Recent Results from NA48/2 *

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Abstract Recent results on radiative $K^{\pm}$ decays from the NA48/2 experiment are reported. From the full NA48/2 data set, about a million $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ decays were reconstructed. Based on this sample, the first measurement of the interference between direct photon emission and inner bremsstrahlung in $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ decays was performed. Stringent limits on CP violation in this decay were also set. In addition, a precise measurement of the branching fraction of $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ is presented. This measurement was based on a data sample of more than 1000 event candidates. Also the related decay $K^{\pm}\rightarrow\pi^{\pm}e^{+}e^{-}\gamma$ has first been observed. Results of the measurement of the decay rate and the decay parameter $\hat{c}$ are summarized.

1 Introduction

Radiative kaon decays offer a unique possibility to study Chiral Perturbation Theory (ChPT). In these decays, the only physical states which appear are pseudoscalar mesons, photons and leptons, and the characteristic momenta involved are small compared to the natural scale of chiral symmetry breaking. In particular, decays with direct photon emission like in the $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ channel and decays with vanishing $\mathcal{O}(p^2)$ contribution to ChPT as in $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ and $K^{\pm}\rightarrow\pi^{\pm}e^{+}e^{-}\gamma$ channels are of theoretical interest.

During the years 2003 and 2004, the NA48/2 experiment at CERN collected the world largest amount of charged kaon decays. The kaon beams had a mean momentum of 60 GeV/c, with K^{+} and K^{-} decays being recorded simultaneously, to cancel systematic effects in CP violation measurements [1]. A 3-track-trigger was used to collect kaon decays into three charged particles, while a 1-track-trigger required a minimum invariant mass of the neutral decay particles to exclude the abundant $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}$ and $K^{\pm}\rightarrow\mu^{\pm}\nu_{\mu}$ decays. Billions of reconstructed kaon decays were recorded.

The NA48 detector is described in detail elsewhere [2]. The main detector components were a magnetic spectrometer, consisting of two sets of drift chambers before and after a dipole magnet providing a momentum resolution of about 1.4% for 20 GeV/c charged tracks, and a liquid-krypton electromagnetic calorimeter with an energy resolution of about 1% for 20 GeV photons and electrons.

2 $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ Decays

The total amplitude of the $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ decay is the sum of two terms: inner bremsstrahlung (IB) and direct emission (DE). The IB component can be predicted from QED corrections to $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}$ with a photon a emitted from the charged pion [3, 4]. For the DE contribution, the photon is emitted from the weak vertex and several studies within the framework of ChPT exist [5–9]. At $\mathcal{O}(p^4)$ of ChPT, direct photon emission can occur through both electric ($\mathcal{X}_E$) and magnetic ($\mathcal{X}_M$) dipole transitions. The magnetic part is the sum of a reducible amplitude, that can be calculated using the Wess-Zumino-Witten functional [10, 11], and a direct amplitude which size is expected to be small. For the electric transition no definite prediction exists. The electric dipole transition of the DE term can interfere with the IB component giving rise to an interference term which can have CP violating contributions.

The properties of the $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ decays can be described in terms of the variables T^{*}_{π} and W, with T^{*}_{π} the kinetic energy of the charged pion in the kaon rest frame and W a Lorenz invariant given by $W^2=(p_{\pi}\cdot\ p_{\gamma})(p_K\cdot\ p_{\gamma})/(m_K^2 m_{\pi}^2)$. After integration over T^{*}_{π}, the differential rate for the $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ process is given by:

$$\frac{\partial^2\Gamma^{\pm}}{\partial W}=\frac{\partial^2\Gamma^{\pm}_{IB}}{\partial W}[1+2\cos(\pm\phi+\delta^1_1-\delta^2_0)m^2_{\pi}m^2_K|\mathcal{X}_E|W^2 +m^4_{\pi}m^4_K(|\mathcal{X}_E|^2+|\mathcal{X}_M|^2)W^4],$$

where the DE term is proportional to W^4 and the INT term is proportional to W^2 and contains the

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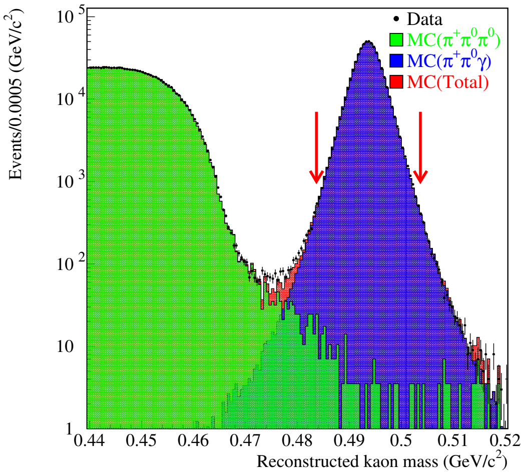

Fig. 1. Selected $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$.

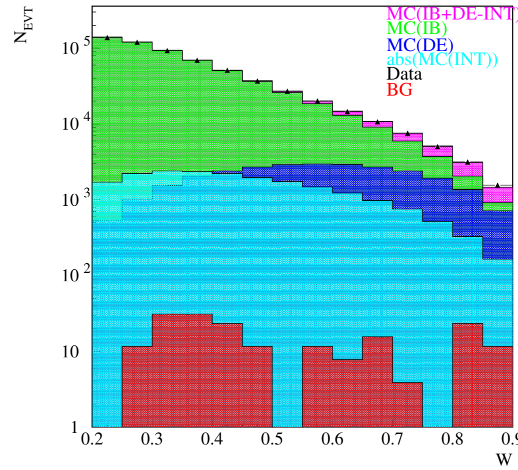

Fig. 2. Maximum-likelihood fit of the W distribution of selected $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$.

CP violating phase ϕ, the strong pion-pion rescattering phases, δ_1^1 and δ_0^2, and the normalized electric and magnetic amplitudes, $\mathcal{X}_E$ and $\mathcal{X}_M$. This different dependence on W allows the extraction of the different decay components. Furthermore, by measuring the INT term it is possible to disentangle the electric and magnetic amplitudes and to investigate possible CP violation in $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$.

The combined DE branching fraction, based on the world total of about 30000 $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ events collected by previous experiments, is Br(DE) $= (4.3 \pm 0.7) \times 10^{-6}$ [12], with the assumption of no interference term. This assumption was consistent with the only previous measurement of Frac(INT) $=$ Br(INT)/Br(IB) $= (-0.4 \pm 1.6)\%$ by the E787 experiment [13]. These measurements were performed in the restricted kinematic region $55 < T_{\pi}^{*} < 90$ MeV. NA48/2 was the first experiment which used both K^{+} and K^{-} events. In addition, a strong suppression of $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ events, based on the excellent performance of the LKr calorimeter, was achieved. This allowed to extend the kinematic region to $0 < T_{\pi}^{*} < 80$ MeV, with a slightly stronger upper cut due to the on-line trigger rejection of $K^{\pm} \to \pi^{\pm}\pi^{0}$ events. The remaining background, coming mainly from $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$, was estimated with Monte Carlo simulated events to be less than 1% of the DE contribution. The probability of misidentifying the odd-photon was estimated to be of the order of 10^{-3}.

As a result, about 1 million of $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ events were reconstructed by NA48/2 (Fig. 1). The extraction of the IB, DE, and INT contributions was done with an extended maximum-likelihood fit of the Monte Carlo W distributions of the single components to the data distribution. The kinematic range was restricted to $0.2 < W < 0.9$, leaving about 600000 events for the fit. The fit to the data is shown in (Fig. 2) and yielded Frac(DE) $= (3.32 \pm 0.15)$ % and Frac(INT) $= (-2.35 \pm 0.35)$ % (for $0 < T_{\pi}^{*} < 80$ MeV). The residuals of the maximum likelihood fit are shown in (Fig. 3). As a cross-check, a simple polynomial fit to the data W distribution, divided by the Monte Carlo IB distribution was performed. The result was in perfect agreement with the maximum-likelihood method. The final result, including also systematic uncertainties, is

$$\mathrm{Frac(DE)}_{0<T_{\pi}^{*}<80\ \mathrm{MeV}} = (3.32 \pm 0.15_{stat} \pm 0.14_{syst}) \times 10^{-2}$$

$$\mathrm{Frac(INT)}_{0<T_{\pi}^{*}<80\ \mathrm{MeV}} = (-2.35 \pm 0.35_{stat} \pm 0.39_{syst}) \times 10^{-2}$$

with a correlation coefficient of -0.93 between both values. Fig. 4 shows the confidence regions for the statistical uncertainties. From this, the electric and magnetic amplitudes can be extracted to

$$\mathcal{X}_E = (-24 \pm 4_{stat} \pm 4_{syst})\ \mathrm{GeV}^{-4},$$

$$\mathcal{X}_M = (254 \pm 11_{stat} \pm 11_{syst})\ \mathrm{GeV}^{-4},$$

with the magnetic amplitude very close to the WZW prediction of about 260 GeV^{-4}. For comparison with previous experiments, a fit with the INT term set to 0 was performed.

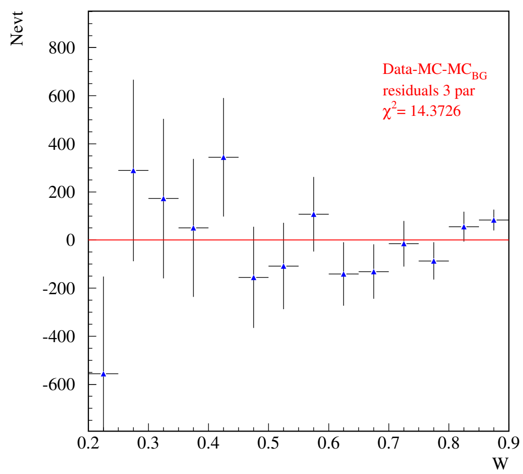

Fig. 3. Fit residuals of maximum-likelihood fit of the W distribution of the selected $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ candidates.

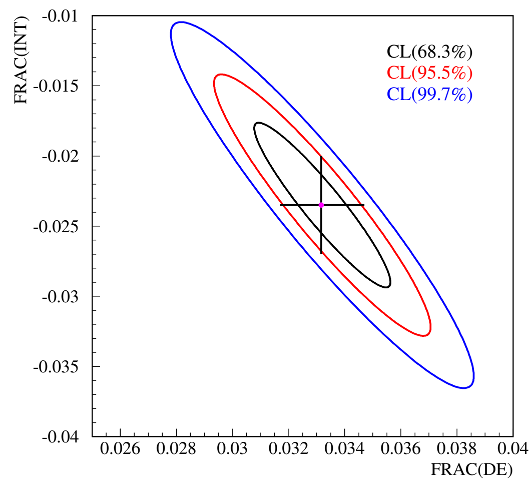

Fig. 4. Contour plot for the DE and INT terms. The cross indicates de 1σ statistical uncertainties of the projections.

The result, extrapolated to the kinematic range $55 < T_{\pi}^{*} < 90$ MeV, was

$$\mathrm{Br(DE)}^{\mathrm{INT}=0}_{55<T_{\pi}^{*}<90\ \mathrm{MeV}} = (2.32 \pm 0.05_{stat} \pm 0.08_{syst}) \times 10^{-6},$$

in clear disagreement with the previous measurements. The χ^2 of this fit was 51.0/12 (compared to 14.3/11 when including the INT term as a free parameter), strongly indicating the need of the INT term for a proper description of the data.

Possible direct CP violation in the decay rate asymmetry of K^{+} and K^{-} into this channel was also investigated. This CP violation would be due to a non-vanishing phase ϕ in the decay rate. A decay rate asymmetry can be expressed in an asymmetry of the total number of events, defined as $A_N = (N_{+} - RN_{-})/(N_{+} + RN-)$, with N_{+} and N_{-} the numbers of K^{+} and K^{-} decays, and R the ratio of K^{+} to K^{-} in the beam, determined from $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays *. Using the complete data set of more than a million decays, NA48/2 found $A_N = (0.0 \pm 1.0_{stat} \pm 0.6_{syst}) \times 10^{-3}$, corresponding to $|A_N| < 1.5 \times 10^{-3}$ at a confidence level of 90 %. Extraction of the CP violating phase ϕ yielded $\sin\phi = -0.01 \pm 0.43$, equivalent to $|\sin\phi| < 0.56$ at 90% CL. Assuming the interference to be the origin of possible CP violation, a fit to the ratio of the W spectra of K^{+} and K^{-}, given by the function $\frac{d\Gamma^{\pm}}{dW} = \frac{d\Gamma^{\pm}_{IB}}{dW}(1 + (a \pm e)W^2 + bW^4)$, was also performed. With the parameters a and b from the DE and INT fractions, a single parameter fit obtained $A_W = (-0.6 \pm 1.0) \times 10^{-3}$, in good agreement with the previous value of A_N.

3 $K^{\pm} \to \pi^{\pm}\gamma\gamma$ Decays

The $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay is of high interest in ChPT, since tree-level contributions at $\mathcal{O}(p^2)$ vanish, thus providing high sensitivity to $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$. The differential decay rate is given by

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

with $y = (E^{*}_{\gamma 1} - E^{*}_{\gamma 2})/m_K$ and $z = m^2_{\gamma\gamma}/m^2_K$. At $\mathcal{O}(p^4)$, only the $\Delta I = 1/2$ invariant amplitudes, A(z) and C(z), contribute. A(z) contains the loop terms, which lead to a characteristic signature in the $\gamma\gamma$ invariant mass, which exhibits a cusp at $2m_{\pi^{\pm}}$ and is favored to be above this value [7]. The tree-level counterterms are included in an unknown parameter, $\hat{c}$, which is predicted to be positive and of $\mathcal{O}(1)$ and needs to be measured. Pole and tadpole diagrams contribute to the C amplitude [14]. At $\mathcal{O}(p^6)$, unitarity corrections could increase the branching fraction by 30 - 40% [15]. From the measurement of the branching ratio and spectrum shape of $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decays, it

*This assumes negligible CP violation in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$, which is consistent with the NA48/2 limit on CP violation in the $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ Dalitz plot.

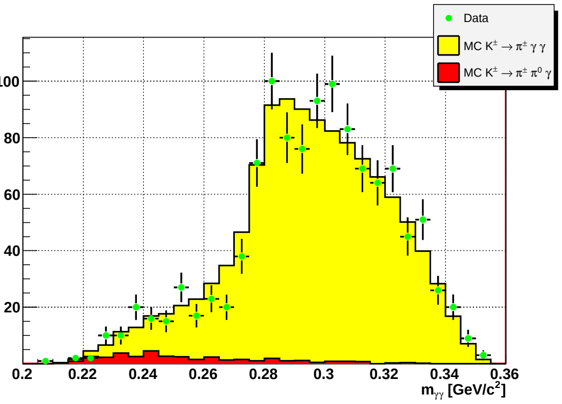

Fig. 5. Invariant $\gamma\gamma$ mass of selected $K^{\pm} \to \pi^{\pm}\gamma\gamma$ candidates.

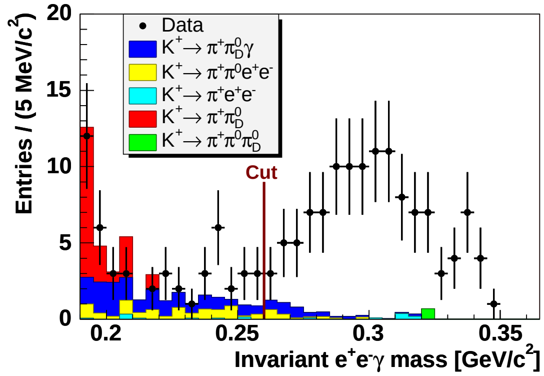

Fig. 6. Invariant $e^+e^-\gamma$ mass of selected $K^{\pm} \to \pi^{\pm}\gamma\gamma$ candidates.

is possible to extract information about the unknown constant $\hat{c}$ and to determine whether the higher order corrections to the theory explain the observed rate. A sample of about 40 % of the complete data set of NA48/2 has been analyzed. Due to the similarity in topology to $K^{\pm} \to \pi^{\pm}\pi^0$ events, which were trigger suppressed, the signal trigger efficiency for this channel was only of about 40%. In total, 1164 $K^{\pm} \to \pi^{\pm}\gamma\gamma$ candidates were reconstructed, which corresponds to 40 times the current world statistics for this channel. The background contribution, mainly from $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ events, was determined from Monte Carlo simulation to be 3.3 %. The invariant $\gamma\gamma$ mass distribution is shown in Fig. 5, exhibiting the expected cusp at twice the pion mass. Obtaining the detector acceptance from a simulation using $\mathcal{O}(p^6)$ ChPT with $\hat{c} = 2$, a preliminary, model-dependent branching fraction was obtained:

$$\mathrm{Br}(K^{\pm} \to \pi^{\pm}\gamma\gamma)_{\hat{c}=2,\mathcal{O}(p^6)} = (1.07 \pm 0.04_{stat} \pm 0.08) \times 10^{-6}$$

The systematic uncertainty is dominated by the trigger efficiency. A model-independent measurement and the extraction of the parameter $\hat{c}$ are in preparation.

4 $K^{\pm} \to \pi^{\pm}e^+e^-\gamma$ Decays

This decay is similar to $K^{\pm} \to \pi^{\pm}\gamma\gamma$ with one photon internally converting into a pair of electrons. NA48/2 has reported the first observation of the decay $K^{\pm} \to \pi^{\pm}e^+e^-\gamma$ using the full statistics collected by the experiment [16]. A total of 120 candidates with 7.3 ± 1.7 estimated background events have been selected in the region with invariant $e^+e^-\gamma$ mass greater than 0.26 GeV/c^2. Invariant $e^+e^-\gamma$ mass of selected candidates is shown in Fig. 6. Using $K^{\pm} \to \pi^{\pm}\pi^0_D$ as normalization channel, the branching ratio has been measured to be

$$\mathrm{Br} = (1.19 \pm 0.12_{stat} \pm 0.04_{syst}) \times 10^{-8}$$

for $m_{e^+e^-\gamma} > 0.26$ GeV/c^2. The parameter $\hat{c}$ was also measured assuming the validity of $\mathcal{O}(p^6)$ ChPT for this channel [17] and found to be $\hat{c} = 0.90 \pm 0.45$.

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