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New NA48 results on CP violation

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Abstract. NA48 has searched for CP violation and rare neutral-kaon decays in data collected in 1998-2002. Results for the decays $K_{L,S} \to \pi^+\pi^-e^+e^-$ and $K_S \to \pi^0 e^+e^-$, and for the measurement of the $K_L \to \pi e\nu$ charge asymmetry, are presented.

PACS. 11.30.Er Discrete symmetries – 13.20.Eb Decays of K mesons – 14.40.Aq Properties of K mesons

1 Introduction

The NA48 experiment was originally designed to measure direct CP-violation effects in neutral-kaon decays to two pions. The experimental layout, described in detail elsewhere [1], includes a spectrometer (drift chambers and a dipole magnet), an electromagnetic calorimeter, and arrangements of scintillators for vetoing photons outside the calorimeter acceptance.

The $K_L \to \pi^+\pi^-e^+e^-$ data, the $K_L \to \pi e\nu$ data, and a fraction of the $K_S \to \pi^+\pi^-e^+e^-$ data were taken using simultaneous K_L and K_S beams during running periods in 1998, 1999 and 2001. Most of the $K_S \to \pi^+\pi^-e^+e^-$ data were collected during a short high-intensity K_S run in 1999. The $K_S \to \pi^0 e^+e^-$ data were recorded during the high-intensity K_S run in 2002.

2 $K_{L,S} \to \pi^+\pi^-e^+e^-$ decays

The decay $K_L \to \pi^+\pi^-e^+e^-$ is expected to proceed via an intermediate state with a virtual photon: $K_L \to \pi^+\pi^-\gamma^* \to \pi^+\pi^-e^+e^-$. The decay amplitude has two components: one from CP-conserving direct emission, the other from the CP-violating decay $K_L \to \pi^+\pi^-$, with inner bremsstrahlung. The interference of the two amplitudes causes the virtual photon to have a circular polarization, leading to an asymmetry $A(\phi)$ in the angle, ϕ, between the $\pi^+\pi^-$ plane and the e^+e^- plane in the kaon centre-of-mass frame [2,3]. Only the CP-conserving inner-bremsstrahlung process contributes to $K_S \to \pi^+\pi^-e^+e^-$, so no asymmetry is expected. Two main background sources have been identified: $K_L \to \pi^+\pi^-\pi^0_D$ decays, which are rejected by strong kinematical cuts against events with missing particles; and fragments of two $K_L \to \pi e\nu$ decays, which are minimised by time constraints and cuts on vertex quality. The distribution of the $\pi\pi ee$ invariant mass for the selected events is shown in Fig. 1. From the 1998

[a] (on behalf of the NA48 Collaboration)

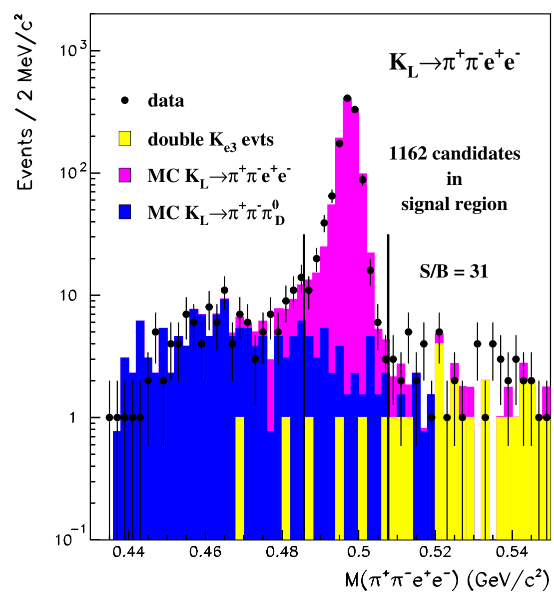

Fig. 1. $\pi\pi ee$ invariant-mass distribution for the vertices passing selection cuts

and 1999 data, 1162 $K_L \to \pi^+\pi^-e^+e^-$ candidates and 621 $K_S \to \pi^+\pi^-e^+e^-$ candidates are found, with respectively $(3.2 \pm 0.5)\%$ and $(0.1 \pm 0.2)\%$ of background in the selected mass interval. The corresponding branching ratios have been determined to be

$$B\ (K_L \to \pi^+\pi^-e^+e^-\ ) = (3.08 \pm 0.09_{stat} \pm 0.15_{sys} \pm 0.10_{norm}) \times 10^{-7}$$
$$B\ (K_S \to \pi^+\pi^-e^+e^-\ ) = (4.71 \pm 0.23_{stat} \pm 0.16_{sys} \pm 0.15_{norm}) \times 10^{-5}.$$

The last uncertainty refers to the uncertainty in the branching ratio of the normalisation channel. The asymmetry measured from the $K_L \to \pi^+\pi^-e^+e^-$ data is

$$A(\phi) = (14.2 \pm 3.0_{stat} \pm 1.9_{sys})\%,$$

Table 1. Contributions to the systematic uncertainty for the measurement of the $K_L \to \pi e \nu$ charge asymmetry

Source	10^{-5}
Trigger	$+26.2 \pm 6.0$
Punch through	-1.4 ± 3.5
Pion ID	-17.1 ± 2.4
Acceptance	0 ± 0.5
Background	0 ± 0.5
Total	$+7.7 \pm 7.2$

which strongly indicates CP violation in the K_L channel, and is in good agreement with the theoretical predictions. As expected, the angular asymmetry for the K_S decay is consistent with zero to within the experimental uncertainty.

3 $K_L \to \pi e \nu$ charge asymmetry

The charge asymmetry in semileptonic K_L decays is an observable of CP violation. For $K_L \to \pi e \nu$ decays it is defined as

$$\delta_L(e) = \frac{\Gamma(K_L \to \pi^- e^+ \nu) - \Gamma(K_L \to \pi^+ e^- \nu)}{\Gamma(K_L \to \pi^- e^+ \nu) + \Gamma(K_L \to \pi^+ e^- \nu)},$$

and is equal to twice $\mathrm{Re}(\varepsilon'/\varepsilon)$ assuming CPT symmetry. In the 2001 run period, about 2×10^8 $K_L \to \pi e \nu$ decays were collected by NA48. During the data taking, the direction of the magnetic field was inverted several times to reduce possible systematic biases. All backgrounds have been estimated to be negligible. The main systematic uncertainties arise from asymmetries in the detection efficiency and in the pion identification, as shown in Table 1. Both of these effects are strongly momentum dependent, and a correction is applied using data from control samples of $K_S \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-\pi^0$. After the correction, no momentum dependency is left, as shown in Fig. 2. The preliminary measurement of the $K_L \to \pi e \nu$ charge asymmetry is

$$\delta_L(e) = (3.317 \pm 0.070_{stat} \pm 0.072_{sys}) \times 10^{-3}$$

in good agreement with the recent KTeV measurement [4].

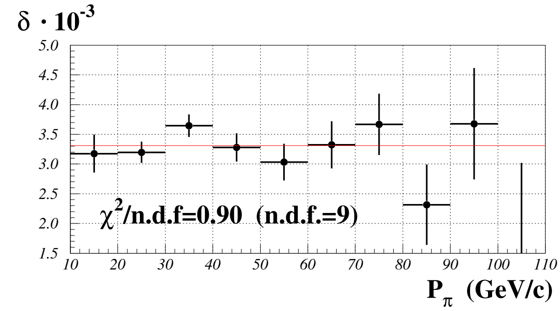

Fig. 2. $K_L \to \pi e \nu$ charge asymmetry as a function of pion momentum

4 $K_S \to \pi^0 e^+ e^-$ decay

Decays of the type $K_L \to \pi^0 l \bar{l}$ are of considerable interest because of their sensitivity to direct CP violation [5]. However, in $K_L \to \pi^0 e^+ e^-$ decays, CP-conserving and indirect CP-violating amplitudes also contribute. The CP-conserving contribution can be evaluated by measuring the low-$m_{\gamma\gamma}$ component of the decay $K_L \to \pi^0 \gamma\gamma$ [6]. The direct and indirect CP violating (CPV) contributions interfere, and their contribution to the branching ratio can be written as [7]

$$B\,(K_L \to \pi^0 e^+ e^-)_{\mathrm{CPV}} \times 10^{12} \simeq 15.3\, a_S^2 - 6.8\, a_S \frac{\mathrm{Im}(\lambda_t)}{10^{-4}} + 2.8 \left(\frac{\mathrm{Im}(\lambda_t)}{10^{-4}}\right)^2,$$

where $\lambda_t = V_{ts}^* V_{td}$ is the relevant combination of CKM matrix elements describing the short distance CP violation. The parameter a_S describes the strength of the indirect CP violating component in the decay $K_L \to \pi^0 e^+ e^-$, and is related to $\mathrm{B}(K_S \to \pi^0 e^+ e^-)$ via [7]

$$\mathrm{B}(K_S \to \pi^0 e^+ e^-) = 5.2 \times 10^{-9}\, a_S^2.$$

From dimensional analysis in chiral perturbation theory, $a_S \sim \mathcal{O}(1)$. A precise measurement of the $K_S \to \pi^0 e^+ e^-$ branching fraction is clearly important for placing a bound on the indirect CP violating term in the K_L decay.

A search for $K_S \to \pi^0 e^+ e^-$ has been made using the 2002 data, taken with a high-intensity K_S beam. For the analysis of the data, signal and control regions were defined as:

$$\textit{signal}: \quad |m_{\gamma\gamma} - M_{\pi^0}| < 2.5 \times \sigma_{\gamma\gamma}$$
$$|m_{ee\gamma\gamma} - M_K| < 2.5 \times \sigma_{ee\gamma\gamma}$$

$$\textit{control}: \quad 3 \times \sigma_{\gamma\gamma} < |m_{\gamma\gamma} - M_{\pi^0}| < 6 \times \sigma_{\gamma\gamma}$$
$$3 \times \sigma_{ee\gamma\gamma} < |m_{ee\gamma\gamma} - M_K| < 6 \times \sigma_{ee\gamma\gamma}$$

where $\sigma_{\gamma\gamma} = 1$ MeV/c^2 and $\sigma_{ee\gamma\gamma} = 4.7$ MeV/c^2. These regions were masked while cuts to reject the background were tuned, using both experimental data and simulated events. A large number of possible sources of background has been studied, taking into account single

Table 2. Contributions to the background for $K_S \to \pi^0 e^+ e^-$

Source	Control region	Signal region
$K_S \to \pi^0{}_D \pi^0{}_D$	0.03	0.007
$K_L \to e^+ e^- \gamma\gamma$	0.11	0.075
$\pi^\pm e^\mp \nu + (\pi^0 \pi^0 (\pi^0))$	0.19	0.069
Total	0.33	0.15

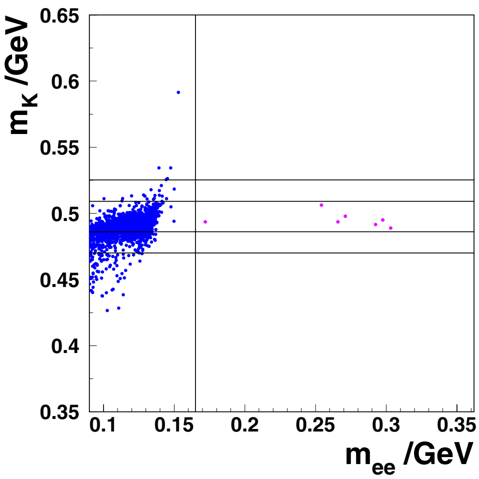

Fig. 3. Scatter plot of $m_{ee\gamma\gamma}$ versus m_{ee} for $K_S \to \pi^0 e^+ e^-$ events. The $m_{ee} > 165$ MeV/c^2 cut is shown. The regions at $3\sigma_K$ and $6\sigma_K$ are indicated

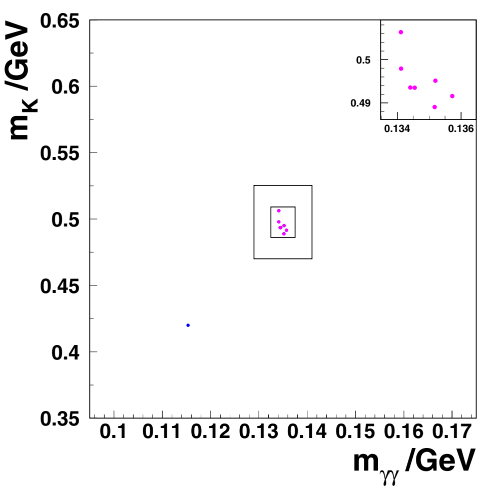

Fig. 4. Scatter plot of $m_{ee\gamma\gamma}$ versus $m_{\gamma\gamma}$ for $K_S \to \pi^0 e^+ e^-$ events. The boxes at 3σ and 6σ in (m_K, m_{π^0}) are indicated. The inset shows an enlargement of the signal box

kaon and hyperon decays and fragments from two decays accidentally coincident in time. The background contribution was minimised by imposing the requirements: $m_{e\gamma} > m_{\pi^0} + 30$ MeV/c^2, to reject events where two photons from different π^0s converted; and $m_{ee} > 165$ MeV/c^2, to reject events where one or more photons from a single π^0 converted. In addition, the background from Ξ^0 and Λ^0 decays was reduced to a negligible level by exploiting the large momentum asymmetry. The main residual background contributions were from $K_S \to \pi^0_D \pi^0_D$, $K_L \to e^+ e^- \gamma\gamma$ and $\pi^\pm e^\mp \nu + (\pi^0 \pi^0 (\pi^0))$ decays, and the total background was estimated to be $0.15^{+0.10}_{-0.04}$ events (Table 2).

When the signal region was unmasked, 7 events were found (Fig. 3 and Fig. 4), corresponding to a signal of $6.85^{+3.8}_{-1.8}$. The number of K_S decays in the fiducial volume was evaluated by counting $K_S \to \pi^0 \pi^0_D$ decays. The acceptance for the $K_S \to \pi^0 e^+ e^-$ channel was calculated using

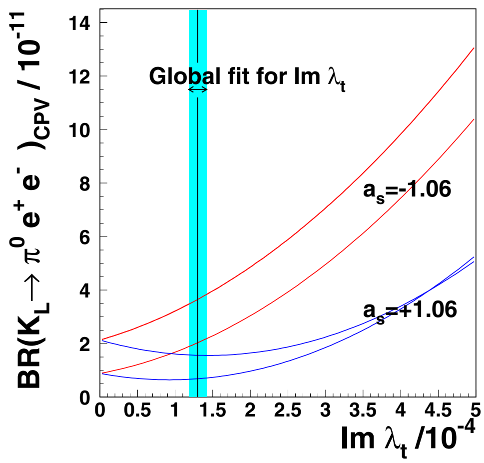

Fig. 5. Branching fraction of $K_L \to \pi^0 e^+ e^-$ as a function of $Im(\lambda_t)$

the amplitude [7] predicted by Chiral Perturbation Theory and a unit form factor. A preliminary measurement of the branching ratio was then obtained:

$$B\ (K_S \to \pi^0 e^+ e^-\ , m_{ee} > 165\ \mathrm{MeV/c^2}) = (3.0^{+1.5}_{-1.2}(stat) \pm 0.1(syst)) \times 10^{-9}$$

$$B\ (K_S \to \pi^0 e^+ e^-\ ) = (5.8^{+2.8}_{-2.3}(stat) \pm 0.8(syst)) \times 10^{-9}.$$

The systematic uncertainty includes the uncertainty on the flux measurement and on the acceptance. The parameter $|a_S|$ was derived from $B(K_S \to \pi^0 e^+ e^-\ )$ to be

$$|a_S| = (1.06^{+0.26}_{-0.21}(\mathrm{stat}) \pm 0.07(\mathrm{syst})).$$

This measurement of $|a_S|$ allows the K_L branching ratio to be calculated as a function of $Im(\lambda_t)$, with a sign ambiguity (Fig. 5). Taking the value $Im(\lambda_t) = (1.30 \pm 0.12) \times 10^{-4}$ [8] from a global fit to b-decays, the CP-violating part of $B(K_L \to \pi^0 e^+ e^-\ )$ can be predicted to be:

$$B\ (K_L \to \pi^0 e^+ e^-\ )_{\mathrm{CPV}} \simeq (17.2_{\mathrm{indirect}} \pm 9.4_{\mathrm{interference}} + 4.7_{\mathrm{direct}}) \times 10^{-12},$$

where the direct CP violation is small compared with the indirect component.

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