PROCEEDINGS OF SCIENCE

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

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The NA48/2 experiment presents preliminary measurements of the form factors of the semileptonic decays of charged kaons, based on 4.0 million $K^{\pm}_{e3}$ and 2.5 million $K^{\pm}_{\mu 3}$ decays, collected in 2004. The result matches the precision of the current world average on the vector and scalar form factors and could allow to significantly reduce the form factor uncertainty on $|V_{us}|$.

XXI International Workshop on Deep-Inelastic Scattering and Related Subjects
22-26 April, 2013
Marseilles, France

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PoS(DIS 2013)135

1. Introduction

Semileptonic kaon decays $K \to \pi l \nu$ offer the access to most precise determination of the CKM matrix element $|V_{us}|$. The hadronic matrix element of these decays is usually described in terms of two form factors (vector $f_+(t)$ and scalar $f_0(t)$ ones), which depend on the squared 4-momentum transfer to the lepton system $t = (p_K - p_\pi)^2$.

It is convenient to normalize all form factors to $f^+(0)$ and define the form factors as $\bar{f}^{+,0}(t)$ with $\bar{f}^{+,0}(0) = 1$. Traditionally, polynomial expansion and pole parameterization of the form factors have been used [1]:

$$\bar{f}_{+,0}(t) = 1 + \lambda'_{+,0}\frac{t}{m_\pi^2} + \frac{1}{2}\lambda''_{+,0}\frac{t^2}{m_\pi^4} \tag{1.1}$$

$$\bar{f}_{+,0}(t) = \frac{M_{V,S}^2}{M_{V,S}^2 - t} \tag{1.2}$$

The quadratic parameterization (1.1) is the simplest one, but it has a strong correlations between fit parameters. The pole parameterization (1.2) uses physical assumption about suitability of some hypothetical resonance masses $M_{V,S}$ as a fit parameters. This allows to reduce the number of fitted parameters.

The NA48/2 experiment has collected in 2004 the largest sample of charged kaons semileptonic decays. Precision measurements of both $K^{\pm} \to \pi^0 \mu^{\pm} \nu$ ($K^{\pm}_{\mu 3}$) and $K^{\pm} \to \pi^0 e^{\pm} \nu$ ($K^{\pm}_{e3}$) form factors are reported here.

2. NA48/2 beam and detectors

Two simultaneous K^+ and K^- beams are produced by 400 GeV/c protons impinging on a beryllium target. Particles of opposite charge with a central momentum of 60 GeV/c and a momentum band of $\pm 3.8\%$ (*rms*) are selected by two systems of dipole magnets, focusing quadrupoles, muon sweepers and collimators. For the particular study reported here, the beam intensity was reduced and the beam momentum restricted to 60 ± 1.8 GeV/c

A detailed description of the detector elements is available in [2]. Charged particles from $K^{\pm}$ decays are measured by a magnetic spectrometer consisting of four drift chambers (DCH1–DCH4) and a dipole magnet located between DCH2 and DCH3. The spectrometer is located in a tank filled with helium at atmospheric pressure and separated from the decay volume by a thin *Kevlar*® window. A 16 cm diameter aluminum vacuum tube centred on the beam axis runs the length of the spectrometer through central holes in the window, drift chambers and calorimeters. Charged particles are magnetically deflected in the horizontal plane by an angle corresponding to a transverse momentum kick of 120 MeV/c. The momentum resolution of the spectrometer is $\sigma(p)/p = 1.02\% \oplus 0.044\% p$ (p in GeV/c). The magnetic spectrometer is followed by a scintillator hodoscope providing accurate timing for charged particles.

A liquid Krypton calorimeter LKr is used to measure the energy of electrons and photons. It is an almost homogeneous ionization chamber with an active volume of ~ 10 m^3 of liquid krypton, segmented transversally into 2 cm $\times$ 2 cm projective cells by a system of Cu-Be ribbon electrodes.

The calorimeter is 27 X_0 thick and has an energy resolution $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ (E in GeV). The space resolution for single electromagnetic showers can be parameterized as $\sigma_x = \sigma_y = 0.42/\sqrt{E} \oplus 0.06$ cm for each transverse coordinate x, y.

A muon veto system MUV is essential to separate muons from hadrons. It is made of 3 scintillator strip planes and 80 cm thick iron walls shielding each plane.

3. $K_{l3}^{\pm}$ events selection and analysis

The event selection required at least one track measured in the spectrometer and two clusters reconstructed in the electromagnetic calorimeter. The track impact points in each detector (DCH, LKr, MUV) had to be within the corresponding fiducial acceptances.

The neutral pions were reconstructed from two photon clusters in the LKr calorimeter, in-time with the track in the spectrometer, isolated from the track impact and with energies above 3 GeV/c each.

The electron identification required the track momentum to be larger than 5 GeV/c , in-time with an associated LKr cluster, with the ratio E/p of the energy measured in LKr and the momentum obtained from the spectrometer between 0.95 and 1.05 and no MUV hit association. The muon identification required the track momentum to be larger than 10 GeV/c to ensure high efficiency in the MUV system, the ratio E/p to be smaller than 0.2 and a MUV hit association.

Kaon longitudinal momentum was calculated in the assumptions of missing neutrino and zero kaon transevrsal momentum with respect to the beam axis. The closest to 60 GeV/c solution was chosen. An absolute value of missing mass squared of the reconstructed $K_{l3}^{\pm}$ event with an undetected neutrino was required to be less than 0.01 $(\mathrm{GeV}/c^2)^2$.

The reconstructed K_{l3} event Dalitz plots are shown on Fig. 1.

For $K_{\mu 3}^{\pm}$ the background from $K^{\pm} \to \pi^{\pm}\pi^0$ events with the subsequent $\pi^{\pm} \to \mu^{\pm}\nu$ decay was suppressed by means of combined cut of the invariant mass $m_{\pi^{\pm}\pi^0}$ (under $\pi^{\pm}$ hypothesis) and π^0 transverse momentum. This cut reduces the background contamination to the level of 0.5% with a 24% loss of signal statistics.

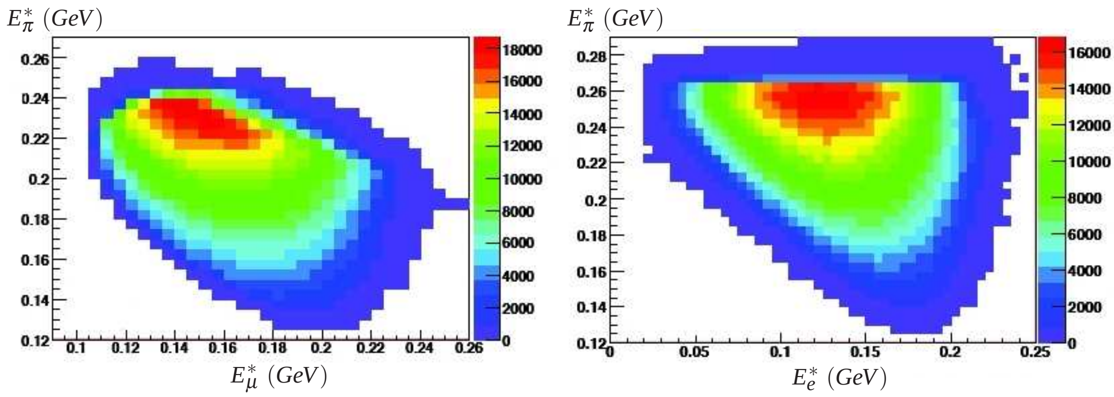

Figure 1: Dalitz plots for $K_{\mu 3}$ (left) and K_{e3} (right) reconstructed decays. E_e^*, E_μ^*, E_π^* are the corresponding particle energies in the kaon rest frame.

Table 1: Preliminary form factor results for the quadratic and the pole parametrizations

Quadratic ($\times 10^{-3}$)	λ'_+	λ''_+	λ_0
$K^{\pm}_{\mu3}$	$26.3 \pm 3.0_{stat} \pm 2.2_{syst}$	$1.2 \pm 1.1_{stat} \pm 1.1_{syst}$	$15.7 \pm 1.4_{stat} \pm 1.0_{syst}$
$K^{\pm}_{e3}$	$27.2 \pm 0.7_{stat} \pm 1.1_{syst}$	$0.7 \pm 0.3_{stat} \pm 0.4_{syst}$	
Combined	27.0 ± 1.1	0.8 ± 0.5	16.2 ± 1.0
Pole (MeV$/c^2$)	m_V		m_S
$K^{\pm}_{\mu3}$	$873 \pm 8_{stat} \pm 9_{syst}$		$1183 \pm 31_{stat} \pm 16_{syst}$
$K^{\pm}_{e3}$	$879 \pm 7_{stat} \pm 7_{syst}$		
Combined	877 ± 6		1176 ± 31

Another source of background is due to $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ events with the $\pi^{\pm}$ decaying and a lost π^0. The corresponding estimated contamination amounts to about 0.1%. It is a small contribution, but it introduces a slope in the Dalitz plot. So the corresponding correction has been applied on the final analysis stage.

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

As a result, $2.5 \cdot 10^6$ $K^{\pm}_{\mu3}$ and $4.0 \cdot 10^6$ $K^{\pm}_{e3}$ decays were selected. The reconstructed Dalitz plot was corrected for remaining background, detector acceptance (simulated by means of Monte Carlo program based on GEANT3 package [3]) and distortions induced by radiative effects. The radiative effects were simulated by using a special Monte Carlo generator developed by the KLOE collaboration [4].

To extract the form factors a two-dimensional fit to the Dalitz plot density was performed. The Dalitz plot was subdivided into 5 MeV $\times$ 5 MeV cells in space of the lepton and pion energies in the kaon center-of-mass. Cells which are not completely inside the decay kinematical limits were not used in the fit.

4. Preliminary results

The preliminary fit results for the quadratic and the pole parametrization are shown in Table 1. The systematic uncertainty was evaluated by varying the analysis cuts and the geometrical acceptance. Additionally, the uncertainty of resolutions of the pion and muon energy in the kaon center of mass, background contribution uncertainty and difference in two independent analyses were taken into account.

The K_{l3} quadratic parameterization fit combined results of recent experiments are shown in Fig. 2. The 68% condence level contours are displayed for both neutral K^0_{l3} (KLOE, KTeV and NA48) and charged $K^{\pm}_{l3}$ decays (ISTRA+ studied K^- only).

The preliminary NA48/2 results presented here are the first high precision measurements obtained with both K^+ and K^- mesons simultaneously. The obtained form factors are in good agreement with the other measurements and compatible with the FlaviaNet combined fit [1]. Preliminary results for the quadratic and pole parametrizations are competitive for K_{e3} and most precise for $K_{\mu3}$.

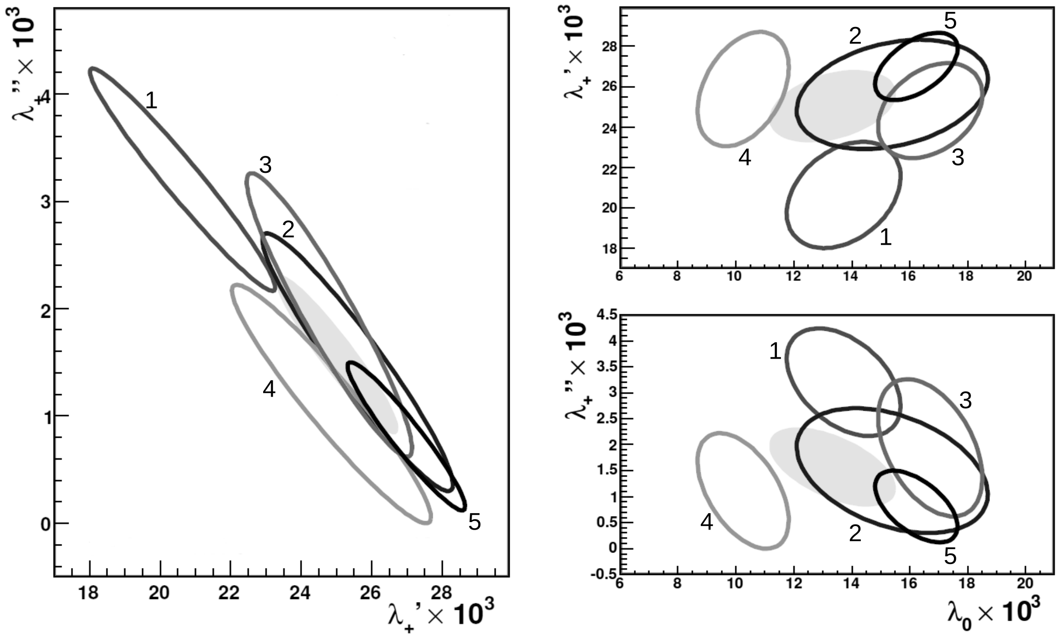

Figure 2: Combined quadratic fit results of K_{l3} modes (68% CL contours) for: 1 - KTeV (K^0, [5]); 2 - KLOE (K^0, [6]); 3 - Istra+ (K^-, [7, 8]); 4 - NA48 (K^0, [9]); 5 - NA48/2 ($K^{\pm}$, the present preliminary results). The **FlaviaNet** kaon working group combined fit results [1] are shown as shaded areas. They do not include the preliminary results presented here.

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