A New Measurement of Re(ε'/ε) by the NA48 Experiment at CERN and Future Plans

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The NA48 experiment at CERN detects concurrently the four decay modes into two pions of the long and short lived neutral kaons. During 1998 and 1999 data taking, statistics in each mode was increased by a factor eight, with respect to the 1997 published data. A new measurement of the double ratio of the four modes has been obtained from these data. This new result on the direct CP violation parameter Re(ε'/ε) is $(15.0 \pm 2.7) \times 10^{-4}$ which, combined with the previous NA48 published result gives Re(ε'/ε) = $(15.3 \pm 2.6) \times 10^{-4}$

1. Direct CP violation.

The CP-violating decay of the long-lived neutral kaon, $\mathrm{K_L}$, into two pions is interpreted to be mainly due to the CP-conserving decay of the K_1 ($CP = +1$) component (CP violation in the $\mathrm{K^0}$-$\mathrm{\bar{K}^0}$ mixing) and is parametrized by the ε parameter ($|\varepsilon| = (2.28 \pm 0.02) \times 10^{-3}$).

The interference of final states amplitudes with different isospin induces CP violation in the decay of the $K_2 (CP = -1)$ component; this contribution to CP violation, called *direct CP violation*, is quantified by the parameter ε'.

The parameter Re(ε'/ε) , which measures the relative amount of *direct CP* to *indirect CP* has already been measured in [1–4].

This presentation describes the latest published measurement of Re(ε'/ε) by the NA48 experiment at CERN [5].

In the Standard Model, a value of ε' different from zero arises naturally from the complex phase of the CKM matrix. Theoretical predictions for the ratio Re(ε'/ε) are typically in the range $(5 - 30) \times 10^{-4}$. The difficulty of the theoretical calculations comes from QCD penguin diagrams and interactions in the final state [6].

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2. NA48 method and detector.

The aim of the NA48 experiment is to evaluate Re(ε'/ε)with an accuracy $\approx 2 \times 10^{-4}$, by measuring the double ratio

$$\begin{aligned} R &= \frac{\Gamma(\mathrm{K_L} \to \pi^0\pi^0)}{\Gamma(\mathrm{K_S} \to \pi^0\pi^0)} \Big/ \frac{\Gamma(\mathrm{K_L} \to \pi^+\pi^-)}{\Gamma(\mathrm{K_S} \to \pi^+\pi^-)} \\ &\simeq 1 - 6 \times \mathrm{Re}(\varepsilon'/\varepsilon) \end{aligned} \tag{1}$$

As the $\mathrm{K_L}$ CP-violating decays are suppressed $\approx$ 200 times compared to 3-body decays, **high rate** is required.

To minimize corrections to the ratio, the four modes are measured:

- **simultaneously** so that effects due to fluxes, inefficiencies, dead time, accidental activities cancel.
- from the **same fiducial volume**: lifetime $< 3.5 \times \tau_s$. To equalize longitudinal distribution between $\mathrm{K_S}$ and $\mathrm{K_L}$, a weight, function of lifetime, is applied to $\mathrm{K_L}$ events so that the acceptance correction is minimized.
- with **high resolution**: magnetic spectrometer for $\pi^+\pi^-$ with uniform magnetic field and homogenous liquid Krypton calorimeter for $\pi^0\pi^0$ to reject backgrounds.

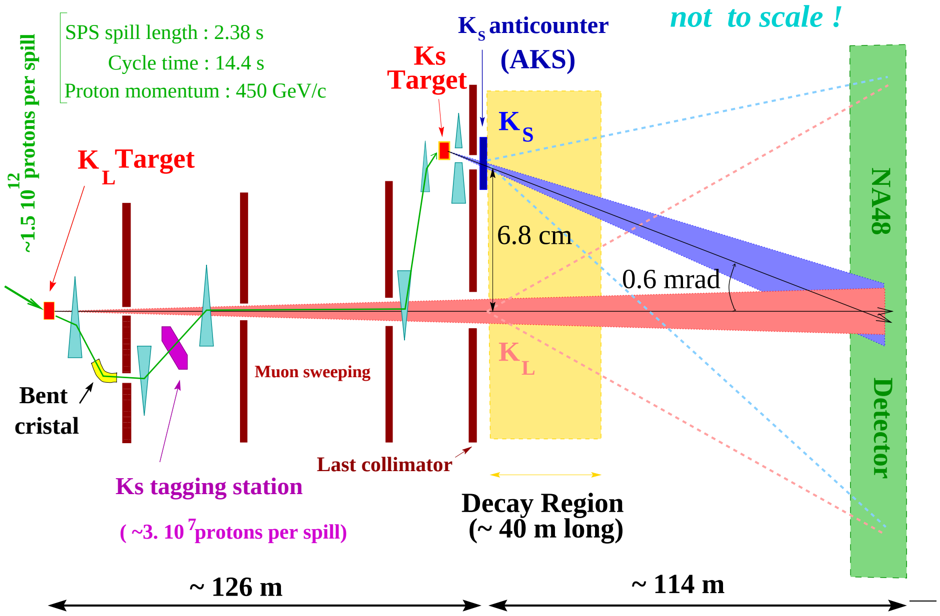

Figure 1. Schematic layout of the simultaneous K_S and K_L beams used by NA48

- in **bins of Kaon energy** to account for residual differences of K_S and K_L energy spectra (20 bins between 70 and 170 GeV).

2.1. NA48 beam line

The NA48 beam line was designed to fulfil these requirements; a schematic view is presented on figure 1.

K_S and K_L beams [7] are both produced by the 450 GeV proton beam of CERN-SPS. The incident beam, $\sim 15 \times 10^{12}$ protons per pulse, hits a first beryllium target (K_L target) located $\sim$ 126 m upstream of the decay volume; charged particles are swept away by magnets; after 126 m, only long-lived kaons (and essentially photons) remain.

A fraction of the protons which did not interact in the target is deviated and sent through a bent crystal [8]. By aligning the incident protons with the crystal, one selects the flux of outgoing protons to be $\sim 3 \times 10^7$ per pulse. The transmitted protons go through the tagging detector which measures very precisely the proton time [9]. The beam is directed to the second beryllium target (K_S target), only $\simeq$ 6 m before the decay region and 7.2 cm above the K_L beam. Decays occuring at the exit of the final collimator, after the K_S target, are dominated by K_S decays.

The two beams converge, with an angle of 0.6 *mrad*, to the centre of the calorimeter, $\sim$ 115 m downstream of the beginning of the decay region.

The beginning of the fiducial region is precisely defined by an anticounter in the K_S line.

2.2. NA48 detectors

- **Tagging detector** K_S and K_L decays are distinguished by time of flight: the fraction of protons directed to the K_S target cross the tagging station [9] which measures the proton time with a resolution better than 200 *ps*. Events with a coincidence inside $\pm 2ns$ are labelled K_S. In charged decays, the vertex position allows to identify vertices coming from the K_S and K_L targets and therefore to measure (see figure 2):

- The **tagging inefficiency**, the probability that a K_S decay is not in coincidence with a proton: $(1.63 \pm 0.03) \times 10^{-4}$.
- The **accidental tagging probability**, the probability that a K_L decay is in coincidence with a random proton: $(11.649 \pm 0.008\%)$.

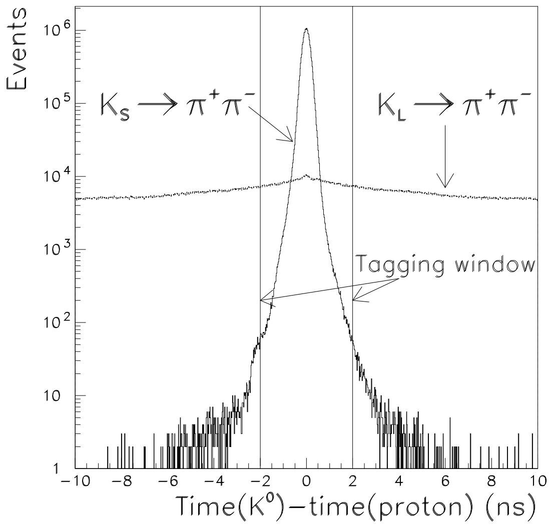

Figure 2. Distribution of the time difference between the event and the closest proton for $K_S \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^+\pi^-$ events identified from their vertex position in the vertical plane.

- **Magnetic spectrometer** Charged decays are measured by a magnetic spectrometer made of four large drift chambers, two located before the magnet, which produces an integrated magnetic field of 0.88Tm, and two after [10]. The momentum resolution is

$$\sigma(p)/p = (0.48 \oplus 0.009 \times p)\%$$

(where p is in GeV/c).

The invariant mass resolution is 2.5 MeV/c^2. The time measured with a plastic scintillator hodoscope has a resolution better than 200 ps.

- **Electromagnetic calorimeter** Neutral decays are reconstructed by a quasi-homogeneous liquid Krypton calorimeter [11]. The calorimeter is segmented in $\sim$ 13000 cells of 2×2 cm^2 section, with pointing geometry. The (pure) calorimeter energy resolution is

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

(where E is in GeV). The π^0 invariant mass resolution is $\simeq$ 1 MeV/c^2 and the event time resolution around 270 ps.

3. Data analysis

Analysis consists in counting events in each mode to evaluate the double ratio R. Table 1 summarizes the statistics accumulated during the two years 1998 and 1999, taking into account the correction from K_L mistagging. A *raw* value of the double ratio R_{raw} is obtained after bining the data as a function of energy. Corrections are then applied (table 2 summarizes the corrections applied on R_{raw}):

Table 1
1998 and 1999 statistics, in millions of events, compared to previous publication.

Statistics (millions)	1997	1998+1999
$K_L \rightarrow \pi^0\pi^0$	0.49	3.29
$K_S \rightarrow \pi^0\pi^0$	0.98	5.21
$K_L \rightarrow \pi^+\pi^-$	1.07	14.45
$K_S \rightarrow \pi^+\pi^-$	2.09	22.22

- **Trigger inefficiencies**: if inefficiencies are K_S-K_L asymmetric they can induce a bias on R. The neutral trigger is a fully pipelined system with a negligible dead time and an efficiency of $(99.920 \pm 0.009)\%$. No correction is applied. The charged trigger inefficiencies induce a correction on R of $(-3.6 \pm 5.2) \times 10^{-4}$.

- **Backgrounds** come from K_L three-body decays. To reject $K_L \to \pi^{\pm}\mu^{\mp}\nu_{\mu}$, $K_L \to \pi^{\pm}e^{\mp}\nu_e$ and K_L scattered on collimators, mass and transverse momentum cuts are applied; the charged background level after these cuts is $(16.9 \pm 3.0) \times 10^{-4}$. Scattered events are not rejected in neutral decays; the correction for this effect is $(-9.6 \pm 2.0) \times 10^{-4}$. To reject $K_L \to 3\pi^0$ with two lost γ, a cut on a χ^2, computed comparing the $\gamma\gamma$ masses and the π^0 mass, is applied; the remaining background is at a level of $(-5.9 \pm 2.0) \times 10^{-4}$. Charged and neutral backgrounds distributions are presented on figure 3

- The **acceptance** correction is reduced by the K_L weighting technique to a level (computed from Monte-Carlo) of $(26.7 \pm 4.1(stat) \pm 4.0(syst)) \times 10^{-4}$.

- The **neutral reconstruction incertainty** leads to an uncertainty $\Delta R = \pm 5.8 \times 10^{-4}$. It is controled in particular by constraining the reconstruction of the begining of the decay region and by studying the non-linearity using electrons.

- The **accidental activity** can induce asymmetric losses and gains in K_S and K_L. Two contributions are taken into account:

  - The K_S-K_L**intensity difference** is estimated by analysing extra hits in detectors and comparing rates from K_S and K_L beams. All results agree that, to within 1%, there is no intensity difference seen by K_S and K_L events: $\Delta R = \pm 10^{-4}$
  - The **contribution from** K_S-K_L**illumination difference** is estimated by superimposing random events to Monte Carlo events and data events, and measuring effects of gains and losses. An upper bound on the contribution from illumination to accidental effet is measured to be $\pm 3 \times 10^4$.

  The uncertainty on accidental effects is $(\pm 4.4) \times 10^{-4}$.

Table 2
Corrections and systematic uncertainties on the double ratio. In order to obtain the effect on $\mathrm{Re}(\varepsilon'/\varepsilon)$, the numbers must be divided by a factor of 6 (Eq. 1).

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

4. Results

Converting the corrected double ratio using equation 1, the following measurement of the direct CP violtion parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$ is obtained:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.0 \pm 1.7(\mathrm{stat}) \pm 2.1(\mathrm{syst})) \times 10^{-4}$$

where the first error is statistical, the second systematic. Figure 4 shows R as a funtion of Kaon energy. Combining this preliminary result with the previously published NA48 result based on data collected during 1997 [4], and combining statistical and systematic errors in quadrature gives:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}$$

5. NA48 Future Plans

In 2001, NA48 collected data for improvements on $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement, with newly rebuilt drift chambers. Analysis of these data is in progress.

The NA48 collaboration is preparing for two more data taking periods, in 2002 and 2003.

5.1. $\mathrm{K_S}$ Rare Decay Program

The beam line is modified to provide a very intense $\mathrm{K_S}$ beam (total kaon flux/pulse $\simeq 1.5 \times 10^5$) to allow study of $\mathrm{K_S}$ rare decays [12]. The physics motivations for this experiment are:

- A measurement of the parameter

$$\eta_{000} = \frac{A(\mathrm{K_S} \to \pi^0\pi^0\pi^0)}{A(\mathrm{K_L} \to \pi^0\pi^0\pi^0)}.$$

  - Re(η_{000}) comes from *CP violation in mixing* $K^0 - \bar{K}^0$.
  - Im(η_{000}) is sensitive to *direct CP violation.*
  - The foreseen sensitivity in NA48 should allow to place a limit on η_{000} at 1% for one year data taking (best result so far by CPLEAR at 10%).

- $B(K_s \to \pi^0 e^+ e^-)$; the study of this decay will allow:
  - To bound indirect CP violation in the decay $\mathrm{K_L} \to \pi^0 e^+ e^-$.
  - To improve the published measurement [13] of $BR(K_s \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$.
  - To observe 7 events/year with no background.

- $K_s \to \pi^0\gamma\gamma$ and $K_s \to \gamma\gamma$; the study of these decays will allow:
  - To test Chiral perturbation theory.
  - To improve the publised measurement [14] of $BR(K_s \to \gamma\gamma) = (2.6 \pm 0.4 \pm 0.2) \times 10^{-6}$
  - To complete the measurement of the preliminary result on $BR(K_s \to \pi^0\gamma\gamma) = (1.36 \pm 0.05) \times 10^{-6}$ [15].

5.2. Charged Kaon Program

The NA48 collaboration plans to take data in 2003 with a modified beam line in order to search for *direct CP violation* in charged kaon decays [16]. The aim is to measure asymmetry in the Dalitz plot for the decays of $K^{\pm}$ into 3 charged pions. With this modified beam and upgraded detector, it would be possible to reach $\sim 1.4 \cdot 10^{-4}$ accuracy on $\Delta g/g$, for one year of data taking (and therefore constrain the models).

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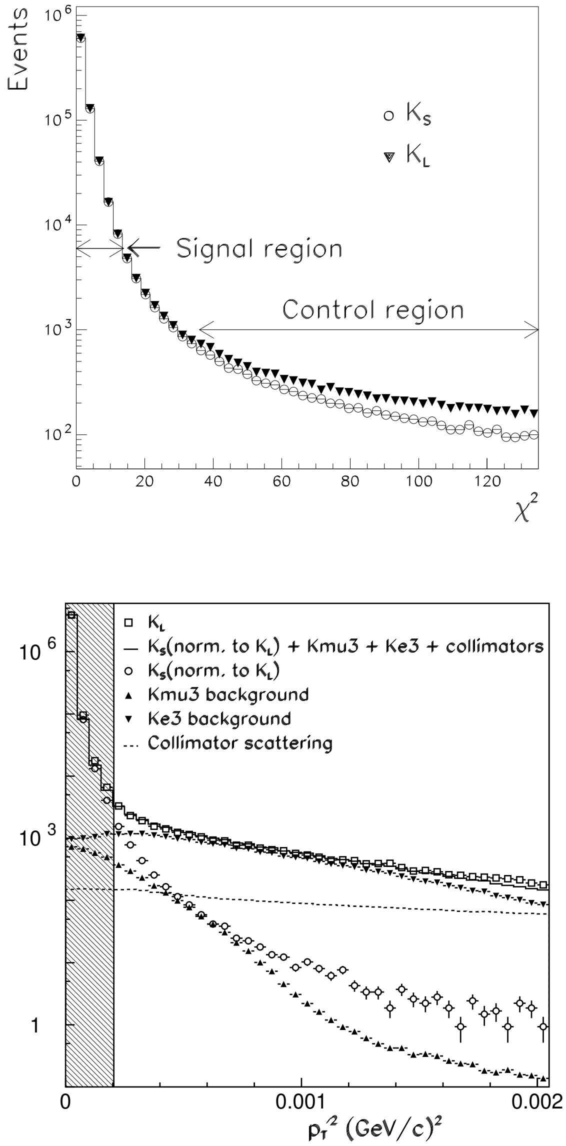

Figure 3. Top: χ^2 distribution for tagged $K_L \to \pi^0\pi^0$ and $K_S \to \pi^0\pi^0$ candidates. Bottom: distribution of transverse momentum $p_T'^2$ for K_L candidates and for all known background contributions for an extended region; the signal region is defined as $p_T'^2 < 0.0002\ GeV/c^2$

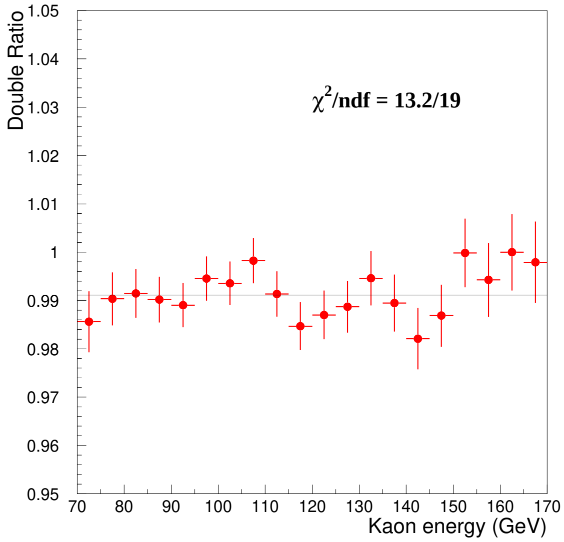

Figure 4. Double Ratio R as a function of Kaon Energy (GeV)