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Tests of Chiral Perturbation Theory in $\mathrm{K_S}$ rare decays at NA48

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Abstract. The NA48 collaboration has performed an extensive study of rare kaon decays. In particular tests of Chiral Perturbation Theory have been done, using data from the $\mathrm{Re}(\varepsilon'/\varepsilon)$ runs in 1998 and 1999 for $\mathrm{K_L} \to \pi^0\gamma\gamma$ and from the NA48/1 High Intensity $\mathrm{K_S}$ for $\mathrm{K_S} \to \gamma\gamma$ and for the first observation of $\mathrm{K_S} \to \pi^0\gamma\gamma$

PACS. 13.20.Eb Decays of K mesons – 14.40.Aq π, K and η mesons

1 Introduction

The program of NA48 included, apart from the measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$, an extensive study of rare kaon decays. Data collected in the 1999 $\mathrm{Re}(\varepsilon'/\varepsilon)$ run were used to study a number of $\mathrm{K_L}$ rare decays. A 40 hours test run in 1999 using a $\mathrm{K_S}$ only beam with 200 times the standard $\mathrm{Re}(\varepsilon'/\varepsilon)$ $\mathrm{K_S}$ intensity was performed to demonstrate the feasibility of a high intensity $\mathrm{K_S}$ program. A specific proposal (NA48/1) was approved and high intensity $\mathrm{K_S}$ data were collected in 2000 and 2002. Specific information on the setup used for the 2000 run, relevant for the results presented here, can be found in [1]. Among the processes studied, we report here results on the radiative non-leptonic decays $\mathrm{K_L} \to \pi^0\gamma\gamma$, $\mathrm{K_S} \to \gamma\gamma$ and $\mathrm{K_S} \to \pi^0\gamma\gamma$.

2 Study of the decay $\mathrm{K_L} \to \pi^0\gamma\gamma$

$\mathrm{K_L} \to \pi^0\gamma\gamma$ decay is important because the decay rate prediction from $\mathrm{O(p^4)}$ χPT is finite, but 2-3 times smaller than the measured one [2]. Going to $\mathrm{O(p^6)}$ and including vector meson exchange, the measured rate is reproduced and a tail at low $\mathrm{m}_{\gamma\gamma}$ is predicted. The vector meson dominance contribution is parametrized by a_v, to be measured, and the low $\mathrm{m}_{\gamma\gamma}$ tail determines the CPC amplitude to the decay $\mathrm{K_L} \to \pi^0 e^+e^-$. Predictions from χPT are $\mathrm{BR}(\mathrm{K_L} \to \pi^0\gamma\gamma) = 1.5\ 10^{-6}$ and a_v = -0.7.

Data from 1998 and 1999 runs were selected using the same trigger as the $\mathrm{K_L} \to \pi^0\pi^0$ mode, which has been used as normalization channel. In this way many systematic uncertainties cancel out.

The background from $\mathrm{K_L} \to \pi^0\pi^0$ is rejected using invariant mass cuts: one pair of photons should be within 3 MeV from the pion mass, while the other should be outside the 110 MeV-160 MeV window. Transverse momentum of the lowest energy unpaired photon should be greater than 40 MeV/c.

The background from $\mathrm{K_L} \to 3\pi^0$ with missing or overlapping photons is rejected on a basis of a variable (z_{max}) designed to estimate the true kaon decay position, assuming a $3\pi^0$ decay. This estimate applied to signal events produces an unphysical result with a distribution mainly populated in the region upstream of the final collimator. The condition z_{max} < -5m rejects ≈ 99% of the $3\pi^0$ background, keeping 46% of the signal.

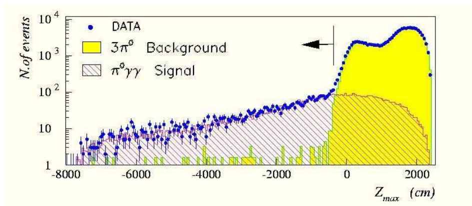

Fig. 1. $\mathrm{K_L} \to \pi^0\gamma\gamma$: *Background rejection*

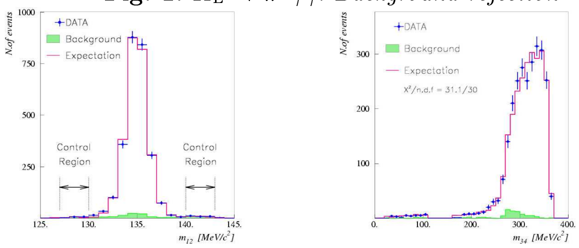

Fig. 2. $\mathrm{K_L} \to \pi^0\gamma\gamma$: *Events in the signal region and* $m_{\gamma\gamma}$ *distribution*

≈ 2500 events were found in the signal region (132 MeV < M_{π^0} < 138 MeV) [3]. Fitting the $\mathrm{M}_{\gamma\gamma}$ distribution, one obtains

$$\mathrm{a}_v = -0.46 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.02_{th}$$

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Using the fitted a_v value, the branching ratio is

$$BR(K_L \to \pi^0\gamma\gamma) = (1.36 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.03_{norm})\cdot 10^{-6}.$$

and the CP conserving part of the $K_L \to \pi^0 e^+e^-$ decay is

$$BR(K_L \to \pi^0 e^+e^-)_{CPC} = (4.7 \pm 2.2)\cdot 10^{-13}$$

3 Study of the decay $K_S \to \gamma\gamma$

$K_S \to \gamma\gamma$ is interesting because it is calculable in $O(p^4)$ χPT with no counterterms and it is sensitive to loops [4] [5] [6]. The theoretical prediction for the BR is $(2.1 \pm 0.2)\cdot 10^{-6}$. NA31 measured [7]

$$BR(K_S \to \gamma\gamma) = (2.4 \pm 0.9)\cdot 10^{-6}$$

With the data from the 1999 HIKs run with a dedicated trigger, NA48 has published [8]

$$BR(K_S \to \gamma\gamma) = (2.58 \pm 0.36_{st} \pm 0.22_{sy})\cdot 10^{-6}.$$

A better measurement has been performed using data from the 2000 run. The normalisation channel is $K_S \to \pi^0\pi^0$.

The $K_S \to \pi^0\pi^0$ background is minimized using a 5 meter fiducial region after the K_S collimator. These decays with two lost γ have a maximum invariant mass of 458 MeV and the reconstructed vertex cannot be less than 9 meters. This number is reduced to 5 meters because of the effect of overlapping showers. Hadronic interactions in the collimator and accidental $\gamma\gamma$ pairs are eliminated with suitable cuts.

The background from $K_L \to \gamma\gamma$ is instead irreducible and it amounts to 1.5 times the K_S channel. The subtraction of this background is done evaluating the K_L flux using $K_L \to 3\pi^0$ and measuring $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$ using the data from the far target run with K_L only. For this measurement the detector conditions are similar to the K_S data taking, so detector systematics cancel. The decay volume is the same as for $K_S \to \gamma\gamma$ and the acceptance differences almost cancel. After subtracting hadronic background and evaluating the systematic uncertainties due to acceptance and background subtraction, we obtain an independent measurement:

$$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0) = (2.81 \pm 0.01_{st} \pm 0.02_{sy})\cdot 10^{-3}$$

The total number of $K_{S,L} \to \gamma\gamma$ is 19916. The global systematic correction is -1.8 ± 1.4 %. Statistical errors on data and on the Montecarlo sample are respectively 2.0% and 0.6%.

The result is

$$BR(K_S \to \gamma\gamma) = (2.78 \pm 0.06_{st} \pm 0.03_{sy} \pm 0.02_{ext})\cdot 10^{-6}$$

This result is compatible with previous measurements, but it shows a 30% difference wrt to $O(p^4)$ χPT predictions, indicating a possible large $O(p^6)$ contribution.

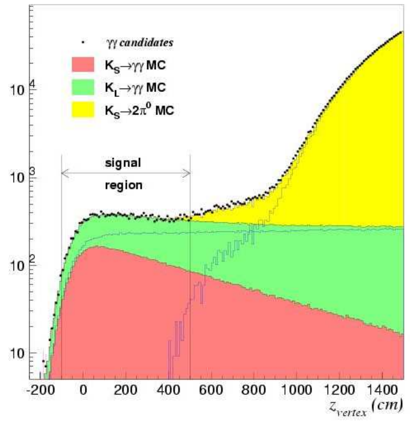

Fig. 3. $K_S \to \gamma\gamma$: *Background rejection*

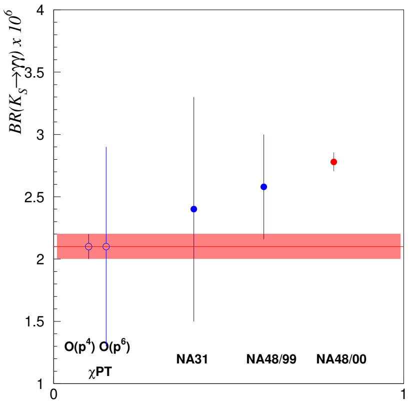

Fig. 4. $K_S \to \gamma\gamma$: *Theoretical predictions and measured values*

4 First observation of $K_S \to \pi^0\gamma\gamma$

The study of $K_S \to \pi^0\gamma\gamma$, as in other radiative non-leptonic kaon decays, is useful to check χPT predictions for the low energy hadron dynamics. In the decay $K_S \to \pi^0\gamma\gamma$ the photon pair is produced by a pseudo-scalar meson. A measurement of the branching ratio can give information on possible extra non-pole contributions [9]. The prediction for the branching ratio is limited to the kinematical region $z = m^2_{\gamma\gamma}/m^2_K > 0.2$ and it is $3.8 * 10^{-8}$[10]. Additional information from the z spectrum can determine, if sufficient statistics is available, the momentum dependence of the weak vertex.

Using data from the 1999 K_S run, NA48 has published [11] the upper limit

$$BR(K_S \to \pi^0\gamma\gamma)_{z>0.2} < 3.3 \cdot 10^{-7}$$

at 90% confidence level.

Data has been collected in the 2000 run using the same trigger for $K_S \to \pi^0\pi^0$ and $K_S \to \pi^0\gamma\gamma$, so that many systematic uncertanties cancel out.

The selection for $K_S \to \pi^0\gamma\gamma$ requires the two best matching photons with the π^0 mass, while the others should have $m^2_{\gamma\gamma}/m^2_K > 0.2$. Cuts on a χ^2 variable built with the sums and differences of the $\gamma\gamma$ pair masses and their resolutions discriminate between $\mathrm{K_S} \to \pi^0\pi^0$ and $\mathrm{K_S} \to \pi^0\gamma\gamma$.

The large background from $\mathrm{K_S} \to \pi^0\pi^0_{\mathrm{D}}$with one photon out of the acceptance is reduced with a cut on the z coordinate of the decay point between -1m and 8m. Most of the background from $\mathrm{K_S} \to \pi^0\pi^0_{\mathrm{D}}$ and even more from $\mathrm{K_L} \to 3\pi^0$ is reconstructed downstream of this region because of the missing energy. Further suppression of $\mathrm{K_S} \to \pi^0\pi^0_{\mathrm{D}}$ background is achieved imposing cuts on the closest z_{π^0} to the collimator, where z_{π^0} are the vertex positions of $\gamma\gamma$ pairs.

Irreducible background from $\mathrm{K_L} \to \pi^0\gamma\gamma$ is estimated from the $\mathrm{K_S} \to \pi^0\pi^0$ rate, assuming equal $\mathrm{K_S}$ and $\mathrm{K_L}$ production at the target. Residual background from $\Xi^0 \to \Lambda^0\pi^0$ with $\Lambda^0 \to n\pi^0$ with one γ escaping and with a narrow n shower is suppressed rejecting asymmetric topologies. Accidental pile-up background is reduced with tight cuts on the shower times, which should be within 1 nsec.

After the selection the final sample consists of 31 events. The normalization sample of about $285{\cdot}10^3$ has been used. The background estimation is 13.7±3.2 events of which the half is due to pile-up accidentals. The probability of observing in the signal region 31 or more events when the background is 13.7±3.2 is $1.5{\cdot}10^{-3}$. In the control region the data agree with the background estimate. 17.3±6.4 signal events are obtained after background subtraction. Acceptances were computed using a Monte Carlo simulation and are 18.6% for $\mathrm{K_S} \to \pi^0\pi^0$ and 7.2±0.3% for $\mathrm{K_S} \to \pi^0\gamma\gamma$.

Normalising to $\mathrm{K_S} \to \pi^0\pi^0$ with the proper ratio of acceptances gives

$$\Gamma(\mathrm{K_S} \to \pi^0\gamma\gamma)_{z>0.2}/\Gamma(\mathrm{K_S} \to \pi^0\pi^0) = (1.57 \pm 0.51_{st} \pm 0.29_{sy}){\cdot}10^{-7}$$

The result is stable against variation of the most relevant cuts. Using $BR(\mathrm{K_S} \to \pi^0\pi^0)$ from PDG one obtains

$$BR(\mathrm{K_S} \to \pi^0\gamma\gamma)_{z>0.2} = (4.9 \pm 1.6_{st} \pm 0.9_{sy}){\cdot}10^{-8} = (4.9 \pm 1.8){\cdot}10^{-8}$$

in agreement with [10].

The z distribution of the events after background subtraction has been compared with z distributions of simulated events using two different decay generators, one with χPT matrix element and the other with pure phase space. The experimental data agree with both calculations and none of the two predictions can be preferred.

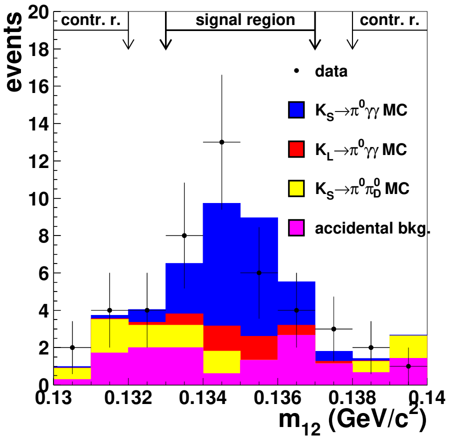

Fig. 5. $\mathrm{K_S} \to \pi^0\gamma\gamma$: *Data and background distribution*

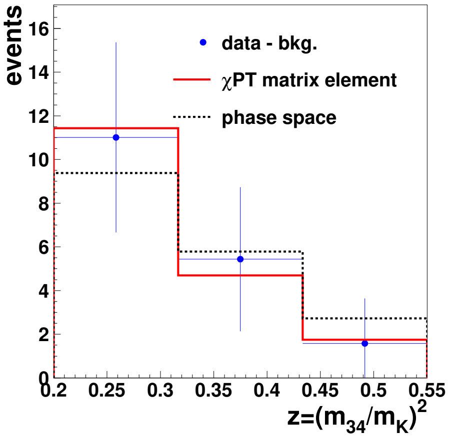

Fig. 6. $\mathrm{K_S} \to \pi^0\gamma\gamma$: z_q *distribution for data and two theoretical models*

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