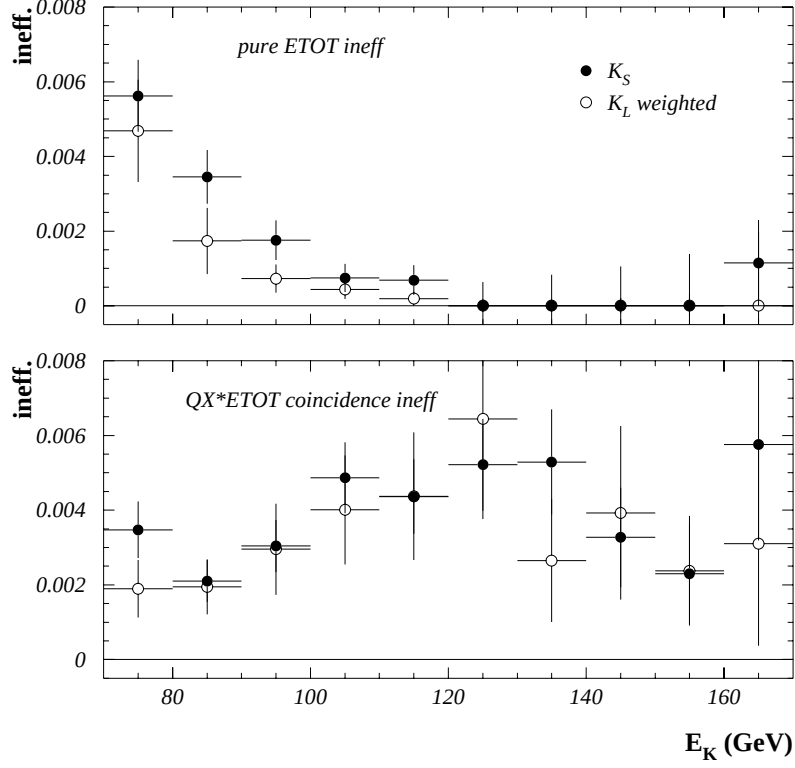


Figure 9.16: The figure on top shows the “pure ETOT” inefficiency for the $K_{\pi\pi}^S$ (full dots) and weighted $K_{\pi\pi}^L$ (hollow dots) events as function of the $K_{\pi^+\pi^-}$ energy. The bottom figure shows the “QX · ETOT coincidence” inefficiencies. In case of energy bins with 0 inefficient events the error bars represent the upper limit equivalent to 0.38 events which corresponds to the confidence level of 68%, i.e. to 1σ ; otherwise the errors are measured with the usual expressions given in footnote^{#11}. The plots share the same horizontal axis, which has been drawn only on the bottom for convenience.

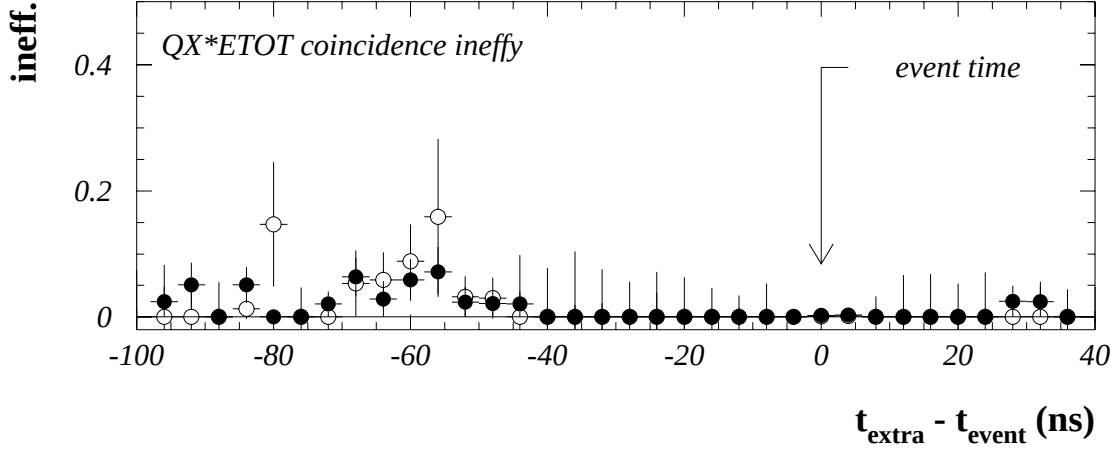


Figure 9.17: The “QX · ETOT coincidence” inefficiency as function of the distance of the accidental track time from the $K_{\pi^+\pi^-}$ decay time are shown for $K_{\pi\pi}^S$ (full dots) and weighted $K_{\pi\pi}^L$ (hollow dots) events. In case of energy bins with 0 inefficient events the error bars represent the upper limit equivalent to 0.38 events which corresponds to the confidence level of 68%, i.e. to 1σ ; otherwise the errors are measured with the usual expressions given in footnote^{#11}.

events. This induces a difference in intensity seen by the charged and the neutral events, and in particular leads to a correction to $\mathcal{R}$ from $\Delta\alpha_{LS} \neq 0$.

Following the same passages that led to eqn. (9.11) an estimate can be carried out for the effect of the charged trigger inefficiency on the accidental tagging.

In particular given an amount $\mathfrak{A}_K$ of inefficiency and the beam correlation term $\langle\eta_S\eta_A\rangle \sim 25\%$ (see Chapter 8) then the relative difference in accidental tagging, caused by this kind of inefficiency $\mathfrak{A}_K$ is:

$$(\overline{\alpha_{LS}} - \alpha_{LS})/\alpha_{LS} = \mathfrak{A}_K \cdot \frac{\langle\eta_S\eta_A\rangle}{1 + \langle\eta_S\eta_A\rangle} \quad (9.21)$$

where a linear dependence of the inefficiency on the intensity is supposed. The expr. (9.21) accounts only for the effect of the intensity dependent fraction of the inefficiency. In particular the “pure ETOT” inefficiency is not discussed because it was shown not to depend on the intensity. The resulting $\overline{\alpha_{LS}} - \alpha_{LS}$ (later referred to as the estimate with the correlation method) for the various sources of inefficiency is reported in table 9.3.

Due to the possibility of reproducing the “QX dead time” condition on neutral events, the accidental tagging probability reduction, caused by the “QX dead time”

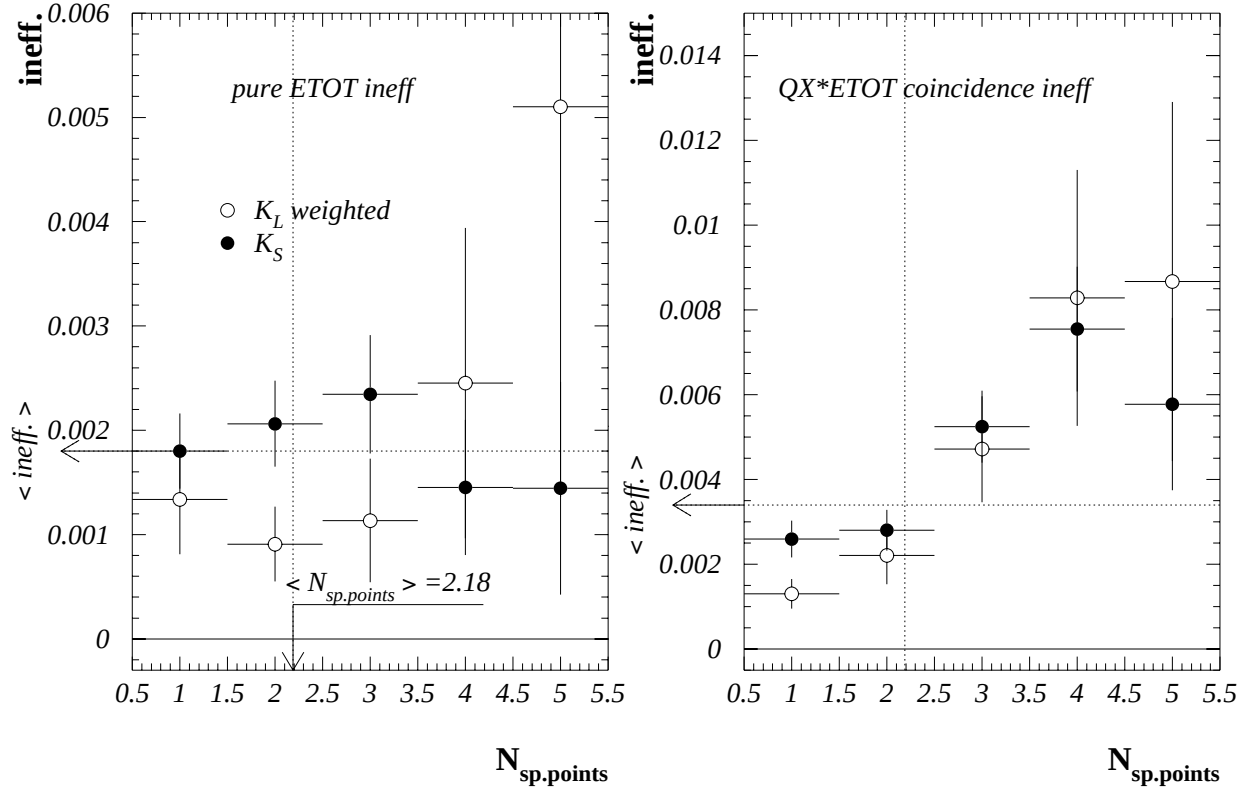


Figure 9.18: The figure to the left shows the “pure ETOT” inefficiency as function of the number of space points for the $K_{\pi\pi}^S$ (full dot) and weighted $K_{\pi\pi}^L$ (hollow dot) events. A $N_{\text{sp.points}}$ number of space points in abscissa corresponds to the presence of at least $N_{\text{sp.points}} - 1$ accidental space points in the event, as explained in the text. The figure to the right relate to the “QX · ETOT coincidence”. The vertical dotted line in the figures is drawn in correspondence of the average number of space points for all the events in the control samples. The horizontal dotted line relates to the average inefficiencies measured in the control samples (see table 9.2).

inefficiency	intensity related inefficiency	$\overline{\alpha_{LS}} - \alpha_{LS}$ with correlation method
“pure Massbox”	0.34%	$0.74 \cdot 10^{-4}$
“QX dead time”	0.38%	$0.84 \cdot 10^{-4}$
“pure QX”	0.07%	$0.16 \cdot 10^{-4}$
“QX · ETOT coincidence”	0.15%	$0.26 \cdot 10^{-4}$

Table 9.3: *The intensity dependence of the inefficiency results in a reduction $\overline{\alpha_{LS}} - \alpha_{LS}$ of the accidental tagging probability. The $\overline{\alpha_{LS}} - \alpha_{LS}$ estimated with the correlation method are shown here. “pure ETOT” inefficiency is not considered as it does not depend on intensity.*

inefficiency, can be measured with precision to be $\overline{\alpha_{LS}} - \alpha_{LS} = (1.5 \pm 0.3) \cdot 10^{-4}$ which is in rough agreement with the estimates in the table.

Unfortunately, the statistics of the control trigger sample used to measure the “pure Massbox”, “pure QX” and “QX · ETOT coincidence” inefficiencies does not allow to measure directly the accidental tagging probability reduction due to this kind of inefficiencies. Nevertheless an estimate is possible, which is based on the observation that the ϵ'/ϵ selected events with extra activity (i.e. accidental tracks or clusters in the read-out window) show an accidental tagging probability higher by $2.5 \cdot 10^{-4}$ with respect to events with no extra activity. If one assumes this to be the case also for inefficient events, then the accidental tagging probability reduction can be measured with the following method, later referred to as **extra activity method** (see [83]).

Let α_{LS}^x and α_{LS}^o be the accidental tagging probability for events with extra activity and with no extra activity respectively; then the above hypothesis is written as: $\alpha_{LS}^x - \alpha_{LS}^o = 2.5 \cdot 10^{-4}$. Let ε and $\aleph \equiv (1 - \varepsilon)$ be the efficiency and the inefficiency that are being studied. Let be P_{all}^x , P^x and $\mathcal{P}^x$ be the probabilities to find some extra activity for all the events, efficient events, and inefficient events respectively. The accidental tagging probability for all events can be written as:

$$\overline{\alpha_{LS}} = P_{all}^x \alpha_{LS}^x + (1 - P_{all}^x) \alpha_{LS}^o = (\alpha_{LS}^x - \alpha_{LS}^o) P_{all}^x + \alpha_{LS}^o \quad (9.22)$$

and for the accidental tagging probability for the efficient events:

$$\alpha_{LS} = P^x \alpha_{LS}^x + (1 - P^x) \alpha_{LS}^o = (\alpha_{LS}^x - \alpha_{LS}^o) P^x + \alpha_{LS}^o \quad (9.23)$$

The reduction for the accidental tagging probability is then:

$$\overline{\alpha_{LS}} - \alpha_{LS} = (\alpha_{LS}^x - \alpha_{LS}^o)(P_{all}^x - P^x) \quad (9.24)$$

where the term $(P_{all}^x - P^x)$ can be written as function of P_{all}^x and $\mathcal{R}^x$ as $(\mathcal{R}^x - P_{all}^x)(1 - \varepsilon)/\varepsilon$. Finally this gives:

$$\overline{\alpha_{LS}} - \alpha_{LS} = (\alpha_{LS}^x - \alpha_{LS}^o)(\mathcal{R}^x - P_{all}^x) \frac{(1 - \varepsilon)}{\varepsilon} \quad (9.25)$$

The measured values for $\varepsilon, \mathcal{R}^x, P_{all}^x$ and the resulting $\overline{\alpha_{LS}} - \alpha_{LS}$ are shown in table 9.4.

	ε	P_{all}^x	$\mathcal{R}^x$	$\overline{\alpha_{LS}} - \alpha_{LS}$
“pure Massbox”	97.72%	6.0%	11.9%	$0.34 \cdot 10^{-4}$
“QX dead time”	99.62%	6.2%	80.0%	$0.70 \cdot 10^{-4}$
“pure QX”	99.92%	5.8%	58.8%	$0.11 \cdot 10^{-4}$
“QX · ETOT coincidence”	99.65%	5.6%	36.1%	$0.26 \cdot 10^{-4}$

Table 9.4: The accidental tagging probability reduction $(\overline{\alpha_{LS}} - \alpha_{LS})$ induced by various charged trigger inefficiency sources. The estimate for $\overline{\alpha_{LS}} - \alpha_{LS}$ is obtained with the method described in the text from the measured values of the efficiencies (ε), the probabilities to find extra activity in all the events (P_{all}^x) and in inefficiency events ($\mathcal{R}^x$).

The results in tables 9.3 and 9.4 are in agreement. In particular the $\overline{\alpha_{LS}} - \alpha_{LS}$ values which relate to pure intensity dependent losses (i.e. “QX dead time” and “pure QX”) are in good agreement.

The overall intensity balance obtained by the Massbox dead time (see Section 9.1.1.3) and the “QX dead time” inefficiency symmetrization is then $\sim 8 \cdot 10^{-4}$.

The charged trigger inefficiencies from which no unbiased symmetrization is possible (i.e. “pure Massbox”, “pure QX” and “QX · ETOT coincidence”) are expected to introduce a residual accidental tagging difference of $\Delta\alpha_{LS} \lesssim 1 \cdot 10^{-4}$.

9.2 Neutral trigger effects

The neutral trigger is an actual pipe-lined trigger and it results to be dead time free and very efficient.

The neutral trigger efficiency is measured with a control sample of events triggered by the T0N signal that is delivered by the neutral hodoscope (see

Sections 2.3.4 on page 59 and 3.3.1.1 on page 65) independently of the $K_{\pi^0\pi^0}$ main trigger. The $K_{\pi^0\pi^0}$ **neutral events** are selected with the standard ϵ'/ϵ criteria, the **overflow**, the Massbox dead time and the “QX dead time” **symmetrizations** included. Among the events in the sample, those which have not the $K_{\pi^0\pi^0}$ main trigger within ± 2 time-slots from the T0N trigger’s one are the inefficiencies. The measured inefficiencies are:

$$\begin{aligned}\mathfrak{A}_S &= (0.06 \pm 0.02)\% \\ \mathfrak{A}_L &= (0.11 \pm 0.04)\% \\ \mathfrak{A}_{L^w} &= (0.11 \pm 0.05)\% \end{aligned} \tag{9.26}$$

for K_S , unweighted and weighted K_L events respectively. They are compatible within the statistical errors.

The source of those $\lesssim 10^{-3}$ losses have an accidental nature [76] mainly due to high energy protons from Λ decays in coincidence within 6.25 ns (i.e. the width of the neutral fine-time time-slot) with the $K_{\pi^0\pi^0}$ event. Given a few percent relative difference (see Section 9.1.1.2 on page 191) $\frac{\langle\eta_A\eta_S\rangle - \langle\eta_A\eta_L\rangle}{1 + \langle\eta_A\eta_L\rangle} \lesssim 1\%$ of the beam correlation, then the expected value for the K_S and K_L inefficiency difference is $\mathfrak{A}_S - \mathfrak{A}_L \sim \frac{\langle\eta_A\eta_S\rangle - \langle\eta_A\eta_L\rangle}{1 + \langle\eta_A\eta_L\rangle} \cdot \mathfrak{A} < 10^{-4}$ which points to the negligible effect of the neutral trigger on $\mathcal{R}$. For this reason a correction is not applied on $\mathcal{R}$ and an error of $10\% \times \mathfrak{A} \sim 1 \cdot 10^{-4}$ is included in the error $\sigma_{\mathcal{R}}$ on $\mathcal{R}$. Notice that $\frac{\langle\eta_A\eta_S\rangle - \langle\eta_A\eta_L\rangle}{1 + \langle\eta_A\eta_L\rangle} \ll 10\%$ so that the contribution on the $\sigma_{\mathcal{R}}$ error evaluation is very conservative.

Conclusions

The charged trigger inefficiencies amount to $\lesssim 5\%$ overall. Part of them allow for an unbiased **symmetrization** with $K_{\pi^0\pi^0}$ **neutral events**. This yields in particular:

- the measured $\mathcal{R}$ has an implicit correction which is not biased by correlations between the charged trigger inefficiencies and other $K_{\pi^+\pi^-}$ **charged events** losses (e.g. **overflow** and reconstruction). On the contrary the correction with the charged control sample would be biased by those correlations.
- a better balancing of the KL beam intensity seen by $K_{\pi^0\pi^0}$ and $K_{\pi^+\pi^-}$ (**N/C intensity balance**). This results in a correct balance of the K_S and K_L intensity correlations with the accidentals intensity which is mandatory for

the **symmetrization** of other effects. Moreover the **N/C intensity balance** results in a smaller (by 10 parts in 10^4) accidental tagging probability difference $\Delta\alpha_{LS}$. In particular the fraction of $\Delta\alpha_{LS}$ which is induced by charged trigger losses jumps from $\sim 10^3$ to 10^4 , the latter being an upper limit for the residual trigger effect on accidental tagging.

- almost half of the charged trigger inefficiency is left to be measured with the same sample of control events. This results in a factor $\sim \sqrt{2}$ gain in the statistical error measurement of inefficiency.

The residual charged trigger inefficiency ($\lesssim 3\%$) comes mostly from the Massbox whose losses are 2.3%. Only 15% of them seems to have an accidental, intensity dependent origin. The correction for the Massbox inefficiency is applied independently in energy bins to $\mathcal{R}$, and yield through the logarithmic estimator an average of $(-4.0 \pm 10.3) \cdot 10^4$.

The inefficiency of ETOT and its coincidence with QX, is dependent on intensity for 20% fraction of the sum of the two (0.5%). It yield a correction to $\mathcal{R}$ of $(+6.8 \pm 5.4) \cdot 10^4$.

The residual QX inefficiency amounts to $0.08 \pm 0.02\%$ on average. The effect is fully accidental and intensity dependent and it is possible, from the beam studies measurements, establish that it should yield a K_S to K_L differential effect on $\mathcal{R}$ by $\lesssim 10^{-5}$. Then $\mathcal{R}$ is not corrected for it and only an error of $10\% \cdot \mathfrak{A} = 10^4$, which is very conservative, is added to the error on $\mathcal{R}$.

In conclusion the charged trigger correction to $\mathcal{R}$ is $(+2.8 \pm 11.6) \cdot 10^4$.

The neutral trigger results to be very efficient ($\mathfrak{A} \lesssim 10^{-3}$). Its effect on the double ratio measurement is to introduce no correction $\mathcal{R}$ and an error $\sigma_{\mathcal{R}}$ of $1 \cdot 10^{-4}$.

10 Rate effects on the reconstruction

Overview

The reconstruction of the charged mode is affected by the overflow, and this is the main effect of rate on the reconstruction. In this chapter a summary about the effect of the overflow on the double ratio is presented.

10.1 The dead time of the Wire Chambers readout

The reconstruction algorithm for the $\pi^+\pi^-$ events is robust against the presence of additional hits in the chambers; on the other hand it is sensitive to the lack of information caused by the overflow (see Section 2.3.1 on page 44). An overflow condition occurs, in a drift chamber plane, when there are more than 8 hits in a single plane, within 100 ns. In this case the Memory Ring buffer is reset, and information about the activity in that drift chamber plane are lost. An additional word is added to the data by the TDC card in order to record the overflow occurrence. For each plane the two overflow signals, which are closest to the event time, one before and the other after the event, are recorded in C**Om**PACT data.

The effect of this readout reset is equivalent to a partial dead-time for both the on-line and the off-line reconstruction, and might result in misreconstruction of tracks and vertices, and yield loss of events in the charged decay mode. While the inefficiency of the charged trigger can be measured with accuracy using the control triggers, on the contrary the effects of the overflows on the event reconstruction is not so easy to be measured; the more, because the intensity related effects are not easily simulated via Monte Carlo.

Nevertheless, the effect should be similar for $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events, and hence cancel in the double ratio. An additional cancellation is achieved by rejecting also the neutral events with the overflow condition set (**symmetrization**). Thus, any charged or neutral event which have a overflow within ± 312.5 ns of the event time is rejected from the analysis.

It is remarkable that the **symmetrization** equalize the intensities of the neutral and charged events, which allow to keep the mistagging correction $\Delta\alpha_{LS}$ at a low level.

The effects residual from non cancellation must anyway be understood and

measured, both for charged and neutral events. It is important to check that neutral events, do not introduce biases (see [74,102]), due to processes, which generate overflow only in neutral mode, and not in charged.

10.1.1 Some phenomenology of the overflows

The main source of the overflows are thought to be high multiplicity events developing along the KL beam line [30].

Table 10.1 shows the overflow probability measured with random events, in normal (central column) and *KS-only* (right column) beam operation mode, and with various requirements on the extra-activity recorded in the event. It is derived from table 7.3 on page 151 (see Chapter 7 for the notation).

randomtype	normal beam mode	<i>KS-only</i> mode
all events	24.3%	$4.1 \pm 0.1\%$
CLU	55.7%	$56 \pm 6\%$
CLU·PRO	61.7%	$72 \pm 7\%$
CLU·PRO·AKS	79.3%	$78 \pm 7\%$
CLU· $\overline{\text{PRO}}$ ·AKS	54.9%	$29 \pm 9\%$

Table 10.1: *The probability of ≥ 1 OVFL in the interval $[-312.5 \div 312.5]$ ns centered on the event time for various types of accidental events (derived from table 7.3).*

It is remarkable that given a probability of 30% of having a CLU in $[-312.5 \div 312.5]$ ns (from table 7.3 where the amount of events in a 80 ns interval are shown) and an enhanced probability of $\sim 55\%$ to have ≥ 1 overflow, one can measure the probability for an overflow to be related to some accidental activity. This is $\mathcal{P}_{\text{AOVFL}} \sim 0.30 \cdot 0.55 \sim 17\%$, out of the overall 24%.

The overflow probability related to KS accidental activity is measured likewise, at the level of 0.5%. This is in agreement with the results of the High Intensity *KS-only* data taken in 1999 [95]. In that occasion, data were taken with a intensity on the KS target 200 times larger the typical one ($3 \cdot 10^7$ ppp). Under these conditions the OVFL probability is measured to be $\sim 30\%$ with scales to 0.15% for typical proton intensity. In order to compare this result with the previous one, it should be noticed that the 1999 High Intensity run was set up without the AKS crystal converter, which explains the difference of the two probabilities, 0.5% and 0.15%.

It turns out that both in normal beam mode, and in *KS-only* mode, a fraction of the overflow probability ($\sim 7\%$), is not accidental related. In the *KS-only* beam mode, this is the bulk of the overflow probability.

This is understood by the observation that some of the drift chamber planes have a significantly higher fraction of overflow than others. This is due to an high level of noise for some wires. By accepting the events with have overflows on those planes, the probability drops of $\sim 5\%$, which is in agreement with the above estimates.

10.1.2 The effects of the overflows on the selected events

Figure 10.1 shows the time of an overflow condition with respect to the trigger time for $K_{\pi^+\pi^-}$ and $K_{\pi^0\pi^0}$ events. In the distribution for the charged mode there is a reduction of the number of events in the interval $[-300 \div +300]$ ns. This is due to events that cannot be reconstructed, since information has been lost due to the memory reset. Since the reconstruction of neutral event does not use information from the drift chambers, there is not similar loss of events around the time of an overflow for neutral decays. Both distributions show a peak around zero, due to the finite length (~ 200 ns) of the overflow signal.

Table 10.2 shows the overflow probability for different kind of events. The higher probability for K_S events is due to the higher beam intensity which the K_S events experience on average.

Random events measure the pure overflow probability. Unfortunately, due to some problems with the data taking for random events, they do not represent faithfully the intensity conditions of the selected $K_{\pi\pi}$ events; the effect is worse for K_L random events, whose intensity is $\sim 9\%$ less than the selected K_L events. Random events of K_S type show, on average, an intensity drop of $\sim 2\%$, with respect to the selected events, and they can be used as a reference in analysis.

Neutral events should experience almost the same overflow probability as random events. A small enhancement can be expected, due to the presence of the $\pi^0\pi^0$ photons, which can produce charged tracks across the spectrometer, trough Dalitz decays or photon conversions. Charged tracks result in a greater number of hits in the chambers wire planes; in other words, the overflow threshold of 8 hits per plane drops to a smaller value, and the overflow probability is enhanced. From comparison between random and neutral K_S events in the table, this enhancement seems to be

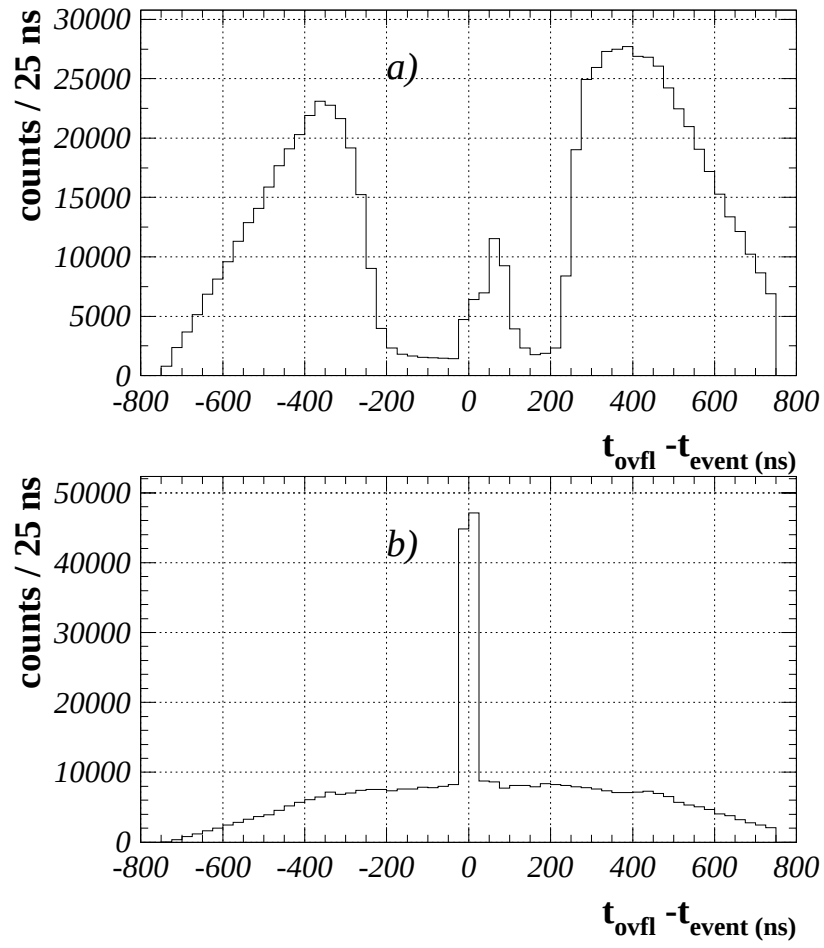


Figure 10.1: *Distribution of the overflow time, for charged (a) and neutral (b) events.*

at level of 0.6%, for neutral events.

This enhancement is expected to yield an even more sizeable effect on charged events: due to the presence of the two charged pion tracks, the effective overflow threshold is 6 hits per chamber plane.

Charged events suffer overflows, first through the trigger (MBOX), which is only $\sim 52\%$ efficient for events with overflow. For the events of the charged trigger control sample (i.e. events with no MBOX trigger required, see table 3.1 on page 71) the overflow probability is still below the level measured with K_S random events. This is understood as an inefficiency of reconstruction and selection. The problem is then to understand the true level of the overflow probability in charged events, independently of the reconstruction. Due to the lower effective threshold, it is expected to be higher than for random and neutral events.

randomtype	Random	Neutral	Charged	Charged control trigger
K_S	24.26 ± 0.03	24.85 ± 0.01	16.38 ± 0.01	23.4 ± 0.1
K_L	24.14 ± 0.03	24.20 ± 0.04	16.20 ± 0.01	23.2 ± 0.3

Table 10.2: Overflow probabilities for various kind of events.

The effect involves not only accidental activity (“uncorrelated” overflows), but also $K_{\pi\pi}$ decay related activity (“correlated” overflows) in the detector. Thus the information from sideband, more than 100 ns^1 far from the event time, gives only a fraction of the true overflow probability for charged events.

The problem was recently addressed with the overlay procedure, (see Section 6.2.5), and in a more general context, the preliminary results are discussed in Section 12.1.3.1. It is found that for neutral events the enhancement of the overflows probability (with respect to the probability for the overflows uncorrelated to the event) is at the level of $0.6 \pm 0.1\%$, which confirms the above estimation. For charged events the enhancement is $1.6 \pm 0.1\%$. This sets the true overflow probability at the level of $\sim 26\%$. Then the reconstruction and selection efficiency for the events with overflow is $\lesssim 85\%$.

Table 10.3, shows the probabilities of overflow for different kinds of events, measured with the K_S -only beam mode. The bulk of the 4% probability for neutral and random events may be explained by noisy wires. The higher overflow probability

¹Overflow integration time.

measured for the charged control trigger events (absolute $\sim 5\%$ enhancement with respect to overflow probability for neutral events), may be due to reconstruction inefficiency, related to the overflow. A similar absolute $\sim 5\%$ enhancement is measured on K_S random events, in normal beam mode, after requiring at least 1 reconstructed vertex in the event (this requirement simulates roughly the $\pi^+\pi^-$ event). This corroborates the hypothesis of low reconstruction efficiency resulting from overflows “correlated” to the event.

randomtype	Random	Neutral	Charged	Charged control trigger
K_S	4.1 ± 0.1	4.4 ± 0.04	6.4 ± 0.05	9.1 ± 0.1

Table 10.3: *Overflow probabilities for varios kind of events with K_S -only beam mode*

Thus the true overflow probability for charged events is estimated to be $\sim 31\%$, and the reconstruction and selection efficiency for events with overflow is $\sim 54\%$.

Conclusions

Despite some features of the overflow effect, which have still to be investigated, one may conclude that the rejection of the overflow in charged events, avoid effects from K_S and K_L differences on the trigger, and on the reconstruction and selection efficiencies ($\sim 52\%$ and $\sim 54\%$ respectively, in case of overflow). Those effects may be sizeable, due to the high degree of inefficiency, and cannot measured with accuracy. Thus if charged events with overflows were not rejected, the double ratio $\mathcal{R}$ would be affected by a huge uncertainty.

Concerning the rejection of the overflows also for neutral events (symmetrization), it helps to equalize the losses suffered by charged events. Furthermore, it balances the instantaneous intensities of neutral and charged events. Thus, not only the losses caused by overflow, but also any other rate effect (related to the difference between neutral to charged losses) is much reduced. For instance, the difference of charged and neutral accidental tagging probability ($\Delta\alpha_{LS}$) drops, due to the symmetrization, from $\sim 30 \cdot 10^{-4}$ to few 10^{-4} .

11 Effects of the in time accidentals on the double ratio $\mathcal{R}$

Overview

The accidental particles produced by the same proton which generated the $K_{\pi\pi}$ require dedicated studies. This kind of in time is particularly dangerous for $K_{\pi\pi}^S$: the KS beam target and dump are much closer to the detector than in the case of the KL beam; besides the collimator and the magnetic field rejection is less effective.

Only the in time activity in the tagger might affect $K_{\pi\pi}^L$ events: if it result in proton-like signals, then an enhancement of the mistagging probability in coincidence with the event is produced, which is not seen in the tagger sidebands. However the measurement of W_{LS} should cope with similar effects.

11.1 The in time accidentals in the KS beam are measured using the sample of selected events

To study the in time background effects on $K_{\pi\pi}^S$ events, the used standard method [57] consists in selecting kaon to $\pi^0\pi^0$ decays collected in *KS-only* beam mode, and analyzing the features of the additional energy clusters in the electromagnetic calorimeter.

The *KS-only* beam mode data are used, because of their negligible ($< 0.5 \cdot 10^{-4}$) contributions from uncorrelated accidental activity and from the K_L component in the KS, which decays into $3\pi^0$.

The events are first selected with all the ϵ'/ϵ analysis requirements, but the in-time extra cluster rejection (anti- $3\pi^0$ cut). Then an extra clusters are selected, with energy $> 1.5\text{ GeV}$ in the calorimeter and with time no more than $\pm 3\text{ ns}$ of the event time. In this sample one expects to find both the genuine in time clusters and those clusters due to photon conversions or π^0 Dalitz decays. These two contributions are finally separated by use of the χ_{relli}^2 (see eqn. 4.5 on page 78) distribution: good $\pi^0\pi^0$ events with or without an additional in time cluster should have the same χ_{relli}^2 distribution¹. On the contrary $\pi^0\pi^0$ events, which undergo

¹The underlying assumption here is that possible kinematical correlations between the $\pi^0\pi^0$ phtons and the additional one do not result in a deformed χ_{relli}^2 distribution.

photon conversions or π^0 Dalitz decays, do present a biased χ^2_{reli} distribution.

The fraction of in time is then estimated as follows: different Monte Carlo samples are produced, with variable amount of in time clusters, while keeping fixed the amount of photon conversions and π^0 Dalitz decays. For each sample, the ratio of the χ^2_{reli} distributions of the Monte Carlo sample and the data sample is tested against a constant hypothesis. The Monte Carlo sample which results in the best ratio points to a fraction of in time well below 10^{-4} .

11.2 The accidentals in *S-only* beam operation mode are studied using the sample of random events

A cross-check is presented of the previous method, which may help the study the in time background. The sample of random events is used. Even though random events record by definition the uncorrelated activity around a good event, they could also provide a rough estimate for the amount of in time activity in KS beam. By tagging the protons in the KS line, and studying the clusters in the electromagnetic calorimeter in coincidence with the protons one simulates the instantaneous intensity conditions for a good K_S decay. Of course this not the same as measuring the genuine activity correlated to the K_S decay events, but it should not differ by orders of magnitude.

The sample of random events taken in *S-only* beam operation mode is used, in order to reduce the amount of accidentals from KL beam. A similar analysis, as was discussed in Section 7.3 on page 149, is repeated. Accidental clusters (CLU), protons (PRO), and AKS hits (AKS) are defined there.

Table 11.1 shows the selected numbers of accidentals in the 80 ns wide time interval $[-30 \div 50]$ ns. The condition of no OVFL in the time window $[-312.5 \div 312.5]$ ns around the accidental time is considered as well.

The measurement of the fraction $f_S^{S\text{-only}}$ of accidentals from KS beam in *S-only* mode, carried out similarly to Section 7.3, is shown in table 11.2. In this case, the average number of protons in 4 ns window is lower of $\sim 10\%$ than in table 7.4. This is due to the absence of the KL beam which contributes for a 10% to the rates of counts in the tagger (see Section 4.3 on page 85).

Notice that, despite the *S-only* beam operation mode, half of the activity comes from the KL line. Some residual degree of activity is expected due to muons from

KL target station and residual background (see *BKG* in Section 7.1 on page 141), which is not dumped in the KL line.

The probability for a proton to produce activity in the KS target and downstream of the KS collimators is at $\sim 1 \cdot 10^{-3}$ level (see *PRO · AKS* in table 11.1); this is in good agreement with the estimate in Section 7.3. The degree of the background in AKS ($\sim 6\%$), i.e. the fraction of AKS hits without proton coincidence, is also in agreement with the previously measured AKS rates (see AKS lower threshold rates in table 7.2 and $\overline{\text{PRO}} \cdot \text{AKS}$ in table 7.3).

	OVFL acc.	OVFL rej.
all events	38194	36646
CLU	71	30
CLU·PRO	47	13
CLU·PRO·AKS	40	9
PRO	76044	72307
AKS	118	75
PRO·AKS	111	69

Table 11.1: The number of all events, of LKR-accidentals and their coincidences (as usual within 4 ns) with protons and AKS hits are shown; these data are taken with KS-only beam mode. The number of protons, AKS hits and PRO·AKS are also shown.

The number of expected KS accidentals is in rough agreement with CLU·PRO·AKS from table 11.1. The average probability of CLU·PRO·AKS (OVFL accepted) per event per ns is $(1.31 \pm 0.21) \cdot 10^{-5}$ which is in fair agreement with the measurement in Section 7.3. This result increases the confidence on the measurement of the ratio between the number of accidentals in KS and KL beam.

The 7 KS accidentals not detected by the AKS (i.e. with signature $\text{CLU} \cdot \text{PRO} \cdot$

	OVFL acc.	OVFL rej.
$\mu_S(t = 10)$ (%)	12.79 ± 0.55	12.60 ± 0.55
$f_S^{S\text{-only}}$ (%)	49 ± 7	34 ± 9
expected K_S accid. (evts)	35 ± 7	10 ± 4

Table 11.2: The measured average number of proton-proton delayed coincidences $\mu_S(t = 10)$, is needed to obtain the fraction $f_S^{S\text{-only}}$ of CLU accidentals in the beam from Eqn. 7.5. The expected number of CLU produced by KS accidentals is shown.

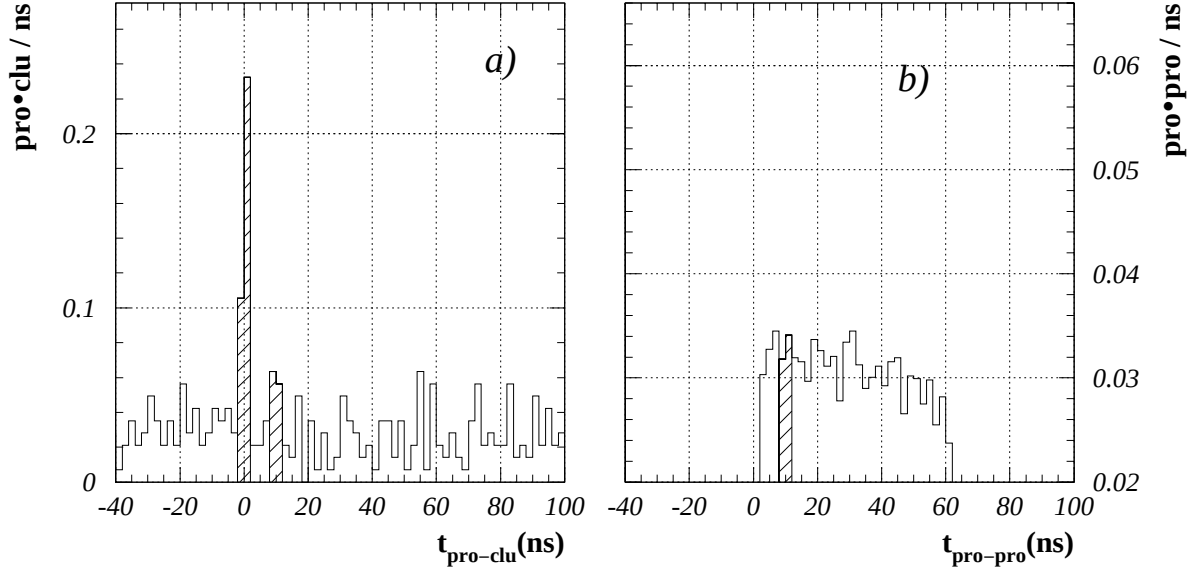


Figure 11.1: a) shows the distribution of time differences ($t_{\text{PRO-CLU}}$) between accidental clusters in a wide time window and protons in the interval $[-30 \div 50]$ ns. It is normalized to the number CLU in the same interval. Figure b) shows the distribution of time differences ($t_{\text{PRO-PRO}}$) between all protons in a wide interval (with $t > 0$) and the protons in the window $[-2 \div 2]$ ns. The difference of the integrals of a) over $[-2 \div 2]$ ns (shaded) and over $[8 \div 12]$ ns (shaded) gives the fraction of K_S accidentals f_S times $(1 - \mu_S(t = 10))$ that is the mean number of protons in a 10 ns delayed coincidence, measured in b) as the integral around $[8 \div 12]$ ns. Notice the modulations of period 5 ns (200 MHz) and 10 ns (100 MHz) typical of the time structure of the beams.

$\overline{\text{AKS}}$) are compatible with the $47 \cdot \alpha_S \sim 5$ events expected as random $\text{CLU} \cdot \text{PRO}$ coincidences. These $\text{CLU} \cdot \text{PRO} \cdot \overline{\text{AKS}}$ accidentals can be quite dangerous in case they were correlated to the K_S decays, At a closer inspection none of them includes a K_S decay, and they seem to be just uncorrelated background from K_S beam. The study has to be continued with more statistics, in order to investigate about possible correlations of those events with K_S decays.

all events	$4.1 \pm 0.1\%$
CLU	$56 \pm 6\%$
CLU·PRO	$72 \pm 7\%$
CLU·PRO·AKS	$78 \pm 7\%$
CLU· $\overline{\text{PRO}} \cdot \overline{\text{AKS}}$	$29 \pm 9\%$

Table 11.3: *The OVFL probability for different type of accidentals (from table 11.1)*

Notice (table 11.3) that accidentals from **KS** beam have very high ($\sim 80\%$) probability of **overflow**, which is in good agreement with the analysis of Section 7.3 on page 149. Moreover the absolute probability of OVFL (in a window of $[-312.5 \div 312.5]$ ns) for a **KS** LKR accidental of 0.6% fits with the value previously measured; the probability for a LKR accidental from **KL** is here at the 0.2% level. The residual $\sim 3\%$ of the overall (4%) OVFL probability is explained by noise in the chambers.

Finally notice the importance of the AKS in-time hits rejection. Besides the aim to define precisely the fiducial decay region for neutral $K_{\pi\pi}$ decays it pushes to a pointless level the in time accidental activity, which is much critical due to the high **overflow** probability.

Conclusions

The accidental activity correlated to the K_S events is studied and measured to be less than 10^{-4} . Thus, it does not affect the double ratio $\mathcal{R}$.

12 Effects of the uncorrelated accidentals on the double ratio $\mathcal{R}$

Overview

The effects of the accidentals on the reconstruction, and selection, of the $K_{\pi^+\pi^-}$ and $K_{\pi^0\pi^0}$ decays are studied.

It was brought up, in Section 6.1.2 on page 123, that the accidental effects are distinguished in two classes, depending on their origin:

- The $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ decays see slightly different fluxes of accidental particles¹. Then, even if the probability of losing an event is exactly the same for K_S and K_L , this results in the bias on $\mathcal{R}$ expressed in eqn. (6.11). This kind of effects are referred to as **purely intensity accidental effects**.
- On the other hand, any difference in the detector illumination by the KS and KL beams, and any difference in the acceptance of the selection criteria, would result in small differences between the fraction of losses induced by accidentals in $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events. The bias on $\mathcal{R}$ is expressed in eqn. (6.13). This kind of effects are referred to as **geometrical accidental effects**.

The technique of overlaying additional extra-activity on the event would describe both the effects, at the same time. In practice, the conditions that were indicated in Section 6.2.5 are not respected. The random events do not reproduce the beam **instantaneous intensity** seen by the $K_{\pi\pi}$ decay events; the difference between the rates measured with the K_S and the K_L random events is not equal to the difference measured with K_S and the K_L events. In other words, the random events are taken without respecting neither the intensity, nor the correlation of the beams.

For these reasons the overlay method with data and with Monte Carlo events, is not reliable in estimating the bias induced on $\mathcal{R}$. Thus the $\mathcal{S}/\mathcal{L}$ decorrelation, and the different fractions of losses between neutral and charged events, must be measured separately.

The overlay method can be used to evaluate the relative difference of the losses of neutral and charged events, but not the absolute value. The fact that the intensity is not correctly measured by the random triggers, will have to be taken into account.

¹This is due to the small beam decorrelation of the K_S and K_L beams measured in Chapter 8.

In the case of the overlay with data, there is an additional caveat; due to the linear overlapping of the random and the event data in the detector, not only the intensity, but also the noise in the detector is doubled. This can induce a bad estimate of the losses related to the measurement of the photon energy in the electromagnetic calorimeter, or a bad estimate of the losses due to the setting of the overflow condition.

Actually, not only the noise, but also any non-linear effect can introduce a bias, in the measurements with overlay events. For instance, if the losses were depending non-linearly on the intensity, then doubling the intensity may lead to a bad estimate of the losses, since the selection criteria are based on thresholds.

In Section 12.1 different techniques will be used to estimate the effects of the accidentals on $\mathcal{R}$ (intensity accidental effects). The overlays will still be used to estimate the effects of the accidentals related to the geometry (geometric accidental effects), as described in Section 12.2. Some cross checks of the result with different techniques, will be studied.

12.1 The intensity dependent losses

Two quantities are necessary to estimate the intensity effects on $\mathcal{R}$:

- i) The measurement of the $\mathcal{S}/\mathcal{L}$ beams decorrelation, which was studied in Chapter 8;
- ii) The differential loss probability for neutral and charged events, which is measured in the following Sections, taking advantage of the three methods that were introduced in Section 6.2.

12.1.1 Method I: the level of extra-activity recorded in the read-out window

The level of extra-activity measured in the event sidebands allows (see Section 6.2.1.3 on page 129) the measurement of the term:

$$\frac{\langle m \rangle_N}{\langle m \rangle_C} = \frac{1 - \lambda^N \langle \eta_m \eta_{\Lambda^N} \rangle}{1 - \lambda^C \langle \eta_m \eta_{\Lambda^C} \rangle} \quad (12.1)$$

Notice that this expression is valid for indicators which accomplish an unbiased measurement of the intensity.

On the other hand, it is derived without introducing a model for the dependence of the losses on intensity. The measurement of the ratio $\langle m \rangle_N / \langle m \rangle_C$ takes into account any² effect which varies with time. For instance, the probability of overflows induced by the noise did change during the run, independently of the intensity variations. Then the ratio of eqn. (12.1) takes into account those variations by the term η_Λ .

Given the indicators of extra-activity, and the selected sidebands, as described in Section 8.2.1 on page 177, the average number of hits measured in charged and neutral events is shown in table 12.1. No distinction between K_S and K_L events is done here and no weight is applied.

		KL beam intensity indicators			KS beam intensity indicators	
		AKL	SP	OVFL	PRO	AKS
$\langle m \rangle_N$	10^{-2}	42.01 ± 0.05	32.53 ± 0.04	31.01 ± 0.04	228.43 ± 0.16	0.558 ± 0.005
$\langle m \rangle_C$	10^{-2}	41.43 ± 0.02	32.35 ± 0.02	30.86 ± 0.02	227.15 ± 0.08	0.517 ± 0.002
$\frac{\langle m \rangle_N}{\langle m \rangle_C} - 1$	10^{-2}	1.40 ± 0.12	0.54 ± 0.14	0.48 ± 0.14	0.57 ± 0.08	6.23 ± 1.10

Table 12.1: *The extra-activity level measured with various intensity indicators for neutral and charged kaon decays. The sideband are defined in Section 8.2.1. No distinction is made between K_S and K_L events.*

The ratios $\langle m \rangle_N / \langle m \rangle_C$ are greater than 1. This feature, common to all the indicators, points to an higher number of event losses for charged than for neutral decay mode. This is equivalent to say that the intensity related losses select higher instantaneous intensities for neutral than for charged events.

This is qualitatively understood in terms of different effects on the reconstruction and the selection of the events for the two decay modes:

- the reconstruction of charged decays suffers from inefficiency induced by the overflows. As it was explained in Chapter 10.1, also the neutral events with the overflow condition set are rejected, but this yields only a first order cancellation. The presence in the DCH of hits related to the two charged pions, causes a slightly higher probability of overflow for charged events.
- The reconstruction of the tracks is more sensitive to the accidental activity,

²i.e. not only effects which depend on the intensity

within the ~ 50 ns before the event, than the reconstruction of photons in the electromagnetic calorimeter.

- The reconstruction of the time of one event is affected by accidentals more for charged than for neutral events.
- The selection of the charged decays is more affected by the intensity effects, than the selection of the neutral decays. This will be quantitatively shown later in this chapter, using the overlay method.

Notice that, as explained in Chapter 9, the symmetrization of the charged trigger dead-time, takes into account most of the accidental induced losses on the trigger system. Nevertheless about $\sim 0.5\%$ of the losses cannot be symmetrized, and this effect is included in the ratio $\langle m \rangle_N / \langle m \rangle_C$. Assuming the linear dependence of this effect on the intensity, and given $\langle \eta^2 \rangle \sim 0.25$, the residual trigger inefficiency accounts, in $\langle m \rangle_N / \langle m \rangle_C$, for extent of $\sim 0.5\% \cdot \langle \eta^2 \rangle / \langle 1 + \eta^2 \rangle \sim 0.1 \cdot 10^{-2}$.

As a first check on the reliability of the intensity indicators, table 12.2 shows the intensities measured in the usual indicator sidebands, which are measured for neutral events with no MBOX and QX dead-time symmetrization applied. Given the $\sim 2.7\%$ measured MBOX dead-time and the $\sim 0.5\%$ QX dead-time and considering the quadratic dependence of the former and the linear dependence of the latter on the intensity, the expected enhancement of $\langle m \rangle_N / \langle m \rangle_C$ is:

$$\sim 2.7\% \cdot \frac{2\langle \eta^2 \rangle}{\langle 1 + 3\eta^2 \rangle} + 0.5\% \cdot \frac{\langle \eta^2 \rangle}{\langle 1 + \eta^2 \rangle} \sim 0.9 \cdot 10^{-2}$$

This is in agreement with the enhancement of the values from table 12.1 to table 12.2.

		KL beam intensity indicators			KS beam intensity indicators	
		AKL	SP	OVFL	PRO	AKS
$\langle m \rangle_N$	10^{-2}	42.39 ± 0.05	32.79 ± 0.04	31.31 ± 0.04	230.42 ± 0.16	0.560 ± 0.005
$\langle m \rangle_C$	10^{-2}	41.43 ± 0.02	32.35 ± 0.02	30.86 ± 0.02	227.15 ± 0.08	0.517 ± 0.002
$\frac{\langle m \rangle_N}{\langle m \rangle_C} - 1$	10^{-2}	2.33 ± 0.12	1.37 ± 0.14	1.44 ± 0.14	1.44 ± 0.08	8.42 ± 0.95

Table 12.2: *The extra-activity level measured with various intensity indicators for neutral and charged events; the standard selections are applied but the MBOX and QX dead-time rejection.*

12.1.1.1 The sensitivity of the indicators to the time structures of the beam

Notice that the hits in the indicator sidebands are grouped in bins of 4 ns (PRO), 10 ns (AKL, AKS) or 25 ns (SP, OVFL): if more than 1 hit is found respectively within these time intervals, only one hit is counted. This is forced by the need not to count twice the same accidental hit. This results in a cutoff of few tens MHz on the frequency of the beam time structure which the method is sensible to. Moreover the cutoff is determined by the double hit resolution of the detectors. In the case of the tagger, AKL and AKS it is better than 10 ns (for each single counter of the detectors). In the case of the OVFL it is determined by the width (~ 200 ns) of the signal, though every plane of wires in the DCH is independent from the others.

The OVFL indicator has frequency cutoff lower than the other indicators, by more than a factor of 20. This is illustrated in figure 12.1, which points to the fact that the huge rate at the beginning of the burst (see the plots of time of the event in the burst) and at the trail of the trains of bunches (see the plots of SPS phase plot) are observed with protons in the tagger, but not by the overflows indicator.

The losses induced by the trigger, the reconstruction and the selection of the events are almost associated to the ~ 100 ns time scale around the event. For instance, the overflow condition is set in the case the number of hits on the DCH plane exceeds 7, within a 100 ns time interval.

12.1.1.2 Biases of the indicators

The indicators must measure the intensity in an unbiased way, i.e. with no direct correlations with the losses. In order to observe potential direct correlations between the hits in the sidebands and the losses, checks are performed releasing some selection conditions. It is found that a very critical condition is the overflow rejection.

Table 12.3 shows the intensities measured on the selected events accepting the overflows. Notice that the overflow condition rejects about $\sim 25\%$ of the events. In the extreme case in which the whole fraction of $\sim 25\%$ is intensity related the rejection of those events induces a relative drop of $\sim 25\% \cdot \frac{\langle \eta^2 \rangle}{\langle 1 + \eta^2 \rangle} \sim 5 \cdot 10^{-2}$ of the measured hit rate in the sideband.

Looking at the difference in the level $\langle m \rangle_N$ measured on neutral events, and comparing table 12.1 with table 12.3, one sees that the AKL and the AKS counts are

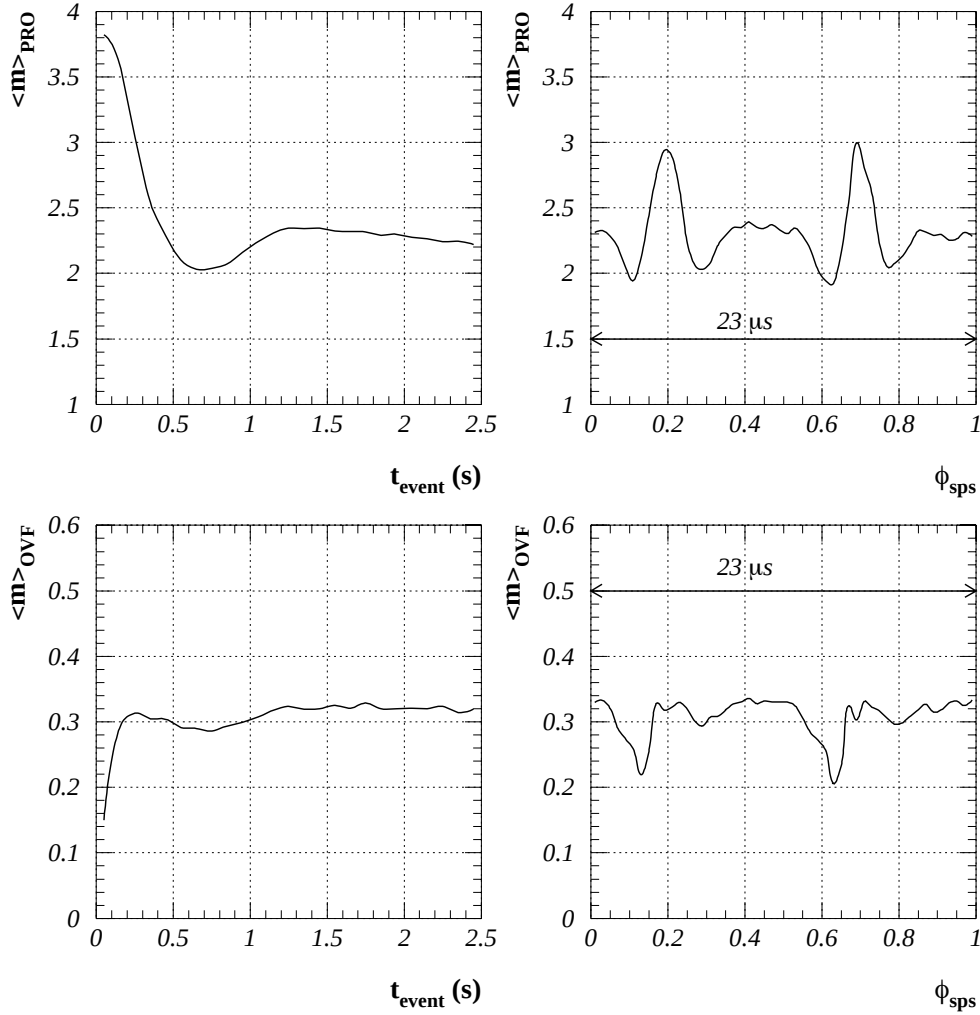


Figure 12.1: The cutoff in the intensity measurement is illustrated here on the sample of the selected neutral events. Top figures a) and b) show the intensity measured by the protons in the tagger as a function respectively of the time of the event in the burst and of the SPS phase ϕ_{SPS} . Bottom figures c) and d) show the intensity measured by the out of time overflows. In the latter case the peaks of huge intensity at the beginning of the burst ($t_{\text{event}} < 0.5$ s) and at the tails of the two trains of protons bunches ($0.15 < \phi_{\text{SPS}} < 0.25$ and $0.65 < \phi_{\text{SPS}} < 0.75$) are cut down. This is due to the different time resolution of the tagger and the overflows; the latter is less than 10 ns and the former is at the level of ~ 200 ns, due to the width (~ 200 ns) of the overflows signal.

		KL beam intensity indicators			KS beam intensity indicators	
		AKL	SP	OVFL	PRO	AKS
$\langle m \rangle_N$	10^{-2}	45.00 ± 0.04	33.96 ± 0.04	36.26 ± 0.04	237.17 ± 0.17	0.835 ± 0.005
$\langle m \rangle_C$	10^{-2}	42.28 ± 0.02	33.40 ± 0.02	35.66 ± 0.02	229.78 ± 0.08	0.543 ± 0.002
$\frac{\langle m \rangle_N}{\langle m \rangle_C} - 1$	10^{-2}	6.45 ± 0.11	1.67 ± 0.12	1.71 ± 0.12	3.21 ± 0.07	53.91 ± 1.04

Table 12.3: *The extra-activity level measured with various intensity indicators for neutral and charged events; the standard selections are applied but the overflow rejection.*

enhanced by more than $\sim 5 \cdot 10^{-2}$. This indicates a bias on the measurement of the intensity with the AKL or the AKS indicators. This is understood as a direct effects of accidental activity which both kills the event and hit the counter. For instance, the overflows due to showers produced upstream of the final collimator have a chance to fire the AKS and the AKL. The direct correlation between the physical event, which both originates the loss and hit the indicator counter, results in an enhanced correlation term $\langle \eta_m \eta_{\Lambda^c} \rangle$. The bias is different for charged and neutral events, then the AKL and AKS cannot be used as intensity indicators for neutral and charged events. Nevertheless they are symmetric for K_S and K_L , and does not infrim the results of Section 8.2.1.

Given its location, the tagger is not expected to suffer from this kind of biases. The rate of protons in neutral events increases, by accepting the overflows, of a 3.6% relative, which translates into about $\sim 18\%$ event losses due to overflows related to the intensity³. In Chapter 10.1, a loss of $\sim 19\%$ of the events was measured accepting overflows generated by noisy wires. This means that not all the 25% overflow probability is related to the intensity. The likeness between the 18% measured here, and the $\sim 19\%$ described in Chapter 10.1, corroborates the assumption that the proton rate, measured in the tagger sidebands, provide an almost unbiased estimator for the intensity.

Unfortunately the OVFL indicator suffers some bias. Although the sideband windows are chosen far from the event time, there is a residual correlation with the overflows close to the event, which induce the losses. For each DCH plane, only the two overflows closest to the event, one before and one after the event time, are

³Indeed it is $18\% \sim 3.6 \cdot \langle 1 + \eta^2 \rangle / \langle \eta^2 \rangle$.

available in COMPACT. Furthermore, the long duration of the OVFL electronic signal (~ 200 ns) enhances the correlation between the overflows far and close to the event.

Both SP and OVFL should have no direct correlation with any other kind of losses: the trigger, reconstruction and selections are not affected by activity further than $\sim \pm 300$ ns from the event time.

12.1.1.3 A first estimate of the effect of the accidental losses on $\mathcal{R}$

Assuming that the tagger is an unbiased indicator of the KS beam intensity, and that SP is an unbiased indicator of the KL beam intensity, it is possible to estimate the effect of the accidental losses on $\mathcal{R}$. Using the expr. 6.31 (see Section 6.2.1.3 on page 129) and given the values in table 12.1 one finds:

$$\frac{\langle m \rangle_N|_S - \langle m \rangle_N|_L}{\langle m \rangle_C} = \frac{1 - \lambda^N \langle \eta_{\Lambda^N} (\eta_S - \eta_L) \rangle}{1 - \lambda^C \langle \eta_{\Lambda^C} (\eta_S - \eta_L) \rangle} \lesssim 15 \cdot 10^{-4} \quad (12.2)$$

that is an upper limit for the bias. The errors on the measurements of $\langle m \rangle_N / \langle m \rangle_C$ for the K_S and the K_L beams are combined quadratically.

Notice that this is obtained with no assumption on any particular dependence of the losses with the intensity.

12.1.1.4 A more accurate estimate of the effect of the accidental losses on $\mathcal{R}$

Assuming that the losses are linearly dependent on the intensity, expr. (6.31) becomes:

$$\frac{1 - \lambda^N \langle \eta_m \eta_A \rangle}{1 - \lambda^C \langle \eta_m \eta_A \rangle} = 1 - (\lambda^N - \lambda^C) \cdot \langle \eta_m \eta_A \rangle \quad (12.3)$$

Figure 12.2 shows the intensity, measured with the OVFL indicator, for charged (fill dot) and neutral (hollow dot) events as a function of the time of the event in the burst t_{event} (a), the run period t_{run} (b), the SPS phase ϕ_{SPS} (c), and the phase of the 220 V beam power supplies (referred to as mains phase) mains phase ϕ_{mains} (d). The four variables show the beam intensity variation at different time scales. In figure 12.3 the losses estimated with eqn. (12.3) are shown. Figures 12.4 and 12.5 show respectively the same distributions, but the rate is measured using the number of protons the tagger. Notice that the losses do not show any variation, over the intensity range probed.

The measured value of the fluctuation term $\langle \eta^2 \rangle \sim 0.25$, and the value of $\langle m \rangle_N / \langle m \rangle_C - 1 \sim 0.55 \cdot 10^{-2}$, measured with the tagger and the space points SP, are translated as follows into the difference $(\lambda^N - \lambda^C) \cdot \langle 1 + \eta^2 \rangle$ of the losses between charged and neutral events:

$$(\lambda^N - \lambda^C) \cdot \langle 1 + \eta^2 \rangle \sim \left(\frac{\langle m \rangle_N}{\langle m \rangle_C} - 1 \right) \frac{\langle 1 + \eta^2 \rangle}{\langle \eta^2 \rangle} \sim -0.028 \pm 0.007 \quad (12.4)$$

The error includes a $\sim 20\%$ statistical indetermination on $\langle m \rangle_N / \langle m \rangle_C$ and a $\sim 10\%$ systematic error on $\frac{\langle 1 + \eta^2 \rangle}{\langle \eta^2 \rangle}$. Given the different correlation of the KL and KS beam intensities with the accidental particle intensity (see Section 8.2.1), an upper limit for the bias on $\mathcal{R}$, due to the accidental related losses, is obtained. Considering a 3σ limit:

$$\left| \Delta \mathcal{R} / \mathcal{R} |_{intensity} \right| = \left| (\lambda_N - \lambda_C) \langle 1 + \eta^2 \rangle \cdot \frac{\langle \eta_L \eta_L - \eta_L \eta_S \rangle}{\langle 1 + \eta^2 \rangle} \right| \lesssim 0.05 \cdot \frac{0.0055}{1.25} \sim 2.2 \cdot 10^{-4} \quad (12.5)$$

The upper limit takes into account the correlation ($\langle \eta \eta \rangle$ term) of the variations of the beam intensity with the variations of the losses, integrated over very different scales of time: from the 100 ns very short times range, up to the 122 days long range time scale of the data taking.

Figure 12.6 shows the bias on $\mathcal{R}$, estimated using the extra-activity method and eqn. 12.5, as a function of the event in the burst t_{event} (a), the run period t_{run} (b), the SPS phase ϕ_{SPS} (c) and the mains phase ϕ_{mains} (d). Within the intensity range (see figures 12.4), the effect does not show large variations: under different intensity conditions, the correction is stable.

12.1.1.5 Comparison with data taken in *KS-only*

Data taken with the *KS-only* beam mode provide an useful tool to study intensity dependent effects. As it was shown in Chapters 7 and 11, the accidental effects on events taken with *KS-only* beam mode, are smaller by a factor of 10 than in normal beam conditions.

The previous analysis is repeated on this data sample. The results are shown in table 12.4. Neutral to charged differences are expected to be compatible with zero. Unfortunately the events are too few to draw any conclusions.

However, one may notices that:

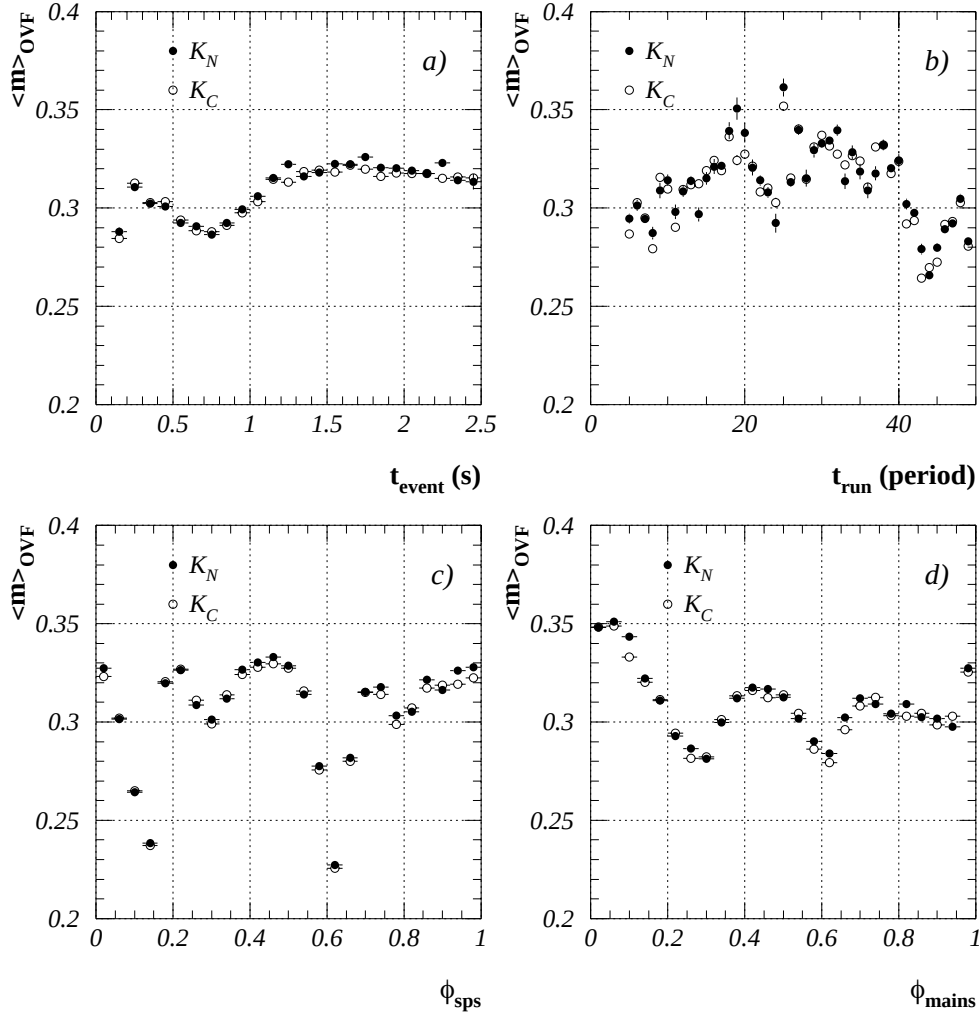


Figure 12.2: The intensity measured with the OVFL indicator for charged (fill dot) and neutral (hollow dot) events as a function of the time of the event in the burst t_{event} (a), the run period t_{run} (b), the SPS phase ϕ_{SPS} (c) and the mains phase ϕ_{mains} (d). These four variables are useful in showing the intensity variations at different time scales. Notice that the OVFL indicator has not full sensitivity to the high frequency beam structures. This can be seen as a saturation in the intensity measured at the beginning of the spill (in figure a) and in correspondence of the tails of the SPS bunch trains (figure b): see figure 12.1.

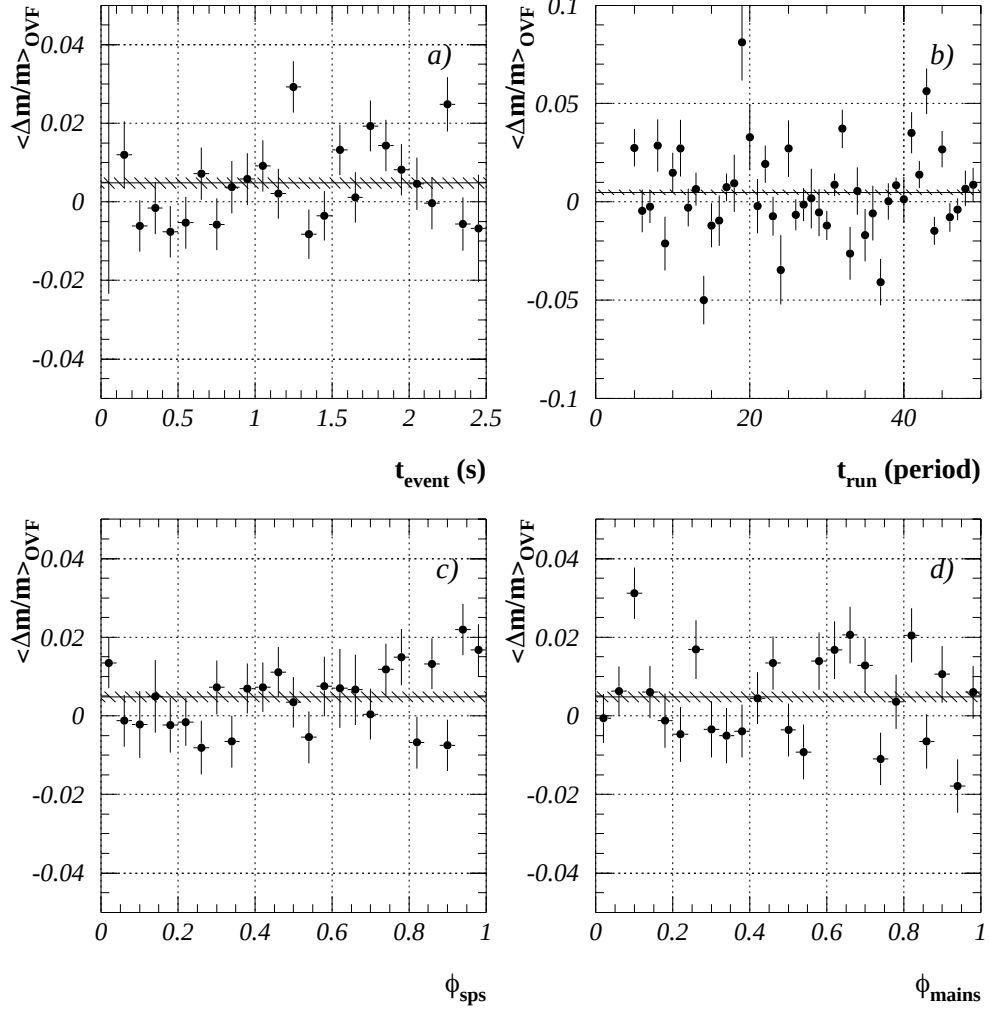


Figure 12.3: The neutral to charged relative intensity difference measured with the OVFL indicator as a function of the time of the event in the burst t_{event} (a), the run period t_{run} (b), the SPS phase ϕ_{SPS} (c) and the mains phase ϕ_{mains} (d). The small average counting rate per event of the OVFL indicator does not allow for a clean observation of any dependence of the relative difference between the neutral and charged rates as a function of the intensity.

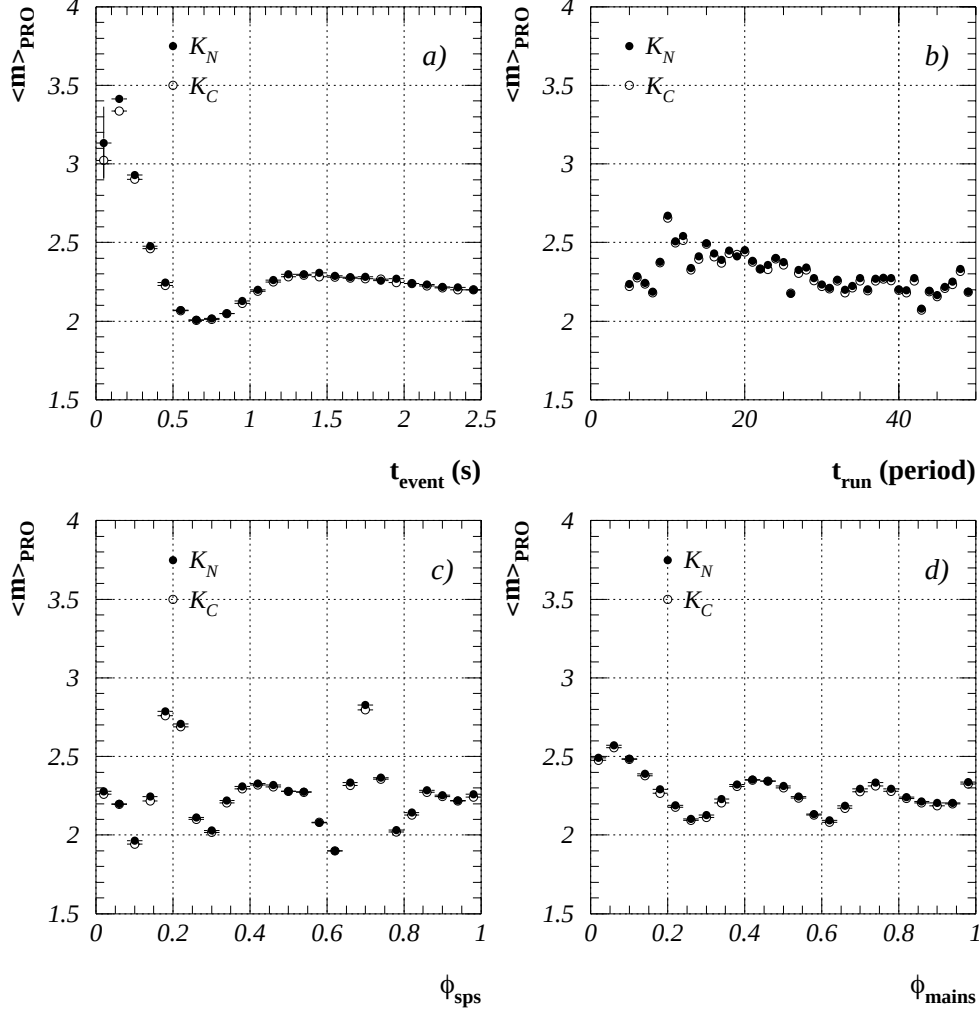


Figure 12.4: The intensity measured with the PRO indicator for charged (fill dot) and neutral (hollow dot) events as a function of the time of the event in the burst t_{event} (a), the run period t_{run} (b), the SPS phase ϕ_{sps} (c) and the mains phase ϕ_{mains} (d). These four variables are useful in showing the intensity variations at different time scales. Notice that the PRO indicator has a good sensitivity to the high frequency beam structures (see caption of figure 12.4).

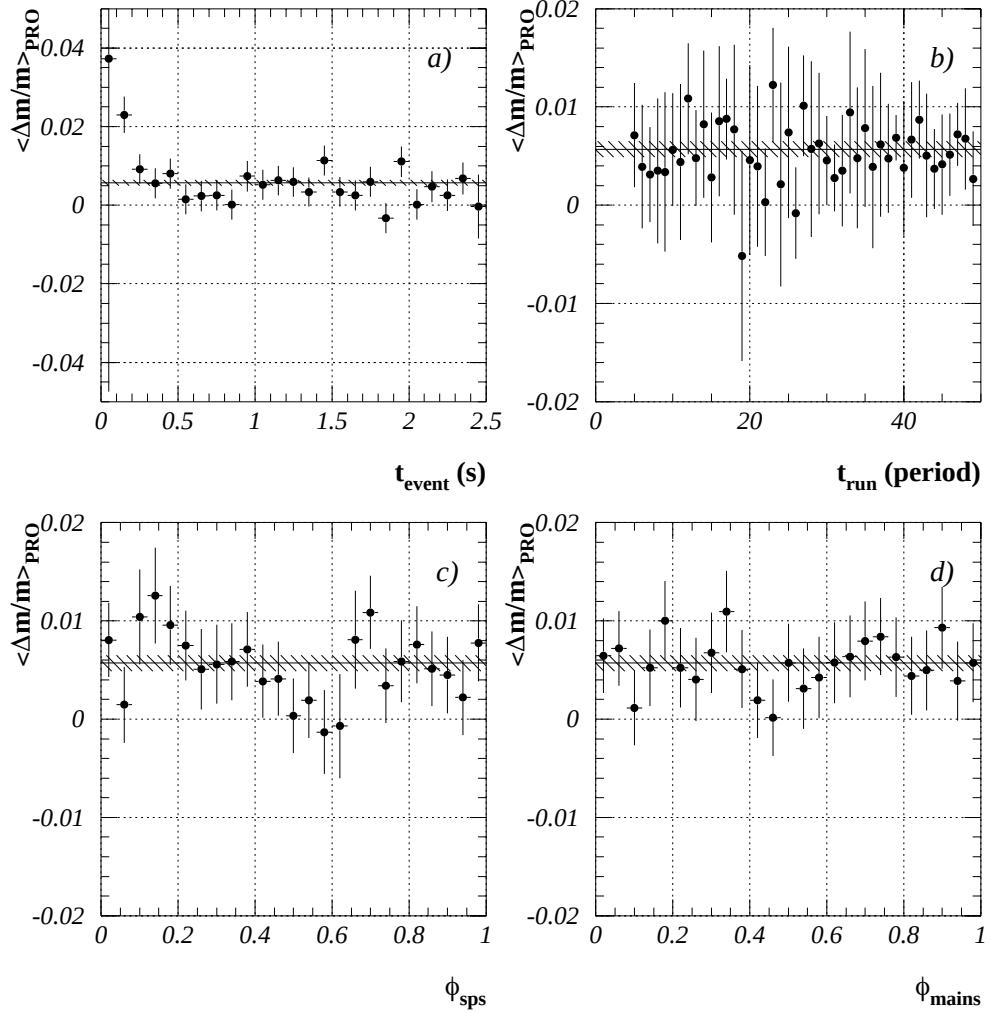


Figure 12.5: The neutral to charged relative intensity difference measured with the PRO indicator as a function of the time of the event in the burst t_{event} (a), the run period t_{run} (b), the SPS phase ϕ_{SPS} (c) and the mains phase ϕ_{mains} (d). The high average counting rate per event of the PRO indicator allows for an observation of some dependence of the relative difference between the neutral and charged rates as a function of the intensity (see figures a,c and d).

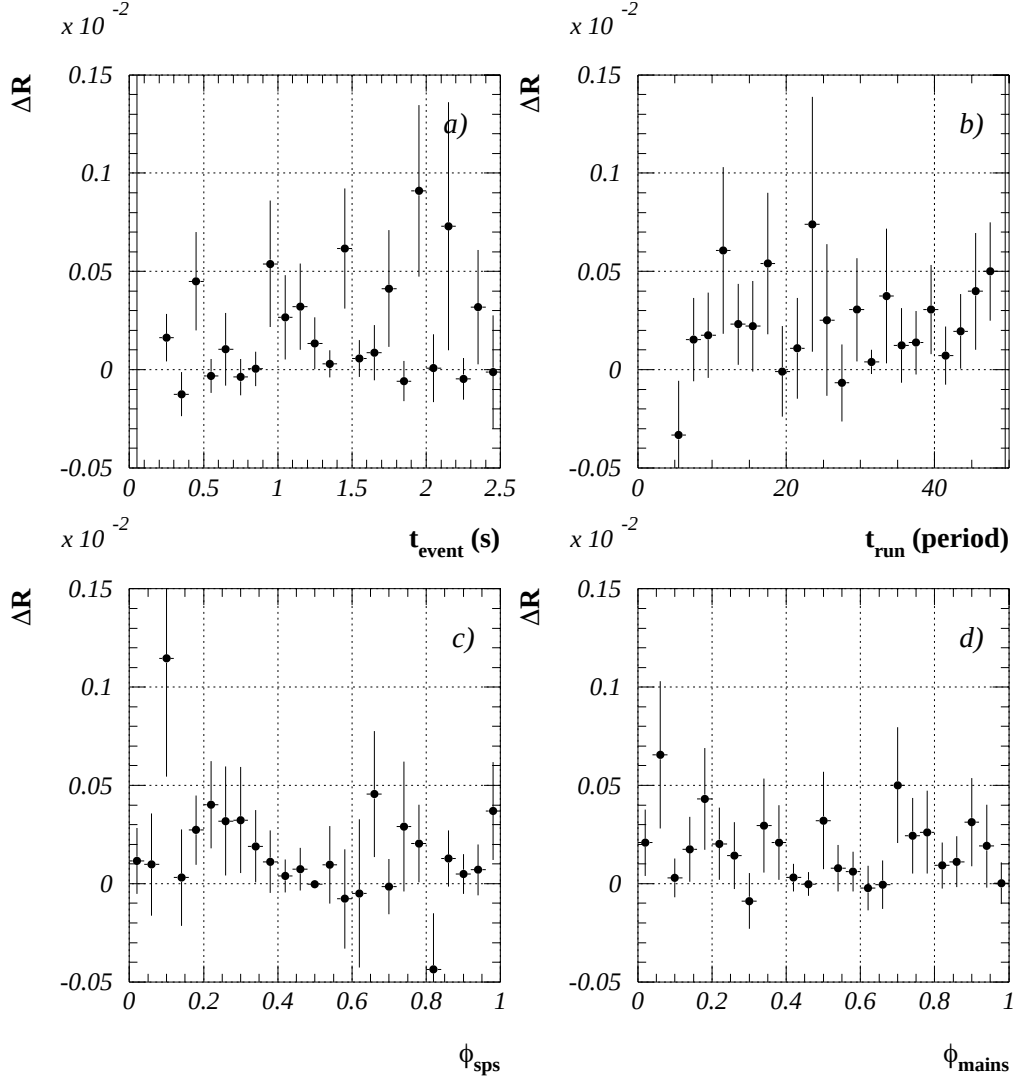


Figure 12.6: The bias on $\mathcal{R}$, estimated using the extra-activity method and eqn. 12.5, as a function of the event in the burst t_{event} (a), the run period t_{run} (b), the SPS phase ϕ_{SPS} (c) and the mains phase ϕ_{mains} (d).

		KL beam intensity indicators			KS beam intensity indicators	
		AKL	SP	OVFL	PRO	AKS
$\langle m \rangle_N$	10^{-2}	29.26 ± 0.32	15.83 ± 0.22	4.37 ± 0.11	198.44 ± 1.26	0.592 ± 0.040
$\langle m \rangle_C$	10^{-2}	28.82 ± 0.15	15.75 ± 0.11	4.39 ± 0.05	197.74 ± 0.61	0.513 ± 0.018
$\frac{\langle m \rangle_N}{\langle m \rangle_C} - 1$	10^{-2}	1.53 ± 1.23	0.48 ± 1.57	-0.51 ± 2.80	0.36 ± 0.71	15.43 ± 8.80

Table 12.4: The extra-activity level measured with various intensity indicators for neutral and charged events in KS-only beam mode.

- The AKL and the SP rates are reduced only by a factor of ~ 2 with respect to the normal running conditions. This is because of the residual muons from the K_L beam, as was already noticed in Chapter 7.1 on page 143, concerning the rates of the clusters and the tracks measured with the *KS-only* mode;
- The residual muons explain also the fact that the OVFL rate is reduced by a larger factor than the AKL and the SP rates: this is also explained by the residual muons from the K_L beam, which induce low multiplicity activity in the detector, and do not yield overflows. Besides, as noticed in Section 10.1, the residual OVFL rate in *KS-only* mode is understood to come mostly by noise in the DCH;
- The proton intensities in the tagger are smaller by a factor of ~ 0.85 , with respect to the normal running conditions. This is due to the particles from the K_L beam, producing additional counts in the tagger.

12.1.1.6 Comparison with the random events

The study of the extra-activity recorded in the **random events** is the best method to estimate the losses in each decay mode. Random events, by definition, are not lost because of the accidentals, while they record the same intensity conditions of the selected events⁴. The difference of the extra-activity level, recorded in sidebands for **random** and selected events, are used to measure the amount of the intensity dependent losses of good events, as was pointed out in Section 6.2.4.1 on page 134, see 6.47.

Unfortunately, during the run in 1998, the $69\ \mu\text{s}$ delay changed, and the **random** triggers were not anymore proportional to the instantaneous intensity seen by the good events. The effect was even more significant for random events of K_L type.

This can be observed in table 12.5, which shows the extra-activity measured with **random events**, of K_L and of K_S types. If the **random** triggers were correctly taken, one would expect that they recorded higher extent of extra-activity, than the selected events. On the contrary, the rate of protons measured with the random K_S events is $\sim 2\%$ lower than the rate measured with the neutral selected K_S decays

⁴Random events can be thought as snapshots of the actual accidental activity in the detector, taken at the $K_{\pi\pi}$ decay event time.

(see table 12.1); in the case of K_L randoms the gap is $\sim 9\%$.

The effect of the **random** triggers not correctly taken, is a serious bias for the analysis shown in this section⁵. Notice that, even if the **random** triggers were correctly taken, the statistical accuracy needed for this analysis would require more events, in order to estimate the relative difference, between the extra-activity measured with the random and with the selected events, which is $\lesssim 1\%$.

		KL beam intensity indicators			KS beam intensity indicators	
		AKL	SP	OVFL	PRO	AKS
$\langle m \rangle_{R_S}$	10^{-2}	41.34 ± 0.07	32.60 ± 0.06	30.98 ± 0.06	225.04 ± 0.25	0.540 ± 0.007
$\langle m \rangle_{R_L}$	10^{-2}	39.92 ± 0.06	32.79 ± 0.06	30.72 ± 0.05	211.59 ± 0.22	0.501 ± 0.006

Table 12.5: *The extra-activity measured with various intensity indicators for random events of K_L and of K_S types. The overflow, and the charged trigger dead time rejections are applied.*

For completeness, tables 12.6, and 12.7 are reported, which show the amount of extra-activity measured respectively for K_S random events in *KS-only* mode, and for K_L random events in *KL-only* mode.

		KL beam intensity indicators			KS beam intensity indicators	
		AKL	SP	OVFL	PRO	AKS
$\langle m \rangle_{R_S}$	10^{-2}	35.44 ± 0.36	17.46 ± 0.24	4.61 ± 0.11	207.55 ± 1.32	0.532 ± 0.038

Table 12.6: *The extra-activity level measured with various intensity indicators for random events in KS-only run.*

		KL beam intensity indicators			KS beam intensity indicators	
		AKL	SP	OVFL	PRO	AKS
$\langle m \rangle_{R_L}$	10^{-2}	42.4 ± 5.4	30.73 ± 4.42	42.9 ± 5.5	44.9 ± 5.6	—

Table 12.7: *The extra-activity level measured with various intensity indicators for random events in KL-only run.*

⁵Nevertheless in analyses where not much accuracy is required, in reproducing the instantaneous intensity of the good events, the **random events** are still usefull. For instance, they are used in the studies described in Chapter 7, and in this chapter, on page 274, whitout inducing serious biases.

12.1.2 Method II: the ratio of neutral and charged selected events in *KS-only* versus *KS+KL* beam operation modes

An other method [105] can be used to measure the neutral and the charged events losses. When the KL beam is switched off, i.e. operating in the *KS-only* mode, the accidental activity in the detector is much reduced⁶. The difference between the losses of the neutral and the charged events, can be measured by using the ratio of the numbers of the neutral and the charged selected events recorded with the two beam operation modes: *KS-only* and *KS+KL* (i.e. the normal mode). The double ratio provides an estimate for the differential losses, as it was brought up in Section 6.2.3 on page 132 (see equation 6.44).

In order to estimate only the reconstruction and the selection intensity related losses, the number of the events is corrected for the trigger efficiencies:

$$\frac{\frac{N_{KS+KL}^S}{C_{KS+KL}^S}}{\frac{N_{KS-only}^S}{C_{KS-only}^S}} = \frac{\frac{1918801}{8270940}}{\frac{37157}{160511}} \quad (12.6)$$

The double ratio is:

$$(\lambda^N - \lambda^C) \cdot \langle 1 + \eta^2 \rangle = -0.0034 \pm 0.0057 \quad (12.7)$$

which is lower than what is measured in (12.4), and leads to a better 3σ limit on the estimated bias on $\mathcal{R}$, at the level of:

$$\left| \Delta \mathcal{R} / \mathcal{R} |_{intensity} \right| = \left| (\lambda_N - \lambda_C) \langle 1 + \eta^2 \rangle \cdot \frac{\langle \eta_L \eta_L - \eta_L \eta_S \rangle}{\langle 1 + \eta^2 \rangle} \right| \lesssim 0.02 \cdot \frac{0.0055}{1.25} \sim 0.9 \cdot 10^{-4} \quad (12.8)$$

It was shown, in Section 6.2.3, that this method relies on the hypothesis of linear dependence of the losses on the intensity.

An other problem of the method is that the long range intensity variations are not taken into account. Since, by definition, the *KS-only* and the *KS+KL* modes are not simultaneous, and few *KS-only* data are available, then the beam intensity variations during the 1998 data taking are not accurately sampled. Hence the fluctuations of

⁶The hypothesis of low accidental activity in in *KS-only* beam mode is fulfilled: it was shown in Chapter 7 that the amount of the event killing accidental activity is well below 10% of the activity in the normal beam operation mode.

the losses in the long range time scale are not included in the result. This effect will be studied directly on $\mathcal{R}$, in the Section 12.1.5.

Figures 12.7 and 12.8 show respectively the neutral to charged ratio and the estimated limit of the bias on $\mathcal{R}$, as functions of the time in the burst (a), of the various run periods (b), of the ϕ_{SPS} (c) and of the ϕ_{mains} . Within the statistical accuracy, no dependences are shown. In other words, under different intensity conditions the effect, if any, seems to be stable.

12.1.3 Method III: the overlay technique

The overlay events, built both from original data and Monte Carlo events, are analyzed with the same criteria than the events for the ϵ'/ϵ analysis, with the following differences:

- The trigger and the tagging effects are not reproduced by the overlay procedure. They were studied separately (see respectively 9 and 5).
- The effects of the reconstruction and of the selection are studied, but the event time reconstruction, is analyzed independently (see Chapter 5). The reconstruction effects related to losses due to the overflow condition are particularly important here. In the case that, either the original event, or the random event have the overflow condition set, the resulting overlay event, is not considered. Only those events that have the overflow, after the overlay is done, are considered as losses (they are later referred to as events with overflow appearance).

The conclusion of the discussion in Section 12.1.1.6 on page 253 was that the random events reproduce the intensity seen by the K_S and the K_L with an accuracy not better than 10%. This prevents the overlay events to be used to measure correlation of the K_S to K_L intensity difference with the neutral to charged loss difference. But they can still be used to evaluate the relative loss difference between neutral and charged events, with an accuracy not better than $\sim 10\%$. Thus the K_S neutral events are compared here with the charged K_S events⁷, after the randoms of both⁸ K_S and K_L type are overlayed.

⁷ K_L events are not considered here, as the K_L weighting is a further complicate.

⁸By using also the K_S events overlayed with the K_L random events, yields a doubled statistical sample of events. Due to the lack of accuracy in the random intensity, the distinction between

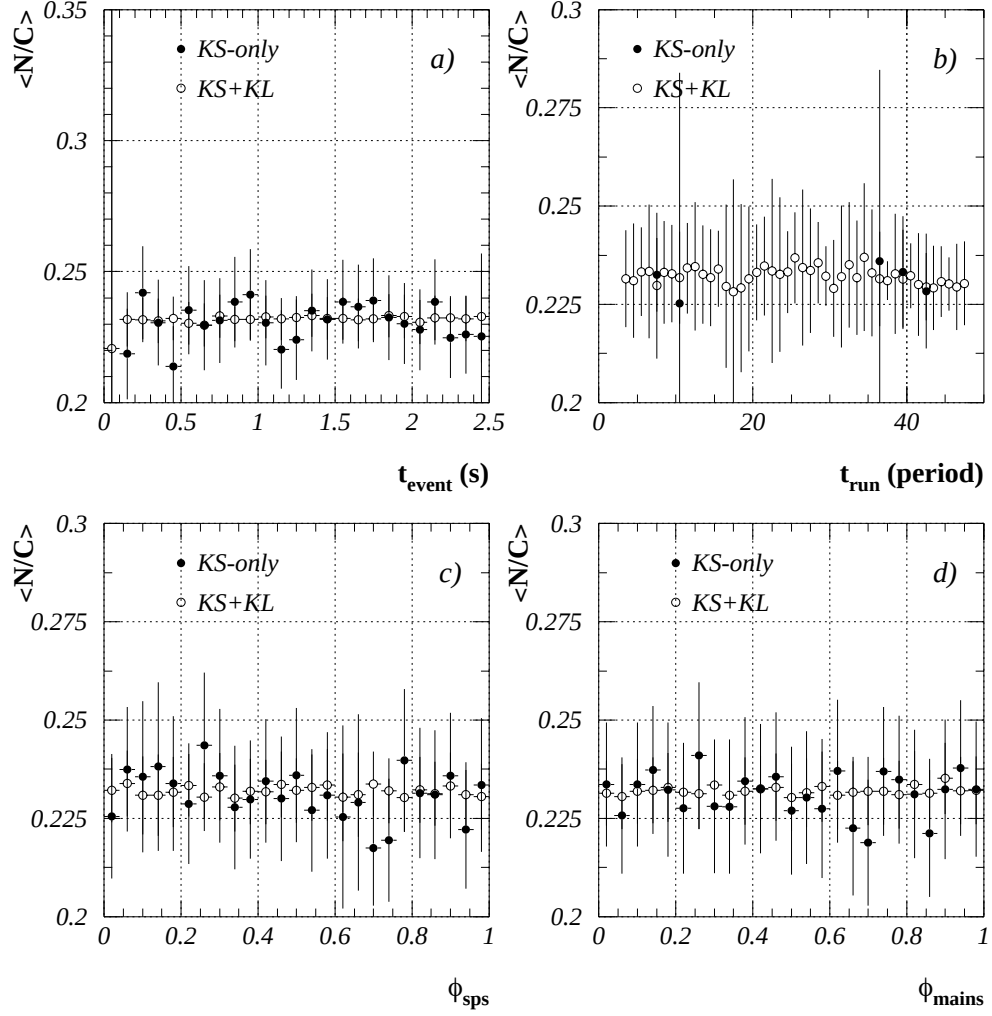


Figure 12.7: The ratio of the neutral to charged (corrected for the trigger efficiency) events is shown as a function of the time of the event in the burst t_{event} (a), the run period t_{run} (b), the SPS phase ϕ_{SPS} (c) and the mains phase ϕ_{mains} (d). The full dot relates to the data taking in *KS-only* beam mode and the hollow dot to the data taking in normal beam conditions (*KS+KL* mode).

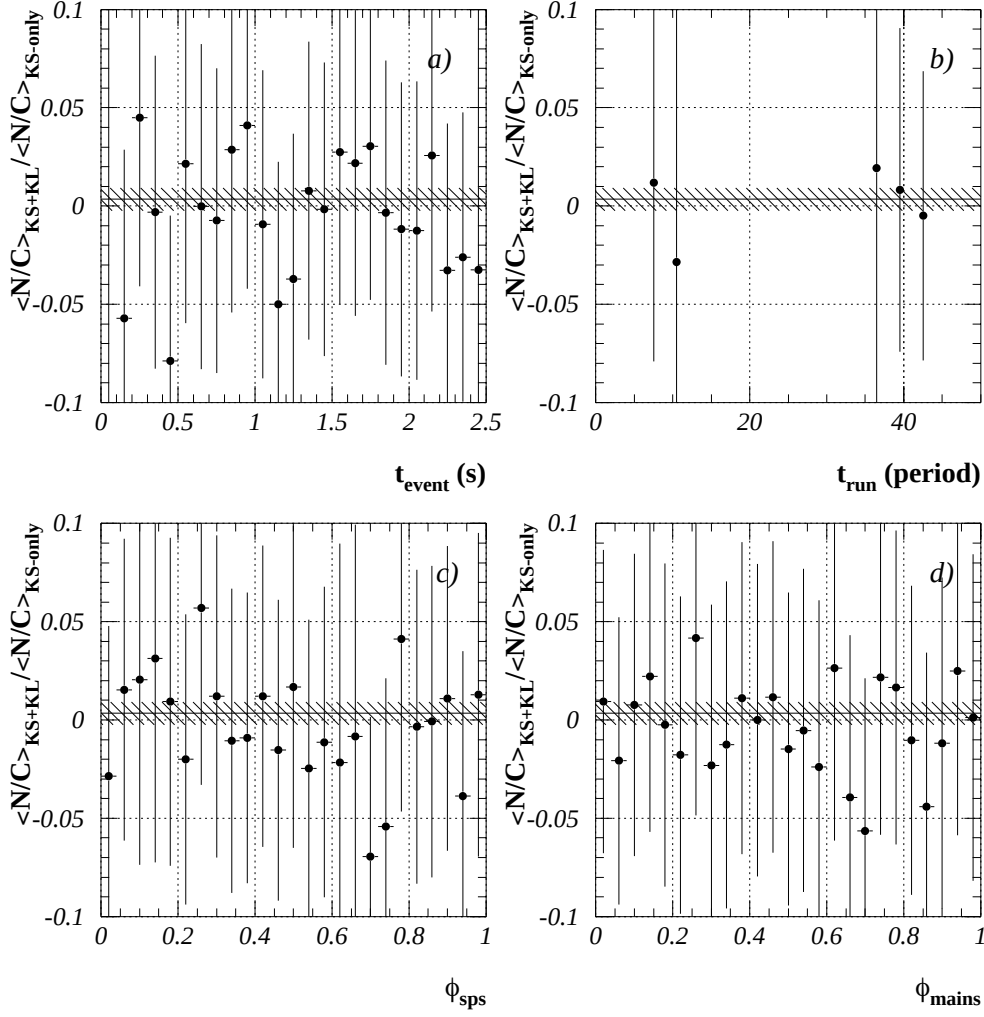


Figure 12.8: The ratio of the relative difference of neutral and charged events in *KS-only* and *KS+KL* beam modes as a function of t_{event} (a), t_{run} (b), ϕ_{sps} (c) and ϕ_{mains} (d). The statistics of the *KS-only* runs is too small to show any intensity dependence of the double ratio.

Table 12.8 shows the number of events that are lost (n_{loss}), or gained (n_{gain}) as a result of overlaying the extra-activity on the original events (see Section 6.2.5 on page 134).

	Data Overlay events			
	Lost events	Common events	Gained events	Total loss probability
$K_{\pi^0\pi^0}^S$	75646	2306630	15614	$2.52 \pm 0.01\%$
$K_{\pi^+\pi^-}^S$	49604	1481308	1452	$3.15 \pm 0.01\%$
difference N/C				$0.63 \pm 0.01\%$

Table 12.8: *The number of lost and gained events, estimated with the overlay technique on data. The total loss probability measured using the expr. (6.48) as explained in Section 6.2.5 on page 134.*

The causes of the overall losses will be investigated in the following sections. We stress the fact that the difference $0.63 \pm 0.01\%$ between the charged and the neutral losses comes almost entirely by the difference in the probability for the events to be rejected by an appeared overflow.

Some problems of the method are:

- The intensity of the random events. In the hypothesis that the losses are linearly proportional to the beam intensity, the charged to neutral loss probability difference can be written as:

$$(\lambda^N - \lambda^C) \cdot \langle 1 + \eta^2 \rangle = -0.0063 \pm 0.0001 \quad (12.9)$$

because of the wrong random average intensity, as explained previously, a relative systematic error of $\sim 10\%$ must be added to the statistical one, resulting in a difference of -0.0063 ± 0.0006 .

- The time difference between the original and the original random event. Figure 12.9 shows, for the overlay events, the difference between the time-stamp of the original and of the overlayed random event. The features of the plot are explained by the overlay procedure: for each original event, the random event to be overlayed is the closest random triggered before the event.

In one burst ~ 10 randoms are collected. This explains why the peak near to random of K_S and of K_L type is not meaningless here.

the zero is shifted to negative times, and why its width is $\sim 1/10$ the burst length. The accumulation of events in the interval $[2 \div 2.25]$ s is due by the first original events in the burst: because no random, from the same burst, is available and, hence, the last random from the previous burst is selected.

The consequence is that the accidental activity, which is overlayed to the first original event, is taken at a different time, which on average correspond to -100 ms before the event. This is a bias for the procedure, which thus correctly takes into account only low frequency structures.

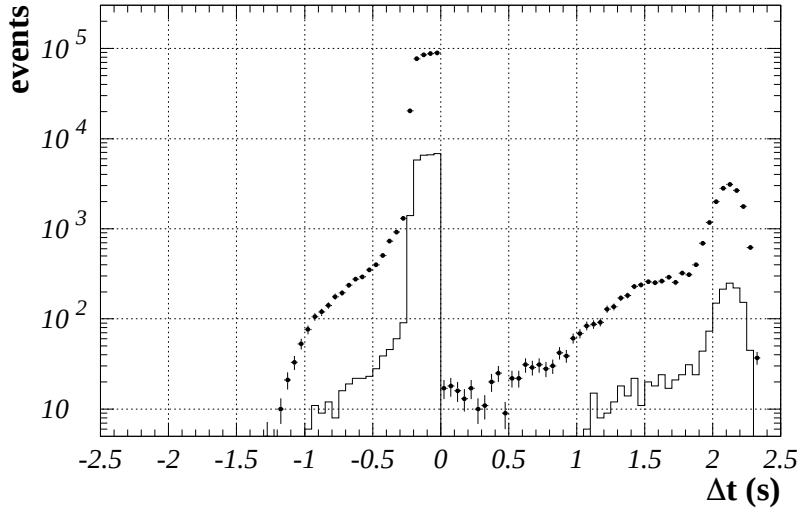


Figure 12.9: *The time difference between the original and the random event are shown, for the events which pass all the selections even after being overlayed, i.e. common events, (full dots), and for the events which are rejected, i.e. losses, (full line).*

- **The non-linear effects.** The effect of the noise in the detector is overestimated in the data overlay. In particular, the probability of losing neutral events is overestimated, due to the doubled noise in the LKR energy measurement, induced by the overlay method. It is roughly estimated that the 2.52 has to be corrected to 2.22 in order to cope with this effect. The difference neutral to charged is then 0.009 ± 0.001 .

On the other hand some overestimation of the noise in the DCH is also expected. In order to cope with the shown biases, and with the doubled

noise and threshold effects, the Monte Carlo overlays are analyzed.

12.1.3.1 Monte Carlo overlay

By using $K_{\pi\pi}$ Monte Carlo events [101] to be overlayed onto the extra-activity detected with the random triggers the real effects of the extra-activity on the events is reproduced. In particular the non-linear effects are treated in the same way as for the real events. Besides, the data overlay is also simulated by overlaying two random events on the same Monte Carlo decay, which is a cross-check for the consistency of the method.

Due to the non reliability of the random to reproduce the $\mathcal{S}/\mathcal{L}$ decorrelation of the beams, also the Monte Carlo overlay events are not fully reliable for the estimation of the overall accidental effect. Nevertheless they are used here to evaluate the difference of the losses for the neutral and charged events, and in Section 12.2 to evaluate the effects due to the geometry.

Table 12.9 shows the number of neutral, and charged lost events, using the method of overlay on Monte Carlo events. The overall probability of losses is lower than in the case of the overlay with data (see table 12.8). The difference is due to the non-linearity effects which are overestimated in the case of the overlay with the real events. This is enforced by the results on the double Monte Carlo overlays (see table 12.10) which are in fair agreement with the probabilities for the data overlays.

	Monte Carlo Overlay events			
	Lost events	Common events	Gained events	Total loss probability
$K_{\pi^0\pi^0}^S$	204	18582	57	$0.6 \pm 0.1\%$
$K_{\pi^+\pi^-}^S$	638	38121	16	$1.6 \pm 0.1\%$
difference $\mathcal{N}/\mathcal{C}$				$1.0 \pm 0.1\%$

Table 12.9: *The number of lost and gained events, estimated with the overlay technique on Monte Carlo events. The total loss probability measured using the expr. (6.48) as explained in Section 6.2.5 on page 134. The shown numbers are from [101].*

The difference between the loss probability for the data overlays (0.009 ± 0.001), the Monte Carlo single and double overlays ($1.0 \pm 0.1\%$ and $1.1 \pm 0.1\%$), are in agreement, which indicates a small influence of the non-linearity effects (noise and

	Double Monte Carlo Overlay events			
	Lost events	Common events	Gained events	Total loss probability
$K_{\pi^0\pi^0}^S$	332	14339	68	$1.8 \pm 0.1\%$
$K_{\pi^+\pi^-}^S$	891	29100	19	$2.9 \pm 0.1\%$
difference $\mathcal{N}/\mathcal{C}$				$1.1 \pm 0.1\%$

Table 12.10: *The number of lost and gained events, estimated with the double overlay technique on Monte Carlo events. The resulting overall loss fractions are compatible with what is found with the overlay technique on data (0.9 ± 0.1), see table 12.8. The numbers shown here are from [101].*

thresholds).

12.1.3.2 The result

The $\sim 1\%$ difference of the losses for the charged and the neutral events, yields the following 3σ upper limit for the bias on $\mathcal{R}$:

$$\left| \Delta \mathcal{R} / \mathcal{R}_{|intensity} \right| = \left| (\lambda_N - \lambda_C) \langle 1 + \eta^2 \rangle \cdot \frac{\langle \eta_L \eta_L - \eta_L \eta_S \rangle}{\langle 1 + \eta^2 \rangle} \right| \lesssim 0.010 \cdot \frac{0.0055}{1.25} \sim 0.5 \cdot 10^{-4} \quad (12.10)$$

which is consistent with the previously estimated limits.

12.1.4 The origin of the charged to neutral difference

Although the overlay method is not that accurate to estimate the overall effect, it is very useful to identify the different sources of inefficiency. Using this method we understand that the 1.0% difference is mainly due to the difference in the overflow probability.

Thus, although the overflows are symmetrized with neutral events, the charged events suffer from an higher (by 0.01) probability of losses due to overflows, which cannot be symmetrized. The fraction of additional losses is understood to come from reconstruction inefficiency generated by accidental extra-activity in the detector. The reason why this inefficiency is measured also with the first method (see method I in Section 12.1.1), is that the method is sensitive to any loss which is not symmetrized with neutral events. Method II (see Section 12.1.2) measures also this inefficiency, because no correction is applied to the number of events, in order to recover the

reconstruction inefficiency.

The losses measured with Method I, expr. (12.5), are probably overestimated due to some bias on the intensity indicators, which provide a measurement of intensity not fully independent of the losses. On the other hand, notice also that Method II do not cover the long range time correlations, and Method III do not cover the short range time scale⁹. While the extra-activity Method I copes with a huge range of time scales. This could also explain the discrepancy in the measured $\mathcal{N}/\mathcal{C}$ differential losses. This is still matter of detailed study.

Finally, the hypothesis of linear dependence of the losses with the intensity is still being investigated.

12.1.5 Summary and cross-checks on $\mathcal{R}$

From the previous sections, it results that the effects of the intensity dependent uncorrelated accidentals are at expected to be less than $\sim 10^{-4}$. A conservative bound is the fixed at $\Delta\mathcal{R}/\mathcal{R}|_{intensity} = 2 \cdot 10^{-4}$, which includes possible non linear dependences of the losses with the intensity.

This is cross-checked in this section, by observing how $\mathcal{R}$ changes under different intensity conditions.

Figure 12.10 shows the variations of $\mathcal{R}$ from the standard value, as a function of the time of the event in the burst t_{event} (a), the run number t_{run} (b), half of the SPS phase¹⁰ ϕ_{SPS} (c), and the mains phase ϕ_{mains} (d). Let us take figure 12.4 as a reference for the intensity of the beam as a function the above mentioned four variables.

The effects which are accounted for the evaluation of $\mathcal{R}$ are the trigger, the mistagging and the background. The correction for $\overline{\Delta W_{LS}}$ is not applied; this introduce a bias of $3 \cdot 10^{-4}$ on average, with a maximum of $15 \cdot 10^{-4}$ during the first 300 ms in the burst. Corrections and systematic errors due to acceptance and energy scale are not included: they are not correlated to accidental effects.

From figures (a) and (c), $\mathcal{R}$ seems to have a residual dependence on intensity, at the beginning of the burst, and in correspondence of the tails of proton bunches in the SPS (see Section 8.1.3 on page 165), i.e. at $\phi_{SPS} \sim 0.2$. However this effect has

⁹due to the timestamp difference between original and the random event.

¹⁰To gain in statistics events with the same SPS phase modulo 0.5 are counted in the same bin.

no clear statistical significance.

Due to the previously established result on accidentals, no effect is expected due to accidentals; on the contrary more checks are needed on the mistagging corrections, which are also rate depending effects.

After rejecting events from the first two bins of the time of the event in the burst, the value of $\mathcal{R}$ changes by $-10 \cdot 10^{-4}$, but is still compatible with the standard value. The conclusion is that $\mathcal{R}$ is quite stable within the effective intensity ranges, shown, for instance, in figures 12.4.

Figure 12.11 shows the shift of $\mathcal{R}$ from the standard value, as is results after applying selections on the intensity of the beam. Three kind of selections are applied:

- The number of protons (PRO) at least 10 ns away from the event time, recorded by the tagger and by the halo counters, is counted to perform the selection. $\mathcal{R}$ is measured within different samples of events, selected by the number of protons (greater/less than 4, 8, and 12 protons). No systematical dependence is seen, with statistical significance;
- The number of overflows recorded in any of the DCH planes (OVFL), out of time by more than ± 325 ns from the event, is counted to perform the selection. $\mathcal{R}$ is measured in the sample of events with a number of overflows greater (less) than 1. No systematical dependence is seen;
- The number of space points (SP) in the DCH, at least 350 ns away of the event, is counted to perform the selection. No significant effect is observed when $\mathcal{R}$ is measured in the sample selected by requiring no space points.

Instead of measuring these effects, and apply the correction on $\mathcal{R}$, one could weight the events in order to balance the K_S to K_L intensity differences. In this case, an intensity indicator has to be found, which is unbiased (with the meaning as in Chapter 6); it should provide a high counting rate, and be sensible also to the highest frequency structures. No intensity indicator is found with such qualities. On the other hand, some indicators provide partial checks.

To probe the double ratio sensitivity to the lowest frequency variations of the intensity (later referred to as “long term” effects), the selected events are used in order to measure the intensity and to yield a weight. For instance, the data taking time can be subdivided into bins containing a fixed number n_L of charged K_L events

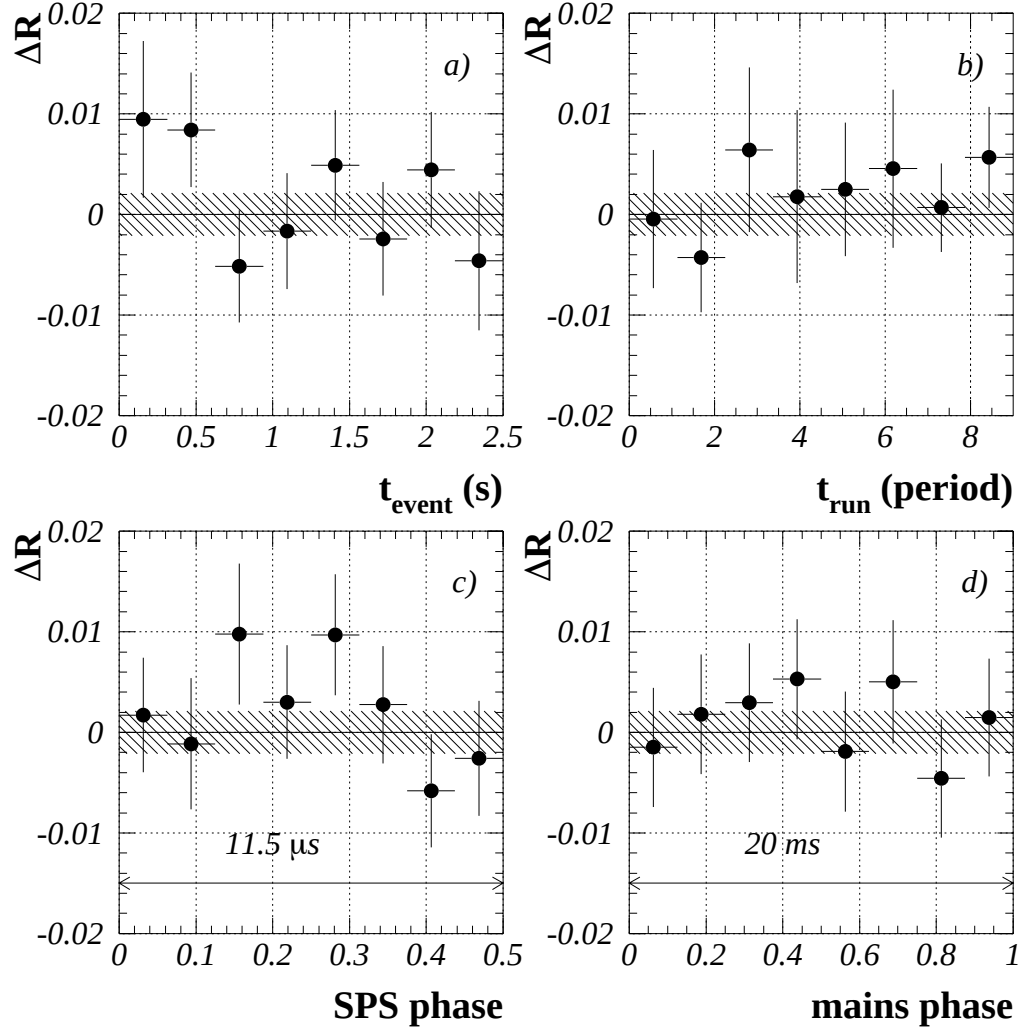


Figure 12.10: The variations of $\mathcal{R}$ measured as functions of the time of the event in the burst t_{event} (a), the run period t_{run} (b), half of the SPS phase¹¹ ϕ_{SPS} (c), and the mains phase ϕ_{mains} (d). See figure 12.6 as a reference for the foreseen shift on $\mathcal{R}$ due to accidentals.

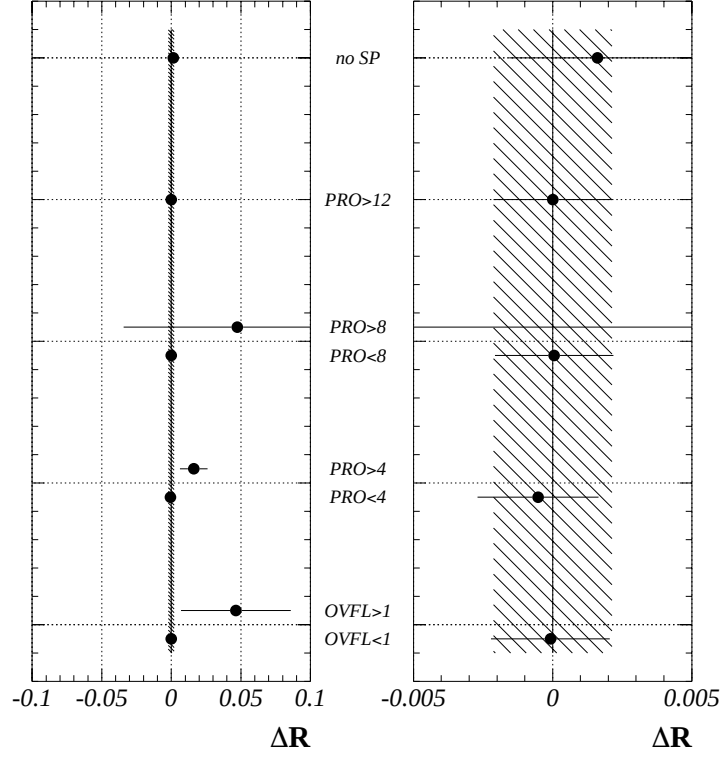


Figure 12.11: The variations of $\mathcal{R}$ resulting after applying various selections on the intensity of the beam. The number of protons, overflows, and space points in the DCH are counted as described in the text, for each event; the events are then rejected depending of the counts, and $\mathcal{R}$ measured on those samples. For example, the sample of events which have more than 4 protons recorded in the tagger (far from the event time) yield a value of $\mathcal{R}$ shifted by $-8 \cdot 10^{-4}$; this is shown in figure on the right. The two figures show the same measures, with different scales of ΔR .

(tagged by the vertex position); then for each bin, the number n_S of charged K_S events is counted and the ratio $w \equiv n_L/n_S$ is used to weight the K_S events in the bin. Figure 12.12 shows the variations of $\mathcal{R}$ measured for different choices of the bin width n_L . No dependence is found.

Notice that this check is complementary to the result of the above Method II, described in Section 12.1.2, which do not cope with the “long term” effects studied here.

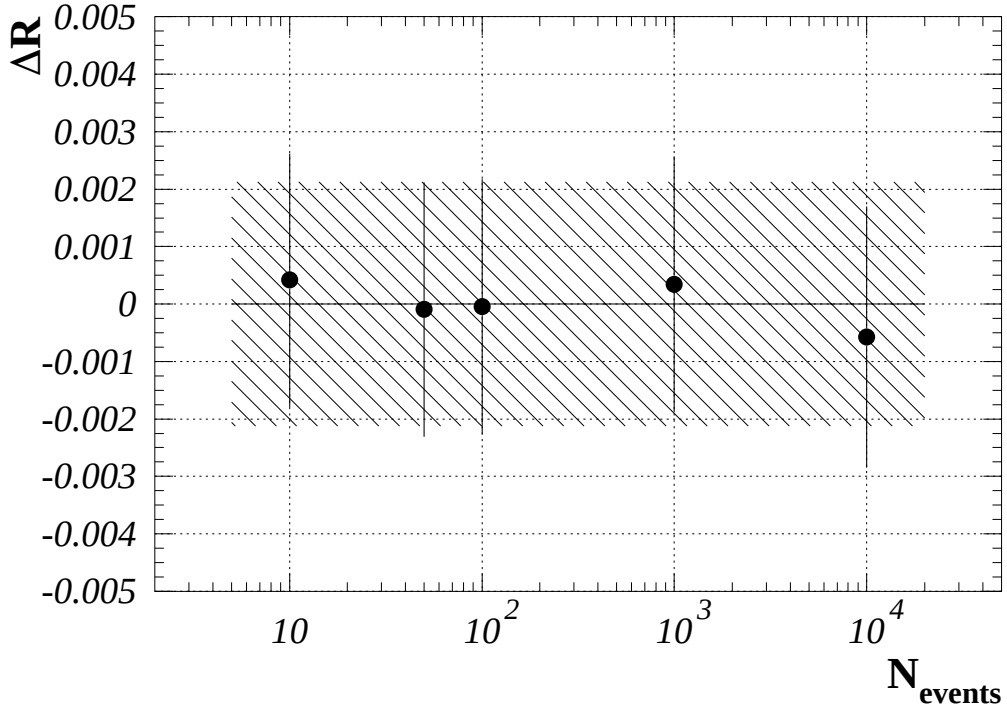


Figure 12.12: The variations of $\mathcal{R}$ measured applying a weight to the K_S events. The data taking period is subdivided into bins, which contain a fixed number n_L of charged K_L events (tagged by the vertex position); for each bin, the number n_S of charged K_S events is counted and the ratio $w \equiv n_L/n_S$ is used to weight both neutral and charged K_S events in the bin.

12.2 The accidental losses due to the differences in the spatial distribution of the $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events in the detector

Even if the actually small difference in the instantaneous intensity measured for $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events were completely negligible, accidentals could still differently affect the $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events.

The spatially distribution of the activity in the detector is slightly different between $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events even after the K_L lifetime weighting. Then, given the spatial distribution of accidental activity in the detector, the $K_{\pi\pi}^S$ and $K_{\pi\pi}^L$ events are in principle spatially correlated to it in a different way. This may result in different acceptance of the selections or efficiency of the reconstruction for K_S and K_L events. This kind of effects are referred to as **geometric accidental effects**.

The overlay technique is useful to figure out the different sources of accidental effects and it is studied first, other cross-check methods will be described later, for example.

12.2.1 Method I: the overlay technique

In order to study the difference of the losses for K_S and K_L events due to geometrical effects, the intensities seen by K_S and K_L events have to be equalized. In this case the effects due to the intensity fluctuation are the same, and only the geometrical effects remain in difference.

In principle, this would be achieved by creating the overlay sample using the same random event for the K_S and the K_L events, and make a correlate analysis¹². In practice, as a first approximation, the overlay sample is created by using both K_S and K_L type random events (“mixed” overlay analysis), almost in the same amount, and the analysis is performed without considering correlations.

Here only the overlay with the real events are analyzed. The geometrical effects with the Monte Carlo overlay are still being matter of study.

Table 12.11 shows, for the four decay modes, the overall losses. The standard selections for the ϵ'/ϵ analysis are applied. The trigger, and the event time

¹²Thus the geometric effects of the same extra-activity on a K_S event and on a K_L event would be observed.

reconstruction inefficiencies are not corrected in the overlay analysis; likewise, any mistagging effect due to the use of the overlay method is not considered.

	$K_{\pi^0\pi^0}$	$K_{\pi^+\pi^-}$
$K_{\pi\pi}^S$	$2.52 \pm 0.01\%$	3.15 ± 0.01
$K_{\pi\pi}^L$	$2.23 \pm 0.04\%$	2.98 ± 0.04
difference $\mathcal{S}/\mathcal{L}$	$0.29 \pm 0.04\%$	0.17 ± 0.04

Table 12.11: *The overall losses measures with the geometric effects analysis on the overlay events. The method is biased by many effects, as described in text.*

The results in table 12.11 show large differential effects between K_S and K_L events. A deeper analysis shows that those results are biased, and need other corrections. The sources for the inefficiency of the reconstruction, and selection, are singled out: figure 12.13, 12.14, 12.15 and 12.16 illustrate the losses, and gains, for the different decay modes.

12.2.1.1 The effect of overflows

The effect of the overflows rejection is one of the main effects in the charged modes. The probability of losing events due to the overflow is $2.68 \pm 0.01\%$ and $2.69 \pm 0.01\%$ respectively for K_S and K_L events. The values are in perfect agreement, as it is expected from other analysis. The overflows rejection does not induce geometrical accidental effects. For instance, see the cross-checks studied in Section 12.2.2.

The possibility exists that the noise of the DCH wires could enhance the losses. This kind of losses is not well managed by the overlay of the randoms with the data, and it will be studied using the Monte Carlo. One finds that the variations in time of the noise are correlated with the variations in time of the K_S to K_L ratio, but the effect is limited to $\lesssim 10^{-4}$ [106]. The geometrical correlations of the the noisy wires with the detector illumination by the KS and KL beams, can induce differential inefficiency of the spectrometer, measured at a level of $\lesssim 10^{-4}$ [62].

The difference of $(5 \pm 3) \cdot 10^{-4}$ between the values of $1.04 \pm 0.01\%$ and $0.99 \pm 0.04\%$ for measured the reconstruction efficiency in the neutral modes is then explained as a statistical fluctuation.

The inefficiency due to the overflows rejection will thus not be considered.

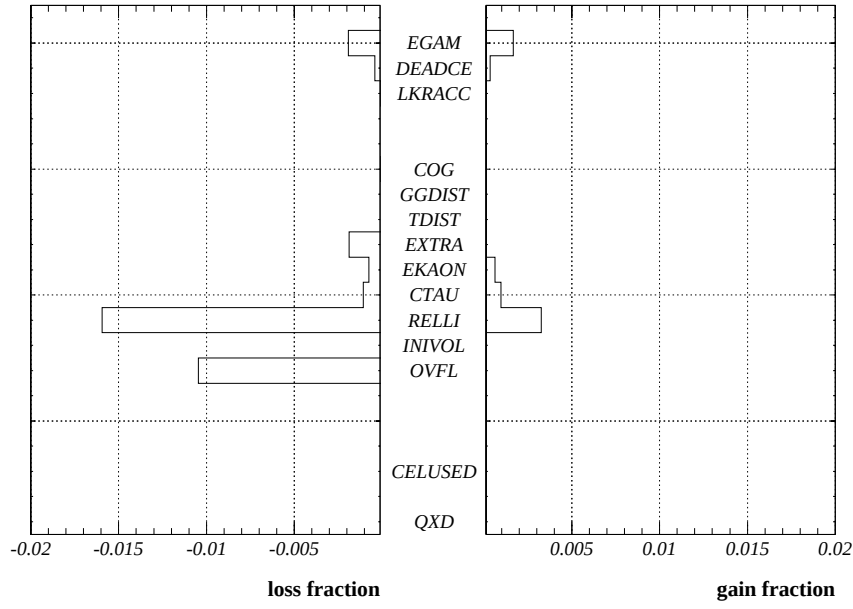


Figure 12.13: The sources of loss and gain for the $K_{\pi^0 \pi^0}^S$ neutral decay mode. The lost events are counted in the right histogram once for every selection it fails.

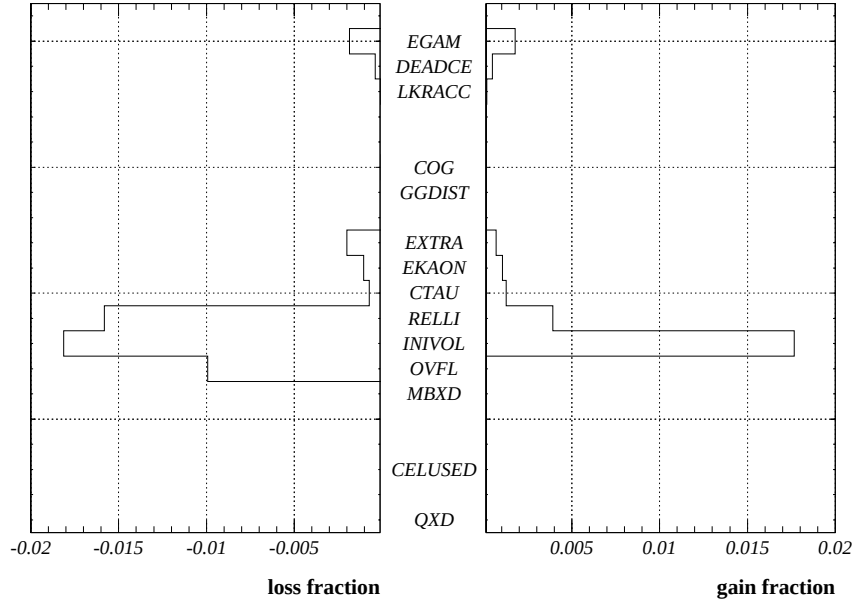


Figure 12.14: The sources of loss and gain for the $K_{\pi^0 \pi^0}^L$ neutral decay mode.

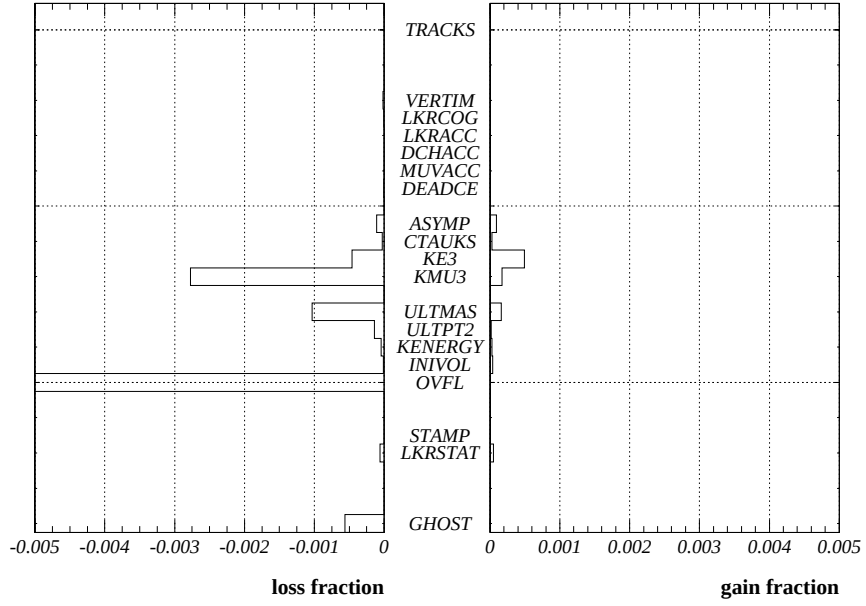


Figure 12.15: The sources of loss and gain for the $K_{\pi^+\pi^-}^S$ charged decay mode. The effect of the overflow is one of the main effect in the charged modes. The fraction of losses due to overflow is $2.68 \pm 0.01\%$. The fraction of events gained due to the $K_{\mu 3}$ and K_{e3} selections are not to be considered, due to the biases in the procedure, as it is noticed in the text.

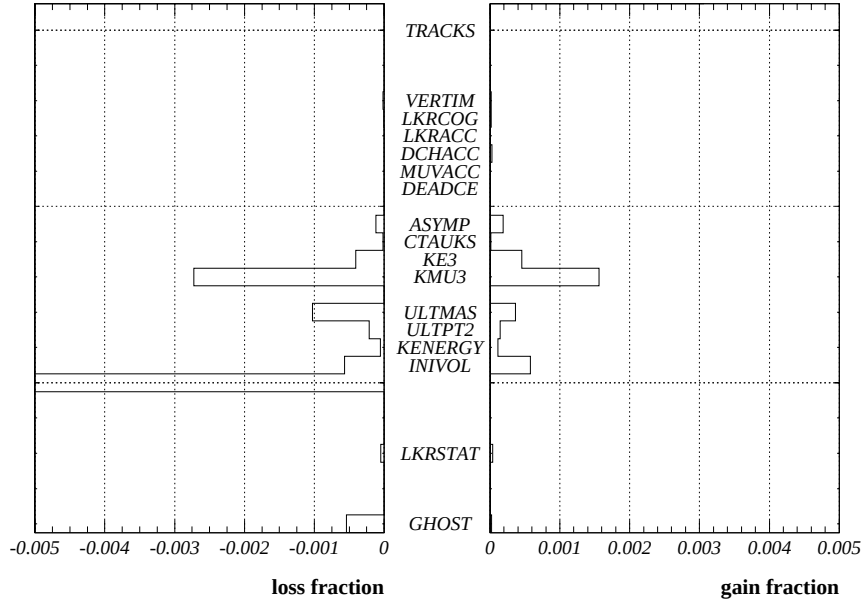


Figure 12.16: The sources of loss and gain for the $K_{\pi^+\pi^-}^L$ charged decay mode. The fraction of losses due to overflow is $2.69 \pm 0.01\%$, which is in perfect agreement with the value measured on K_S events. The fraction of events gained due to the $K_{\mu 3}$ and K_{e3} selections are not to be considered.

12.2.1.2 The charged background and the overlay

The muon hit reconstruction is based on the time of the tracks. It may happen that a $K_{\mu 3}$ decay is originally identified as $K_{\mu 3}$ event, but, after the overlay of the extra-activity is done, it is identified as $K_{\pi^+\pi^-}$ event, due to a misreconstruction of the muon track time by the MUV. This kind of events are not true gains, since before the overlay they did not belong to the true $K_{\pi^+\pi^-}$ sample, and have to be rejected.

An analogous effect is expected for true K_{e3} decays, which are identified as $K_{\pi^+\pi^-}$ events after the overlay, due to some shift of the reconstructed track position¹³ at the electromagnetic calorimeter. In this case the match between the cluster and the track is lost, and the rejection by the E/p selection fails.

Both the effects enhance the amount of background in the samples after the overlay. They can be accounted by either subtracting the different backgrounds before and after the overlay, or not considering the gains due to the background rejection criteria. The former approach is more correct, but the latter is adopted here as a first approximation.

12.2.1.3 The neutral background and the overlay

The amount of background is also enhanced in the neutral K_L mode. True background events ($K_{\pi^0\pi^0\pi^0}$ with 5 photons in the calorimeter) that were rejected before the overlay, might be accepted, after the overlay, due to a new combination of the photons into two pairs resulting in a better χ^2_{relli} of the two π^0 masses (RELLI selection). Besides, the time of one of the photons can be shifted out of the rejection interval for the in-time extra activity photons.

Therefore the gains due to the RELLI and EXTRA selections for both K_S and K_L neutral events are not considered¹⁴.

¹³Given the amount of K_{e3} and $K_{\mu 3}$ events in the control sample, this points to an inefficiency for the tracks time and position reconstruction (at least for the tracks of the $K_{\mu 3}$ muons) at the level of $\sim 10^{-3}$.

¹⁴A more detailed analysis should be performed by subtracting the neutral background on the overlayed sample.

12.2.1.4 Residual main effects and errors

Table 12.12 shows the resulting overall losses for the four decay modes. Notice that, after removing the biases due to the background, the overall losses are no more asymmetrical between K_S and K_L in both neutral and charged modes.

Although the overall amount of losses is reduced, the error in the neutral mode is still at the level of $4 \cdot 10^{-4}$ due to the selection of the beginning of the fiducial volume (INIVOL selection) in the K_L neutral mode. Even though the sum of the three terms: $\sum_i (w_i)_{loss} - \sum_i (w'_i)_{gain} - \sum_i (w'_i - w_i)_{common}$ (see eqn. 6.49 on page 135) is zero (see figure 12.14 for the gain and losses in K_L mode), the errors on the individual terms add up in quadrature.

The two main causes for the losses in the neutral decay mode are: the selection on the χ^2_{reli} of the two π^0 masses, for both the K_S and K_L modes, and the selection of the fiducial volume for the K_L mode. Both are caused mainly by the worsened resolution for the measurement of the photon energy in the electromagnetic calorimeter, due to accidental photons or noise. They can also be studied in a more naive analysis with higher statistics, as illustrated, for instance, in the Subsection 12.2.2.

Neutral K_L mode have more losses and gains than neutral K_S mode. This is understood by an average increase of energy in the electromagnetic calorimeter, due to the additional extra-activity, that shifts backward the reconstructed neutral vertex. This effect causes loss of events at the beginning of the fiducial region, and gains at its end. The losses are expected to be balanced by the gains when also the increase of the event weight ($\sum_i (w'_i - w_i)_{common}$) is accounted for. An imperfect balance may be induced by the geometrical acceptance, which depends on the longitudinal position of the decay vertex. The systematic bias, due to this effect, is expected to be smaller than the $4 \pm 4 \cdot 10^{-4}$ effect that is quoted in the following. The matter is still under investigation.

12.2.1.5 Energy dependence and bin migration

Shifts of the reconstructed energy, due to additional extra-activity, might cause event migration over energy bins. In the case those shifts are not negligible, they may couple with the small $\lesssim 10\%$ differences in shape of the K_S and K_L energy spectra, and induces a distortion of the double ratio dependence on the kaon energy (see [59][on page 79]). This effect is measured to be negligible, due to the fact that

	$K_{\pi^0\pi^0}$	$K_{\pi^+\pi^-}$
$K_{\pi\pi}^S$	$1.74 \pm 0.01\%$	0.46 ± 0.005
$K_{\pi\pi}^L$	$1.70 \pm 0.04\%$	0.47 ± 0.005
difference $\mathcal{S}/\mathcal{L}$	$0.04 \pm 0.04\%$	0.01 ± 0.01

Table 12.12: *The overall losses measures with the geometric effects analysis on the overlay events, after some biases and corrections are applied, as described in text.*

the additional accidental activity shift the energy spectrum by no more than 50 MeV, on average.

12.2.1.6 The result

The bias on $\mathcal{R}$, due to geometrical accidental effects different for K_S and K_L , is found to be at the level of:

$$\Delta\mathcal{R}/\mathcal{R}|_{\text{geometry}} \equiv \delta\lambda^N - \delta\lambda^C \sim (4 \pm 4) \cdot 10^{-4} \quad (12.11)$$

where the dominant contribution comes from $\delta\lambda^N \sim (4 \pm 4) \cdot 10^{-4}$ in the neutral mode. For the charged mode the limit is smaller: $\delta\lambda^C \lesssim 1 \cdot 10^{-4}$.

If the analysis is performed without applying the lifetime weighting to the K_L events, the losses do not change by more than $2 \cdot 10^{-4}$, which corroborates the result. Inefficiencies for K_L events do not changes in case the weighting is removed.

Other methods are envisaged to further reduce these limits, which, we feel, overestimate the actual effects. In particular, the overlay method with Monte Carlo events will be soon available, with high statistics. The overlay with the data is indeed biased by the effects of noise, and other non-linearities, which are better accounted for with the Monte Carlo overlay. Furthermore some effects can be studied in a more naive way, but with much higher statistics, as shown in the next Subsection.

12.2.2 Method II: the geometrical correlation

In order to study the accidental effects on $\mathcal{R}$ due to the K_S and K_L different geometrical correlations between the $K_{\pi\pi}$ event, and the accidental particles crossing the detector, other methods may be exploited.

For example, the effect is studied, that out-of-time tracks have on the

reconstruction of the charged pions.

Let us measure the two dimensional distribution (x, y) of the impact points at DCH1 of the tracks reconstructed in the random events. Let us convolute this distribution with the impact points of the selected charged pions, reconstructed in the $K_{\pi^+\pi^-}$ decay events. In particular, the distribution of the square distance (r^2) of the random tracks with the selected pion tracks, is determined, and later referred as to $distr_A$. Let us then measure the convolution between the selected pions tracks, found in $K_{\pi^+\pi^-}$ events, and the out-of-time accidental tracks found in the same events; this will later referred as to $distr_B$. The probability of finding an accidental track within a squared distance r^2 , from the selected pion track can be measured by normalizing to 1 the two distributions $distr_A$ and $distr_B$, and integrating them in the squared distance from 0 to r^2 . The difference between the two distributions is expected to be given by the trigger, and the reconstruction inefficiencies, induced by the presence of an accidental track next to the pion from a $K_{\pi^+\pi^-}$.

Figure 12.17,a shows the integrated distributions $distr_A$ and $distr_B$ for the selected charged K_S events. Figure 12.17,b shows their ratio. The efficiency is found to be $\sim 100\%$ in the case no accidental track is found within ~ 30 cm ($r^2 \sim 900$ cm²).

If the values of the non integrated distributions $distr_A$ and $distr_B$ are taken in correspondence to the average distance between the out-of-time track and a pion track (~ 80 cm), and their ratio is multiplied by the overall probability of finding an out-of-time track in the readout window ($\sim 3\%$), then the absolute trigger, and reconstruction inefficiency is found, due to accidental tracks. This is at the level of 10^{-3} .

The ratio of the integrated distribution ($distr_B$) for the K_S and the K_L events (dots in figure 12.17,c) is found to be compatible at the level of 1% with the ratio of the integrated distribution ($distr_A$) for the K_S and the K_L events (full line in figure 12.17,c). In other words, the losses induced on the selected events by the geometrical correlations with the accidental tracks are very low ($\sim 10^{-3}$), furthermore they are the same for K_S and K_L , well below the $\sim 10^{-4}$ level.

12.2.3 Summary and cross-checks on $\mathcal{R}$

The above result (Method I):

$$\Delta\mathcal{R}/\mathcal{R}|_{geometry} \equiv \delta\lambda^N - \delta\lambda^C \sim (4 \pm 4) \cdot 10^{-4}$$

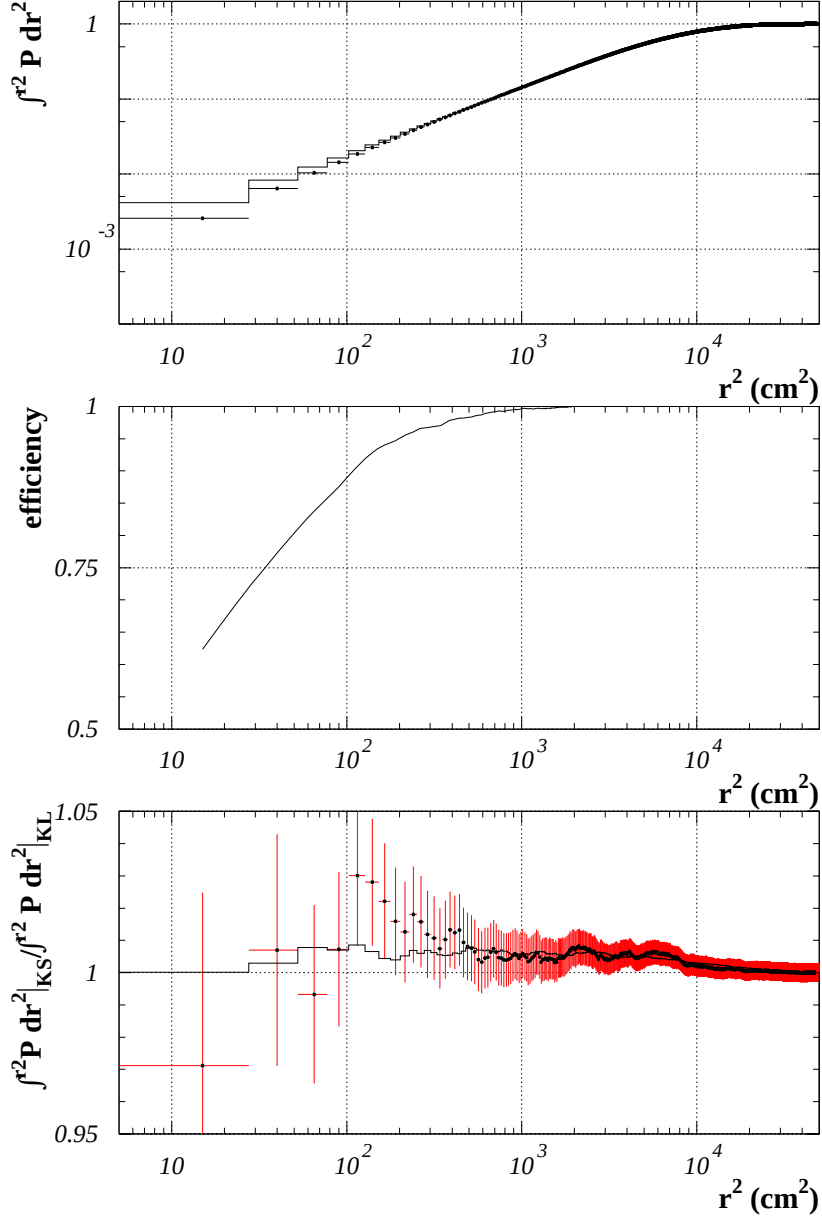


Figure 12.17: The distributions ($distr_A$) and ($distr_B$), described in the text, are shown integrated between 0 and r^2 , as a function of r^2 , for the charged K_S events in figure a. Figure b shows the ratio of the two integrated distributions. Figure c shows the ratio of the integrated distribution ($distr_B$) for K_S and K_L events (dotted distribution), and the ratio of the integrated distribution ($distr_A$) for K_S and K_L events (full line distribution).

is dominated a specific source of systematic uncertainty, namely the fiducial volume selection. It is expected that the overlay method overestimates the measurement; other cross-checks like that of Section 12.2.2 (Method II) are being studied to analyze the extra activity in the electromagnetic calorimeter, and to further reduce the systematic uncertainty $\Delta\mathcal{R}/\mathcal{R}|_{\text{geometry}}$.

Here some examples of cross-check on $\mathcal{R}$ are performed, in order to probe its stability with respect to variations of the geometrical occupancy of the accidentals.

First, if the analysis is performed without applying the lifetime weighting to the K_L events, the losses do not change by more than $2 \cdot 10^{-4}$, which corroborates the result. Inefficiencies for K_L events are unchanged if the weighting is not applied.

A cross-check on the stability of $\mathcal{R}$ with respect to the effects of extra activity is presented. The full ϵ'/ϵ analysis is performed with the additional rejection of events in which an out-of-time track is found in the upper part ($y > 0$) of the transverse plane, at the DCH1 position. The resulting $\mathcal{R}$ is compatible with the standard analysis, and with the analysis performed by rejecting events with accidental tracks in the lower part of the DCH1 ($y < 0$). Table 12.13 shows the deviations of these measurements of $\mathcal{R}$ from the average $\mathcal{R}$ measured with the standard selections.

Analysis	$\Delta\mathcal{R}(10^{-4} \text{ units})$
Rejection of accid. track with $y < 0$	0 ± 4
Rejection of accid. track with $y > 0$	-3 ± 4
Rejection of accid. cluster with $y < 0$	$+5 \pm 4$
Rejection of accid. cluster with $y > 0$	$+10 \pm 4$

Table 12.13: Cross-checks on $\mathcal{R}$ stability to accidental geometric effects. Given the measurement of $\mathcal{R}$ with the standard analysis, additional selection criteria may be imposed to the events. For instance the presence of an accidental track crossing the DCH1 in the upper (lower) semi-plane, is required to reject an events. The deviations of the cross-check measurements of $\mathcal{R}$ from the standard measurement are show to be compatible with 0, within the errors. The statistical and systematical errors which are common to both the standard measurement and the cross-check measurement errors are extracted and only the independent errors are considered.

Table 12.13 shows the results obtained for the same kind of measurements, performed by rejecting events in presence of an accidental cluster impinging onto the electromagnetic calorimeter in the upper (lower) semi-plane. The deviations of

the measured $\mathcal{R}$ are higher but still compatible with the standard measurement of $\mathcal{R}$.

Conclusions

The accidental effects on the event reconstruction and selection are analyzed. Various consistent methods are envisaged to study the accidental effects related either to the different beam intensities, or to the different illumination of the detector by the two beams.

The intensity induces a systematic bias on the measurement of the double ratio $\mathcal{R}$ which can be limited to:

$$\Delta\mathcal{R}/\mathcal{R}|_{intensity} \equiv (\lambda^N - \lambda^C) \langle \eta_A(\eta_S - \eta_L) \rangle \lesssim 2 \cdot 10^{-4} \quad (12.12)$$

the geometry results in a bias which is:

$$\Delta\mathcal{R}/\mathcal{R}|_{geometry} \equiv \delta\lambda^N - \delta\lambda^C \sim (4 \pm 4) \cdot 10^{-4} \quad (12.13)$$

which is dominated by the statistics of the random events sample.

The overall accidental effect on the double ratio $\mathcal{R}$ is thus estimated to be $\Delta\mathcal{R}/\mathcal{R} = 4.0 \pm 4.5 \cdot 10^{-4}$. Several weights, related either to the intensity, or to the geometry of the accidentals, are applied to the events in the analysis of the double ratio. $\mathcal{R}$ is very stable with respect to those weights, which points to an even smaller effect on $\mathcal{R}$.

13 The measurement of ϵ'/ϵ with 1998 data

13.1 Summary of the systematic uncertainties on $\mathcal{R}$

All the corrections and uncertainties on the double ratio are summarized in the table 13.1. The systematic related to the accidental losses includes both the uncorrelated and the correlated accidental effects, and is dominated by the geometrical effects, as explained in the previous chapter. It should be noted that all corrections on $\mathcal{R}$ are smaller than few permille, in accordance with the design of the experiment. The biggest correction, due to the accidental tagging, has a very small uncertainty ($\ll 10^{-4}$). The biggest uncertainty, namely the error on trigger efficiency for $\pi^+\pi^-$ has pure statistical nature: the knowledge of the trigger inefficiency is limited by the number of events collected with the auxiliary trigger.

13.2 The measurement of $\mathcal{R}$

The number of selected events are shown in table 4.1, which is reported below (in table 13.2). The value of double ratio before corrections is:

$$\mathcal{R}_{raw} = 0.98170 \pm 0.00171$$

where the error is the statistical one. The final double ratio $\mathcal{R}$ is computed in each bin and the various corrections are applied separately bin per bin. This yields:

$$\mathcal{R} = 0.99375 \pm 0.00171 \pm 0.00176$$

where the first error is statistical and the second is systematic (from the applied corrections). Figure 13.1 shows the result in every bin of kaon energy.

13.3 The value of ϵ'/ϵ

The double ratio $\mathcal{R}$ and the violation parameter ϵ'/ϵ are related to first order in ϵ'/ϵ by equation(2.1):

$$\mathcal{R} \approx 1 - 6 \cdot \text{Re}(\epsilon'/\epsilon) \tag{13.1}$$

then the above value of $\mathcal{R}$ yields:

$$\text{Re}(\epsilon'/\epsilon)|_{1998} = (10.4 \pm 2.9_{(\text{stat.})} \pm 2.9_{(\text{syst.})}) \cdot 10^{-4}$$

	Correction	Uncertainty
	$\times 10^{-4}$	
Charged Trigger Efficiency	+2.8	± 11.6
Neutral Trigger Efficiency	-	-
Tagging Inefficiency and Accidentals	+77.7	-
Difference N/C in Tagging Inefficiency	-	± 3.0
Difference N/C in Accidental Tagging	+11.8	± 5.3
Accidental losses	+4.0	± 4.6
Charged Background	+9.9	± 2.9
Beam Scattering	-10.0	± 3.0
Neutral Background	-4.7	± 0.9
Charged Energy and Geometry Scale	+2.0	± 2.0
Neutral Energy and Geometry Scale	-	± 7.0
Acceptance	+27.0	± 8.0
Total	120.5	± 17.6

Table 13.1: Corrections and uncertainties to $\mathcal{R}$. In order to be insensitive to the difference in the beam momentum spectra, the range used ($[70 - 170]$ GeV) in kaon energy is divided in 20 bins. The double ratio $\mathcal{R}$ is computed in each bin and the various corrections are applied separately bin per bin. Many of the uncertainties are of statistical nature, for instance the highest contribution on the overall systematic error, namely the error on trigger efficiency for $\pi^+\pi^-$, is limited by the number of events collected in the control sample. The systematic related to the accidental losses includes both the uncorrelated and the correlated accidental effects, and is dominated by the geometrical effects, as explained in the previous chapter. The sources of errors are completely independent, thus they are added in quadrature to yield the total uncertainty.

Decay mode	Unweighted	Weighted
$K_L \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$	1001443	283825
$K_S \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$	1918801	
$K_L \rightarrow \pi^+ \pi^-$	4334563	1222422
$K_S \rightarrow \pi^+ \pi^-$	8043669	

Table 13.2: The four statistical samples of the selected events.

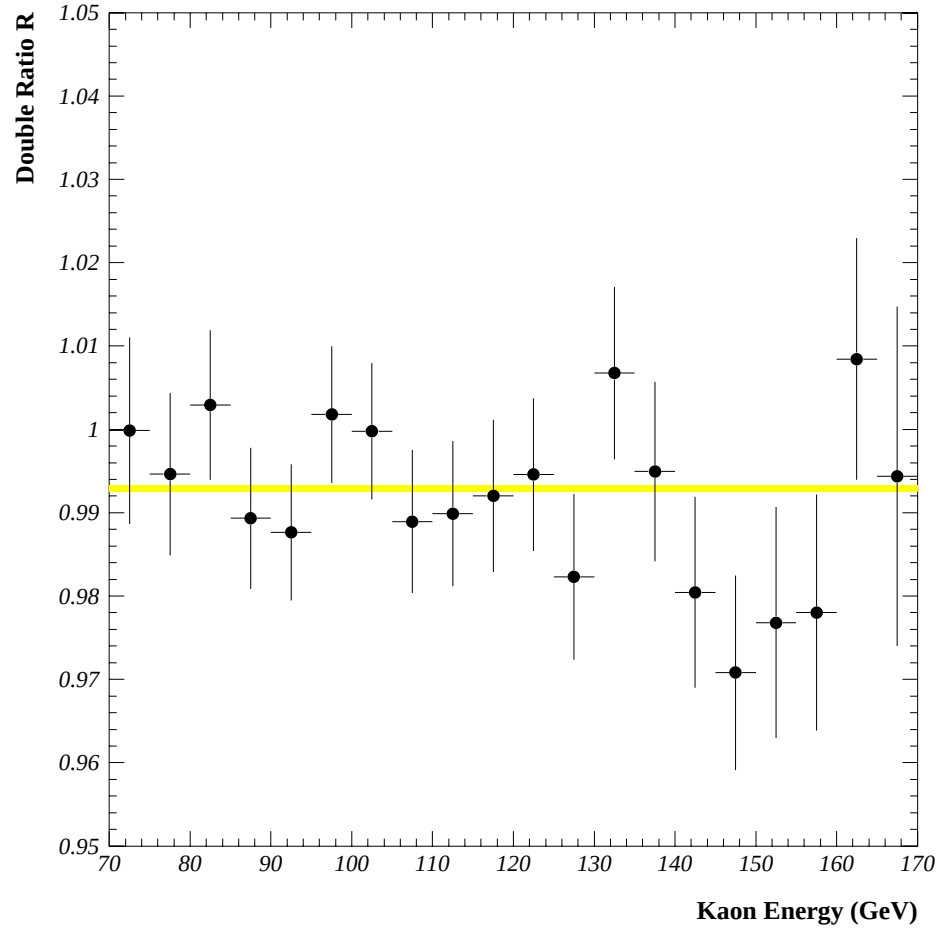


Figure 13.1: *The double ratio $\mathcal{R}$ measured in the energy bins, after all corrections are applied.*

where the first quoted error is statistical, and the second is systematic. The two errors combined in quadrature yield $4.1 \cdot 10^{-4}$, which corresponds to 2.5 standard deviations above zero. Thus on the basis of the sole 1998 data, the direct CP violation can be established with a high degree of confidence (99% CL). The result corroborates the previous measurement by NA48, based on the 1997 data:

$$\text{Re}(\epsilon'/\epsilon)|_{1997} = (18.5 \pm 4.5_{(\text{stat.})} \pm 5.8_{(\text{stat.})}) \cdot 10^{-4}$$

If the two results are combined, considering a systematic common error of $2 \cdot 10^{-4}$, they yield:

$$\text{Re}(\epsilon'/\epsilon)|_{\text{NA48 combined}} = (12.0 \pm 3.6) \cdot 10^{-4}$$

which is the most precise measurement, to date. It is shown with the previous measurements in figure 13.2.

This is equivalent to the asymmetry (see eqn. 1.20):

$$\mathcal{A}_{dir} \equiv \frac{\Gamma(K_0 \rightarrow \pi^+ \pi^-) - \Gamma(\bar{K}_0 \rightarrow \pi^+ \pi^-)}{\Gamma(K_0 \rightarrow \pi^+ \pi^-) + \Gamma(\bar{K}_0 \rightarrow \pi^+ \pi^-)} = (3.8 \pm 1.1) \cdot 10^{-6}$$

A weighted average of the above combined NA48 result, with the KTeV, NA31, and E731 measurements, gives:

$$\text{Re}(\epsilon'/\epsilon)|_{\text{world}} = (17.7 \pm 2.3) \cdot 10^{-4}$$

with a $\chi^2/ndf = 12.5/3$, which departs from 1 by a huge amount. As suggested by the PDG [65], the error is rescaled by $\sqrt{(\chi^2/ndf)} = 2$, yielding the “world” average:

$$\text{Re}(\epsilon'/\epsilon)|_{\text{world}} = (17.7 \pm 4.6) \cdot 10^{-4}$$

which is the red band of figure 13.2.

13.4 Conclusions and future

Figure 13.3 summarizes the actual perspective of the experimental measurements and the theoretical predictions of $\text{Re}(\epsilon'/\epsilon)$.

The experimental results firmly establish the direct CP violation. The 1999 NA48, and KTeV data are expected to improve the error, and fix an exact result for $\text{Re}(\epsilon'/\epsilon)$. The KLOE experiment will test the result with a different technique.

From the theoretical point of view, much work is on-going to improve the computations of the hadronic matrix elements. Even if the typical predictions

for $\text{Re}(\epsilon'/\epsilon)$ are below 10^{-3} , it is too early to say that the Standard Model accomodates the experimental result, or new physics is needed. On the other hand, the unambiguous measurements of $\text{Re}(\epsilon'/\epsilon)$ rules out the possibility that a superweak interaction is the only source of CP violation in the neutral kaon system.

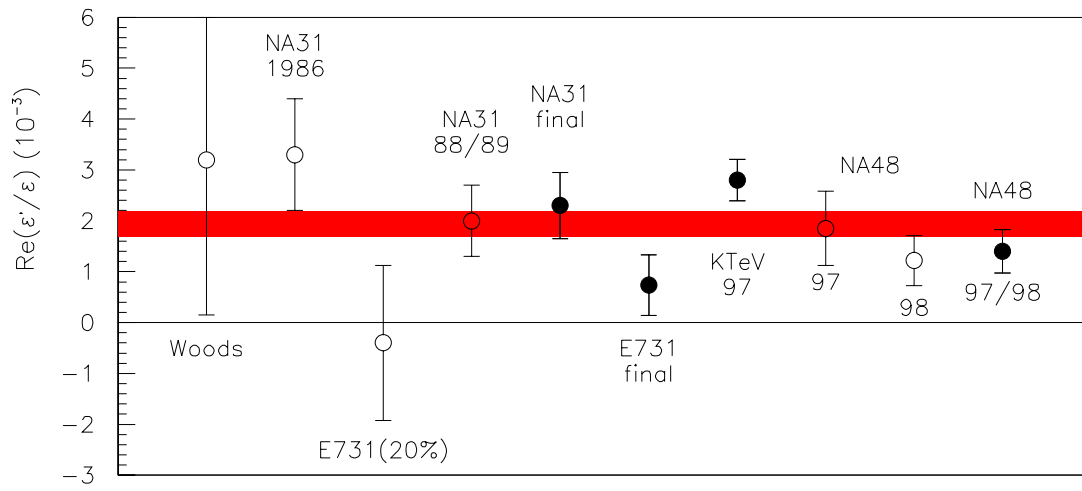


Figure 13.2: All the measurements of ϵ'/ϵ , and their “world” average (red band).

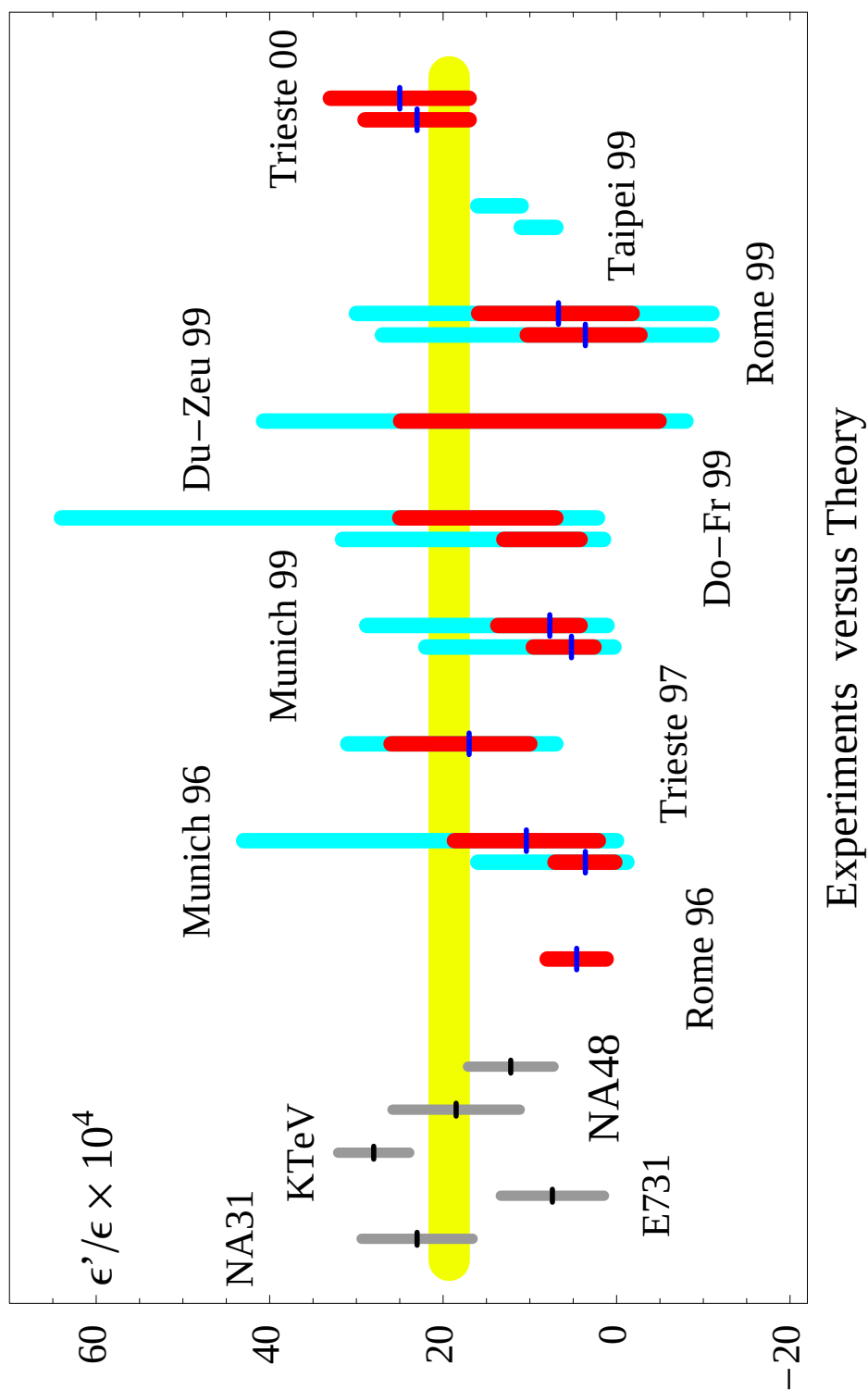


Figure 13.3: The value of ϵ'/ϵ : comparison between measurements and theoretical estimations.

Conclusions

This dissertation is devoted to an analysis of the data taken by the NA48 experiment in 1998. The first two chapters are devoted to introduce the theoretical basis of the CP violation, the NA48 experimental setup, and the principles of the measurement. The selection of data samples, the strategy of the analysis is then described.

The following chapters concern the studies of the rate effects on the measurement, which are the main subject of the thesis; they are introduced in Chapter 6. The rate effects mainly matter with the time and the space occupation of the detector by the accidental particles, which are tentatively described in Chapter 7. There, the accidental activity which illuminates the detector is found to come almost completely ($> 96\%$) from the KL beam line. The rate of the neutral particles is ~ 1 MHz, mainly given by photons. The charged particles are counted at a similar rate of ~ 1 MHz; the ratio between low multiplicity and high multiplicity events is $\sim 3 : 2$.

In Chapter 8 the time structure of the beam intensities are studied. Although the intensity fluctuations are conspicuous ($\approx 50\%$ rms), they are measured to have almost the same phase: the time auto-correlation of the KL beam ($\eta_L \eta_L \sim 0.25$) turns out to differ from the cross-correlation between the KL and the KS beams ($\eta_L \eta_S$) only by $\approx 2\%$ relative. Therefore the two beams are simultaneous to a large extent. Also the auto-correlation for the KS beam is higher than that for the KL by 10% relative.

The trigger, the reconstruction, the selection of the events, and the tagging of the kaons are deeply involved with rate effects. In order to study all these effects, the main technique exploited in this thesis is to analyze extra-activity recorded in the read-out time windows of the sub-detectors.

The trigger inefficiencies are studied in detail in Chapter 9. The charged trigger dead-time is measured to be $\lesssim 3\%$, and to exhibit a $\sim 0.1\%$ difference between K_S and K_L events. However, by symmetrizing the dead-time with the neutral events, i.e. by rejecting also the neutral events which are taken during charged trigger dead-time, the latter has no effects on $\mathcal{R}$. Once the trigger dead-time and the overflows are symmetrized, the trigger inefficiency is measured to be at the level of $\lesssim 3\%$, and to be the same for K_S and K_L events. It is found that most ($\approx 80\%$ relative) of the residual trigger inefficiency is not related to rate effects,

and hence have small impact in defining the beam intensity, which is experienced by the selected events. A small correction on $\mathcal{R}$ due to the trigger inefficiency is measured to be: $\Delta\mathcal{R} = +2.8 \pm 11.6$. The error, which is the main contribution to the systematic uncertainty on $\mathcal{R}$, has a pure statistical origin. It is determined by the amount of events recorded with the control trigger.

Chapter 10 reports about the actual understanding of the overflow condition, which is a dead-time of the DCH read-out, and affects both the trigger, and the reconstruction. The overflow in charged events happens with a probability of $\approx 26\%$; in $\approx 80\%$ of the cases, the overflow originating from high multiplicity events, while the residual 20% is due to noise of the chamber wires. For neutral events the probability is $\approx 25\%$. The effects of the overflow on $\mathcal{R}$ are much reduced by means of the symmetrization, i.e. by rejectiong both the charged and the neutral events with overflow. This avoids effects on $\mathcal{R}$ due to difference between the K_S and K_L , in the trigger efficiencies, and in the reconstruction and selection efficiencies. Notice that in presence of overflow the trigger is only $\approx 50\%$ efficient, and the reconstruction is only $\approx 45\%$ efficient. The symmetrization also balances the instantaneous intensities of neutral and charged events; thus, not only the difference in the number of lost (due to the overflow) events, but also the induced (by the overflow) intensity difference, between charged and neutral events, are much reduced. The residual $\approx 1\%$ of the charged events lost due to overflow, but not accounted by the symmetrization, is taken into account in the accidental correction to $\mathcal{R}$, which is summarized in the next chapters.

Chapter 11 describes the measurements of the effects on $\mathcal{R}$ due to accidental particles which are generated by the same primary proton which produced the kaon. The effects of this in-time background are measured, by an independent analysis, to be at the level of $\lesssim 10^{-4}$.

In Chapter 12 all the previous results are collected, and conclusions about the rate effects on $\mathcal{R}$ are drawn. It is found, by means of various methods, that the high event rate has almost negligible ($< 2 \cdot 10^{-4}$) effects on $\mathcal{R}$. This is due to the actual simultaneity of the K_S and K_L beams, and to the selection of similar intensities (by means of the symmetrization) for the charged and the neutral decay modes. Furthermore, cross-checks are performed, which show that $\mathcal{R}$ is very stable, under various intensity conditions.

Accidental effects on $\mathcal{R}$ are also studied, which can be produced by the different

spatial correlation of the K_S and K_L decays with the accidental particles. This effect on $\mathcal{R}$ is (over)estimated at the level of $(4 \pm 4) \cdot 10^{-4}$.

Finally, the measurement of $Re(\epsilon'/\epsilon)$ with the 1998 data is presented. The result, $Re(\epsilon'/\epsilon) = (10.4 \pm 4.1) \cdot 10^{-4}$, corroborates the previous measurement by NA48, $Re(\epsilon'/\epsilon) = (18.5 \pm 7.3) \cdot 10^{-4}$. The combined result

$$Re(\epsilon'/\epsilon) = (12.0 \pm 3.6) \cdot 10^{-4}$$

is equivalent to the CP violating asymmetry:

$$\mathcal{A}_{dir} \equiv \frac{\Gamma(K_0 \rightarrow \pi^+ \pi^-) - \Gamma(\bar{K}_0 \rightarrow \pi^+ \pi^-)}{\Gamma(K_0 \rightarrow \pi^+ \pi^-) + \Gamma(\bar{K}_0 \rightarrow \pi^+ \pi^-)} = (3.8 \pm 1.1) \cdot 10^{-6}$$

and is the most precise measurement to date. It establishes definitely the existence of the direct CP violation in the neutral kaon decay.

Appendix

Direct CP violation effects in neutral kaon system are relevant also for Quantum Mechanics.

In [16] it is shown that the measurement of non-zero ϵ'/ϵ is one of the best tests of the Bell's locality and allows to reject a wide class of local “hidden-variable” theories. In particular, Bell's locality is assumed and a Clauser-Horne inequality is derived for hidden-variable theories, which reproduce neutral kaon's phenomenology and comply with the stochastic independence of neutral kaon decays. Then the inequality is showed to be violated if ϵ'/ϵ is measured to be different from zero.

Let us think of a Stern-Gerlach-like experiment with a couple of correlated neutral kaons emitted by a source. They are observed by two detectors (A and B) where their decay mode is identified. In this experiment the decay mode corresponds to the directions along which the spin is measured in the more usual spin-polarization experiments. Let us identify in the detectors the decay modes $K \rightarrow \pi l \nu$, $K \rightarrow \pi^0 \pi^0$ and $K \rightarrow \pi^+ \pi^-$ (respectively referred to as a, b, c), and measure the probabilities $P(f_A, f_B)$ that a kaon is found in the final state f_A and the other one in the state f_B (where $f_{A,B} = a, b$ or c), at a proper time τ .

Let us suppose that the correlations detected in A and B are “locally explicable”, i.e. suppose that there are variables λ which, if only we knew of them, would allow decoupling of the correlation probability:

$$P(f_A, f_B, \lambda) = P(f_A, \lambda)P(f_B, \lambda) \quad (13.2)$$

By considering some probability distribution $f(\lambda)$ over these complementary variables one finds the average probability:

$$P(f_A, f_B) = \int f(\lambda)P(f_A, \lambda)P(f_B, \lambda) \quad (13.3)$$

Quantum Mechanics give predictions for these average probabilities.

It can be shown that, independently of the variables λ and of the distribution $f(\lambda)$, from eqn. (13.3) the following Clauser-Horne inequality must hold:

$$|P(a, b) - P(a, c)| \leq P(c, b) \quad (13.4)$$

at any fixed proper time τ . Then inequality can be expressed in terms of the direct CP violation parameter ϵ' as:

$$|Re(\epsilon')| \leq 3|\epsilon'|^2 \quad (13.5)$$

If ϵ'/ϵ is measured to be different from zero, then inequality eqn. (13.5) is violated. This doesn't require necessarily correlation measurements. Indeed, given the measurement of $\text{Re}(\epsilon'/\epsilon)$ by NA48 ($\text{Re}(\epsilon'/\epsilon) = (12.0 \pm 3.6) \cdot 10^{-4}$) and given the phases of ϵ and ϵ' equal to $\approx \pi/4$, it follows: $|\text{Re}(\epsilon')| = (1.9 \pm 0.6) \cdot 10^{-6}$ and $|\epsilon'|^2 = (7.3 \pm 4.3) \cdot 10^{-12}$, which allows us to establish a violation of eqn. (13.5) at a 3σ level.

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