Recent results in Kaon Physics from NA48/1

M. Clemencic (for NA48/1 Collaboration) [a]

[a]Dipartimento di Fisica Sperimentale dell'Università e Sezione dell'INFN di Torino, I-10125 Torino, Italy

A search for the rare decays $K_S \to \pi^0 e^+ e^-$ and $K_S \to \pi^0 \mu^+ \mu^-$ has been made by NA48/1 experiment at CERN SPS. The data were collected during 2002 in 89 days of run with a high-intensity K_S beam. Seven $K_S \to \pi^0 e^+ e^-$ candidates have been observed with an expected background of 0.15 events. The $K_S \to \pi^0 \mu^+ \mu^-$ observed candidates were six with a background expectation of $0.22^{+0.18}_{-0.11}$ events. The measured branching ratios are

$$\mathrm{BR}(K_S \to \pi^0 e^+ e^-, m_{ee} > 0.165\,\mathrm{GeV/c^2}) = (3.0^{+1.5}_{-1.2} stat \pm 0.2 syst) \times 10^{-9}$$

and

$$\mathrm{BR}(K_S \to \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} stat \pm 0.2 syst) \times 10^{-9}$$

The results has been compared to test the Chiral Perturbation Theory and to estimate the CP violating component of the corresponding K_L decays.

1. Introduction

The branching ratio of $K_L \to \pi^0 l^+ l^-$ contains three contributions: a CP conserving part that can be estimated from $\mathrm{BR}(K_L \to \pi^0 \gamma\gamma)$, an indirect CP violating part that can be evaluated from $\mathrm{BR}(K_S \to \pi^0 l^+ l^-)$ and a direct CP violating part that can give a measurement of the imaginary parameter η of the unitarity triangle. The branching ratios of $K_S \to \pi^0 l^+ l^-$ decays, never observed before, are fundamental to make it possible to extract from the $K_L \to \pi^0 l^+ l^-$ an independent measurement of η.

2. Experimental Setup

The detector built by the NA48 Collaboration to measure the $Re(\epsilon'/\epsilon)$ parameter of the $K_{S,L}$ decays has been used, with few modifications, to perform the described searches.

2.1. Beam

The neutral K_S beam has been produced by the interaction of a 400 GeV proton beam, extracted from the CERN SPS accelerator, with a Beryllium target. The spill length was 4.8 s out of 16.8 s cycle time. The intensity of the proton beam was fairly constant during the spill with an average intensity of 5×10^{10} protons per spill.

In order to reduce the contamination of the neutral kaon beam by photons (mainly from decays of π^0 produced in the target), a platinum absorber 24 mm thick was placed between the target and the main sweeping magnet which deflected charged particles. A 5.1 m thick collimator, the axis of which formed an angle of 4.2 mrad to the proton beam direction, selected a beam of neutral long-lived particles (K_S, K_L, Λ^0, Ξ^0, n and γ). On average $2 \times 10^5 K_S$ per spill decayed in the fiducial volume downstream of the collimator with energy between 60 and 200 GeV.

2.2. Detector

In order to minimize interactions of the neutral beam, the collimator was immediately followed by a ~ 90 m long evacuated tank. The tank was terminated by a Kevlar window 0.3% radiation length (X_0) thick, except for the region near the beam which is continued in a vacuum pipe through the center of the downstream detector.

2.2.1. Tracking

The detector included a charged spectrometer contained in a helium gas volume. It consists of four drift chambers, two before and two after a dipole magnet with a horizontal transverse kick of 265 MeV/c. Each chamber had four views consisting of two sense wire planes. The spatial resolution achieved is of 150 μm in each projection. The spectrometer momentum resolution was parametrized as

$$\sigma_p/p = 0.48\% \oplus 0.015\% \times p$$

where p is in GeV/c. This gave a resolution of 3 MeV/c^2 on reconstructing the mass of the kaon in a $K_S \to \pi^+\pi^-$ decay. The track time resolution was ~ 1.4 ns.

2.2.2. Electromagnetic Calorimetry

The detection and measurement of the electromagnetic showers were achieved with a $27\,X_0$ thick liquid krypton calorimeter (LKR). The energy resolution was parametrized as[4]

$$\sigma_E/E = 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$$

where E is in GeV. The calorimeter was subdivided into 13500 cells of transverse dimension 2 cm × 2 cm, which resulted in a transverse position resolution, for a single photon of energy larger than 20 GeV, better than 1.3 mm. The π^0 mass resolution was 0.8 MeV/c^2 while the time resolution for a single shower was better than 300 ps.

2.2.3. Scintillator Detectors and Muon Detector

A scintillator hodoscope was located between the spectrometer and the calorimeter. It consisted of two planes, segmented in horizontal and vertical strips and arranged in four quadrants. The time resolution for the hodoscope system was 200 ps.

Downstream the LKR there was an iron-scintillator sandwich hadron calorimeter followed by muon counters (MUC) which consisted of three planes of plastic scintillators, each shielded by an 80 cm thick iron wall. The first two planes consisted of 25 cm wide horizontal and vertical scintillator strips, with a length of 2.7 m. The third plane consists of horizontal 44.6 cm wide strips and was mainly used to measure the efficiency of the other two planes. The central strips of each plane was split with a gap of 21 cm in order to accommodate the beam pipe.

The fiducial volume of the experiment was determined by the acceptance of the LKR calorimeter together with seven rings of scintillation counters which surrounded the decay volume to veto activity outside this region.

2.2.4. Trigger and Readout

The detector was sampled every 25 ns with no dead time and the samples were recorded in a time window of 200 ns encompassing the event trigger time. In this way it has been possible to investigate the accidental activity using appropriated sidebands.

For both $K_S \to \pi^0 e^+e^-$ and $K_S \to \pi^0\mu^+\mu^-$ a first stage hardware trigger and a second stage software trigger were used. The hardware trigger conditions were essentially made by the request of two tracks with a vertex within 90 m from the end of the collimator. For $K_S \to \pi^0 e^+e^-$ a minimum energy in the LKR of 30 GeV was required, while for $K_S \to \pi^0\mu^+\mu^-$ the minimum required energy in the LKR was 15 GeV and a request of two hits in the MUC was added. The software trigger was simply a refinement of the hardware condition. The events that satisfied the trigger conditions were recorded and reprocessed with improved calibrations to obtain the final data sample.

3. Analysis Strategy

$K_S \to \pi^0 e^+e^-$ and $K_S \to \pi^0\mu^+\mu^-$ are very rare decays (expected BR $\sim 10^{-9}$) so a *blind analysis* strategy has been chosen. For both the decay modes a signal region and a control region were chosen and kept masked until the final set of cuts was defined. The cuts were tuned in order to maximize the ratio signal/background within the signal regions with the help of Monte Carlo simulation.

4. $K_S \to \pi^0 e^+ e^-$ Decay

4.1. Signal and Control Region

The signal region for $K_S \to \pi^0 e^+ e^-$ was defined as:

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

while the control region was:

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

To evaluate the resolutions, $\sigma_{m_{ee\gamma\gamma}}$ and $\sigma_{m_{\gamma\gamma}}$, we studied the decay channel $K_S \to \pi^0 \pi^0_D$[1] which gave $\sigma_{m_{\gamma\gamma}} = 1\,\mathrm{MeV/c^2}$ and $\sigma_{m_{ee\gamma\gamma\gamma}} = 6.5\,\mathrm{MeV/c^2}$ in agreement with the Monte Carlo simulation.

4.2. Event Selection

The signal channel $K_S \to \pi^0 e^+ e^-$ required the identification of an electron and a positron accompanied by two extra clusters in the LKR.

Track reconstructed from the spectrometer which match an LKR cluster, in time and space, were labelled as an *electron* or a *positron* if the condition $0.95 < E/p < 1.05$ was satisfied.

Events with an extra track close in time to the event candidate were rejected. Cuts on the time of the clusters and tracks were also applied.

4.3. Background

Many possible sources of background were studied. They fall in two categories:

- a single kaon or hyperon which reproduced an event falling into the $K_S \to \pi^0 e^+ e^-$ signal region
- fragments from two primary decays which happen to coincide in time and space and fall into the signal box.

The background contributions were reduced by imposing additional requirements.

The most relevant sources of background are from $K_S \to \pi^0 \pi^0$ where one or more photons

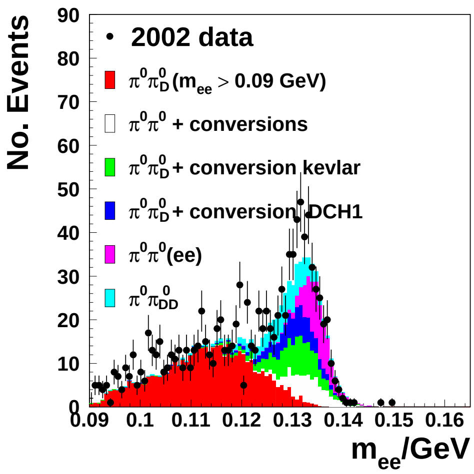

Figure 1. Distribution of m_{ee} after all the cuts have been applied. Superimposed we show the Monte Carlo predictions from all important sources.

from one or both the π^0s convert (either internally or externally). Those background events were rejected requiring $m_{ee} > 165\mathrm{MeV/c^2}$. In fig. 1 we show the distribution for data (full dots) and superimposed the contributions from all relevant background sources.

The background from $\Xi^0 \to \Lambda\pi^0$ and $\Lambda \to p\pi^-$ decays was reduced to a negligible level by exploiting the large momentum asymmetry in both the $\Lambda\pi^0$ and $p\pi^-$ final states. $K_S \to \pi^0 e^+ e^-$ candidates were required to have $(P_\Lambda - P_{\pi^0})/(P_\Lambda + P_{\pi^0})$ smaller than 0.4 or $(P_p - P_{\pi^-})/(P_p + P_{\pi^-})$ smaller than 0.5. A similar cut was used to remove $\overline{\Xi^0}$ and $\overline{\Lambda}$.

Three sources of background were found to be not negligible:

1. $K_{L,S} \to e^+ e^- \gamma\gamma$
   Using $K_L \to e^+ e^- \gamma\gamma$ data from the 2001 run and extrapolating to the signal region, the background from this channel was estimated to be $0.08^{+0.03}_{-0.02}$ events.
2. $K_S \to \pi^0_D \pi^0_D$
   This was evaluated using full Monte Carlo

[1] π^0_D is the Dalitz decay $\pi^0 \to e^+ e^- \gamma$.

simulation. The estimated background in the signal region was less than 0.01 events.

3. *Accidental backgrounds*
This component was studied using data with the timing requirements relaxed. Events in the time sidebands, satisfying all the other cuts, were used to extrapolate the background from the control to signal region. The contribution due to this component was $0.07^{+0.07}_{-0.03}$ events in the signal region.

4.4. Normalization

In order to obtain the $K_S \to \pi^0 e^+ e^-$ branching ratio, the K_S flux was calculated using the channel $K_S \to \pi^0 \pi^0_D$ for normalization which was selected by the same trigger. $K_S \to \pi^0 \pi^0_D$ decays were also used to measure the trigger efficiency.

The total number of K_S decaying within the fiducial volume was $(3.51 \pm 0.17) \times 10^{10}$.

4.5. Result

When the signal region was unmasked seven events were found (fig. 2).

To calculate the $K_S \to \pi^0 e^+ e^-$ acceptance, the amplitude for the decay was taken from the Chiral Perturbation Theory prediction given in [5].

The branching ratio for $m_{ee} > 0.165\,\mathrm{GeV/c^2}$ was computed:

$$\mathrm{BR}(K_S \to \pi^0 e^+ e^-, m_{ee} > 0.165\,\mathrm{GeV/c^2}) = (3.0^{+1.5}_{-1.2}(\mathrm{stat}) \pm 0.2(\mathrm{syst})) \times 10^{-9}. \quad (1)$$

Using a vector matrix element with no form factor dependence, the measured branching ratio was extrapolated to the full m_{ee} spectrum, obtaining

$$\mathrm{BR}(K_S \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3}(\mathrm{stat}) \pm 0.8(\mathrm{syst})) \times 10^{-9}. \quad (2)$$

The systematic error is dominated by the uncertainty in the extrapolation due to the form factor dependence.

5. $K_S \to \pi^0 \mu^+ \mu^-$ Decay

5.1. Signal and Control Region

As for the $K_S \to \pi^0 e^+ e^-$ search, the signal and control regions were defined using the reconstructed π^0 and kaon masses:

- signal region
$|m_{\gamma\gamma} - M_{\pi^0}| < 2.5 \times \sigma_{m_{\gamma\gamma}}$
$|m_{\mu\mu\gamma\gamma} - M_K| < 2.5 \times \sigma_{m_{\mu\mu\gamma\gamma}}$

- control region
$3 \times \sigma_{m_{\gamma\gamma}} < |m_{\gamma\gamma} - M_{\pi^0}| < 6 \times \sigma_{m_{\gamma\gamma}}$
$3 \times \sigma_{m_{\mu\mu\gamma\gamma}} < |m_{\mu\mu\gamma\gamma} - M_K| < 6 \times \sigma_{m_{\mu\mu\gamma\gamma}}$

The similarity between $K_S \to \pi^0 \mu^+ \mu^-$ and $K_L \to \pi^0 \pi^+ \pi^-$ allowed us to use the latter to evaluate $\sigma_{m_{\gamma\gamma}}$ and $\sigma_{m_{\mu\mu\gamma\gamma}}$. These were measures to be $\sigma_{m_{\gamma\gamma}} = 0.8\,\mathrm{MeV/c^2}$ and $\sigma_{m_{\mu\mu\gamma\gamma}} = 3\,\mathrm{MeV/c^2}$.

5.2. Event Selection

The muon identification was done by extrapolating the charged tracks reconstructed in the spectrometer to the MUC and associating them with MUC hits using spatial and time cuts.

Cuts chosen in order to improve the trigger efficiency reduce the background were applied.

Events with extra tracks or clusters were rejected.

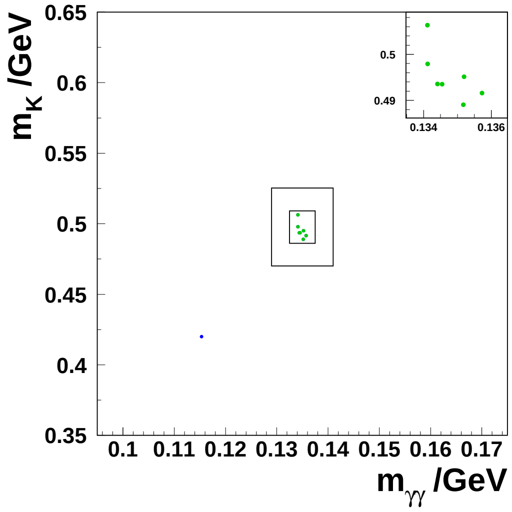

Figure 2. Scatter plot of $m_{ee\gamma\gamma}$ versus $m_{\gamma\gamma}$ for events passing all the cuts. The region 3σ and 6σ are shown.

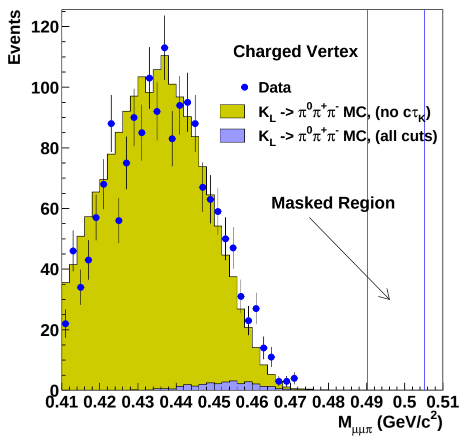

Figure 3. Distribution of $m_{\mu\mu\gamma\gamma}$ after all the cuts but $c\tau$ cut. The vertical lines indicate the signal region.

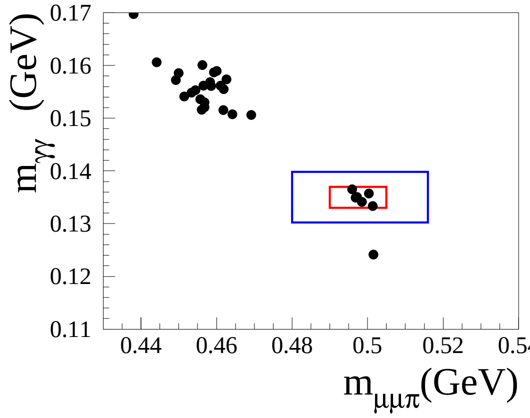

Figure 4. Scatter plot of $m_{\gamma\gamma}$ versus $m_{\mu\mu\gamma\gamma}$ for events passing all the cuts. The region 3σ and 6σ are shown.

5.3. Background

As for the $K_S \to \pi^0 e^+ e^-$ decay, many possible background sources were studied. The main background sources identified were:

1. $K_{L,S} \to \mu^+\mu^-\gamma\gamma$
   Using $K_L \to \mu^+\mu^-\gamma\gamma$ branching ratio measured by KTeV Collaboration[6], Monte Carlo simulation and assuming equal decay rate for K_S decay, the background contribution was estimated to be $0.04^{+0.04}_{-0.03}$ events.

2. $K_L \to \pi^+\pi^-\pi^0$, where both pions have decayed in flight
   For this decay $m_{\mu\mu\gamma\gamma}$ is below the kaon mass. The Monte Carlo describe well the distribution (fig. 3) and permit to estimate the background contribution to be < 0.018 90%CL.

3. *Accidental backgrounds*
   From the time sidebands, 6 events were found in the signal region, which, with the appropriated scaling, give background contribution of $0.18^{+0.18}_{-0.11}$ events.

5.4. Normalization

The K_S flux has been measured using $K_S \to \pi^+\pi^-$ events from a minimum bias trigger.

The total number of K_S decays in the considered fiducial region has been estimated to be $(2.50 \pm 0.08) \times 10^{10}$.

5.5. Result

After unmasking the signal region, 6 events were found (fig. 4).

The branching ratio was measured to be:

$$\mathrm{BR}(K_S \to \pi^0\mu^+\mu^-) = (2.9^{+1.5}_{-1.2}(\mathrm{stat}) \pm 0.2(\mathrm{syst})) \times 10^{-9}. \quad (3)$$

The result is consistent within error with recent predictions based on Chiral Perturbation Theory[5].

6. Discussion

6.1. Test of Chiral Perturbation Theory

Chiral Perturbation Theory (χPT) can be used to predict the branching ratio for $K_S \to \pi^0 l^+ l^-$ and the corresponding dilepton mass spectrum, m_{ll}. The measurements presented here test these predictions and constrain the parameters of the model.

The $K_S \to \pi^0 l^+ l^-$ branching ratios can be expressed as a function of two parameters, a_s and b_s[5]. Using Vector Meson Dominance model (VMD), which predicts $b_s = 0.4 a_s$[5], we can obtain $|a_s|$ from the relations[7]

$$\mathrm{BR}(K_S \to \pi^0 e^+ e^-) \simeq 5.2 \times 10^{-9} a_s^2 \quad (4)$$

$$\mathrm{BR}(K_S \to \pi^0 \mu^+ \mu^-) \simeq 1.2 \times 10^{-9} a_s^2 \quad (5)$$

The results presented here give $|a_s|_{ee} = 1.06^{+0.26}_{-0.21} \pm 0.07$ and $|a_s|_{\mu\mu} = 1.54^{+0.40}_{-0.32} \pm 0.06$.

The ratio $\mathrm{BR}(K_S \to \pi^0 \mu^+ \mu^-)/\mathrm{BR}(K_S \to \pi^0 e^+ e^-)$ is found to be $0.49^{+0.35}_{-0.29} \pm 0.08$ in reasonable agreement with the VMD model prediction of 0.23.

6.2. CPV components of $K_L \to \pi^0 l^+ l^-$

The CP violating part of $K_L \to \pi^0 l^+ l^-$ branching ratio can be estimated using the results for the corresponding K_S decays and the global fit for $\mathrm{Im}(\lambda_t)$ [2][5]. We obtain

$$\mathrm{BR}(K_L \to \pi^0 e^+ e^-)_{CPV} \times 10^{12} \approx 17.2_{mixing} \pm 9.4_{interference} + 4.7_{direct} \quad (6)$$

$$\mathrm{BR}(K_L \to \pi^0 \mu^+ \mu^-)_{CPV} \times 10^{12} \approx 8.8_{mixing} \pm 3.3_{interference} + 1.8_{direct} \quad (7)$$

REFERENCES

1. J. R. Batley *et al.* [NA48/1 Collaboration], Phys. Lett. B **576**, 43 (2003)
2. J. R. Batley *et al.* [NA48/1 Collaboration], CERN-PH-EP/2004-025
3. J. R. Batley *et al.* [NA48 Collaboration], Phys. Lett. B **544**, 97 (2002)
4. G. Unal [NA48 Collaboration], in: IX International Conference on Calorimetry, October 2000, Annecy France, arXiv:hep-ex/0012011
5. G. D'Ambrosio, G. Ecker, G. Isidori and J. Portoles, Journal of High Energy Physics **08**, 004 (1998)
6. A. Alavi-Harati *et al.* [KTeV Collaboration], Physical Review D **62**, 112001 (2000)
7. G. Buchalla, G. D'Ambrosio and G. Isidori, Nuclear Physics B **672**, 387 (2003)

[2] $\lambda_t = V_{td} V_{ts}^*$