First result on $\mathrm{R}e(\varepsilon'/\varepsilon)$ measurement from the NA48 experiment at CERN

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1 Introduction

The breakdown of CP symmetry and time-reversal symmetry [1] has been observed so far only using decays of the neutral kaons [2], and is mainly manifested in the mixing of the two CP eigenstates, parametrized by ϵ, and caused by an effective $\Delta S = 2$ interaction [4]. In the context of the Standard Model, CP violation arises in the Higgs sector [3] as a universal feature of weak interactions, and direct CP violation in the decay amplitudes $K_L \to 2\pi$, parametrized by ϵ', is also predicted.

Computations of ϵ'/ϵ within the Standard Model [5] mostly fall in the range $(0 \div 10) \cdot 10^{-4}$ [6].

To first order in the small parameter $|\epsilon'/\epsilon|$, the measurable double ratio of decay widths is

$$R \equiv \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \simeq 1 - 6\,\mathrm{Re}(\epsilon'/\epsilon)$$

Two previous measurements of $\mathrm{Re}(\epsilon'/\epsilon)$ were only marginally consistent: experiment NA31 at CERN [7] measured $(23 \pm 6.5) \cdot 10^{-4}$, showing evidence of direct CP violation, while experiment E731 at FNAL [8] measured $(7.4 \pm 5.9) \cdot 10^{-4}$, consistent with no effect. A recent result from Fermilab experiment E832 [9] supports the presence of direct CP violation: $(28.0 \pm 4.1) \cdot 10^{-4}$.

The NA48 collaboration at CERN has recently obtained a new measurement of $\mathrm{Re}(\epsilon'/\epsilon) = (18.5 \pm 7.3) \cdot 10^{-4}$ from the above double ratio, based on the first data collected by the experiment. The event statistics on which this result is based represents $\approx 10\%$ of the total amount expected at the end of the experiment.

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2 The NA48 technique

The double ratio measurement exploits the cancellation of several effects, thus allowing a good control of systematic uncertainties. In NA48 the four decay modes are collected simultaneously in the same decay region, therefore minimizing the sensitivity to accidental activity and variations of beam intensity and detection efficiencies. K_L and K_S decays are provided by two quasi-collinear neutral beams, produced by protons hitting two targets at different distances from the detector.

The K_L and K_S decay momentum spectra are made similar by the choice of targeting angles, and residual differences are accounted for by performing the analysis in small kaon energy bins.

The difference in longitudinal decay position spectra (lifetime) leads to asymmetric acceptance differences between charged and neutral modes. This issue is addressed by collecting K_L and K_S decays only in the region where both are present, and by weighting the K_L events in the analysis with a function of their proper time of decay. In such a way, at the loss of some statistical power, the longitudinal decay position distributions are made equal for 2π decays originating from either beam, achieving a good cancellation of acceptance differences, and thus avoiding large corrections - which would require relying on very accurate modelling and simulations of the apparatus.

The above minimization of biases and corrections represents the general approach of the NA48 experiment, and is consistently applied wherever it is relevant.

2.1 Beams and K_S tagging

The K_L beam is produced by $1.1 \cdot 10^{12}$ protons slow extracted from the SPS during each 2.4 s spill (450 GeV/c momentum) impinging on a beryllium target located 126 m upstream of the beginning of the fiducial decay region; the effect of the small K_S component in this beam is only significant at energies above 140 GeV.

A small fraction of the non-interacting protons ($3 \cdot 10^7$ per pulse) is deflected towards a second target, similar to the first and located 6 m upstream of the beginning of the fiducial region, by exploiting *channelling* on a single bent crystal [10]. On its way to this K_S production target, the proton beam crosses an array of scintillator counters. This device [11] measures the time of passage of individual protons with 120 ps resolution and $\simeq$ 4 ns double-pulse separation, and is used to *tag* the K_L or K_S character of a decay, by comparing the event time, as reconstructed by the detectors, with the time of the closest proton on this beam line.

The neutral beam emerging from the second target, producing mostly

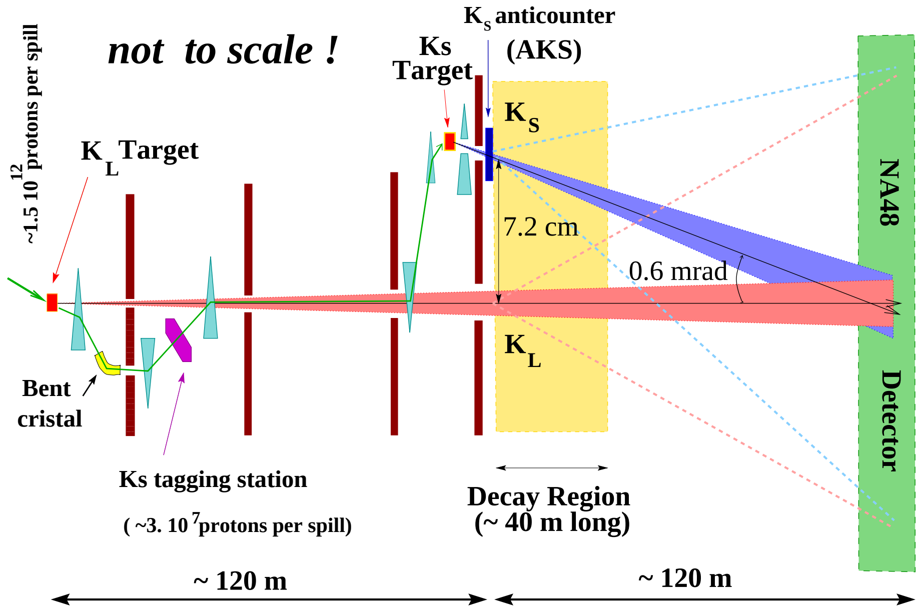

Figure 1: Schematic drawing of the NA48 beam setup.

K_S (and hyperon) decays, crosses a scintillator veto counter (AKS) preceded by an iridium crystal converter, which defines the upstream end of the decay region.

The two neutral beams converge in the centre of the detector at a 0.6 mrad angle, travelling in vacuum in order to reduce hit rates and accidental effects.

2.2 Detector and performance

To collect the large amount of events required, while minimizing the amount of background events, fast and high-performance detectors and trigger systems are used, with fully pipelined and dead-timeless readout.

$K_{L,S} \rightarrow \pi^0\pi^0$ decays are detected in a fine-grained quasi-homogeneous liquid krypton calorimeter, working as an ionization chamber with longitudinal tower structure [12]. By exploiting projective geometry, the calorimeter allows to measure angles between photons independently of their initial conversion depth.

The initial current induced by the ionization drift on copper ribbon electrodes in the ≈ 13000 2×2 cm^2 cells is read and continuously flash-digitized at 40 MHz, allowing for a fast response and an intrinsic time resolution better than 300 ps for photon energies above 20 GeV.

During 1997 the calorimeter had to be operated at reduced electrode voltage, resulting in a slightly worse signal to noise ratio and a small ($\approx$

0.5%) correction for space charge accumulation; moreover, a 4 cm wide column of cells was not powered, giving a $\approx 20\%$ acceptance loss.

The energy resolution measured in 1997 was $\sigma(E)/E = 3.2\%/\sqrt{E(\text{GeV})} \oplus 125\,\text{MeV}/E \oplus 0.5\%$ and the spatial resolution better than 1.3 mm above 20 GeV, resulting in a π^0 mass resolution of 1.1 MeV/c^2. The calorimeter response was stable during the run within 0.1%.

The main detector for $K_{L,S} \to \pi^+\pi^-$ decays is a magnetic spectrometer, consisting of four large drift chambers and a dipole magnet providing a 265 MeV/c transverse momentum kick. Each chamber [13] has four double planes of staggered wires strung at 45° with respect to each other; their spatial resolution is $\simeq 90\ \mu$m and their efficiency $\simeq 99.5\%$. The momentum resolution was measured in 1997 to be $\sigma(p)/p = 0.5\% \oplus 0.009\% \cdot p$ (GeV/c), resulting in a K^0 mass resolution of 2.5 MeV/c^2.

A two-plane plastic scintillator hodoscope in front of the calorimeter is used to measure the arrival time of charged pions with a resolution of $\simeq$ 200 ps per track.

Other detectors comprise a scintillating fibre hodoscope inside the liquid krypton volume, giving redundant time information for neutral decays, an iron-scintillator hadron calorimeter for triggering purposes, and a plastic scintillator muon veto counter system.

2.3 Triggers

The trigger system for neutral decays [14] is a fully pipelined, dead-timeless, programmable system, based on the information provided by 64 + 64 horizontal and vertical electromagnetic calorimeter projections. This system continuously computes, for each 25 ns time bin, the deposited energy momenta, the longitudinal decay vertex position and the number of clusters close in time, allowing a massive reduction of the $K_L \to 3\pi^0$ background, resulting in an output rate of $\simeq$ 1.9 kHz.

The trigger for charged decays [15] is a two-level system, the first one being provided by hardware hodoscope cross quadrants coincidences and an energy threshold from the combination of the two calorimeters' outputs. The second level, based on drift chambers' information, consists of hardware coordinate builders and a farm of fast processors which compute the invariant mass and the longitudinal decay vertex position of the kaon candidates, allowing a large reduction of the background from three-body K_L decays, with $\simeq$ 1.2 kHz output rate. The charged trigger system introduces 0.3% dead time, which is continuously monitored.

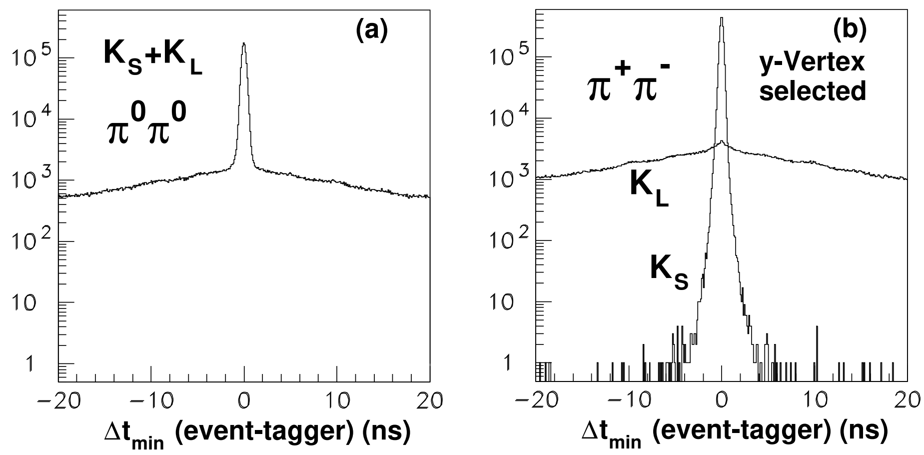

Figure 2: Minimum event-tagger time difference: (a): $\pi^0\pi^0$, (b) $\pi^+\pi^-$.

3 Data analysis

The double ratio is insensitive in first order to all sources of biases which are common to the two beams or to the two 2π decay charge modes, being biased only by the small effects which can be ascribed to only one of the four decay modes, or by the differential component of beam- or detector-related effects.

A first source of possible biases is due to the K_S tagging technique: K decays are labelled as K_S whenever a proton is detected by the tagger system on the beam line towards the K_S production target, within a $\pm$ 2 ns window around the event time, as reconstructed by the charged hodoscope or the electromagnetic calorimeter.

For charged decays, the decay vertex transverse position resolution is good enough to identify the beam to which a decaying K belongs without ambiguities. Not being available for neutral decays, this independent tagging information is not used for the final analysis, but it is used to study the tagging systematics.

The presence in the beam line of an accidental proton close in time to a K_L decay can lead to the mistagging of this decay as a K_S: the probability of this happening is measured for charged decays to be $(11.19 \pm 0.03)\%$, and its effect on R is negligible in first order, being *a priori* the same for charged and neutral decays[1]. A very small effect is actually induced by the rate dependence of the charged trigger inefficiency, which leads to a slightly higher effective beam rate for detected neutral decays. The K_L to K_S mistagging probability for neutral decays is measured by studying the

[1]This effect, if not corrected for, would only dilute a non-zero value of $\mathrm{Re}(\epsilon'/\epsilon)$, but it could not create a fake signal of direct CP violation.

number of accidental proton coincidences in several 4 ns wide time windows, offset from the central one used for tagging; the effect on the double ratio due to the charged/neutral difference in these mistagging probabilities is $\Delta R = (-18 \pm 9) \cdot 10^{-4}$.

A second potential tagging-related bias is due to tagging inefficiencies or time reconstruction tails, resulting in a K_S event being mistagged as K_L. This effect could be in principle quite different for charged and neutral decays; however, redundant time information shows that most of the effect is due to inefficiencies in the tagger itself, and therefore charged/neutral symmetric. The K_S to K_L mistagging probability for charged decays is directly measured to be $(1.5 \pm 0.1) \cdot 10^{-4}$ by using the decay vertex transverse position information. For neutral decays, this probability was measured using K_S-only special runs, $K_S \to \pi^0 e^+ e^- \gamma$ decays and $2\pi^0$ decays in which a photon converts in the material in front of the detector; in these cases the beam to which the K belongs can be identified by the transverse vertex position. The resulting effect on the double ratio is $\Delta R = (0 \pm 6) \cdot 10^{-4}$.

Trigger efficiencies were measured by using data continuously collected with less restrictive independent trigger conditions. The neutral trigger efficiency was measured to be (0.9988 ± 0.0004) and equal for K_S and K_L decays. The overall charged trigger efficiency was measured to be (0.9168 ± 0.0009), the inefficiency being mostly due to a temporary time misalignment in the logic. The net effect on R due to the K_S-K_L asymmetry of this inefficiency is measured to be $\Delta R = (-9 \pm 23) \cdot 10^{-4}$, limited in its precision by the size of the control sample.

To reconstruct $2\pi^0$ events, the longitudinal vertex position is computed from the measured energies E_i and positions (x_i, y_i) of the four clusters in the calorimeter:

$$z_{\mathrm{vertex}} = z_{\mathrm{cal}} - \sqrt{\sum_{i,j>i} E_i E_j [(x_i - x_j)^2 + (y_i - y_j)^2]} / m_K$$

assuming the invariant mass of the 4 detected photons to be the kaon mass m_K. A χ^2 variable is defined, describing the match of the photon pairs invariant mass with the π^0 mass, and the residual $K_L \to 3\pi^0$ background after cutting on this variable is measured to be less than 1 per mille, resulting in a shift $\Delta R = (8 \pm 2) \cdot 10^{-4}$.

The $\pi^+\pi^-$ reconstruction exploits the detailed knowledge of the measured magnetic field, although the K energy is defined using the tracks opening angle and ratio of momenta, therefore being largely insensitive to it. The background from K_L semi-leptonic decays is reduced by comparing the measured track momenta and deposited energy in the electromagnetic calorimeter (for K_{e3}), and by using the muon veto counters (for $K_{\mu 3}$). Further cuts are made on the reconstructed $\pi^+\pi^-$ invariant mass and on a rescaled K transverse momentum variable, in which K_S and K_L have sim-

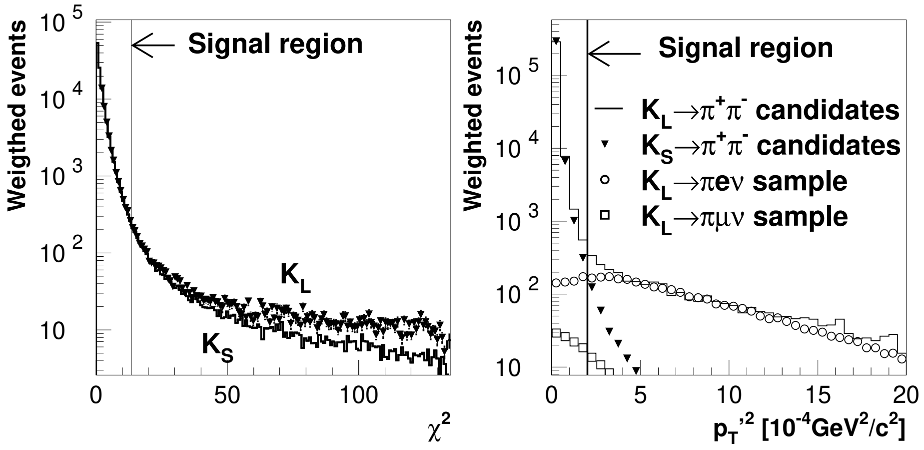

Figure 3: Backgrounds to neutral and charged K_L $\pi\pi$ decays.

ilar resolution despite the large difference in target to average decay vertex distance.

The residual background in the charged mode is measured to be around 2 per mille, and the resulting effect on R is $\Delta R = (-23 \pm 2 \pm 4) \cdot 10^{-4}$, where the first error is statistical and the second systematic.

A fraction $\approx 20\%$ of $\pi^+\pi^-$ events were lost in 1997 due to the loss of drift chambers' data in case of high hit multiplicity; the occurrence of this condition was monitored, and an equivalent requirement was imposed on $\pi^0\pi^0$ events, resulting in a negligible measured effect on R.

A small fraction ($\approx 0.5 \cdot 10^{-3}$) of $K \to \pi^+\pi^-$ with high transverse momentum are due to multiple K_L scattering and regeneration on collimators. Since this kind of events are not removed in the $\pi^0\pi^0$ sample, they cause a shift $\Delta R = (+12 \pm 3) \cdot 10^{-4}$.

Using simultaneous beams, R is largely insensitive to accidental effects caused by the high rate environment, and moreover the beam intensities are highly correlated, resulting in the same measured accidental activity for K_S and K_L events. The effect of accidentals is studied by software overlaying randomly triggered events (proportional to beam intensities) to normal events: the observed $\approx 2\%$ net variation in the number of accepted events is highly K_S- K_L symmetric and corresponds to an effect $\Delta R = (2 \pm 14) \cdot 10^{-4}$, determined with limited precision due to the amount of overlaid events.

The effect of extra activity in the detectors correlated in time with K_S production was measured to affect R by less than $3 \cdot 10^{-4}$.

The absolute energy scale, which is directly linked to the longitudinal decay position for $\pi^0\pi^0$, is fixed by fitting the position of the edge of the

AKS veto counter in the data to a precision of $5 \cdot 10^{-4}$. The scale factor is cross-checked using neutral decays with charged tracks and special runs in which a π^- beam (replacing the K_L) impinges on a thin target producing π^0 and η decays with a well-known vertex position. The scale is stable in time within $5 \cdot 10^{-4}$, and the overall uncertainty on R due to it is $\pm 5 \cdot 10^{-4}$.

Other effects linked to the 0.3% calorimeter maximum non-linearity and to residual non uniformities give an overall uncertainty of $\pm 11 \cdot 10^{-4}$ on R.

The accepted range of kaon energies is between 70 and 170 GeV; the analysis is performed in 20 energy bins, to be insensitive to the different K_S and K_L decay energy spectra, and the results are averaged using an unbiased estimator.

The beginning of the fiducial region for K_S, which have a steep decay vertex longitudinal position distribution, is defined in hardware by the absence of signals from the AKS veto counter, located ≈ 6 m downstream of the K_S production target, and its length is defined to be 3.5 proper K_S lifetime units: in this way the sensitivity of R to the knowledge of the absolute neutral energy scale is reduced.

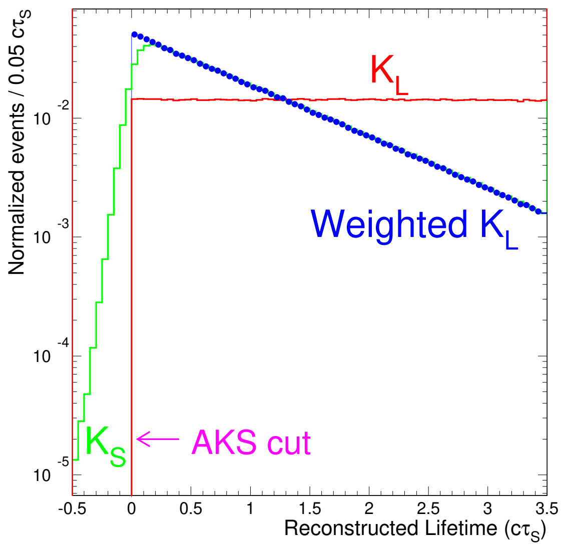

Figure 4: K_S and K_L longitudinal decay vertex distributions.

In order to minimize the K_S-K_L acceptance differences due to the different decay vertex distributions, the K_L decays are weighted according to the ratio of their expected 2π decay rate to the one from the K_S beam, thus making the two distributions equal. Residual small acceptance differences, due to the acollinearity and different divergence of the two beams, have been modelled by a detailed Monte Carlo simulation of the apparatus. Their overall effect is $\Delta R = (-29 \pm 11 \pm 5) \cdot 10^{-4}$ (MC statistical and systematic error).

	Correction (10^{-4})	Uncertainty (10^{-4})	
Tagging dilution	+18	$\pm$ 9	(stat.)
Tagging inefficiency	0	$\pm$ 6	(stat.)
Charged trigger eff.	+9	$\pm$ 23	(stat.)
Reconstruction eff.	0	$\pm$ 3	
Neutral background	-8	$\pm$ 2	
Charged background	+23	$\pm$ 4	
Beam scattering	-12	$\pm$ 3	
Accidental activity	-2	$\pm$ 14	(stat.)
Energy scale/linearity	0	$\pm$ 12	
Charged vertex	0	$\pm$ 5	
Acceptance	+29	$\pm$ 12	(MC stat.)
Total	+57	$\pm$ 35	

Table 1: Corrections applied on R and their systematic uncertainties (divide by 6 to get the corresponding values for $\mathrm{Re}(\epsilon'/\epsilon)$).

$K_L \to \pi^0\pi^0$	$K_S \to \pi^0\pi^0$	$K_L \to \pi^+\pi^-$	$K_S \to \pi^+\pi^-$
$0.49 \cdot 10^6$	$0.98 \cdot 10^6$	$1.07 \cdot 10^6$	$2.09 \cdot 10^6$

Table 2: Sample sizes after cuts, background and tagging corrections (without lifetime weighting).

4 Result and conclusions

The final result after corrections is

$$\mathrm{Re}(\epsilon'/\epsilon) = (18.5 \pm 4.5 \pm 5.8) \cdot 10^{-4}$$

where the first error is statistical and the second is systematic although, as mentioned above, its main component is statistical in nature, being given by the size of the auxiliary samples used to measure the various effects.

Combining the errors in quadrature the result is $\mathrm{Re}(\epsilon'/\epsilon) = (18.5 \pm 7.3) \cdot 10^{-4}$. This measurement confirms the existence of direct CP violation in $K_L \to \pi\pi$ decays.

The world average (rescaling errors as required by the PDG [16]) was $\mathrm{Re}(\epsilon'/\epsilon) = (21.7 \pm 6.1) \cdot 10^{-4}$ before this measurement; including it, the average becomes $\mathrm{Re}(\epsilon'/\epsilon) = (21.3 \pm 4.6) \cdot 10^{-4}$.

It should be noted that NA48 has collected data in 1998 and is currently running with significant improvements in detector performance and rate capability, corresponding to several times the statistics on which the present result is based.

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