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Recent results from the NA48 experiment at CERN

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Abstract. The NA48/2 experiment presents a final result of the charged kaon semileptonic decays form factors measurement based on 4.28 million K_{e3}^{\pm} and 2.91 million $K_{\mu3}^{\pm}$ selected decays collected in 2004. The result is competitive with other measurements in $K_{\mu3}^{\pm}$ mode and has a smallest uncertainty for K_{e3}^{\pm} , that leads to the most precise combined K_{f3}^{\pm} result and allows to reduce the form factor uncertainty of $|V_{US}|$. The NA48/2 experiment at CERN collected a very large sample of charged kaon decays into multiple final states. From this data sample we have reconstructed about 1663 events of the very rare decay $K^{\pm} \rightarrow \mu^{\pm} \nu e^{+} e^{-}$ over almost negligible background in the region with $m(e^{+} e^{-})$ above 140 MeV, which is of great interest in Chiral Perturbation Theory. We present the m_{ee} spectrum and a model-independent measurement of the decay rate for this region.

1. Introduction

The main purpose of the NA48/2 experiment at the CERN SPS was a search for the direct CP violation in K^{\pm} decay to three pions [1]. The experiment used simultaneous K^{+} and K^{-} beams with momenta of 60 GeV/c propagating through the detector along the same beam line.

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 a liquid krypton electromagnetic calorimeter (LKr) with an energy resolution of about 1% for 20 GeV photons and electrons. For the selection of muons, a muon veto system (MUV) was essential to distinguish muons from pions.

The data used for the form factor (FF) 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 GeV/c in the electromagnetic calorimeter.

Radiative decays of K mesons can be used to test theories describing low energy Quantum Chromodynamics (QCD). Chiral Perturbation Theory (ChPT) is one of the successful frameworks for such calculations. This theory is an effective field theory that describes QCD below the scale Λ of $O(1\text{GeV})$. The pseudo-scalar meson masses are below the cutoff scale and an expansion can be performed in terms of (p/Λ) , called the chiral expansion. The Standard Model can be tested using radiative decays in next-to-leading order in the chiral expansion without any further assumptions.

The phase space is dominated by Inner Bremsstrahlung from the final state muon, which is a pure QED process and its contribution to the branching ratio can be calculated exactly. The intriguing part of the phase space is the invariant mass of the $e^{+}e^{-}$ pair in the region $M_{ee} > 140\text{MeV}/c^2$, where the ChPT form factors have an important contribution to the branching ratio. We use a MC generator based on [2] with all form factors computed up to $O(p^4)$ in ChPT. Radiative corrections are included in the MC generation using the PHOTOS package. However, above $M_{ee} = 140\text{MeV}/c^2$ the phase space is greatly



reduced, therefore a large number of decayed kaons is needed in order to measure precisely the very small branching ratio.

2. K_{l3} form factors

Semileptonic kaon decays $K^\pm \rightarrow \pi^0 l^\pm \nu$ (K_{l3}) offer the most precise determination of the CKM matrix element $|V_{US}|$ [3], that require both a branching ratio and a FFs experimental measurement. K_{l3} precision FFs measurement results based on the NA48/2 data analysis are presented in this paper.

The K_{l3} decay width in the absence of electromagnetic effects can be represented by the Dalitz plot density depending on the lepton and pion energies in kaon rest frame E_l and E_π respectively [4]:

$$\frac{d^2\Gamma_0(K_{l3})}{dE_l dE_\pi} = N(Af_+^2(t) + Bf_+(t)f_-(t) + Cf_-^2(t)), \quad (1)$$

where $t = (P_K - P_\pi)^2 = m_K^2 + m_\pi^2 - 2m_K E_\pi$, N is a normalization constant and $f_-(t) = (f_+(t) - f_0(t))(m_K^2 - m_{\pi^+}^2)/t$. Here $f_+(t)$ and $f_0(t)$ are the so called vector and scalar K_{l3} FFs, respectively. m_K is a mass of K^\pm , m_π is a mass of π^0 and m_{π^+} is a mass of π^+ . Definitions of the implemented parameterizations are shown

	$f_+(t)$	$f_0(t)$
Quadratic	$1 + \lambda'_+ t/m_\pi^2 + \frac{1}{2}\lambda''_+(t/m_\pi^2)^2$	$1 + \lambda'_0 t/m_\pi^2$
Pole	$\frac{M_V^2}{(M_V^2 - t)}$	$\frac{M_S^2}{(M_S^2 - t)}$
Dispersive	$\exp\left(\frac{(\Lambda_+ + H(t))t}{m_\pi^2}\right)$	$\exp\left(\frac{(\ln[C] - G(t))t}{(m_K^2 - m_\pi^2)}\right)$

Table 1. Definitions of the FF parameterizations used in the analysis

in the table 1: the Quadratic [5] parameterization (fit parameters λ'_+ , λ''_+ , λ'_0), the Pole [6] (fit parameters M_V , M_S) and the Dispersive [7] one (fit parameters Λ_+ , $\ln[C]$).

2.1. The K_{l3} events reconstruction and selection

The data selection requires one track in the magnetic spectrometer and a time coincidence with at least two clusters in the LKr from the π^0 decay. The track had to be inside the geometrical acceptance of the detector, and needed a good reconstructed decay vertex, proper timing and a momentum $p > 5\text{GeV}/c$ in case of electrons. For muons the momentum needed to be greater than $10\text{GeV}/c$ to ensure proper efficiency of the MUV system. To identify a track as the electron we require $2.0 > E/p > 0.9$, where E is the energy deposited in the LKr and p is the momentum measured in the spectrometer, and no signal in the MUV system. To identify the track as a muon we require an associated hit in the MUV system and $E/p < 0.9$.

Longitudinal K_{l3} decay position Z_n (neutral vertex Z coordinate) is defined as a longitudinal position of π^0 decay, reconstructed from LKr data assuming PDG [8] value for π^0 mass. The transverse neutral vertex coordinates (X_n , Y_n) are calculated as the impact point position of the reconstructed charged track on the Z_n plane.

For the kaon momentum (P_K) measurement we direct Z axis along the beam average position in space, measured from $3\pi^\pm$ data. In the assumptions of $m(\nu) = 0$ and kaon flight along the beam axis (that means availability of the measured $P_t(\nu) = -P_t$), two solutions of quadratic equation for P_K exist: $P_K = P_{1,2} = (\phi P_Z \pm \sqrt{d})/(E^2 - P_Z^2)$, where $\phi = 0.5(M_K^2 + E^2 - P_t^2 - P_Z^2)$, $d = \phi^2 P_Z^2 - (E^2 - c x P_Z^2)(M_K^2 E^2 - \phi^2)$ and E , P_t , P_Z are the total energy and total momentum of all the registered particles π^0 , l .

The background contribution has been estimated using the NA48/2 Monte Carlo. For K_{e3} the background from $K^\pm \rightarrow \pi^\pm \pi^0$ (2π) significantly contributes to the signal. A cut in the $P_t(\nu) \geq 0.03\text{GeV}/c$ of the event reduced this background to less than 0.027%. For $K_{\mu 3}$ selection, essential background may come from 2π decays with a subsequent $\pi^\pm \rightarrow \mu^\pm \bar{\nu}$. The cuts in $m(\pi^\pm \pi^0)$ and $m(\mu \bar{\nu})$

reduces the contamination to 0.0264%. For both $K_{\mu 3}$ and $K_{e 3}$ samples the $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays can contribute to the background. Its estimated contribution is about 0.183% for $K_{\mu 3}$ and 0.0286% for $K_{e 3}$.

The total statistics of selected data is 4.28×10^6 events for $K_{e 3}$, and 2.91×10^6 events for $K_{\mu 3}$ selection.

2.2. Preliminary results on the K_{l3} form factors

To extract the FF a events-weighting fit is performed in $5 \times 5 \text{ MeV}$ cells in the Dalitz plot of $E_{\pi^0}^*$ vs E_l^* energies, computed in the kaon rest frame. The $K_{e 3}$ and $K_{\mu 3}$ Dalitz plots were fitted simultaneously with a common set of the fit parameters MINUIT [9] package called from the ROOT [10] interface minimizes χ^2 by means of parameters variation, and in such a way the resulting fit parameter values, their errors (table 2) and correlation coefficients (table 3) are found. The fit quality is defined by the following values

Quadratic	λ'_+	λ''_+	λ_0
$K_{\mu 3}$	$23.32 \pm 3.08_{\text{stat}} \pm 3.50_{\text{syst}}$	$2.14 \pm 1.06_{\text{stat}} \pm 0.96_{\text{syst}}$	$14.33 \pm 1.11_{\text{stat}} \pm 1.25_{\text{syst}}$
$K_{e 3}$	$23.52 \pm 0.78_{\text{stat}} \pm 1.29_{\text{syst}}$	$1.60 \pm 0.30_{\text{stat}} \pm 0.39_{\text{syst}}$	
K_{l3}	$23.35 \pm 0.75_{\text{stat}} \pm 1.23_{\text{syst}}$	$1.73 \pm 0.29_{\text{stat}} \pm 0.41_{\text{syst}}$	$14.90 \pm 0.55_{\text{stat}} \pm 0.80_{\text{syst}}$
Pole	m_V	m_S	
$K_{\mu 3}$	$879.1 \pm 8.1_{\text{stat}} \pm 13.5_{\text{syst}}$	$1196.4 \pm 18.1_{\text{stat}} \pm 28.8_{\text{syst}}$	
$K_{e 3}$	$896.8 \pm 3.4_{\text{stat}} \pm 7.6_{\text{syst}}$		
K_{l3}	$894.3 \pm 3.2_{\text{stat}} \pm 5.4_{\text{syst}}$	$1185.5 \pm 16.6_{\text{stat}} \pm 35.5_{\text{syst}}$	
Dispersive	Λ_+	$\ln[C]$	
$K_{\mu 3}$	$23.55 \pm 0.50_{\text{stat}} \pm 0.97_{\text{syst}}$	$186.68 \pm 5.12_{\text{stat}} \pm 9.23_{\text{syst}}$	
$K_{e 3}$	$22.54 \pm 0.20_{\text{stat}} \pm 0.62_{\text{syst}}$		
K_{l3}	$22.67 \pm 0.18_{\text{stat}} \pm 0.55_{\text{syst}}$	$186.12 \pm 4.91_{\text{stat}} \pm 11.09_{\text{syst}}$	

Table 2. Fit results for the Quadratic ($\times 10^3$), Pole (MeV/c^2) and Dispersive ($\times 10^3$) Parameterisation

of χ^2/ndf : 1004.6/1073 for the Quadratic Parameterization, 1001.1/1074 for the Pole and 998.3/1074 for the Dispersive one.

	λ''_+	λ_0		m_S	$\ln[C]$
λ'_+	-0.954	-0.076	m_V	-0.278	
λ''_+		0.035	Λ_+		-0.035

Table 3. Full uncertainty correlation coefficients for K_{l3} Quadratic, Pole and Dispersive Parametrizations

The NA48/2 is the first experiment measuring the FF using both K^+ and K^- . In $K_{\mu 3}$ the result is dominated by the statistical error, for $K_{e 3}$ by the systematic. The NA48/2 $K_{e 3}$ and $K_{\mu 3}$ in agreement within each other and our combined results are competitive with the current world average.

3. The $K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^-$ analysis

The analysis of the mode $K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^-$ ($K_{\mu \nu ee}$) is based on the reconstruction of a three-track vertex. Two of those tracks have to be identified as electrons using the LKr calorimeter and to have an invariant mass $M_{ee} > 140 \text{ MeV}/c^2$. The third track has to be compatible with a muon, acting as a minimum ionising particle (MIP) in the LKr and leaving a signal in the MUV detector.

3.1. Event selection

The $K_{\mu ee}$ selection is characterized by the presence of three charged tracks and a missing momentum carried away by the undetected neutrino. The missing mass for such a mode is equivalent to a neutrino mass squared and should be zero for signal events. The phase space region of $M_{ee} > 140 \text{ MeV}/c^2$ is experimentally clean, because decays with e^+e^- pairs coming from $K^\pm \rightarrow \pi^\pm\pi^0$ or $K^\pm \rightarrow \pi^0\mu^\pm\nu_\mu$ decay with a following $\pi^0 \rightarrow e^+e^-\gamma$ decay ($m_{\pi^0} = 135 \text{ MeV}/c^2$) are fully suppressed.

The three tracks have to form a good vertex inside the 98m long decay volume of the experiment and to have a total charge of $|Q| = \pm 1$. Each of the tracks has to pass through the geometrical acceptance of the DCH, HOD, LKr and MUV detector and to have momenta in the range between 3 and $50 \text{ GeV}/c$. The showers in the LKr produced by the charged tracks have to be isolated from each other by at least 20cm to avoid overlapping showers. The total momentum of the three tracks has to be $p_{3\text{track}} < 66 \text{ GeV}/c$ in order to be consistent with the beam kaons. A cut is applied on the invariant mass of the muon-neutrino system of $M_{\mu\nu} > 170 \text{ MeV}/c^2$, to suppress events coming from $K^\pm \rightarrow \pi^\pm e^+e^-$ followed by $\pi^\pm \rightarrow \mu^\pm\nu_\mu$.

The particle identification is based on the LKr calorimeter and the MUV system. The ratio E/p of the energy deposited in the LKr divided by the total momentum distinguishes between muons, pions and electrons. The muon is required to leave only a small fraction of its energy in the LKr ($E/p < 0.2$) and to have a positive identification in the MUV detector. Electrons should leave all their energy in the LKr with an energy deposition shower shape different from the shape of hadronic showers produced by pions. To distinguish between genuine electrons and misidentified pions we require $0.95 < E/p < 1.05$ and use a linear discriminant variable, which makes use of the different shape and starting point of the created showers. This discriminant provides almost complete suppression of pions coming from $K_{3\pi}$ or $K^\pm \rightarrow \pi^+\pi^-\pi^0$ decays.

The mode $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ ($K_{3\pi}$) is chosen as normalization for the $K_{\mu ee}$ branching ratio measurement, because the topologies of both decays are similar.

The NA48/2 detector recorded more than 10^{11} decayed kaons in the fiducial volume of the experiment, which makes it suitable for rare decay rate measurements as $K_{\mu ee}$. The acceptance for this decay mode is M_{ee} dependent and of the order of 12-15%

3.2. Background

After the full selection only small fraction of background processes survives. The remaining background is composed of decays with multiple pions in the final state misidentified as either muons or electrons. It has three components: $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$, $K^\pm \rightarrow \pi^+\pi^-\pi^0$ followed by two Dalitz decays of the two π^0 s ($\pi^0 \rightarrow e^+e^-\gamma$). The two electrons have to come from two different π^0 decays so the M_{ee} can be higher than $140 \text{ MeV}/c^2$. The background contamination coming from those modes can be studied directly in data using Wrong Sign (WS) selection. The WS selection is the same as the signal selection, but requiring two same-sign electrons/positrons and an opposite sign muon ($\mu^+e^-e^-$ or $\mu^-e^+e^+$). Those Lepton Flavor Violating modes do not exist in the SM, therefore the only surviving events come from processes constituting the background for the $K_{\mu ee}$ selection. A scaling factor is applied to the WS selected data in order to take into account that the modes with three pions in the final state have two possibilities to enter the signal selection and only one to enter the WS selection.

3.3. Results

After the event selection, 1663 signal candidates are observed with an estimated background contamination of $54 \pm 10(\text{stat}) \pm 5(\text{syst})$ events. The total number of kaons decayed in the fiducial volume of the experiment is $(1.56 \pm 0.01) \times 10^{11}$ as obtained from the number of normalisation events corrected for acceptance, trigger efficiency and branching ratio. The branching ratio is computed for each of the $z = (M_{ee}/M_K)^2$ bins (15 bins in total) and shown on figure 1. The results obtained in each bin are then summed to get the total branching ratio. This minimizes the effect of the z dependence of the signal acceptance. The total model-independent branching ratio in the phase space $M_{ee} \geq 140 \text{ MeV}/c^2$ is $Br(K^\pm \rightarrow \mu^\pm\nu_\mu e^+e^-) = (7.84 \pm 0.21(\text{stat}) \pm 0.08(\text{syst}) \pm 0.06(\text{ext})) \times 10^{-8}$. Radiative corrections,

not available in [2] have been included in the acceptance calculation using the PHOTOS package. The systematic uncertainty is 1.2% and is dominated by the effect of radiative corrections on the signal acceptance and the background contamination. The external error is due to the uncertainty on the normalization channel branching ratio $Br(K^\pm \rightarrow \pi^\pm \pi^+ \pi^-)$ [8].

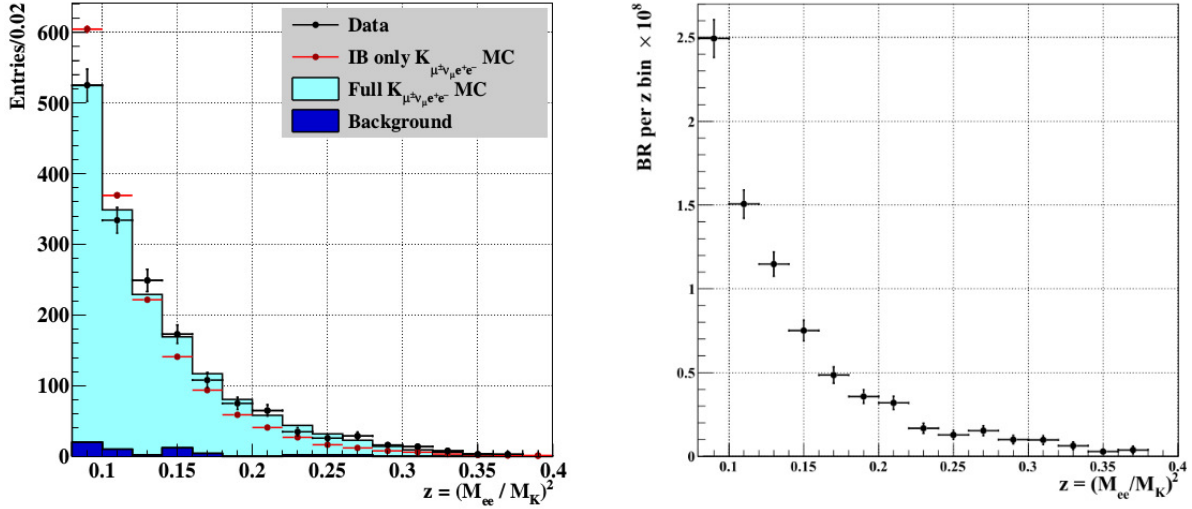


Figure 1. On the left: z distribution after the final selection. Data is presented with points with errorbars. On the right: Branching ratio of the process $K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^-$ calculated for each bin of the z distribution. The final result is the sum of the individual contributions in each bin.

Conclusion

K_{l3} form factors measurement is performed by NA48/2 experiment on the basis of 2004 run data. Result is competitive with the other ones in $K_{\mu 3}^\pm$, and a smallest error in K_{e3}^\pm has been reached, that gives us also the combined result with the smallest error.

The branching ratio of the $K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^-$ decay mode has been measured with 3% background contamination in the phase space region $M_{ee} > 140 \text{ MeV}/c^2$. The achieved uncertainty is improved by a factor 1.5 with respect to the previous most precise measurement [11] and is statistically dominated. It is the first measurement of this mode where radiative corrections are included. The observed spectrum is in agreement with the predictions by ChPT [2]. The result is also compatible with previous measurements [11],[12].

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