

Study of the rare decay $K^\pm \rightarrow \pi^\pm \gamma\gamma$ in the NA48/2 and NA62 experiments at CERN

Mauro Piccini*

INFN - Sezione di Perugia, Via A. Pascoli, 06123 Perugia, Italy

E-mail: Mauro.Piccini@pg.infn.it

A sample of about 300 $K^\pm \rightarrow \pi^\pm \gamma\gamma$ rare decays with a background contamination below 10% has been collected by the NA48/2 and NA62 experiments at CERN during low intensity runs with minimum bias trigger configuration. The measurements of the decay spectrum and rate provide a crucial test of the Chiral Perturbation Theory (ChPT) describing weak processes at low energy.

1 Introduction

Radiative non-leptonic kaon decays can provide fundamental tests for the predictivity of the Chiral Perturbation Theory (ChPT) in order to describe weak processes at low energy. In this respect, an early prediction from ChPT for the rate of the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ decay is reported in¹. In the ChPT framework, the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ process is described by two non-interfering contributions: one for the pion and kaon loop amplitudes depending on an unknown \hat{c} parameter ($\hat{c} \sim O(1)$) which represents the total contribution of the counter-terms, the other taking into account for the pole amplitude². Once the two contributions are considered, the di-photon invariant mass $m_{\gamma\gamma}$ spectrum exhibits a characteristic cusp at twice the charged pion mass due to the dominance of the pion loop amplitude. Higher order unitarity corrections ($O(p^6)$ and above) modify the lowest order $O(p^4)$ decay spectrum significantly: in particular, they lead to a non-zero value of

*for the NA48/2 and NA62 Collaborations: F. Ambrosino, A. Antonelli, G. Anzivino, R. Arcidiacono, W. Baldini, S. Balev, J.R. Batley, M. Behler, S. Bifani, C. Biino, A. Bizzeti, B. Bloch-Devaux, G. Bocquet, V. Bolotov, F. Bucci, N. Cabibbo, M. Calveti, N. Cartiglia, A. Ceccucci, P. Cenci, C. Cerri, C. Cheshkov, J.B. Chèze, M. Clemencic, G. Collazuol, F. Costantini, A. Cotta Ramusino, D. Coward, D. Cundy, A. Dabrowski, G. D'Agostini, P. Dalpiaz, C. Damiani, H. Danielsson, M. De Beer, G. Dellacasa, J. Derré, H. Dibon, D. Di Filippo, L. DiLella, N. Doble, V. Duk, J. Engelfried, K. Eppard, V. Falaleev, R. Fantechi, M. Fidecaro, L. Fiorini, M. Fiorini, T. Fonseca Martin, P.L. Frabetti, A. Fucci, S. Gallorini, L. Gatignon, E. Gersabeck, A. Gianoli, S. Giudici, A. Gonidec, E. Goudzovski, S. Goy Lopez, E. Gushchin, B. Hallgren, M. Hita-Hochgesand, M. Holder, P. Hristov, E. Iacopini, E. Imbergamo, M. Jeitler, G. Kalmus, V. Kekelidze, K. Kleinknecht, V. Kozhuharov, W. Kubischta, V. Kurshetsov, G. Lamanna, C. Lazzeroni, M. Lenti, E. Leonardi, L. Litov, D. Madigozhin, A. Maier, I. Mannelli, F. Marchetto, G. Marel, M. Markytan, P. Marouelli, M. Martini, L. Masetti, P. Massarotti, E. Mazzucato, A. Michetti, I. Mikulec, M. Misheva, N. Molokanova, E. Monnier, U. Moosbrugger, C. Morales Morales, M. Moulson, S. Movchan, D.J. Munday, M. Napolitano, A. Nappi, G. Neuhofer, A. Norton, T. Numao, V. Obraztsov, V. Palladino, M. Patel, M. Pepe, A. Peters, F. Petrucci, M.C. Petrucci, B. Peyaud, R. Piandani, M. Piccini, G. Pierazzini, I. Polenkevich, I. Popov, Yu. Potrebenikov, M. Raggi, B. Renk, F. Retière, P. Riedler, A. Romano, P. Rubin, G. Ruggiero, A. Salamon, G. Saracino, M. Savrié, M. Scarpa, V. Semenov, A. Sergi, M. Serra, M. Shieh, S. Shkarovskiy, M.W. Slater, M. Sozzi, T. Spadaro, S. Stoynev, E. Swallow, M. Szleper, M. Valdata-Nappi, P. Valente, B. Vallage, M. Velasco, M. Veltri, S. Venditti, M. Wache, H. Wahl, A. Walker, R. Wanke, L. Widhalm, A. Winhart, R. Winston, M.D. Wood, S.A. Wotton, O. Yushchenko, A. Zinchenko, M. Ziolkowski.

the differential decay rate at $m_{\gamma\gamma} = 0$ ³. The total decay rate, extracted in a model dependent approach, is predicted to be around 10^{-6} , with the pole amplitude contributing at the level of 5% or less^{3,4}.

From the experimental point of view, the only published result by the E787 experiment at BNL⁵ is based on 31 K^+ decay candidates in the kinematic region $100 \text{ MeV}/c < p_{\pi^*} < 180 \text{ MeV}/c$, where p_{π^*} is the π^+ momentum in the K^+ rest frame. This contribution describes the $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ analyses based on the minimum bias samples collected with high trigger efficiency by the NA48/2 and NA62 experiments in the years 2004 and 2007. The resulting $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ sample is 10 times larger than the BNL E787 one and allows the measurement of \hat{c} and the extraction of the Branching Ratio of the decay.

2 Description of $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay

In the ChPT framework the kinematic variables used to describe the $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay are:

$$y = \frac{p(q_1 - q_2)}{m_K^2}, \quad z = \frac{(q_1 + q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2, \quad (1)$$

where p is the 4-momentum of the kaon, $q_{1,2}$ are the 4-momenta of the two photons, $m_{\gamma\gamma}$ is the di-photon invariant mass and m_{π} is the charged pion mass. The differential decay rate up to next-to-leading order in the ChPT framework is parameterized in the following way³:

$$\frac{\partial\Gamma}{\partial y \partial z}(\hat{c}, y, z) = \frac{m_K}{2^9 \pi^3} \left[z^2 (|A(\hat{c}, z, y^2) + B(z)|^2 + |C(z)|^2) + \left(y^2 - \frac{1}{4} \lambda(1, r_{\pi}^2, z) \right)^2 |B(z)|^2 \right], \quad (2)$$

where $r_{\pi} = m_{\pi}/m_K$, m_{π} is the charged pion mass, $\lambda(1, r_{\pi}^2, z) = 1 + r_{\pi}^4 + z^2 - 2(r_{\pi}^2 + z + r_{\pi}^2 z)$ and $A(\hat{c}, z, y^2)$ and $B(z)$ are the loop amplitudes; the latter appears only at next-to-leading $O(p^6)$ order and is dominant at low z . $C(z)$ is the pole amplitude. The ChPT predictions for the decay spectrum and rate are:

- a cusp in the differential decay width ($d\Gamma/dz$) distribution at the di-pion threshold ($z_{th} = 4r_{\pi}^2 = 0.320$)
- a non-zero differential rate at $z = 0$ and a y^2 -dependence of the differential rate arising both at next-to-leading order $O(p^6)$.

3 The NA48/II and NA62 experiments: beam and detector

In the 2003-2004 (2007) years the NA48/2 (NA62) experiments have collected data on charged kaon decays. The beam and the detectors were the same for both the experiments with only minor changes. Two simultaneous K^+ and K^- beams were produced by a 400 GeV/ c proton beam delivered by the CERN SPS and impinging on a berillium target. The beamline was designed to select kaons with a momentum range of $(60 \pm 3) \text{ GeV}/c$ in NA48/2 and $(74 \pm 1) \text{ GeV}/c$ in NA62. In NA48/2 the data used for the present analysis were collected in 2004 during a dedicated run with a special trigger setup which only requires one or more tracks in the magnetic spectrometer and at least a energy deposit of 10 GeV/ c in the electromagnetic calorimeter. Also the intensity of the beam was lowered and the momentum spread was reduced to obtain an acceptable rate of events to be recorded. Almost the same trigger was used during the entire 2007 run (~ 100 days) of NA62, with an average downscale factor of ~ 20 applied to the number of triggers at software level.

The main components of the NA48/2 detector were a magnetic spectrometer, composed by four drift chambers with a dipole magnet in the middle deflecting charged particles in the horizontal plane, and a liquid krypton electromagnetic calorimeter (LKr) with an energy resolution

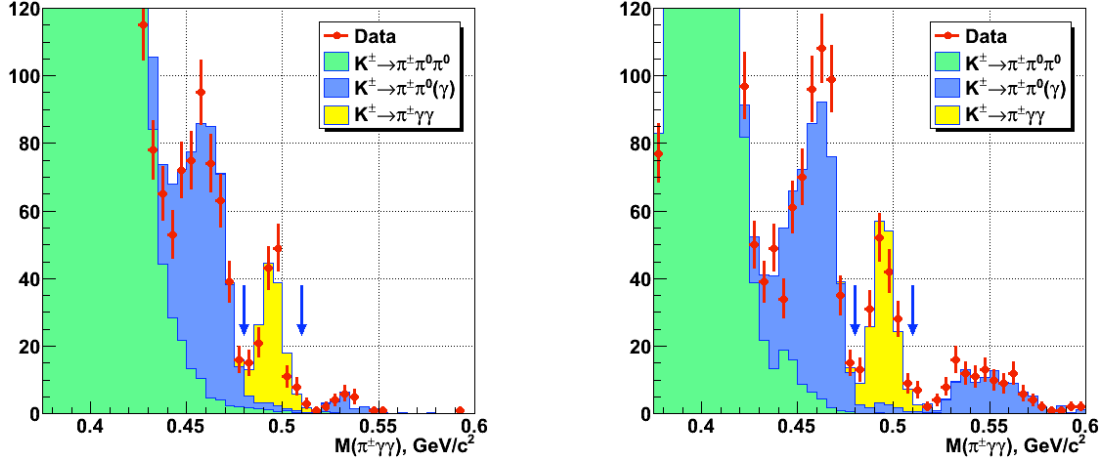


Figure 1: The $\pi^\pm\gamma\gamma$ invariant mass for the 2004 (left) and 2007 (right) samples; vertical arrows show the limits of the signal region.

of about 1% for 20 GeV photons and electrons. Giving the different kaon momenta between 2004 and 2007 the p_t kick of the dipole magnet was 120 MeV/c for NA48/2 and 265 MeV/c for NA62. A fast signal for the trigger was produced by a charged hodoscope (CHOD) consisting of two planes of horizontal and vertical scintillator strips. The NA48/2 detector is described in detail elsewhere⁶.

4 Event selection and reconstruction

The decay vertex was defined searching for the Closest Distant of Approach (CDA) between the pion track and the nominal K^\pm beam directions. The longitudinal coordinate of the such vertex was selected to be inside the fiducial decay volume (62 m region) of the experiment. In order to identify the pion, one and only one track was required to be reconstructed from the information collected by the spectrometer, the track had to match the acceptances of the main detectors (LKr, CHOD) and the measured momentum was required to be within 10 (8) and 40 (50) GeV/c for the NA48/2 (NA62) data. The ratio E/p between the energy E deposited by the track in the LKr and the momentum p measured by the spectrometer was required to be lower than 0.85.

To identify the two photons two independent clusters were required in the LKr with energy greater than 3 GeV. Both clusters had to be in time with the reconstructed pion track. The invariant mass of the pion and of the two photons was then computed taking into account the position of the decay vertex. Such reconstructed $\pi^\pm\gamma\gamma$ invariant mass was required to be in the range (0.48-0.51) GeV/c² (± 15 MeV/c² from K^\pm mass). A cut requiring $0.2 < z < 0.54$ was applied, the lower limit allowing to reject the $K^\pm \rightarrow \pi^\pm\pi^0$ background. After such selection criteria were applied to the two data samples collected in 2004 by NA48/2 and in 2007 by NA62, the number of observed events in the signal region was 147 and 175 respectively (see figure 1).

Table 1: Signal statistics and main background contributions for the two samples.

	2004	2007
$K^\pm \rightarrow \pi^\pm\gamma\gamma$ candidates	147	175
$K^\pm \rightarrow \pi^\pm\pi^0(\gamma)$ background	11.0 ± 0.8	11.1 ± 1.0
$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ background	5.9 ± 0.7	1.3 ± 0.3
$K^\pm \rightarrow \pi^\pm\gamma\gamma$ signal	130 ± 12	163 ± 13

As shown in Table 1, the main background comes from the decay $K^\pm \rightarrow \pi^\pm\pi^0(\gamma)$, with a

photon eventually lost. Non negligible background is also produced by the decay $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ with two photons lost, such contribution is higher in the NA48/2 sample because of the worse resolution on the $\pi^\pm \gamma \gamma$ invariant mass. The two background contributions were estimated from MonteCarlo simulation, the overall background is at the level of 9%.

5 Results

After all the selection criteria were applied, the values of the \hat{c} parameter in the framework of the ChPT $O(p^4)$ and $O(p^6)$ parameterizations have been measured performing likelihood fits to the z spectra coming from data (see Figure 2). The MonteCarlo outputs for signal ($O(p^4)$ and $O(p^6)$ generators according to³⁾ and for background components were directly compared to data. In Table 2 the results from the fits of the 2004 and 2007 data in the two different theoretical

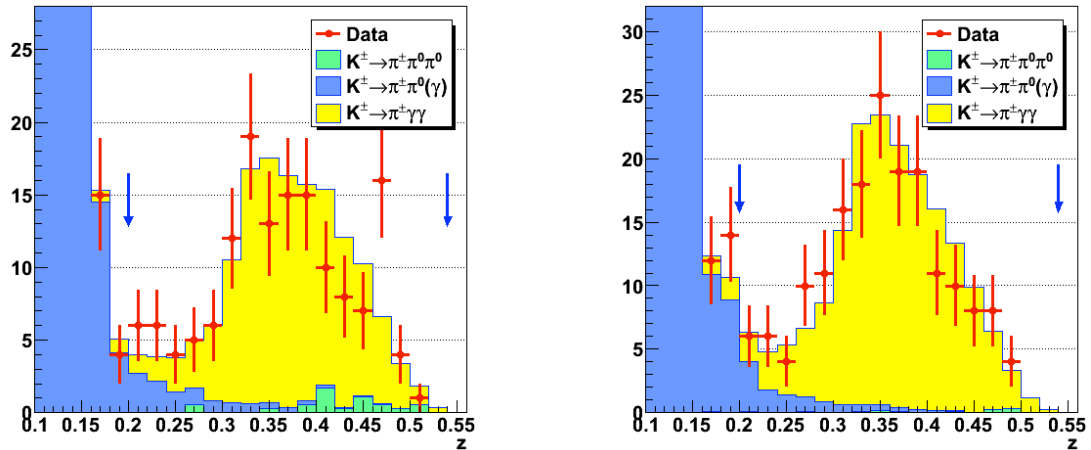


Figure 2: Distribution of the z variable for the 2004 (left) and 2007 (right) samples; vertical arrows show the limits of the signal region.

frameworks are listed. The results are then combined taking into account the correlations between the systematic errors. The main contribution to the systematic errors comes from the

Table 2: Extracted values of \hat{c} for the 2004 and 2007 samples in the ChPT $O(p^4)$ and $O(p^6)$ frameworks. Combined results are also listed.

	2004	2007	Combined
\hat{c} at $O(p^4)$	$1.36 \pm 0.33_{stat} \pm 0.07_{syst}$	$1.71 \pm 0.29_{stat} \pm 0.06_{syst}$	$1.56 \pm 0.22_{stat} \pm 0.07_{syst}$
\hat{c} at $O(p^6)$	$1.67 \pm 0.39_{stat} \pm 0.09_{syst}$	$2.21 \pm 0.31_{stat} \pm 0.08_{syst}$	$2.00 \pm 0.24_{stat} \pm 0.09_{syst}$

background evaluation. Other effects (for example trigger efficiency and pion mis-identification) were also studied and give small contributions. Once \hat{c} is measured, a Branching Ratio value (model dependent) of the decay can also be analytically derived. In the $O(p^6)$ framework, the preliminary measurement of \hat{c} gives the value $BR(K^\pm \rightarrow \pi^\pm \gamma \gamma) = (1.01 \pm 0.06) \times 10^{-6}$.

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