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Measurement of the decay rate and the parameter α_{K^*} of the decay $K_L \rightarrow \mu\mu\gamma$

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Abstract. The rate of the decay of the neutral K meson into $K^0_L \to \mu\mu\gamma$ has been measured with the NA48 detector at the CERN SPS. A total of 59 events has been observed with an estimated background of 14 events. The overall Kaon flux was determined to be 1.2×10^9. This observation corresponds to a branching ratio of $\left(3.4 \pm 0.6_{stat} \pm 0.4_{sys}\right) \times 10^{-7}$. Using this branching ratio the parameter α_{K^*} describing the relative strength of the two contributing amplitudes to this decay, through intermediate pseudoscalar or vector-like mesons, was measured to be $\alpha_{\mathbf{K}^*} = -0.04^{+0.24}_{-0.21}$.

1 Introduction

The decay of the long-lived neutral K meson, $K_L \to \mu\mu\gamma$, sheds light on the structure of the $K_L \to \gamma^*\gamma$ vertex. Phenomenological models of this structure include vector meson dominance of the photon propagator [1] and QCD models involving penguin diagrams and pole diagrams [2]. Bergström, Massó and Singer parametrized the form factor of K_L Dalitz decays by introducing a free parameter α_{K^*} describing the relative strength of weak transitions between two pseudo-scalar mesons ($K_L \to \pi^0, \eta, \eta' \to \gamma^*\gamma$) or between two vector-like mesons in the intermediate state ($K_L \to K^*\gamma \to \rho, \omega, \phi\, \gamma \to \gamma^*\gamma$) [3]. There is a $1/s$ dependence ($s = m^2_{\ell\ell}/m^2_K$) in the differential rate of the Dalitz decay and the invariant two lepton mass is constrained to be greater than $2 \cdot m_\ell$. As a consequence in the electron mode the dielectron mass spectrum is most sensitive to the form factor, while in the muon mode the measurement of the branching fraction provides the most sensitive test. The first measurement of the parameter α_{K^*} was performed by the NA31 experiment at CERN in the $K_L \to e^+e^-\gamma$ channel [4]. Other measurements were made at Brookhaven (BNL experiment E845 [5]) and Fermilab (FNAL experiment E799 [6]) in the electron and the muon modes, respectively. Here we report the result obtained with data from a first run of the NA48 experiment.

2 Experimental setup and data taking

The NA48 experiment at the CERN SPS is designed to measure the direct CP violation parameter ϵ'/ϵ in the neutral kaon system with an accuracy of 2×10^{-4}. Long-lived kaons with an average momentum of 100 GeV/c are produced by 450 GeV/c protons striking a beryllium target located 126 m upstream of the beginning of the decay region. Charged particles are removed by sweeping magnets, and a neutral beam is defined by collimation to ± 0.15 mrad. The final collimator is located about 100 m upstream of the detector and is followed successively by an 88 m long evacuated tube and by a helium-filled tank which contains the drift chambers. The neutral beam continues in an evacuated beam pipe with a diameter of 16 cm through a central hole in the detector. Decays occurring in the upstream part of the evacuated region are measured. The outer diameter of each of the subdetectors is typically 2.5 m. All detector components except for the liquid Krypton calorimeter and the third out of four drift chambers were available during this run. We summarize the properties of the detector elements relevant for the present analysis:

- A magnetic spectrometer with two drift chambers in front and one after a dipole magnet operated to produce a 267 MeV/c transverse momentum kick. Each drift chamber is composed of four double planes with staggered wires to resolve left-right ambiguities. The wire orientations in the four views are horizontal, vertical, and $\pm 45°$ with respect to the horizontal plane. The resolution of a coordinate in a single drift chamber is 110 μm, the mean momentum resolution of the three-chamber spectrometer is $\Delta p/p$ = 0.6%, giving a resolution on the invariant kaon mass from $K_L \to \pi^+\pi^-$ decays of 2.8 MeV/c^2 on average;
- A scintillator hodoscope located in front of the calorimeter to trigger on charged particles;
- A sampling calorimeter made of iron plates and scintillator planes designed to measure hadronic showers with a readout in horizontal and vertical projections. During the beam period in 1995 it was also used to determine the energy of electromagnetic showers. The energy resolution was measured to be $23\%/\sqrt{\text{E(GeV)}}$ and $69\%/\sqrt{\text{E(GeV)}}$ for electromagnetic and hadronic showers, respectively.
- A muon counter system consisting of three planes of plastic scintillator with an 80 cm thick iron wall in front of each plane. The first two planes have 25 cm wide horizontal and vertical scintillator strips, the third one horizontal strips with 44.6 cm width.

A more complete description of the apparatus can be found elsewhere [7].

The analysis presented here is based on data from a first short run in 1995 with a proton intensity of about 4×10^{11} protons in each 2.4 s long SPS spill. The $\mu\mu\gamma$ candidates and the $\pi\mu\nu$ normalization candidates were selected with a two-particle trigger. All candidates must have at least two particles in the scintillator hodoscope and an energy deposition of more than 8 GeV in the calorimeter (MB trigger). The $K_L \to \mu\mu\gamma$ candidates are required to have in addition two hits in each of the first two planes of the muon detector. The relative efficiency of these two triggers was measured to be (95.6 $\pm$ 2.5)% using $K_L \to \pi^+\pi^-\pi^0$ events with two decayed charged pions obtained from data taken with the MB trigger.

3 Event selection and analysis

The data sample has been used to select $K_L \to \mu\mu\gamma$ candidates and $K_L \to \pi\mu\nu$ normalization events. After a preselection requiring at least two charged tracks and one electromagnetic shower, the data set consists of about 3.1×10^6

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events. To select $K_L \to \mu\mu\gamma$ candidates, two sets of cuts are applied in order to (a) select fully reconstructable events without ambiguities and (b) suppress potential background. For the decay $K_L \to \mu\mu\gamma$, two background sources are relevant: (1) $K_L \to \pi^+\pi^-\pi^0$ events in which both charged pions decay in front of the detector, or are misidentified as muons, and one photon is outside the acceptance of the detector; (2) $K_L \to \pi\mu\nu$ events in which the charged pion decayed and a photon not correlated with the kaon decay products is detected simultaneously.

3.1 Selection of $K_L \to \mu\mu\gamma$ candidates

$K_L \to \mu\mu\gamma$ candidates must meet the following requirements:

- There is only one electromagnetic shower with an energy of at least 8 GeV without a charged track pointing to it within a distance of 12 cm.
- There are only two charged tracks which point to hits in both of the first two planes of the muon counter. The distance from the beam axis of the charged tracks at the position of the first drift chamber is between 10 cm and 130 cm and greater than 12 cm in the calorimeter. The momentum of each of the tracks has to be larger than 3 GeV/c. The z-position of the common vertex is between 0 and 90 m downstream of the final collimator. The vertex is reconstructed with a closest distance of approach (cda) of less than 4 cm. Monte Carlo (MC) studies show that this cut removes about 30% of the $K_L \to \pi^+\pi^-\pi^0$ background events where both charged pions decay in front of the detector but only 1.1% of the $K_L \to \mu\mu\gamma$ events.
- The variable $p_0'^2$ [8], which is the square of the kaon momentum in the system where the longitudinal momentum of the charged tracks, with respect to the line joining the decay vertex and the target, is zero, has to be lower than -0.01 (GeV/c)^2. Note that $p_0'^2$ is calculated using only the charged track momenta under a $K_L \to \pi^+\pi^-\pi^0$ hypothesis. This cut removes about 96% of the $K_L \to \pi^+\pi^-\pi^0$ background events but only 3.5% of the $K_L \to \mu\mu\gamma$ MC events.
- The square of the reconstructed transverse momentum of the kaon with respect to the line joining the decay vertex and the target must be less than 0.002 (GeV/c)^2. This cut removes about 91 % of the $K_L \to \pi\mu\nu$ plus accidental gamma at this stage of the selection, but only 1.5 % of the $K_L \to \mu\mu\gamma$ MC events.
- The ratio of the squares of the transverse momentum of the three particles and the transverse momentum of the muon pair $R = p_T^2(\mu\mu\gamma)/p_T^2(\mu\mu)$ must be less than 0.05. This cut removes another 70% from the background MC events of the different background channels and about 4.3% of the $K_L \to \mu\mu\gamma$ MC events (see Fig. 1).

After these cuts 317 $K_L \to \mu\mu\gamma$ candidates remain. Figure 2 shows the distribution of the invariant $\mu\mu\gamma$ mass for these events. Also shown is the expectation of the mass resolution as obtained from a Monte Carlo simulation of the $K_L \to \mu\mu\gamma$ decay.

The space coordinates of the photon can only be measured with an accuracy limited by the strip width (11.9 cm) in the calorimeter; these coordinates are recalculated using the condition that the p_T of the event should be zero for $K_L \to \mu\mu\gamma$ events. Using these recalculated positions for the mass calculation, the resolution in the invariant mass can be improved from 13.7 MeV/c^2 to 5.2 MeV/c^2 while the signal to background ratio increases by a factor of three. The cuts on the invariant mass (485 MeV/c^2 $< M_{\mu\mu\gamma} <$ 510 MeV/c^2) and the regions used for background subtraction are indicated by the arrows.

There are 59 events in the signal region. The background is obtained by linear interpolation from the two side windows. It is found to be 14 events.

3.2 Normalization

The normalization of the $K_L \to \mu\mu\gamma$ events is obtained from $K_L \to \pi\mu\nu$ events. To select the $K_L \to \pi\mu\nu$ events, the following cuts are applied:

- Candidates must have one shower in the calorimeter with an energy of at least 9.4 GeV and a distance to the beam axis of more than 12 cm.
- They must have two reconstructed charged tracks which meet the same requirements on detector geometry as the $K_L \to \mu\mu\gamma$ candidates. One track must point to the shower in the calorimeter, the other one to a hit in each of the first two planes of the muon counters. The momentum of the track associated with the shower in the calorimeter has to be greater than 18.6 GeV/c, the momentum of the muon track has to be greater than 3 GeV.
- The reconstructed decay vertex must fulfil the same requirements as the vertex of the $K_L \to \mu\mu\gamma$ candidates.
- The same cut on the $p_0'^2$ variable as for $K_L \to \mu\mu\gamma$ candidates is applied in order to suppress $K_L \to \pi^+\pi^-\pi^0$ background.

After these cuts 15988 $K_L \to \pi\mu\nu$ events remain.

3.3 Acceptance determination and kaon flux

For $K_L \to \mu\mu\gamma$ decays, an acceptance of $(11.0 \pm 0.2_{stat})$% was determined from 40000 Monte Carlo events using a full detector simulation based on GEANT. The calculation was checked with a simpler Monte Carlo program using only smeared values for energy and space coordinates of the tracked particles. Both results agreed. The matrix element for the simulation was taken from [9]. The acceptance for $K_L \to \pi\mu\nu$ decays is $(10.9 \pm 0.1_{stat})$% as determined from 225000 Monte Carlo events. The decay $K_L \to \pi e\nu$ with subsequent decay π to μ is indistinguishable from this channel; this has also been studied by Monte Carlo and the acceptance is found to be (0.5 ± 0.04)%.

The $K_L \to \pi\mu\nu$ normalization events were scaled down by a factor of 2560 during the data taking. The efficiency of this downscaling was measured to be (95.9 ± 0.9)%, leading to a effective downscaling factor of $2455 \pm 22_{stat}$.

Using the number of $K_L \to \pi\mu\nu$ normalization events, the $K_L \to \pi\mu\nu$ branching ratio of 0.2717±0.0025 [10], the

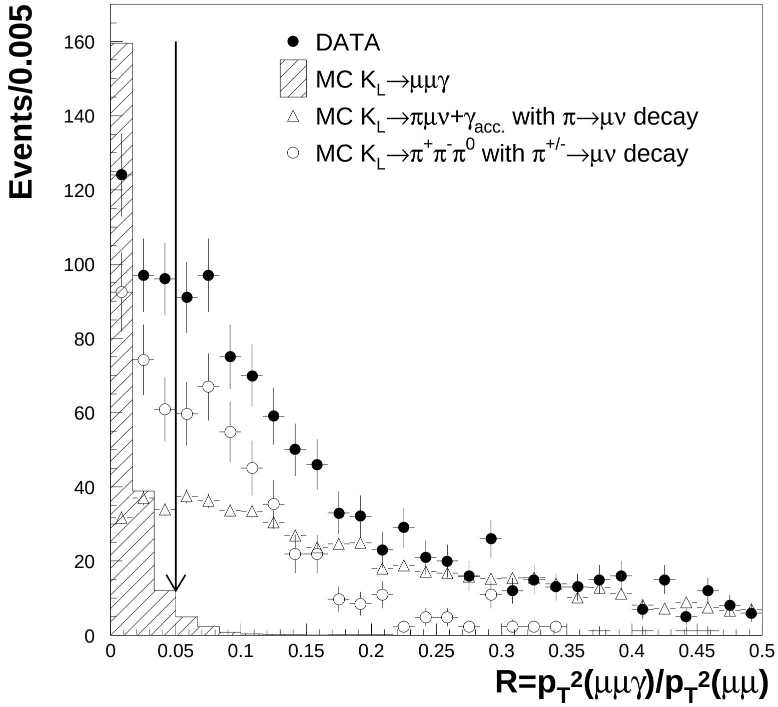

Fig. 1. Distribution of the p_T^2 ratio (R) for $K_L \to \mu\mu\gamma$ candidates, $K_L \to \mu\mu\gamma$ MC events, $K_L \to \pi^+\pi^-\pi^0 \to \mu^+\nu\,\mu^-\overline{\nu}\,\gamma\gamma$ and $K_L \to \pi\mu\nu + \gamma_{acc.}$ background MC events. The normalization of the Monte Carlo events is arbitrary

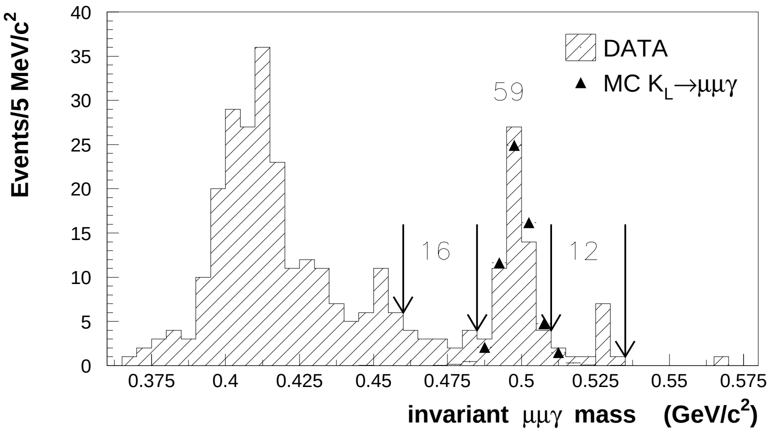

Fig. 2. Invariant mass of $K_L \to \mu\mu\gamma$ candidates and $K_L \to \mu\mu\gamma$ Monte Carlo events. The number of events in the regions defined by the arrows are indicated

forementioned acceptance and the effective down-scaling factor, the number of kaon decays is determined to be $(1.22 \pm 0.02_{stat}) \times 10^9$.

4 Results

From the number of $K_L \to \mu\mu\gamma$ events, their acceptance and the kaon flux, the result for the branching ratio is $BR(K_L \to \mu\mu\gamma/all) = (3.4 \pm 0.6_{stat.}) \times 10^{-7}$.

The systematic error on the branching ratio has been estimated by varying the cuts that have the most important influence on the acceptance for $K_L \to \mu\mu\gamma$ events. These are the cuts on the minimum photon energy, the minimum momenta of the tracks, the p_T^2, the p_T^2-ratio (R), the $p_0'^2$ variable, the cda and the cut on the minimum kaon momentum. Table 1 gives a summary of the cuts varied and the change of the branching ratio. The resulting systematic error on the branching ratio is +9% −8% obtained by adding the positive and negative contributions separately in quadrature. An additional contribution of ±8% to the systematic error results from the variation of the regions from which the background is subtracted. Another source of a systematic error came from the measurement of the efficiency of the downscaling, this error was evaluated to be −4.3%. The error resulting from a relative reconstruction efficiency between $K_L \to \mu\mu\gamma$ and $K_L \to \pi\mu\nu$ candidates turned out to be compatible with zero.

Table 1. Systematic error sources

cut changed		from		to	Change of BR
E_γ [GeV]	$>$	**8**	$\to$	12	−2.0%
p_μ [GeV/c]	$>$	**3**	$\to$	7	−7.0%
$p_0'^2$ [(GeV/c)^2]	$<$	**−0.01**	$\to$	0	−2.6%
$p_0'^2$ [(GeV/c)^2]	$<$	**−0.01**	$\to$	−0.02	+8.5%
cda [cm]	$<$	**4**	$\to$	2	−1.9%
p_T^2 [(GeV/c)^2]	$<$	**0.002**	$\to$	0.001	+0.7%
$p_T^{2\,ratio}$	$<$	**0.05**	$\to$	0.02	+1.3%
$p_{\mu\mu\gamma}$ [GeV]	$>$	**14**	$\to$	25	−1.7%

The final result on the branching ratio is:

$$\frac{\Gamma(K_L \rightarrow \mu\mu\gamma)}{\Gamma(all)} = (3.4 \pm 0.6_{stat} \pm 0.4_{sys.}) \times 10^{-7}$$

Using the formula given in [3] for the dependence of the branching ratio on the parameter α_{K^*}, the result can be translated into a value for α_{K^*} of:

$$\alpha_{K^*} = -0.04^{+0.24}_{-0.21}$$

This result is in good agreement with former measurements of α_{K^*} from the $K_L \rightarrow \mu\mu\gamma$ branching ratio [6] and from the slope of the m_{ee} distribution of the $K_L \rightarrow ee\gamma$ decay [4] [5].

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