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

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Abstract. The NA48/2 experiment presents preliminary measurements of the form factors of the semileptonic decays of charged kaons, based on 4.3 million K_{e3} and 3.5 million $K_{\mu 3}$ decays, both with negligible background.

1. Introduction

The unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix can be tested experimentally, which is an important tool for exploring the limits of the Standard Model. Any observed deviation from the unitarity would either undermine the validity of the Standard Model or indicate the existence of a fourth generation of fermions. A violation of one of the unitary constraint can be written as:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM}. \quad (1)$$

Where Δ_{CKM} parameterizes possible deviations from the Standard Model induced by new physics operators. The uncertainty on Δ_{CKM} is dominated by the uncertainty on $|V_{us}|$. The present accuracy on $|V_{us}|$ allow us to set bounds on Δ_{CKM} around 0.1%, which translate into bounds on the effective scale of new physics on the order of 10 TeV [1].

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Within the Standard Model, semileptonic kaon decays can provide the experimentally most accurate and theoretically cleanest way for determination of the element $|V_{us}|$ of the CKM matrix [2]. Theoretical input to the $|V_{us}|$ determination can be divided in two parts: vector and axial couplings between hadronic states and radiative corrections. In the limit of SU(3) symmetry, the vector current hadronic coupling can be described by Clebsch-Gordan coefficients, while the vector-axial current includes two empirical parameters. This gives a smaller theoretical uncertainty to the determination of the $|V_{us}|$ value from pure vector current processes such as K_{l3}. The value of $|V_{us}|$ is extracted from the rate of the photon inclusive semileptonic decay $K \to \pi l \nu(\gamma)$ $(l = e, \mu)$

$$\Gamma(K_{l3(\gamma))}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^l\ (\lambda_{+0})(1 + \delta^l_{SU(2)} + \delta^l_{EM})^2, \quad (2)$$

where we have the following inputs from experiment: $\Gamma(K_{l3(\gamma))})$ – branching ratios and kaon lifetime; $I_K^l\ (\lambda_{+0})$ – the integral of the differential decay rate, including from factor variation over phase space.

The inputs from theory: C_K is a Clebsch-Gordan coefficient (1 for the K^0 and $1/\sqrt{2}$ $K^{\pm}$ for the decay); G_F – the Fermi constant determined from muon lifetime; S_{EW} – the universal short distance electroweak correction, 1.0232(3) [4]; $f_+(0)$ – vector form factor at zero momentum transfer $[q^2 = (p_K - p_\pi)^2 = 0]$, 0.959(5) [1]; $\delta^l_{SU(2)}$ – the isospin breaking correction (0 for K^0 and 0.029(4) for $K^{\pm}$) [5]; δ^l_{EM} – the long distance electromagnetic correction [5].

To extract $|V_{us}|$ from the K_{l3} decays using Eq. (2), one needs to measure the K_{l3} decay rate, compute $I_K^l\ (\lambda_{+0})$, and make use of theoretical results on $f_+(0)$, $\delta^l_{SU(2)}$, δ^l_{EM}.

2. K_{l3} form factor parameterizations

The hadronic matrix element of the semileptonic kaon decays is usually described in terms of two dimensionless form factors $f_{\pm}(t)$, parameterized as a function of the squared four momentum $t = (p_K - p_\pi)^2$ transfered to the lepton system

$$M = \frac{G_F}{2} V_{us}(f_+(t)(P_K + P_\pi)^\mu \bar{u}_l \gamma_\mu (1+\gamma_5)\bar{u}_\nu + f_-(t) m_l \bar{u}_l (1+\gamma_5)\bar{u}_\nu). \quad (3)$$

K_{l3} form factors are usually parameterized to express vector $f_+(t)$ and scalar $f_0(t)$ exchange contributions and $f_0(t)$ is defined as a linear combination of $f_{\pm}(t)$:

$$f_0(t) = f_+(t) + t/(m_K^2 - m_\pi^2) f_-(t). \quad (4)$$

Since the term $f_-(t)$ is proportional to the lepton mass, it is negligible in K_{e3} decays and can be measured in $K_{\mu 3}$ decays only. As the vector form factor at zero momentum transfer can not be directly measured, it is common to normalize all form factors to it:

$$\bar{f}_+(t) = f_+(t)/f_+(0), \qquad \bar{f}_0(t) = f_0(t)/f_+(0), \qquad \bar{f}_+(0) = \bar{f}_0(0) = 1. \quad (5)$$

Several parameterizations of the form factors are known, but only two of them, the Taylor expansion and the pole parameterization are used in this analysis. In the first case (called also quadratic parameterization) the normalized form factors are functions of t with slopes $\lambda'_{0,+}$ and curvatures $\lambda''_{0,+}$

$$\bar{f}_{+,0}(t) = 1 + \lambda'_{+,0}(t/m^2_{\pi^\pm}) + 0.5\lambda''_{+,0}(t/m^2_{\pi^\pm})^2. \quad (6)$$

The disadvantage of such a parameterization is related to the strong correlation between the λ parameters and absence of physical meaning.

This is avoided in the pole parameterization (Eq. (7)), which assumes that one single resonance vector (1^-) or scalar (0^+) is responsible for the process, the corresponding masses, m_V and m_S, are the only free parameters and can be estimated from the fit.

$$\bar{f}_+(t) = m_V^2/(m_V^2 - t), \qquad \bar{f}_0(t) = m_S^2/(m_S^2 - t). \tag{7}$$

3. The NA48/2 experiment

The NA48/2 experiment beam line was designed to deliver simultaneous K^+ and K^- beams with momentum of (60 ± 3) GeV/c, produced by a 400 GeV/c primary proton beam from the CERN SPS. The kaons decayed in a 114 m long vacuum volume. The momenta of the charged decay products were measured by a magnetic spectrometer consisting of four drift chambers (DCHs) and a dipole magnet. The momentum resolution of the spectrometer was $\Delta p/p = 1.02\% \oplus 0.044 \times p$. A scintillator hodoscope (HOD), located after the spectrometer, produced fast trigger signals and measured the time of arrival of charged particles with an offline resolution of 150 ps. The electromagnetic energy deposit of particles was measured by a liquid krypton calorimeter (LKr) with an energies resolution of $\Delta E/E \approx 1\%$ for a typical energy of 20 GeV. The data used in this analysis were collected in 2004 during a dedicated run with a special trigger setup, which required at least one charged track in the magnetic spectrometer and at least 10 GeV energy deposited in the LKr. Muons were identified by means of a muon veto system (MUV) consisting of three planes of alternating horizontal and vertical scintillator strips separated by 80 cm thick iron walls. A more detailed description of the NA48/2 detector can be found in [6].

4. Event selection and background rejection

To select K_{l3} decays, one track in the magnetic spectrometer and at least two photons in the electromagnetic calorimeter were required. The track needed to have a good reconstructed decay vertex and proper timing with respect to the trigger and π^0 cluster candidates in the LKr. The track momentum requirements were $p > 5$ GeV/c for electron and $p > 10$ GeV/c for muon to ensure proper efficiency of the MUV. A track was identified as a muon if it had a hit in the MUV and $E/p < 0.2$, where E is the track energy measured by the LKr and p is the track momentum. A track was identified as a electron if $0.95 < E/p < 1$ and no hit in the MUV. Clusters in the LKr were required to have $E > 3$ GeV/c and being well isolated from each other and from any track associated cluster. A cut on the $\gamma\gamma$ invariant mass, $|m_{\gamma\gamma} - m_{\pi^0}^{PDG}| < 10$ MeV/c, calculated from the charged decay vertex and the kaon flight direction, was applied to select the π^0. Due to the undetected neutrino, the missing mass squared of the K_{l3} events should satisfy $m^2_{miss} < 0.01$ (GeV/c)^2 under a $K^\pm$ hypothesis.

One of the main background channels in the K_{l3} decays is $K^\pm \to \pi^\pm\pi^0$ ($K_{2\pi}$), where $\pi^\pm$ mis identification can fake both e and μ and in addition $\pi^\pm$ decay in flight contributes to the $K_{\mu3}$ signal. In case of K_{e3} the $K_{2\pi}$ background was rejected by applying a cut on transverse momentum, which reduces this background to less than 0.1% while losing only ∼3% of the signal. For $K_{\mu3}$ a combined requirement of the invariant mass $m_{\pi^\pm\pi^0}$ (under $\pi^\pm$ hypothesis) and on the π^0 transverse momentum was used. This cut reduces the contamination down to 0.5% but causes ∼24% loss of signal events.

Another background source is $K^\pm \to \pi^\pm\pi^0\pi^0$ with $\pi^\pm$ decays in flight and one lost π^0. Its estimated contribution is ∼0.1% and no specific cut was used.

After all cuts 4.0×10^6 $K^\pm_{e3}$ and 2.5×10^6 $K^\pm_{\mu3}$ events are selected.

Table 1. Preliminary form factor fit results for the quadratic and pole parameterizations. For the combined result statistical and systematic uncertainties were combined.

	Quadratic			Pole	
	$\lambda'_+[10^{-3}]$	$\lambda''_+[10^{-3}]$	$\lambda_0[10^{-3}]$	M_V [MeV/c^2]	M_S [MeV/c^2]
$K^{\pm}_{e3}$	$27.2 \pm 0.7 \pm 1.1$	$0.7 \pm 0.3 \pm 0.4$		$879 \pm 3 \pm 7$	
$K^{\pm}_{\mu 3}$	$26.3 \pm 3.0 \pm 2.2$	$1.2 \pm 1.1 \pm 1.1$	$15.7 \pm 1.4 \pm 1.0$	$873 \pm 8 \pm 9$	$1183 \pm 31 \pm 16$
comb.	27.0 ± 1.1	0.8 ± 0.5	16.2 ± 1.0	877 ± 6	1176 ± 31

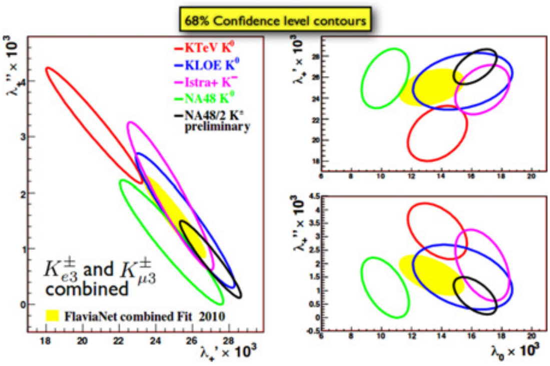

Figure 1. Combined quadratic fit results for the λ parameters. The ellipses are 68% confidence level contours. For comparison the combined fit from the FlaviaNet kaon working group is shown [1].

5. Fitting procedure

To extract the form factors, a two dimensional fit to the Dalitz plot density was performed

$$\rho(E^*_l, E^*_\pi) = \frac{d^2N(E^*_l, E^*_\pi)}{dE^*_\mu dE^*_\pi} \propto Af^2_+(t) + Bf_+(t)(f_0 - f_+)\frac{m^2_K - m^2_\pi}{t} + C\left[(f_0 - f_+)\frac{m^2_K - m^2_\pi}{t}\right]^2 \quad (8)$$

where A, B, and C are kinematical terms and E^*_{l3} and $E^*_{\pi^0}$ are the lepton and pion energies in the kaon rest frame. To obtain E^*_{l3} and $E^*_{\pi^0}$ the corresponding four momenta were boosted into the kaon rest frame. In the calculation the kaon energy was computed for each event under the assumption of a tree-body decay with an undetected neutrino (assuming no transverse component of the momentum of the kaon). In this way the energy resolution in the Dalitz plot was improved, especially in the high energy region of the pion. The reconstructed Dalitz plots were corrected for detector acceptance, remaining background channels and distortions induced by radiative effects. The radiative effects were simulated by using a special Monte Carlo generator developed by the KLOE collaboration [7]. For the fit, the Dalitz plot was subdivided into 5×5 MeV^2 cells. Cells which crossed or were outside of the kinematical border were not used in the fit.

6. Results and conclusions

Preliminary results for both the quadratic and the pole parameterization are summarized in Table 1. The systematic uncertainties were evaluated by varying the vertex selection cuts and the geometrical acceptance by small amounts. In addition variations were applied on pion and lepton energies in the kaon center of mass system. The presented preliminary results of NA48/2 are the first high precision measurements performed with charged kaons ($K^{\pm}$). The obtained form factors are in good agreement and competitive with the world average (Fig. 1).

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