STUDY OF THE RARE DECAY $K^\pm \rightarrow \pi^\pm \gamma \gamma$ AND HIGH PRECISION MEASUREMENT OF THE FORM FACTORS OF THE SEMILEPTONIC DECAYS $K^\pm \rightarrow \pi^0 \ell^\pm \nu$

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The NA48/2 experiment presents preliminary measurements of the form factors of the charged kaon semileptonic decays. The $Ke3$ and $K\mu3$ results are in good agreement allowing for a combined result which matches the precision of the current world average on the vector and scalar form factors. Recent study of the rare decay $K^\pm \rightarrow \pi^\pm \gamma \gamma$ from the NA48/2 and NA62 data samples is also reported.

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1. The NA48/2 experiment

The beam line has been designed to deliver simultaneous narrow momentum band K^+ and K^- beams derived from the primary 400 GeV/c protons extracted from the CERN SPS. Secondary beams with central momenta of 60 GeV/c (for NA48/2) or 74 GeV/c (for NA62-RK) were used. The beam kaons decayed in a fiducial decay volume contained in a 114 m long cylindrical vacuum tank. The momenta of charged decay products were measured in a magnetic spectrometer. The spectrometer comprised four drift chambers (DCHs), two upstream and two downstream of a dipole magnet which provided a horizontal transverse momentum kick of 120 MeV/c (for NA48/2) or 265 MeV/c (for NA62-RK) to charged particles. Each DCH was composed of eight planes of sense wires. A plastic scintillator hodoscope (HOD) producing fast trigger signals and providing precise time measurements of charged particles was placed after the spectrometer. Further downstream was a liquid krypton electromagnetic calorimeter (LKr), an almost homogeneous ionization chamber with an active volume of 7 m³ of liquid krypton, 27X₀ deep, segmented transversally into 13248 projective 2x2 cm² cells and with no longitudinal segmentation. The LKr information is used for photon measurements and charged particle identification. An iron/scintillator hadronic calorimeter and muon detectors were located further downstream. A detailed description of the detector can be found in Ref. 1.

2. Semi-leptonic Kaon Decays

The hadronic matrix element of $K\ell 3$ decays is described by two dimensionless form factors $f_{\pm}(t)$, which depend on the squared four-momentum $t = (p_K - p_{\pi})^2$ transferred to the lepton-neutrino system. Usually, form factors are re-formulated to express the vector $f_+(t)$ and scalar $f_0(t)$ exchange contributions, and $f_0(t)$ can be described as a linear combination of $f_{\pm}(t)$:

$$f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_{\pi}^2} f_-(t) \quad (1)$$

with $f_+(0) = f_-(0)$ by construction. As $f_+(0)$ cannot be measured directly, it is common to normalize all form factors to it:

$$\tilde{f}_+(t) = f_+(t)/f_+(0) \quad \tilde{f}_0(t) = f_0(t)/f_+(0) \quad (2)$$

Being proportional to the lepton mass squared, the contribution of $f_-(t)$ can be measured only in $K\mu 3$ decays. To describe the form factors, different parameterizations are available among which the ones used in this work are: a) The Taylor expansion, called quadratic parametrization:

$$\tilde{f}_{+,0}(t) = 1 + \lambda'_{+,0} \left(\frac{t}{m_{\pi^+}^2} \right) + \lambda''_{+,0} \left(\frac{t}{m_{\pi^+}^2} \right)^2 \quad (3)$$

b) Pole parameterization:

$$\tilde{f}_+(t) = \frac{m_V^2}{m_V^2 - t} \quad \tilde{f}_0(t) = \frac{m_S^2}{m_S^2 - t} \quad (4)$$

2.1. The $K\ell 3$ form factor measurement in NA48/2

The semileptonic form factor measurement reported here is based on a dedicated 56 hour run in 2004 at lower beam intensities and reduced momentum byte (60 ± 1.8) GeV/c. Data were recorded using a minimum bias trigger condition. The data sample acquired contains 4.0 million $K_{e3}^{\pm}$ and 2.5 million $K_{\mu 3}^{\pm}$.

2.2. Fitting procedure

To extract the form factors, two dimensional fits to the Dalitz plot densities $\rho(E_{\ell}^*, E_{\pi}^*)$, with $(\ell = e, \mu)$, are performed using the formula:

$$\rho(E_{\ell}^*, E_{\pi}^*) = \frac{d^2 N(E_{\ell}^*, E_{\pi}^*)}{dE_{\ell}^* dE_{\pi}^*} \approx Af_+^2(t) + Bf_+(t)(f_+(t) - f_0(t)) \frac{m_K^2 - m_{\pi}^2}{t} + C \left[(f_+(t) - f_0(t)) \frac{m_K^2 - m_{\pi}^2}{t} \right]^2 \quad (5)$$

where A, B, C are kinematical terms. The reconstructed Dalitz plots are then corrected for detector acceptance, distortions induced by radiative effects and finally the distribution of remaining background is subtracted. The radiative effects are simulated by using a MC simulation developed by the KLOE collaboration.³

Quadratic(10^{-3})	λ'_+	λ''_+	λ_0
$K_{\mu 3}^{\pm}$	$26.3 \pm 3.0_{sta} \pm 2.2_{sys}$	$1.2 \pm 1.1_{sta} \pm 1.1_{sys}$	$15.7 \pm 1.4_{sta} \pm 1.0_{sys}$
$K_{e3}^{\pm}$	$27.2 \pm 0.7_{sta} \pm 1.1_{sys}$	$0.7 \pm 0.3_{sta} \pm 0.4_{sys}$	
$K_{\mu 3}^{\pm} K_{e3}^{\pm}$ comb.	26.98 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole	m_V		m_S
$K_{\mu 3}^{\pm}$	$873 \pm 8_{sta} \pm 9_{sys}$		$1183 \pm 31_{sta} \pm 16_{sys}$
$K_{e3}^{\pm}$	$879 \pm 3_{sta} \pm 7_{sys}$		
$K_{\mu 3}^{\pm} K_{e3}^{\pm}$ comb.	877 ± 6		1176 ± 31

The results for the quadratic and the pole parametrization fits are listed in the table above for $Ke3$, $K\mu 3$, and $K\ell 3$ combined fits. The systematic uncertainties include different checks: changes of the cuts defining the vertex quality and the geometrical acceptance by small amounts, variations of the resolutions of pion and muon energies in the kaon center of mass system and variations of the background due to $\pi \rightarrow \mu$ have been performed. Finally the differences in the results of two independent analyses is included.

In Fig. 1 the combined NA48/2 fit result is compared with results reported by recent experiments on $K\ell 3$ FF.² The preliminary NA48/2 results presented here are the first high precision measurements obtained using both K^+ and K^- mesons. The form factors are in good agreement with the measurements done by other experiments and compatible with the 2010 combined fit reported by FlaviaNet.²

Fig. 1. Combined quadratic fit results for $K\ell 3$ decays. The ellipses are 68% confidence level contours. For comparison the combined fit from the FlaviaNet² kaon working group is shown.

3. The $K \rightarrow \pi^\pm \gamma \gamma$ decay

Measurements of radiative non-leptonic kaon decays provide crucial tests for the ability of the Chiral Perturbation Theory (ChPT) to explain weak low energy processes. In the ChPT framework, the $K^\pm(p) \rightarrow \pi^\pm(p_3)\gamma(q_1)\gamma(q_2)$ differential decay rate can be parametrized as:⁴

$$\frac{\partial^2 \Gamma}{\partial x \partial y} = \frac{m_K}{(8\pi)^3} \left[z^2(|A+B|^2 + |C|^2) + \left(y^2 - \frac{1}{4} \lambda(1, z, r_\pi^2) \right)^2 \cdot (|B|^2 + |D|^2) \right] \quad (6)$$

where $z = m_{\gamma\gamma}^2/m_K^2$ and $y = p \cdot (q_1 - q_2)/m_K^2$. The dominant contribution at $O(p^4)$ comes from the loop term $A(z, \hat{c})$, including the pion and kaon loop amplitudes, the B and D terms are zero and the Wess-Zumino-Witten term C accounts for $\sim 10\%$ of the total decay rate. The $\hat{c}$ can be written in terms of parameters of the $\mathcal{L}^4$ weak chiral Lagrangian (N_i):⁴

$$\hat{c} = \frac{128\pi^2}{3} [3(L_9 + L_{10}) + N_{14} - N_{15} - 2N_{18}]. \quad (7)$$

Higher order unitarity corrections from $K^\pm \rightarrow 3\pi^\pm$ decays, including the main $O(p^6)$ contribution as well as those beyond $O(p^6)$, have been found to contribute significantly to the BR (up to 30-40%) and to the shape of $M_{\gamma\gamma}$ spectrum.⁴ The total decay rate is predicted to be $BR(K^\pm \rightarrow \pi^\pm \gamma \gamma) \sim 10^{-6}$. The only $K^\pm \rightarrow \pi^\pm \gamma \gamma$ experimental observation published so far is by the BNL E787 experiment:⁵

$$BR(K^\pm \rightarrow \pi^\pm \gamma \gamma)_{E787} = (1.1 \pm 0.3 \pm 0.1) \cdot 10^{-6} \quad \text{with} \quad \hat{c} = 1.8 \pm 0.6 \quad (8)$$

based on 31 K^+ decay candidates in the kinematic region $100 \text{ MeV}/c < p_\pi < 180 \text{ MeV}/c$ (p_π is the π^+ momentum in the K^+ rest frame). The value of the BR

quoted in Eq. 8 refers to the entire kinematical range and is obtained with a MC extrapolation using the value 1.8 for $\hat{c}$.

3.1. The data analysis

The new measurements described here have been performed using minimum bias data sets collected during a 3-day special NA48/2 run in 2004 with 60 GeV/c $K^\pm$ beams, and a 3-month NA62 run in 2007 with 74 GeV/c $K^\pm$ beams. The effective kaon fluxes collected are similar, but the background conditions and resolution on kinematic variables differ significantly. Signal events are selected in the region $z = (m_{\gamma\gamma}/m_K)^2 > 0.2$ to reject the $K^\pm \rightarrow \pi^\pm\pi^0$ background peaking at $z = 0.075$. In total 147 (175) decays candidates are observed in the 2004 (2007) data set, with backgrounds contaminations of 12% (7%) from $K^\pm \rightarrow \pi^\pm\pi^0(\pi^0)(\gamma)$ decays with merged photon clusters in the LKr calorimeter. The data spectra of the z kinematic variable, together with the signal and background expectations, are displayed in Fig. 2: they clearly exhibit the cusp at the two-pion threshold as predicted by the ChPT. The values of the $\hat{c}$ parameter in the framework of the ChPT $O(p^4)$ and $O(p^6)$ parameterizations according to Ref. 4 have been measured by performing likelihood fits to the data. The uncertainties are dominated by the statistical ones

Fig. 2. The $z = (m_{\gamma\gamma}/m_K)^2$ spectrum with MC expectations for signal, best fit, and backgrounds: on the left 2004 and on the right 2007 data samples. The signal region, $0.2 < z < 0.52$, is within the blue arrows.

while the systematic ones are mainly due to the background estimates uncertainties. The $O(p^6)$ parametrization involves a number of external inputs fixed as follows: the polynomial contribution terms are $\eta_1 = 2.06$, $\eta_2 = 0.24$ and $\eta_3 = -0.26$ as suggested in Ref. 4, while the $K^\pm \rightarrow 3\pi^\pm$ amplitude parameters come from a fit to the experimental data.⁶ Along with the separate 2004 and 2007 preliminary results, the combined results are also presented in the table below:

	$\hat{c} \ O(p^4)$ fit	$\hat{c} \ O(p^6)$ fit	BR $O(p^6)$ fit
2004 data	$1.36 \pm 0.33_{stat} \pm 0.07_{syst}$	$1.67 \pm 0.39_{stat} \pm 0.09_{syst}$	$(0.94 \pm 0.08) \cdot 10^{-6}$
2007 data	$1.71 \pm 0.29_{stat} \pm 0.06_{syst}$	$2.21 \pm 0.31_{stat} \pm 0.08_{syst}$	$(1.06 \pm 0.07) \cdot 10^{-6}$
Combined	$1.56 \pm 0.22_{stat} \pm 0.07_{syst}$	$2.00 \pm 0.24_{stat} \pm 0.09_{syst}$	$(1.01 \pm 0.06) \cdot 10^{-6}$

The measured BR, in agreement with the E787 one, improves the precision of the measurement by a factor ~ 5 . The obtained value of $\hat{c}$, for both the $O(p^4)$ and $O(p^6)$ fits, is in very good agreement with the previous measurement by E787.⁵ The same parameter has been already estimated by NA48/2 using the decay $K^\pm \rightarrow \pi^\pm e^+ e^- \gamma$, obtaining a compatible result: $\hat{c} = 0.90 \pm 0.45$.⁷

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