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High precision measurement of the form factors of the semileptonic decays $K^{\pm} \to \pi^0 l^{\pm} \nu \, (K_{l3})$

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Semileptonic kaon decays provide one of the cleanest environments to study the weak interaction with high precision. Using a run with minimal trigger conditions, the NA48/2 experiment has accumulated samples of 4.0×10^6 $K^{\pm}_{e3}$ and 2.5×10^6 $K^{\pm}_{\mu 3}$ events. These data allow precise measurements of the form factors in various parametrizations. This report describes the event selections and the fitting procedure and gives a preliminary result.

The XIth International Conference on Heavy Quarks and Leptons
11-15 June, 2012
Prague, The Czech Republic

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1. Introduction

Semileptonic kaon decays (K_{l3}, $l = \mu, e$) provide the most accurate and theoretically cleanest way to measure the CKM matrix element $|V_{us}|$ [1]. In addition, tight constraints on new physics can be given by testing the $V - A$ structure in $K_{\mu 3}$ decays [2] or lepton universality. For all these measurements, the knowledge of the decay form factors is crucial: Since they determine the Dalitz plot structure, both the detector acceptance (needed to measure the decay rate) and the phase space integral (for deriving $|V_{us}|$ from the decay rate) heavily depend on the form factors. Moreover, the above-mentioned searches for new physics give an additional reason for precise measurements of both K_{e3} and $K_{\mu 3}$ form factors.

The hadronic matrix element of K_{l3} 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 system. The $K_{l3}^{\pm}$ decays are usually described in terms of the vector form factor f_+ and the scalar form factor f_0 defined as [1]:

$$f_0(t) \;=\; f_+(t) + \frac{t}{m_K^2 - m_\pi^2}\, f_-(t). \tag{1.1}$$

The functions f_+ and f_0 are related to the vector (1^-) and scalar (0^+) exchange to the lepton system, respectively. Being proportional to the lepton mass squared, the contribution of f_- can be neglected in K_{e3} decays. By construction $f_0(0) = f_+(0)$. Since $f_+(0)$ is not directly measurable, it is customary to factor out $f_+^{K^0\pi^-}(0)$ and to normalize all form factors to this quantity, so that:

$$\bar{f}_+(t) \;=\; \frac{f_+(t)}{f_+(0)}, \quad \bar{f}_0(t) \;=\; \frac{f_0(t)}{f_0(0)} \;=\; \frac{f_0(t)}{f_+(0)} \tag{1.2}$$

To describe the form factors, two different parametrizations are used in this report. Widely known and most used is the Taylor expansion, called quadratic parametrization in the following:

$$\bar{f}_{+,0}(t) \;=\; 1 + \lambda'_{+,0}\,\frac{t}{m_\pi^2} + \lambda''_{+,0}\,\frac{t^2}{m_\pi^4} \tag{1.3}$$

where λ' and λ'' are the slope and the curvature of the form factors, respectively. The disadvantage of this parametrization is related to the strong correlations between the parameters and the absence of a physical meaning. To reduce the number parameters and to add a physical motivation the pole parametrization is also commonly used:

$$\bar{f}_+(t) \;=\; \frac{M_V^2}{M_V^2 - t}, \quad \bar{f}_0(t) \;=\; \frac{M_S^2}{M_S^2 - t}. \tag{1.4}$$

In this parametrization, dominance of single vector (V) or scalar (S) resonances is assumed and the corresponding pole masses M_V and M_S are the only free parameters.

A more recent parametrization is a dispersive approach [2], which makes use of the fixation of $f(t)$ at the so-called Callan-Treiman point $t = \Delta_{K\pi} \equiv m_K^2 - m_\pi^2$ in the limit of chiral symmetry. This parametrization is especially sensitive to new physics in the quark currents.

Another recent parametrization is given by a complex expansion in $t = q^2$, using analyticity and crossing symmetry [3].

The latter two parametrizations have not been used for the preliminary analysis presented in this report.

2. The NA48/2 Experiment

In the years 2003 and 2004 the NA48/2 experiment collected data from charged kaon decays. Two simultaneous K^+ and K^- beams were produced by $400\,\mathrm{GeV}/c$ primary protons delivered by the CERN SPS. The NA48/2 beamline selected kaons with a momentum range of (60 ± 3) GeV/c. The data used for form factor analysis were collected in 2004 during a dedicated run with a special trigger setup which required one or more tracks in the magnetic spectrometer and an energy deposit of at least $10\,\mathrm{GeV}/c$ in the electromagnetic calorimeter. Also the intensity of the beam was lowered and the momentum spread was reduced.

The main components of the NA48/2 detector were a magnetic spectrometer, composed by four drift chambers and a dipole magnet deflecting the charged particles in the horizontal plane and providing a momentum resolution of 1.4 % for $20\,\mathrm{GeV}/c$ charged tracks, and a liquid krypton electromagnetic calorimeter (LKr) with an energy resolution of about 1 % for 20 GeV photons and electrons. For the selection of $K^{\pm}_{\mu 3}$ decays, a muon veto system (MUV) was essential to distinguish muons from pions. It consisted out of three planes of alternating horizontal and vertical scintillator strips. Each plane was shielded by a 80 cm thick iron wall. The inefficiency of the system was at the level of one per mil for muons with momentum greater than $10\,\mathrm{GeV}/c$ and the time resolution was below 1 ns. The NA48 detector is described in detail elsewhere [4].

3. Event Selection

The detector can measure only the charged lepton and the two photons from the π^0 decay; the neutrino leaves the detector unseen. To select the decay, one track in the magnetic spectrometer and at least two clusters in the electromagnetic calorimeter were required. The track had to be inside the geometrical acceptance of the detector, and needed a good reconstructed decay vertex, proper timing and a momentum $p > 5\,\mathrm{GeV}/c$ in case of electrons. For muons the momentum needed to be greater than $10\,\mathrm{GeV}/c$ to ensure proper efficiency of the MUV system. To identify the track as a muon, an associated hit in the MUV system and $E/p > 0.2$ was required, where E is the energy deposited in the LKr calorimeter and p the track momentum. For electrons a range of $0.95 < E/p < 1.05$ and no associated hit in the MUV system were required. The neutral pions were reconstructed by two photon clusters in the LKr calorimeter, which had to have an energy $E_{\gamma} > 3\,\mathrm{GeV}/c$, be well isolated from any track hitting the calorimeter, and in time with the track in the spectrometer. Finally, the missing mass squared was required to satisfy $m^2_{\mathrm{miss}} < (10\,\mathrm{MeV}/c^2)^2$ under a $K^{\pm}$ hypothesis.

For $K^{\pm}_{e3}$, only background from $K^{\pm} \to \pi^{\pm}\pi^0$ significantly contributes to the signal. A cut in the transverse momentum of the event reduced this background to less than 0.1 % while losing only about 3 % of the signal.

For $K^{\pm}_{\mu 3}$ the background from $K^{\pm} \to \pi^{\pm}\pi^0$ events with $\pi^{\pm}$ decay in flight was suppressed by using a combined requirement on the invariant mass $m_{\pi^{\pm}\pi^0}$ (under $\pi^{\pm}$ hypothesis) and on the π^0 transverse momentum. This cut reduces the contamination to 0.5 %, but causes a loss of statistics of about 24 %. Another background source are $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ events with $\pi^{\pm}$ decay in flight and one π^0 not reconstructed. Its estimated contribution is about 0.1 % and no specific cut was applied.

After all cuts, the selected samples amount to 4.0×10^6 $K^{\pm}_{e3}$ and 2.5×10^6 $K^{\pm}_{\mu 3}$ events.

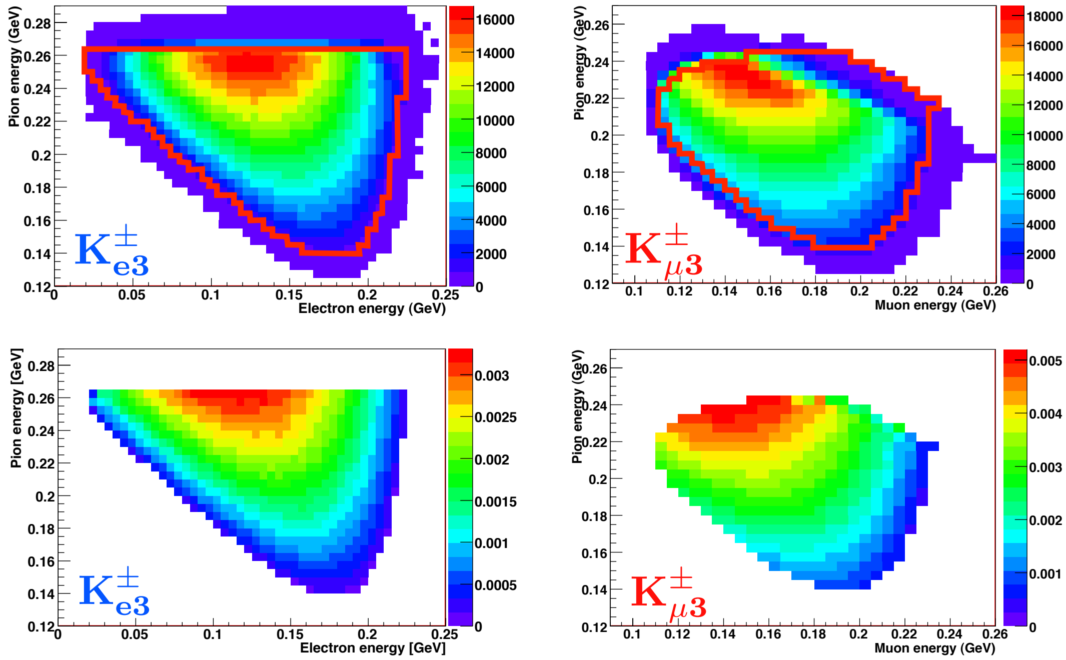

Figure 1: Top: Reconstructed Dalitz plots for $K^{\pm}_{e3}$ (left) and $K^{\pm}_{\mu 3}$ events (right) before any correction for background, acceptance and radiative effects. The red line encloses the region used by the form factor fit. Bottom: Dalitz plot densities for $K^{\pm}_{e3}$ (left) and $K^{\pm}_{\mu 3}$ (right) as used in the fit. All corrections are applied.

4. Fitting procedure

To extract the form factors, two dimensional fits to the Dalitz plot densities ($l = e, \mu$)

$$\rho(E^{\star}_l, E^{\star}_\pi) \;=\; \frac{d^2 N(E^{\star}_l, E^{\star}_\pi)}{dE^{\star}_l \, dE^{\star}_\pi} \;\approx\; A\, f_+^2(t) + B\, f_+(t)\,(f_+(t) - f_0(t))\, \frac{m_K^2 - m_\pi^2}{t} + C \left[(f_+(t) - f_0(t))\, \frac{m_K^2 - m_\pi^2}{t} \right]^2 \qquad (4.1)$$

were performed. To obtain the lepton and pion energies $E^{\star}_l$ and $E^{\star}_\pi$ in the kaon rest frame, the reconstructed lepton and pion four-momenta were boosted into the kaon rest frame. Instead of using the mean beam energy of 60 GeV/c, the kaon energy was computed from the decay products and assuming no transverse component of the momentum of the kaon. This leaves two solutions for the longitudinal component of the neutrino momentum, from which the one closer to 60 GeV/c was used. In this way the energy resolution in the Dalitz plot, in particular for high pion energies, was greatly improved. The obtained Dalitz plots for both $K^{\pm}_{e3}$ and $K^{\pm}_{\mu 3}$ are shown in Fig. 1 (top), together with the regions accepted by the form factor fit (see below).

The reconstructed Dalitz plots were then corrected for remaining background, detector acceptance and distortions induced by radiative effects. The radiative effects were simulated by using a special Monte Carlo generator developed by the KLOE collaboration [5]. It was checked, that this generator gave the same corrections as a recent calculation within Chiral Perturbation Theory with fully inclusive real photon emission [6]. For the fit, the Dalitz plots were subdivided into cells of

	λ'_+ [10^{-3}]	λ''_+ [10^{-3}]	λ_0 [10^{-3}]
$K^{\pm}_{e3}$	$27.2 \pm 0.7 \pm 1.1$	$0.7 \pm 0.3 \pm 0.4$	
$K^{\pm}_{\mu 3}$	$26.3 \pm 3.0 \pm 2.2$	$1.2 \pm 1.1 \pm 1.1$	$15.7 \pm 1.4 \pm 1.0$
combined	27.0 ± 1.1	0.8 ± 0.5	16.2 ± 1.0

Table 1: Preliminary form factor fit results for the quadratic parametrization with statistical and systematic uncertainties. For the combined result both uncertainties were combined.

	M_V [MeV/c^2]	M_S [MeV/c^2]
$K^{\pm}_{e3}$	$879 \pm 7 \pm 7$	
$K^{\pm}_{\mu 3}$	$873 \pm 8 \pm 9$	$1183 \pm 31 \pm 16$
combined	877 ± 6	1176 ± 31

Table 2: Preliminary form factor fit results for the pole parametrization with statistical and systematic uncertainties. For the combined result both uncertainties were combined.

5 MeV $\times$ 5 MeV. Cells which crossed or were outside of the kinematical borders were not used in the fit. The obtained Dalitz plot densities, with all corrections applied, are shown in Fig. 1 (bottom).

5. Preliminary Results

The fit results for the quadratic and the pole parametrization are listed in Tables 1 and 2, respectively. The systematic uncertainties were evaluated by changing the cuts defining the vertex quality and the geometrical acceptance by small amounts. In addition, we applied variations to the resolutions of pion and muon energies in the kaon center of mass system, we varied the $\pi \to \mu$ background and took into account the differences in the results of two independent analyses that were realized in parallel.

For comparison the combined $K^{\pm}_{l3}$ quadratic fit results as reported by recent experiments [1] are shown in Fig. 2. The 68 % confidence level contours are displayed for both neutral (KLOE, KTeV and NA48) and charged K_{l3} decays (ISTRA+ studied K^- only). The preliminary NA48/2 results presented here are the first high precision measurements done with both K^+ and K^- mesons. The form factors are in good agreement with the measurements done by the other experiments (except $K^0_{\mu 3}$ from NA48 [7]) and compatible with the combined fit done by FlaviaNet [1].

6. Future perspectives for form factors at NA62

The NA62 experiment, using the same beam line and detector of NA48/2, collected data in 2007 for the measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ and made tests for the future $K^+ \to \pi^+ \nu \bar{\nu}$ experiment. The collected data contain samples of about 40×10^6 K^+_{e3} and 20×10^6 $K^+_{\mu 3}$ events, respectively. A special K_L run was also taken: it provides K^0_{e3} and $K^+_{\mu 3}$ samples of about 4×10^6 events each. With these statistics NA62 is able to realize even higher precision measurements of the form factors of all K_{l3} channels as available already today.

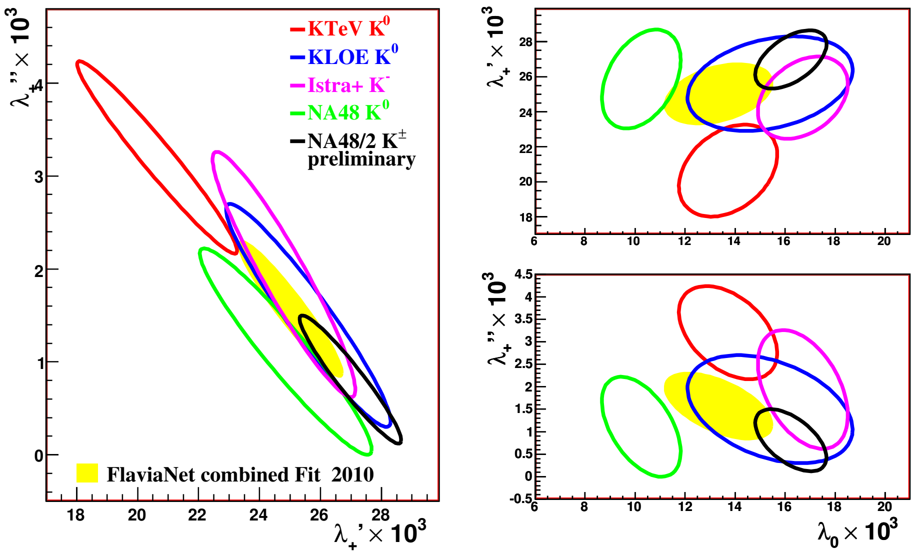

Figure 2: Combined quadratic fit results for K_{l3} decays. The ellipses are 68 % confidence level contours. For comparison the combined fit from the FlaviaNet kaon working group is shown [1].

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