RESULTS ON CP VIOLATION FROM THE NA48 EXPERIMENT AT CERN

LYDIA ICONOMIDOU-FAYARD
LAL, Université d'Orsay, bât. 200, 91898 Orsay, France

ON BEHALF OF THE NA48 COLLABORATION
NA48 is a Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Vienna and Warsaw collaboration

In this article the current status and latest results of the NA48 experiment at CERN are given. We present in more details the analysis performed for the Re(ε'/ε) measurement with the combined statistics accumulated during the 1998 and 1999 data periods. Reviewing the NA48 rare decay program, we select to underline the new results on the branching ratio and the a_V factor for the decay $K_L \to \pi^0\gamma\gamma$ and the $K_L \to \pi^+\pi^-$ e^+e^- CP violating decay.

1 Introduction

1.1 The NA48 experiment at CERN

The main goal of NA48 is the precise measurement of Re(ε'/ε) in the neutral kaon system. In order to achieve an accuracy of $\sim 2 \times 10^{-4}$ the optimization of the detector and beams has been conceived to allow the minimisation of the sensitivity to systematic effects. Moreover, several data taking periods have been carried out, namely in 97, 98, 99 and 2000, to accumulate adequatly large statistics. A first result was published in 1999, based on the data sample recorded during the first year [1]. A second, more precise result, was announced on May 2001, coming out from the combined 98 and 99 data and also exploiting information from the special 2000 run for checking purposes. The corresponding analysis will be presented in this article. During the summer 2001, NA48 records its last sample dedicated to Re(ε'/ε) measurement with a better beam duty cycle and new drift chambers.
The NA48 trigger bandwidth allows to record in parallel with the Re(ε'/ε) program, several rare kaon decay channels that we will review here. Some of these decays are interesting for testing Chiral Perturbation theory. Others are related to CP-Violation. Finaly, several rare modes can probe extensions of the Standard Model.

1.2 CP Violation in neutral kaons

A small non-conservation of the CP symmetry manifests in the neutral kaon system through the observation of the forbidden decay mode $K_L \to 2\pi$. Shortly after the discovery [2] the standard Model described theoreticaly the phenomenon [3]: the bulk of CP violation in the kaon system is due to the mixing of CP eigenstates K_1 and K_2, inside the physical particles K_S and K_L:

$$K_S = K_1 + \varepsilon K_2 \qquad K_L = K_2 + \varepsilon K_1$$

This main contribution to the CP Violation is called *indirect* and it is indicated by the parameter ε. A second weaker but measurable component can arise in the kaon decay process [4]: comparing the size of CP Violation in the $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$ one measures the strength of this component, called *direct* and represented by the parameter ε'. Direct CP violation is expected to be $\sim$1/1000 of the indirect component. The ratio Re(ε'/ε) is only weakly bounded by theory to be between 0 and 30×10^{-4}, essentially because of large uncertainties in the hadronic part of the computation [5]. An experimental measurement of Re(ε'/ε) accurate to few 10^{-4} becomes therefore necessary to detect direct CP-Violation.

1.3 The observables and the NA48 method

The measurable quantity $\mathrm{Re}(\varepsilon'/\varepsilon)$ is connected to the double ratio R of four decay rates as follows:

$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \Big/ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} \approx 1 - 6 \times \mathrm{Re}(\varepsilon'/\varepsilon)$$

In experimental conditions this becomes:

$$R_{exp} = \frac{Nb(K_L \to \pi^0\pi^0)}{Nb(K_S \to \pi^0\pi^0)} \Big/ \frac{Nb(K_L \to \pi^+\pi^-)}{Nb(K_S \to \pi^+\pi^-)} \approx 1 - 6 \times \mathrm{Re}(\varepsilon'/\varepsilon)_{exp}$$

where branching ratios have been replaced by the numbers of detected events in each final mode within the acceptance of the experiment. To obtain the true double ratio R one has to correct the measured R_{exp} by a factor A_{corr} which would take into account all acceptance, trigger and analysis effects, such that:

$$R_{true} = R_{exp} + A_{corr} \qquad (1)$$

In practice, measuring accurately $\mathrm{Re}(\varepsilon'/\varepsilon)$ is equivalent to measure accurately the correction factor A_{corr}. All experimental efforts will concentrate to identify, minimise and precisely quantify all possible sources of biases.

Notice that since R is a double ratio, a series of effects affecting simultaneously all four decay modes would cancel. This feature is fully exploited in NA48: $\mathrm{K}_L \to \pi^0\pi^0$, $\mathrm{K}_L \to \pi^+\pi^-$, $\mathrm{K}_S \to \pi^+\pi^-$ and $\mathrm{K}_S \to \pi^0\pi^0$ are concurrently recorded thanks to the use of two almost parallel beams. This implies that beam flux variations, trigger or detector instabilities affect similarly at least two of the four components and therefore leave the double ratio invariant at first order. Geometrical acceptance doesn't vanish in the double ratio: indeed, because of the very different K_L and K_S lifetimes and the no-similar kinematics of $\pi^+\pi^-$ and $\pi^0\pi^0$ final modes, this particular correction can reach up to $\pm$ 10% on R, depending on the kaon energy. In order to avoid a such large contribution to A_{corr}, the K_L decay spectrum is weighted to behave like the K_S one, so that the acceptance correction is minimised.

CP-conserving processes pollute to some extent the two K_L samples. These are $\mathrm{K}_L \to \pi e \nu$ and $\mathrm{K}_L \to \pi \mu \nu$ decays behaving like $\mathrm{K} \to \pi^+\pi^-$ and $\mathrm{K}_L \to \pi^0\pi^0\pi^0$ with missing or fused photons and satisfying all selection criteria of $\mathrm{K}_L \to \pi^0\pi^0$. Their effect doesn't vanish in the double ratio and has to be carefully studied. Finaly, all residual corrections have to be evaluated and combined into A_{corr}.

2 The NA48 Beams

K_S and K_L beams [6] are both produced by the 450 GeV proton beam delivered by the SPS. An amount of $\sim 1.5 \times 10^{12}$ protons per pulse hit a first berylium target located $\sim$126 m upstream of the decay volume. The outcoming beam is let flying through long collimation and bending magnets (fig. 1). This distance of $\sim$126 m is enough for the K_S component to almost completely decay, so that at the exit of the final collimator a pure K_L beam is dominating.

The protons surviving after the K_L target are deviated and sent to cross a bent crystal [7]. By tuning the incidence angle, one selects the flux of transmitted protons following the crystaline planes to be $\sim 3 \times 10^7$ per pulse. The bending acts in an only 6 cm length without cancelling the upstream deflection on other charged particles. The transmitted protons pass through a tagging station which measures very precisely the crossing time of all protons. After several deflections this beam is sent to strike a second target, located $\sim$6 m before the decay volume and 7.2 cm above the K_L beam. An outcoming K_S beam is therefore dominating the decays at the exit of the final collimator. The two, K_S and K_L, beam axes are slightly converging in order to intersect at the centre of the

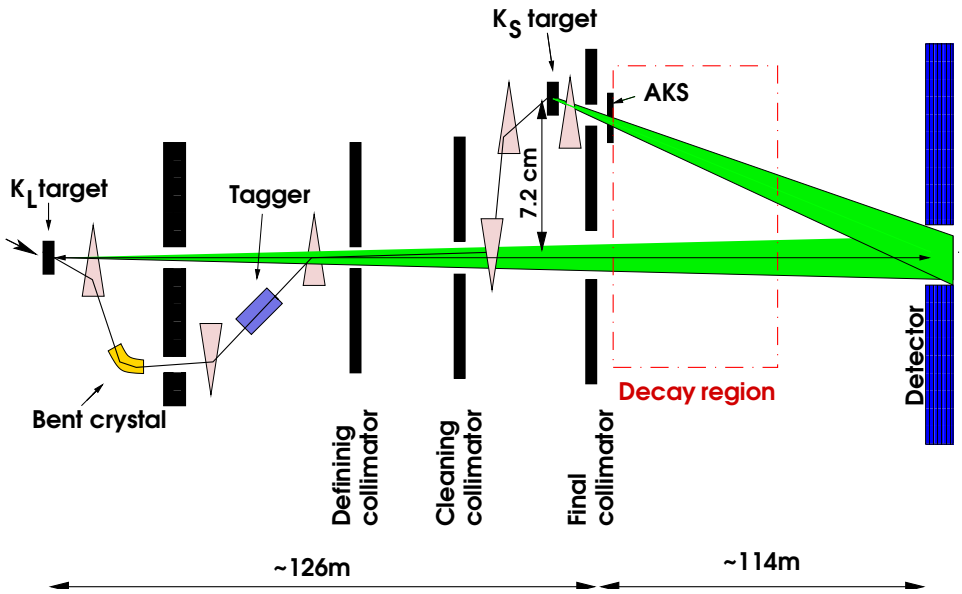

Figure 1. Schematic view of the beam lines.

detector 120 m away and illuminate similarly the sensitive NA48 volume.

Since K_S and K_L beams are both produced by the same primary proton beam they undergo the same intensity fluctuations, at first order. Beam extraction from the SPS makes that K_S/K_L ratio can vary by $\pm 10\%$ during the burst. Slower variations during the data taking periods can originate from changes in the beam steering. Along the two years the variance of the K_S/K_L intensity ratio was $\sim 9\%$. This ratio is continuously monitored and applied as weighting factor to the data to make the result insensitive to eventual unaccounted detector variations effects.

Beams are tuned such that within the decay volume the kaon energy spectra for K_S and K_L decays are similar to $\pm 15\%$ in the energy range used in the analysis, namely from 70 to 170 GeV.

3 The Detector

The NA48 detector is designed to precisely identify and reject the CP-conserving component of the K_L decays and to be able to register high rates for long periods in stable conditions.

Charged particles are measured by a magnetic spectrometer housed in a tank filled with helium. Two drift chambers are located before and two after the central dipole magnet which produce an integrated magnetic field of 0.88 Tm. This corresponds to a transverse momentum kick of 265 MeV/c. Each chamber [8] consists of eight wire planes oriented following four directions, X,Y, U and V. This allows to solve reconstruction ambiguities and to have sufficient redundancy in case of wire inefficiencies. The momentum resolution is $\sigma(p)/p = 0.48\% \oplus 0.009 \times p\%$ where p is in GeV/c. The kaon mass is reconstructed in $\pi^+\pi^-$ decays with a resolution of 2.5 MeV.

Neutral decays are measured by the LKr calorimeter [9]. This is a quasi-homogeneous device consisting of $\sim 10\ m^3$ of liquid Krypton and of readout electrodes, made of 50 μm $\times$ 18 mm $\times$ 125 cm Cu-Be-Co ribbons pulled in longitudinal projective towers pointing to the centre of the decay region. A cell is defined by an anode in between two

cathodes, such that the calorimeter is segmented in ∼13000 cells of 2×2 cm^2 section. The initial current readout technique reinforces the uniformity of the energy response and provides high rate capability. Cell-to-cell response is equalised down to 0.15% by comparing the cluster energy to the momentum measured by the spectrometer of electrons from $K_L \to \pi e \nu$ decays. The pure calorimeter resolution is found to be:

$$\frac{\sigma(E)}{E} = \frac{(3.2 \pm 0.2)\%}{\sqrt{E}} \oplus \frac{(9 \pm 1)\%}{E} \oplus (0.42 \pm 0.05)\%$$

After all corrections the energy response is linear within 0.1%. The position of a cluster is reconstructed with a resolution of 1mm in both directions.

The tagger station [10] is made of two ladders of scintillator fingers, crossing the beam horizontally and vertically. Counter widths are decreasing from 3.0 mm at the edges to 0.2 mm in the center of the ladder, following the beam profile in order to equalise the counting rates. A small overlap between two adjacent counters guarantees the complete coverage of the beam. A proton crossing the tagging station is measured by at least two counters, one in the horizontal and one in the vertical ladder. The reconstructed time per counter is known to ∼140 ps and the separation of two close protons is effective down to 4-5 ns.

At the exit of the final collimator an anticounter [11] vetoes all upstream decays of the K_S beam (AKS). Its sharp edge gives the geometrical reference used for checking the stability of the energy scale.

An hadronic calorimeter following the LKr offers energy measurement contributing to the trigger. A series of muon counters provide time information to identify $K_L \to \pi \mu \nu$ decays.

4 The analysis

The data analysis for the $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement is done in the following steps:

1. $\pi^+\pi^-$ and $\pi^0\pi^0$ decays are reconstructed
2. These two samples are then identified as originated from the K_S or the K_L beam, using the tagging information
3. The remaining 3-body background is subtracted from the K_L sample in both $\pi^+\pi^-$ and $\pi^0\pi^0$ modes
4. Corrections are applied and the corresponding systematic uncertainties are evaluated
5. The double ratio is computed and its stability with respect to several variables is checked

4.1 $\pi^+\pi^-$ and $\pi^0\pi^0$ reconstruction

Charged decays are reconstructed using the hits found in the drift chambers. Hits are combined to tracks. Tracks found in the two chambers before the magnet are extrapolated back and the decay vertex is defined as their closest distance of approach in space. The kaon energy is computed from the opening angle between the two tracks before the magnet and the ratio of two pions momenta. This method makes the measurement independent from momentum scale uncertainties. Only the distance scale is sensitive to the geometry differences between the two first chambers and also on their relative distance, contributing to the double ratio by $(2.0 \pm 2.8) \times 10^{-4}$. Time information for the decay is provided by the scintillator hodoscope with a precision of ∼140 ps.

Neutral decays are reconstructed from energies and positions of the photons measured by the calorimeter. The assumption that the invariant mass of the four photons is the kaon mass allows to reconstruct the longitudinal coordinate of the vertex. Then

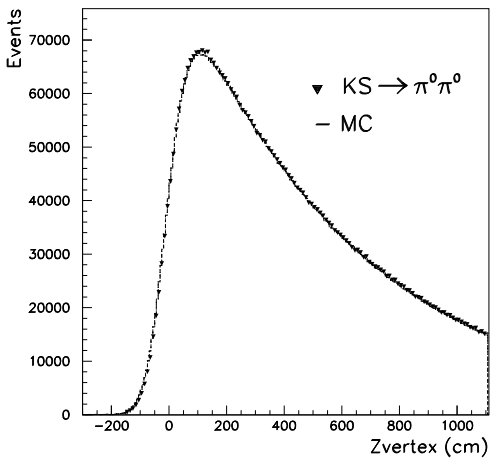

Figure 2. Distribution of the reconstructed vertex position of $K_S \to \pi^0\pi^0$ candidates. The nominal AKS position is at Z_{vertex}=0

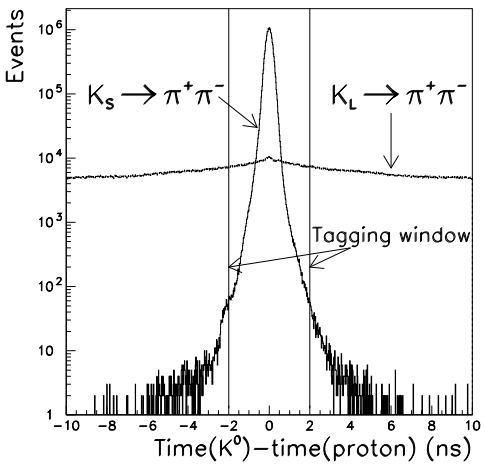

Figure 3. Distribution of the event time minus the closest proton time for $K_S \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-$ events identified from their vertex position in the vertical plane

combining the four showers to photon pairs one chooses the two closest to the nominal π^0 mass. This fully reconstructs the K$\to \pi^0\pi^0$ final modes while in case of $K_L \to \pi^0\pi^0\pi^0$ with missing photons no resonant $\gamma-\gamma$ mass is found. The calorimeter provides very precise time information for the decay. A combination of the four photon times gives the event time with an accuracy of ∼220 ps.

The decay volume is determined such that the sensitivity of the result on uncertainties -essentially related to the neutral energy scale and acceptance- are minimised. Events are accepted if the kaon energy belongs to the range from 70 to 170 GeV and if their longitudinal decay vertex position is no more than 3.5 times the K_S lifetime starting from the K_S anti-counter position. The use of a common decay volume implies that the energy and lifetime definition should be the same for $\pi^+\pi^-$ and $\pi^0\pi^0$ decays. In charged decays the scale is given by the geometry of the two first chambers as quoted above. In neutral decays, the LKr information defines both energy and vertex scales. To control the correctness and stability of the energy scale we compare the reconstructed position of the sharp AKS edge to its nominal value (figure 2). Any deviation is corrected by a global factor applied to the response of all channels. Uncertainties on the energy reconstruction are deeply studied and are related to energy leakage between close showers, non-linearities, residual energy and transverse scales and non gaussian tails [12]. The total effect on the double ratio leads to an uncertainty of $\pm 5.8\times10^{-4}$.

4.2 Distinguishing a K_S from a K_L

An event will be classified as coming from the K_S beam if a proton is found in the tagger within ±2 ns. Figure 3 shows the distribution of the event time minus its closest proton time for $K_S \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-$ identified as such from their vertex position in the vertical plane.

In case of true K_S decays, almost all events have a proton in coincidence within

± 2 ns. The small fraction of events lying outside the tagging window corresponds to time reconstruction inefficiencies and it is called α_{SL}. This will cause K_S decays to be mislabelled K_L and it must be corrected in the result. On the other hand, because of the high counting rate in the tagging station, K_L decays can accidentally have a time coincidence with a proton. The result must therefore be corrected for the fraction of K_L decays (called α_{LS}) mis-accounted as K_S. In addition the double ratio is particularly sensitive to eventual differences of α_{LS} and α_{SL} between $\pi^+\pi^-$ and $\pi^0\pi^0$ modes. Tagging misidentification factors require therefore a precise measurement in both modes.

$K_S \to \pi^+\pi^-$ decays recognised by their vertex position allow the study of *tagging inefficiency* α_{SL}. The fraction of $(1.63\pm0.03)\times10^{-4}$ of events having the closest proton time further than 2 ns (see figure 3) have been scrutinized and found to be due in $\sim$80% of cases to mis-reconstruction of the proton time. This is therefore symmetricaly affecting $\pi^+\pi^-$ and $\pi^0\pi^0$ such that the double ratio remains invariant. However an eventual efficiency difference of the event time reconstruction has to be considered between the hodoscope and the LKr calorimeter, providing information for $\pi^+\pi^-$ and $\pi^0\pi^0$ events respectively. This is studied looking at $K\to \pi^0\pi^0$ and $K_L \to \pi^0\pi^0\pi^0$ events with a photon conversion. The two electron tracks allow the time reconstruction from the hodoscope while the photons contained in the event give the decay time information from the calorimeter. The number of cases where these two time estimators differ by more than 2 ns corresponds to the differential inefficiency between the hodoscope and the calorimeter. This method allows to show that α_{SL} is identical for $K_S \to \pi^+\pi^-$ and $K_S \to \pi^0\pi^0$ with an uncertainty of $\pm0.5\times10^{-4}$. This translates to $\pm3\times10^{-4}$ uncertainty on the double ratio. This result has been crosschecked and confirmed with $\pi^0\pi^0$ data recorded with a single K_S beam and also with $K\to \pi^0\pi^0$ events with a subsequent Dalitz decay, where the track vertex reconstruction in the vertical plane provides the beam origin.

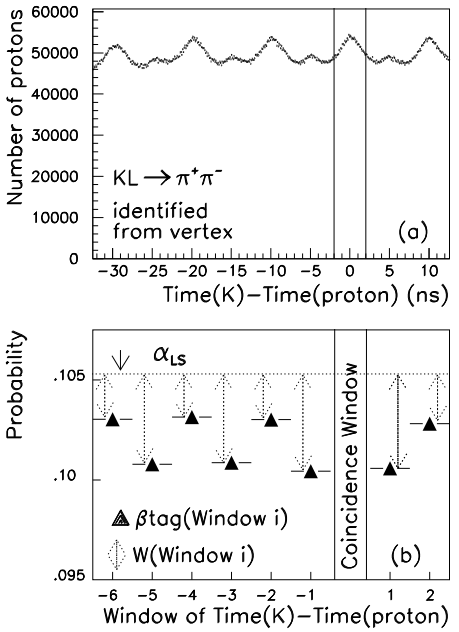

Figure 4. In (a) distribution of proton times with respect to event time for $K_L \to \pi^+\pi^-$ events identified from their vertex. In (b) variables α_{LS}, β_{tag} and W are schematically shown for tagged K_L events.

We call *dilution* the fraction α_{LS} of K_L events misidentified as K_S because of an accidental coincidence with a proton. This only depends on the proton rate in the tagger and must equally affect both decay modes. $K_L \to \pi^+\pi^-$ events recognised by their vertex allow to measure α_{LS}=(10.649$\pm$0.008)% (see figure 4.a). A direct evaluation of α_{LS} in $K_L \to \pi^0\pi^0$ decays is not possible. We use, instead of the coincidence window, out-of-time windows, 4 ns wide, in events tagged as K_L. This is done for both $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$ events, using several such windows to increase the statistical accuracy. Because K_L tagged events do not have any proton in coincidence, the dilution β_{tag} measured in lateral windows is smaller than

α_{LS} by a quantity W (see figure 4.b). W^{+-} is measured directly in $\pi^+\pi^-$ using $K_L \to \pi^+\pi^-$ identified from vertex. For W^{00} we use $K_L \to \pi^0\pi^0\pi^0$ events assuming that their tagging properties are identical to those of the $K_L \to \pi^0\pi^0$ sample. We exploited a special K_L run taken in 2000 to confirm this hypothesis. Combining all the available information we found that:

$$\begin{aligned}\Delta\alpha_{LS} &= \alpha^{00}_{LS} - \alpha^{+-}_{LS} \\ &= (\beta^{00}_{LS} + W^{00}) - (\beta^{+-}_{LS} + W^{+-}) \\ &= (4.3 \pm 1.8) \times 10^{-4}\end{aligned}$$

This difference indicates that $\pi^0\pi^0$ events are recorded in slightly higher intensity conditions than $\pi^+\pi^-$. This has been quantitatively explained by the higher sensitivity of the charged events to the accidental activity at both trigger and reconstruction levels. From these two contributions one would expect $\Delta\alpha_{LS}$ =(3.5±0.5) $\times 10^{-4}$ in good agreement with the measurement. $\Delta\alpha_{LS}$ implies a correction on the double ratio of +(8.3±3.4)$\times 10^{-4}$.

4.3 Background subtraction

K_L events contain a fraction of the 3-body decays, highly suppressed by trigger conditions and analysis cuts. In charged mode case, $K_L \to \pi\mu\nu$ and $K_L \to \pi e\nu$ events can mimic good $\pi^+\pi^-$ decays if the electron or the muon is not recognised by the E/p variable or the muon vetoes respectively. Because of the undetected neutrino of these 3-body modes the missing transverse momentum of the decay, $P_T^{'2}$, is larger than in a $\pi^+\pi^-$ event (see figure 5). Moreover the reconstructed 2-track invariant mass follows different distributions than in $\pi^+\pi^-$. Studying the correlation of $P_T^{'2}$ versus $M_{\pi^+\pi^-}$ in different control regions for $\pi^+\pi^-$, $K_L \to \pi\mu\nu$ et $K_L \to \pi e\nu$ identified samples, allows to determine the contamination of the signal region.

We found that the $K_L \to \pi^+\pi^-$ sample contains after all cuts 16.3×10^{-4} of 3-body residual background, dominated by

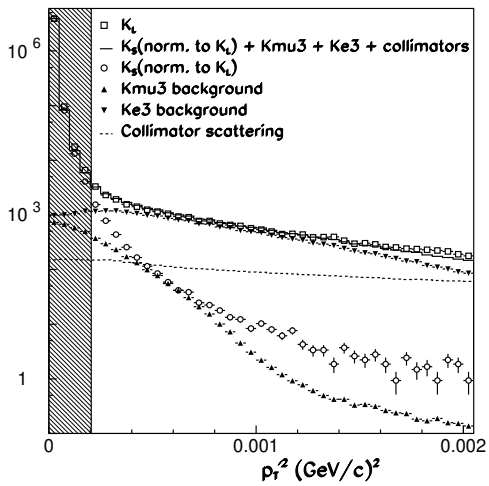

Figure 5. Distribution of tranverse momentum $P_T^{'2}$ and comparison of the data with all known components. The signal region is defined for $P_T^{'2} < 0.0002 GeV/c^2$

$K_L \to \pi e\nu$. The corresponding correction on the double ratio is (16.8±3.0)$\times 10^{-4}$ where the error takes also into account systematic variations related to the control region choices. Notice that $P_T^{'2}$ is the component of the tranverse momentum which is orthogonal to the kaon line of flight, reconstructed in DCH1 and assumed to come from the target. The advantage of this definition is to equalise the distributions for K_S and K_L decays despite the very different positions of the corresponding targets. Only a small asymmetry of $\leq 2 \times 10^{-4}$ remains between the two beams because of no gaussian tail effects.

When $K_L \to \pi^0\pi^0\pi^0$ events have two photons either escaping acceptance or fused, the two reconstructed invariant $\gamma - \gamma$ masses do not agree with the nominal π^0 one. This is observed looking at a χ^2 variable testing this compatibility as shown in figure 6. In $K_L \to \pi^0\pi^0$ candidates an excess of events is observed for high values of χ^2 with respect to $K_S \to \pi^0\pi^0$, where the existing tail corresponds to events with converted photons or with hadronic photoproduction. The amount

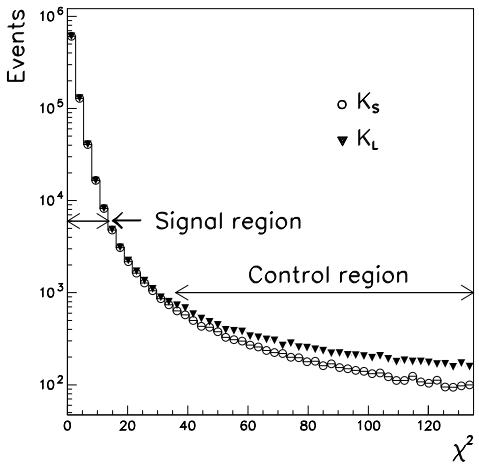

Figure 6. The χ^2 distribution for tagged $K_L \to \pi^0\pi^0$ and $K_S \to \pi^0\pi^0$ candidates

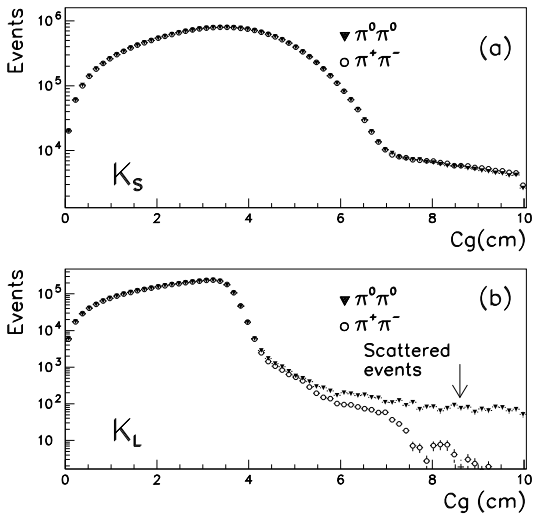

Figure 7. Centre of gravity distributions for K_S and K_L events after all cuts.

of remaining background in $K_L \to \pi^0\pi^0$ is checked in a control region, properly subtracting the normalised K_S from the K_L integrated population. The extrapolated fraction of 3-body pollution under the $\pi^0\pi^0$ signal results to a correction on the double ratio of $(-5.9\pm2.0)\times10^{-4}$.

K_S beam is free from physical background. The $\Lambda \to p\pi^-$ decays are eliminated down to $\leq 10^{-4}$ level, by a track momentum asymmetry cut applied to both beams.

Kaon scattering in the inner edges of the collimators may modify the kinematics of an event. In K_S beam, scattering may happen at the level at the final collimator and also when kaons cross the anticounter. In both cases, the transverse momentum of the event is enhanced. After all cuts, the amount of scattered events in the final sample is almost identical in $\pi^+\pi^-$ and $\pi^0\pi^0$ modes: the halos of centre of gravity distributions, populated by the halo of the beam and the scattered events, are very similar, as shown in figure 7.a. In K_L case, kaons or accompanying neutrons in the halo of the beam can scatter or double-scatter in the aperture of the collimators, producing in some cases a K_S component. K_S particle decays are indeed observed in K_L beam at high transverse momenta accumulating around the kaon invariant mass: they all originate from the lips of the two last collimators and they decay with the K_S lifetime. These scattered events are asymmetrically rejected in $\pi^+\pi^-$ and $\pi^0\pi^0$ modes as indicated by the different halos of the centre of gravity distributions (figure 7.b). The corresponding correction is computed to be $(-9.6\pm2.0)\times10^{-4}$ on the double ratio.

4.4 Double ratio, corrections and systematics

After all cuts, tagging and background corrections we obtained for the combined 98+99 data periods a statistics of 3.29M of $K_L \to \pi^0\pi^0$, 5.21M of $K_L \to \pi^+\pi^-$, 14.45M of $K_S \to \pi^0\pi^0$ and 22.22M of $K_S \to \pi^+\pi^-$decays. Before combining these four samples to obtain the double ratio one

has to apply some corrections. The method of the double ratio and the simultaneous data taking of the four modes implies that most of the effects cancel in the result at first order. Eventual differential effects can survive and have to be considered. Such are for instance the tagging corrections presented in 4.2. Another effect concerns trigger inefficiencies. In charged mode, $\sim$ 2% of the events are lost at the trigger level essentially because of wire inefficiencies and of information spoiled in presence of accidentals. This amount is identical between K_S and K_L down to (-3.6±5.2)$\times 10^{-4}$. The neutral trigger is efficient to 99.920±0.009% level with no measurable K_S -K_L difference. Dead times are applied commonly in all four modes in order to guarantee cancellation and identical intensity conditions.

The high rates of the K_L beam makes occasionally possible the mismeasurement of a good event because of additional activity. This may create losses of good events. The high correlation of beam variations between K_S and K_L together with the concurrent data taking lead to no observable bias on the double ratio due to accidental losses within a $\pm 4.2\times 10^{-4}$ uncertainty.

A no cancelling effect in the double ratio is the acceptance correction. K_S and K_L acceptances are not identical because of the very different corresponding lifetimes. To avoid a correction on R as large as ±10% depending on the kaon energy, we choose to weight the K_L decay spectrum by the ratio between K_S and K_L decay intensities into $\pi\pi$ taking into account the interference term as well. This procedure makes by definition the detector to be illuminated similarly by the two beams. A small residual effect is due to the 0.6 mrad convergence angle between K_S and K_L beam lines, causing an acceptance difference in $\pi^+\pi^-$ events essentially in the first chamber around the beam pipe (see figure 8). This is evaluated using a large statistics Monte Carlo simulating the two

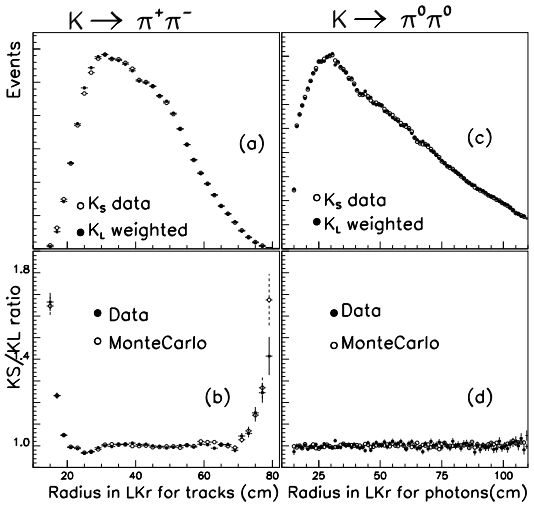

Figure 8. Illumination of the calorimeter by $\pi^+\pi^-$ tracks for K_S and weighted K_L events in (a). The K_S/K_L ratio is shown in (b) where the residual effect around the beam pipe is seen. In neutral mode K_S and weighted K_L decays illuminate similarly the calorimeter (shown in c and d). The distributions are shown for events in a kaon energy range from 95-100GeV

beams and detector geometry, parametrising particle interactions and using a photon shower library generated by GEANT. The correction on the double ratio is found to be (+26.7±4.1(stat)±4.0(syst))$\times 10^{-4}$. The systematic error accounts for uncertainties on beam halo variations, beam shapes, particle interactions in charged mode and wire inefficiencies.

In table 1 we give all corrections applied to the double ratio R_{exp} and their uncertainties. The double ratio is corrected by A_{corr}=(35.9±12.6)$\times 10^{-4}$, the biggest effects coming from acceptance, charged background, scattering and tagging. The quoted errors account for both statistical and systematic uncertainties and in some cases are still statistically limited.

The double ratio is computed in 20 bins of 5 GeV in kaon energy in order to further decrease the effect of the remaining energy spectra difference between K_L and K_S. All

Table 1. Table of corrections applied to the double ratio with their uncertainties

		in 10^{-4}	
Trigger inefficiency in $\pi^+\pi^-$		-3.6	$\pm$ 5.2
AKS inefficiency		$+1.1$	$\pm$ 0.4
Reconstruction effects	of $\pi^0\pi^0$	—	$\pm$ 5.8
	of $\pi^+\pi^-$	$+2.0$	$\pm$ 2.8
Background subtraction	to $\pi^0\pi^0$	-5.9	$\pm$ 2.0
	to $\pi^+\pi^-$	$+16.9$	$\pm$ 3.0
Beam scattering in K_L		-9.6	$\pm$ 2.0
Accidental tagging		$+8.3$	$\pm$ 3.4
Tagging inefficiency		—	$\pm$ 3.0
Acceptance correction	statistical	$+26.7$	$\pm$ 4.1
	systematic		$\pm$ 4.0
Accidental activity		—	$\pm$ 4.4
Long term intensity variations of K_S/K_L		—	$\pm$ 0.6
Total A_{corr}		$+35.9$	$\pm$ 12.6

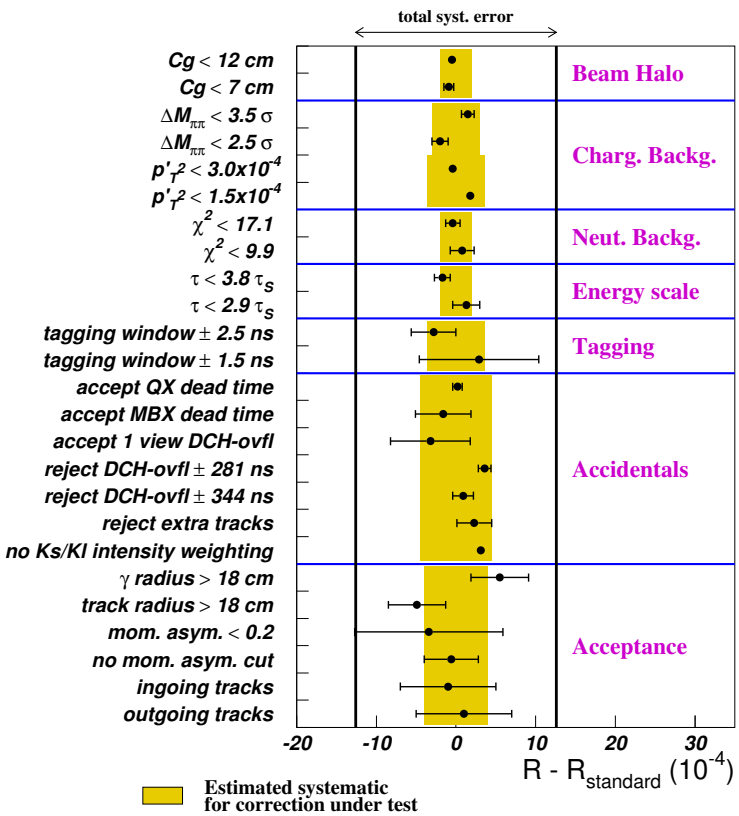

Figure 9. Stability of the double ratio when varying selection criteria

corrections are applied in bins and the 20 values are averaged using an unbiased estimator. The result is:

$$R=0.99098\pm0.00101(stat)\pm0.00126(syst)$$

A large number of systematic checks were devoted to verify the stability of the result with a change in the event selection. We cumulate the output of the most important tests in figure 9 where the deviations of the double ratio with respect to its standard value are shown for a series of modifications we did in the procedure. All these checks demonstrated the stability of the result within the allowed systematic range. Moreover, the result was found to be stable with the data taking time , time within the burst, proton revolution phase in the SPS, magnetic field sign in the spectrometer and 50 Hz phase.

The corresponding $Re(\varepsilon'/\varepsilon)$ value on 98+99 data [13] is obtained subtracting R from 1 and dividing by six:

$$Re(\varepsilon'/\varepsilon)=(15.0\pm1.7(stat)\pm2.1(syst))\times10^{-4}$$

which, combined with the published 97 result gives:

$$Re(\varepsilon'/\varepsilon)=(15.3\pm2.6)\times10^{-4}$$

This result confirms the existence of a direct CP-Violating component in the neutral kaon decays at the level of 5.9σ. The 2001 new world average, combining the four most precise experimental results from NA31 [14], E731 [15], KTeV [16] and the combined 97+99+99 NA48 value becomes:

$$Re(\varepsilon'/\varepsilon)=(17.2\pm1.8)\times10^{-4}$$

5 Review of the NA48 rare decay program

Several K_S and K_L rare decay channels have been looked at in NA48. Table 2 gives a non exhaustive list of observations or limits obtained with NA48 data. We will concentrate here on two results concerning the recently

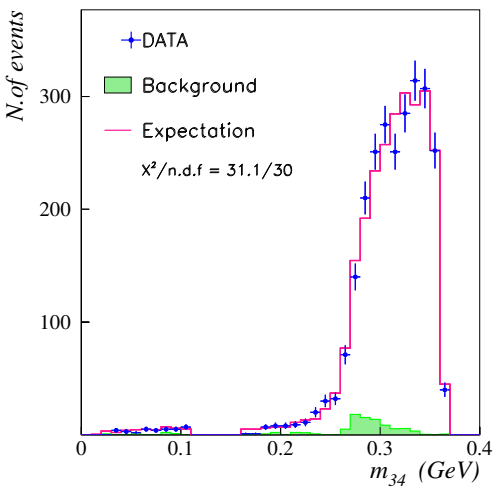

Figure 10. Distribution of the invariant $\gamma-\gamma$ mass, M_{34}, of the non resonant photons

updated analysis of $K_L\to\pi^0\gamma\gamma$ and the CP-Violating mode $K_L\to\pi^+\pi^-e^+e^-$. More information on rare decays in NA48 can be found in references [17].

5.1 $K_L\to\pi^0\gamma\gamma$

The interest of this mode resides in the fact that, in Chiral Perturbation Theory one needs to include $O(p^6)$ calculations and vector meson contribution to reproduce the observed rate. These two terms account actually for 1/3 of the total amplitude. Moreover the measurement of this decay gives constraints to the CP conserving amplitude contributing to $K_L\to\pi^0e^+e^-$, via a two photon intermediate state.

The reconstruction of this mode uses information of the LKr. An event must contain one $\gamma-\gamma$ pair compatible with π^0 mass and a second $\gamma-\gamma$ pair not compatible. The main background comes from $K_L\to\pi^0\pi^0$ and $K_L\to\pi^0\pi^0\pi^0$ decays. $K_L\to\pi^0\pi^0$ with a photon conversion before the magnet destroys the π^0 reconstruction. These cases are rejected requiring no hits in the first three drift chambers. $K_L\to\pi^0\pi^0\pi^0$ decaying in-

Table 2. List of some of the rare decays results obtained in NA48

Mode	Branching ratio	Events	Status
$K_L \to \pi^0\gamma\gamma$	$(1.36\pm0.05)\times10^{-6}$	2588	preliminary
$K_S \to \pi^0$ e^+e^-	$< 1.4 \times 10^{-7}$ (90% CL)		published
$K_S \to \gamma\gamma$	$(2.58\pm0.42)\times10^{-6}$	149	published
$K_S \to \pi^+\pi^-e^+e^-$	$(4.3\pm0.4)\times10^{-5}$	921	preliminary
$K_L \to \pi^+\pi^-e^+e^-$	$(3.1\pm0.2)\times10^{-7}$	1337	preliminary
$K_L \to e^+e^-e^+e^-$	$(3.7\pm0.4)\times10^{-8}$	132	preliminary
$K_L \to e^+e^-\gamma$	$(1.06\pm0.05)\times10^{-5}$	6864	published
$K_L \to e^+e^-\gamma\gamma$	$(6.3\pm0.5)\times10^{-7}$	492	preliminary

side the collimator can fake the signal. Dedicated variables have been studied to reduce this background to a small level. In total we have a signal of 2588 events found in the 98+99 data sample, with an estimated background of only 3.3%. The distribution of the invariant $\gamma - \gamma$ mass for the non resonant photon pair is shown in figure 10. The low mass region ($M_{\gamma\gamma} < 260$ MeV) is particularly sensitive to the amount of vector meson production, represented by the coupling constant a_V. Fitting our data with a likelihood function including the shape predicted by χPT calculations up to $O(p^6)$ and for several a_V values, we found the best χ^2 for:

a_V=-0.46±0.03(stat)±0.04(syst+theory)

Using this coupling constant we obtain the following branching ratio:

BR($K_L \to \pi^0\gamma\gamma$)=
(1.36±0.03(stat)±0.4(syst))×10^{-6}

where the systematic error is shared between experimental and theoretical uncertainties. A publication is in preparation.

5.2 $K_L \to \pi^+\pi^- e^+ e^-$

CP Violation appears in the kaon system through small quantities, namely ε∼0.2% and $\varepsilon' \sim 10^{-6}$. The $K_L \to \pi^+\pi^-e^+e^-$ decay demonstrates that K_L can also exhibit strong CP-violating phenomena. Indeed, this channel arises through two diagrams essentially: the inner-breamsstrahlung, violating CP, and the direct emission, CP conserving process. Because the ratio of these two contributions is almost one ($\sim \eta\times(2M_K/E_\gamma)^2$ where E_γ is the virtual photon energy in the centre of mass), the interference is enhanced. Looking at the angle ϕ between the $\pi^+\pi^-$ and e^+e^- planes one can observe strong CP asymmetries.

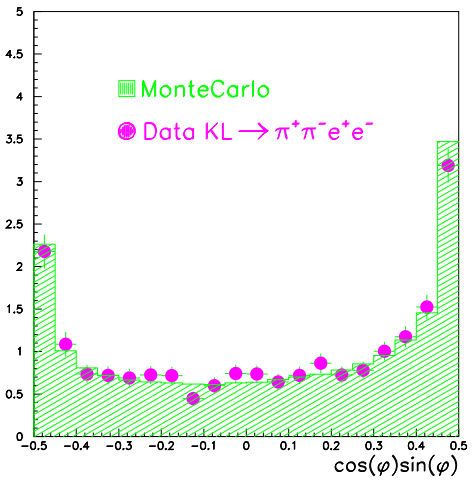

Figure 11. Cos(ϕ)sin(ϕ) distribution for $K_L \to \pi^+\pi^-e^+e^-$ decays

We detected 1337 events after all cuts. The cos(ϕ)sin(ϕ) distribution is shown in figure 11 where it is also compared with Monte Carlo simulation. After acceptance correc-

tions the measured asymmetry is:

$$A=(13.9\pm2.7(stat)\pm2.0(syst))\%$$

The branching ratio of this decay is found to be:

$$BR=(3.1\pm0.1(stat)\pm0.2(syst))\times10^{-7}$$

The measured asymmetry is in agreement with theoretical predictions and previous results [19]. Moreover NA48 detected the first signal of $K_s \to \pi^+\pi^-e^+e^-$ decays [20]. This mode conserves CP symmetry. It allows therefore to check eventual effects of final states interactions on the $\cos(\phi)\sin(\phi)$ distribution, in which case, the K_L mode would have been also affected. In K_S beam we measured an asymmetry compatible with zero, based in a sample of 921 events. The observed asymmetry of 13.9% in $K_L \to \pi^+\pi^-e^+e^-$ decays is therefore only due to the indirect CP Violation present in this rare process.

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