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Precision measurement of the form factors of the charged kaon semileptonic decays $K^{\pm}_{l3}$ by the NA48/2 experiment at CERN

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The final result on the charged kaon semileptonic form factors from the NA48/2 experiment is presented. The measurement is based on 4.28 million $K^{\pm}_{e3}$ and 2.91 million $K^{\pm}_{\mu 3}$ events collected in 2004 with very low background ($< 0.1\%$ and $\sim 0.2\%$, respectively). The joint analysis of these samples provides the most precise combined measurement of $K^{\pm}_{l3}$ form factors.

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1. Introduction

The $K^{\pm} \to \pi^0 l^{\pm} \nu$ ($K^{\pm}_{l3}$) differential decay rate as a function of the lepton ($l = e, \mu$) and pion energies E^*_l, E^*_π in the kaon rest frame (Dalitz plot) can be parametrized[1] in terms of two functions of the lepton-neutrino invariant mass $t = (P_K - P_\pi)^2$, the vector $f_+(t)$ and scalar $f_0(t)$ form factors. These form factors are involved in the determination of the $|V_{us}|$ CKM matrix element through the phase space integrals of differential rates[2]. The f_0 contribution to the K_{e3} decay can be neglected as it is heavily suppressed by the smallness of the electron mass. In this work we use three different K_{l3} form factors parametrizations, listed in Table 1: Quadratic[3], Pole[4] and Dispersive[5]. External functions $H(t)$ and $G(t)$ in the Dispersive parametrization depend on five extra parameters, which are evaluated [5] from experimental data and theoretical considerations.

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	$f_+(t)$	$f_0(t)$	parameters
Quadratic[3]	$1 + \lambda'_+(t/m^2_\pi) + \lambda''_+(t/m^2_\pi)^2$	$1 + \lambda'_0(t/m^2_\pi)$	λ'_+ , λ''_+ , λ'_0
Pole[4]	$M^2_V/(M^2_V - t)$	$M^2_S/(M^2_S - t)$	M_V , M_S
Dispersive[5]	$\exp\left(\frac{(\Lambda_+ + H(t))t}{m^2_\pi}\right)$	$\exp\left(\frac{(\ln[C] - G(t))t}{m^2_K - m^2_\pi}\right)$	Λ_+ , $\ln[C]$

Table 1: Parametrizations of the K_{l3} form factors $f_+(t)$ and $f_0(t)$.

2. Beam and detectors

The NA48/2 experiment has been taking data in the years 2003 and 2004, detecting in-flight decays of charged kaons to search for direct CP violation in $K^{\pm} \to 3\pi$ decays[6]. It used two simultaneous oppositely charged beams of (60 ± 3) GeV/c momentum produced by 400 GeV/c primary CERN SPS protons impinging on a berylllium target. Decays of beam kaons inside a 114 m long fiducial volume were recorded by downstream detectors.

A magnetic spectrometer, consisting of a dipole magnet and four drift chamber stations, measured trajectories of charged particles with a spatial resolution of 100 μm, achieving a momentum resolution $\Delta p/p = (1.0 \oplus 0.044 p[\mathrm{GeV/c}])\%$. The spectrometer was followed by a scintillator hodoscope (HOD) consisting of two planes segmented into horizontal and vertical strips, with $\sim 150\,\mathrm{ps}$ time resolution.

Photons and electrons were precisely measured by a a Liquid Krypton electromagnetic calorimeter (LKr), consisting of a $27 X_0$ almost homogeneous ionization chamber with high-granularity tower read-out, providing an energy resolutions $\Delta E/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 9\%/E[\mathrm{GeV}] \oplus 0.42\%$ and a position resolution of about 1.5 mm. The ratio E_{LKr}/p between the energy deposited in the LKr and the momentum measured by the spectrometer is used for particle identification.

An iron-scintillator hadronic calorimeter (HCAL), three planes of scintillators for muon detection (MUV) and several photon veto detectors completed the experimental apparatus, a detailed description of which can be found in [7].

3. Data selection

The data sample was collected during a dedicated 4-day period in 2004, with a trigger selecting events with one charged track in the spectrometer and a minimum energy of 10 GeV deposited in the LKr. Offline event selection requires at least two isolated energy clusters in the LKr consistent with photons of energy above 3 GeV, and the sum of their energies above 15 GeV. The decay vertex longitudinal position Z_v is reconstructed from the photon energies and positions at LKr, assuming they are produced in the decay of a π^0, i.e. constraining their invariant mass $M_{\gamma\gamma}$ to be consistent with the π^0 mass value[3].

A charged track is also required, with a momentum above 5 GeV/c (10 GeV/c) for the K_{e3} ($K_{\mu 3}$) selection. Tracks with $E_{\mathrm{LKr}}/p > 0.9$ are identified as electrons or positrons, while muon identification is based on the MUV. The decay vertex transverse position (X_v, Y_v) is defined by back-extrapolating the track at $z = Z_v$. A wide Z_v-dependent cut is applied to the distance between the vertex and the beam axis to include most events produced in the decay of a 3% additional beam halo component. The kaon momentum P_K is determined assuming the kaon line of flight along the beam axis and a massless missing neutrino. From the two possible P_K solutions (P_1 and P_2), the one closest to the beam momentum central value is chosen.

Specific kinematic cuts on neutrino momentum are applied in the K_{e3} selection in order to exclude very low momentum regions, which are sensitive to beam shape details: $P_T(\nu) > 0.03$ GeV/c, $P_L(\nu)^2 > 0.0014$ (GeV/c)^2, where 'T' and 'L' refer to transverse and longitudinal components, respectively, w.r.t. the beam axis.

The following background-suppressing kimenatic cuts are applied in the $K_{\mu 3}$ selection:
– $M(\pi^{\pm}\pi^0) < 0.47\ \mathrm{GeV}/c^2$ and $M(\pi^{\pm}\pi^0) + P_T(\pi^0)/c < 0.6\ \mathrm{GeV}/c^2$ (against $K^{\pm} \to \pi^{\pm}\pi^0$)
– $M(\mu^{\pm}\nu) > 0.18\ \mathrm{GeV}/c^2$ (against $K^{\pm} \to \pi^{\pm}\pi^0$ followed by $\pi^{\pm} \to \mu^{\pm}\nu$)
– $|P_2 - P_1| < 60\ \mathrm{GeV}/c$ (against $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ followed by $\pi^{\pm} \to \mu^{\pm}\nu$)
where $M(\pi^{\pm}\pi^0)$ and $M(\mu^{\pm}\nu)$ invariant masses are calculated assuming the charged particle to be a pion or a muon, respectively.

Finally, for both selections the vertex position is required to be consistent (within experimental uncertainty) with a point on the beam axis. The Dalitz plots distributions of the selected samples, consisting of 4.28 million K_{e3} and 2.91 million $K_{\mu 3}$ events, are shown in Figure 1. Background contamination is estimated from Monte Carlo simulated samples of several $K^{\pm}$ decay modes (see Table 2) and results very small ($< 0.1\%$ in K_{e3}, $\sim 0.2\%$ in $K_{\mu 3}$).

4. Measurement of the $K^{\pm}_{l3}$ form factors

Monte Carlo (MC) $K^{\pm}_{l3}$ samples have been simulated using the KLOE generator[8] with a proper implementation of radiative effects. The $K^{\pm}_{l3}$ form factors are determined by minimising a χ^2 estimator defined as the sum of contributions $(D_{i,j} - MC_{i,j})^2/[(\delta D_{i,j})^2 + (\delta MC_{i,j})^2]$ over bins (i, j) of the Dalitz plot containing at least 20 events, where $D_{i,j}$ is the background-subtracted number of data events, $MC_{i,j}$ is the number of simulated events in the same bin obtainted by reweighting the MC events for the current iteration form factor parameter values, $\delta D_{i,j}$ and $\delta MC_{i,j}$ are the corresponding errors. The fit is performed separately for the K_{e3} and $K_{\mu 3}$ samples or jointly by extending the summation over both Dalitz plot with a common set of fit parameters.

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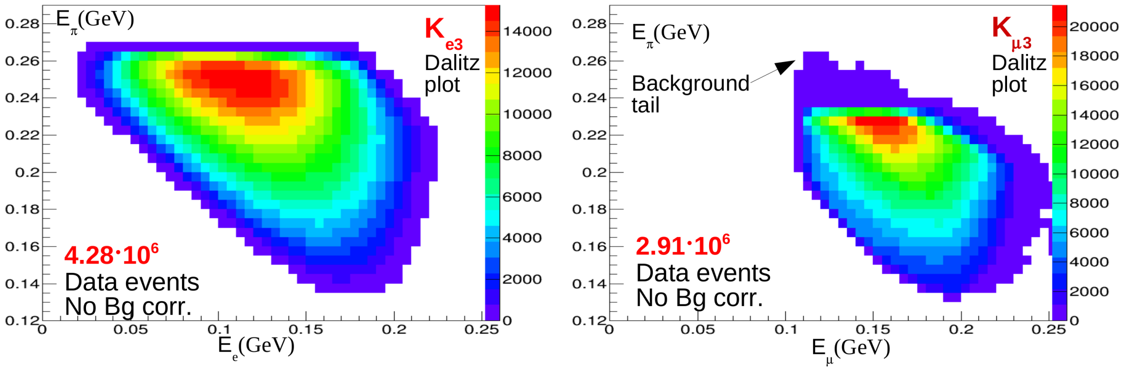

Figure 1: Dalitz plot distribution (in 5 MeV×5 MeV cells) of K_{e3} (left) and $K_{\mu3}$ (right) selected events.

Decay	BR [%]	$N_{\text{gen.}}$ [10^6]	F_e [10^{-3}]	F_μ [10^{-3}]
$K^{\pm} \to \pi^{\pm}(\pi^0 \to 2\gamma)$	20.66	393.2	0.270	0.264
$K^{\pm} \to \pi^{\pm}2(\pi^0 \to 2\gamma)$	1.761	62.5	0.286	1.833
$K^{\pm} \to \pi^{\pm}(\pi^0 \to e^+e^-\gamma)$	1.174	1.5	0.049	0.000
$K^{\pm} \to \pi^{\pm}\gamma(\pi^0 \to 2\gamma)$	0.0275	35.3	0.004	0.044
$K^{\pm} \to \pi^0(\mu^{\pm} \to e^{\pm}\nu\nu)\nu$	0.03353	174.3	0.004	0.000

Table 2: Background contamination estimate. For each simulated decay mode the branching ratio BR, the number of generated events N_{gen} and the background contamination F_e (F_μ) in K_{e3} ($K_{\mu3}$) are reported.

Parametrization	Quadratic			Pole		Dispersive	
	λ'_+ [10^{-3}]	λ''_+ [10^{-3}]	λ'_0 [10^{-3}]	M_v [MeV]	M_S [MeV]	Λ_+ [10^{-3}]	ln[C] [10^{-3}]
Central values	23.55	1.73	14.90	894.3	1185.5	22.76	180.1
Stat. error	0.75	0.29	0.55	3.2	16.6	0.18	4.9
Syst. error	1.23	0.41	0.80	5.4	35.5	0.55	11.1
Total error	1.44	0.50	0.97	6.3	4.9	0.58	12.1
χ^2/NDF	1005/1073			1001/1074		998/1074	

Table 3: $K^{\pm}_{l3}$ form factors parameters measured with a $K_{e3} + K_{\mu3}$ joint analysis

The joint $K^{\pm}_{l3}$ analysis form factor results are reported in Table 3. Correlation coefficients are: $\rho(\lambda'_+, \lambda''_+) = -0.954$, $\rho(\lambda'_+, \lambda'_0) = -0.076$, $\rho(\lambda''_+, \lambda'_0) = 0.035$; $\rho(M_v, M_S) = -0.278$; $\rho(\Lambda_+, \ln[C]) = -0.035$. The systematic error contributions are related to the kaon beam simulation, LKr calibration, background, trigger efficiency, acceptance, radiative corrections and to the external uncertainty introduced by the extra parameters of the Dispersive parametrization. The measured $K^{\pm}_{l3}$ form factors parameters λ''_+, λ'_+, λ'_0 of the Quadratic parametrization and their correlations are shown in Figure 2 and compared to measurements by previous experiments. The NA48/2 result represents the most precise form factor measurement from a combined $K^{\pm}_{l3}$ analysis.

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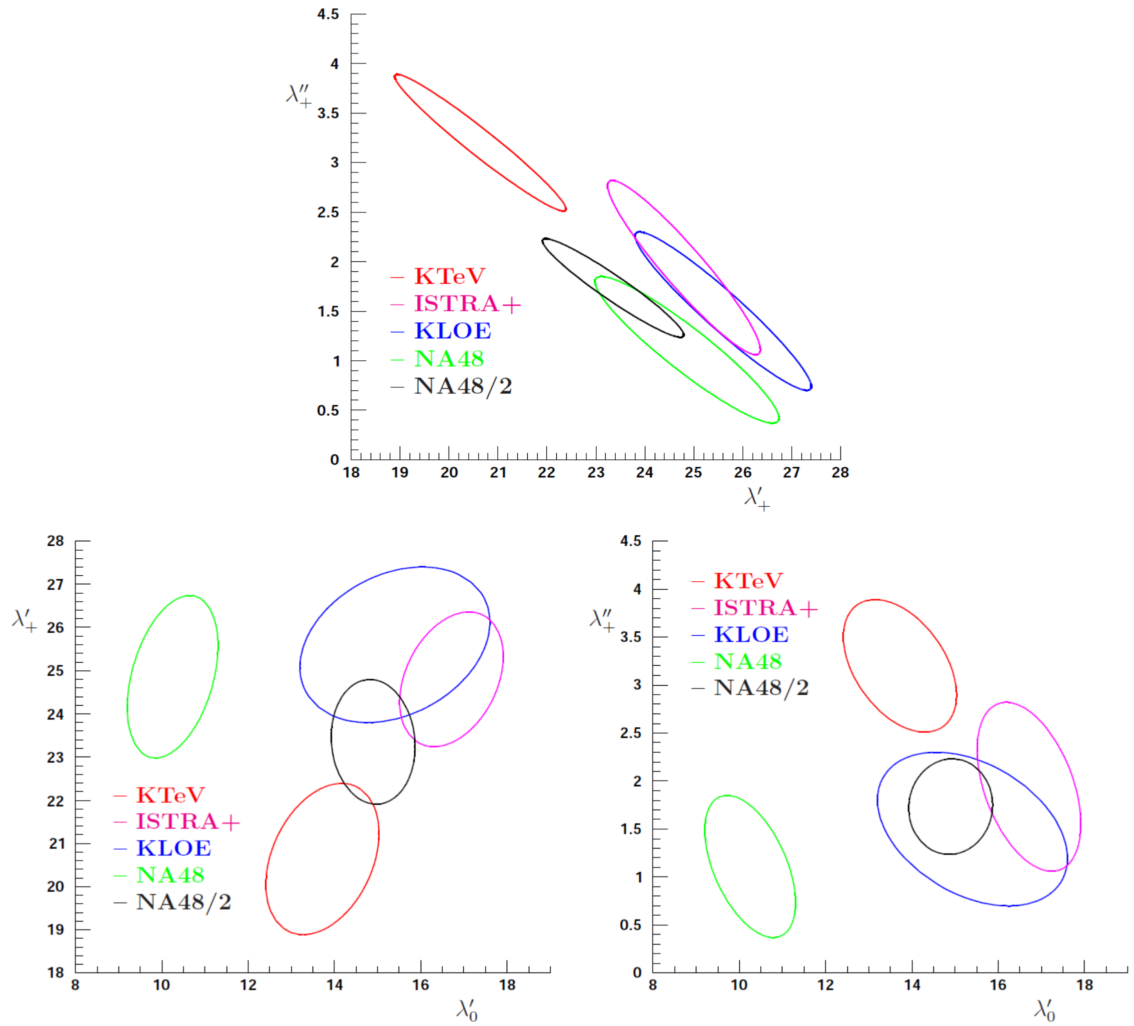

Figure 2: Correlation plots (1σ contours) of $K^{\pm}_{l3}$ form factors parameters (Quadratic parametrization) λ'_{+}, λ''_{+}, λ'_{0} in units 10^{-3} from $K_{e3}+K_{\mu 3}$ joint analysis. NA48/2 results are shown, together with those of previous experiments[9].

References

[1] L.M. Chounet, J.M. Gaillard, M.K. Gaillard, *Phys. Rep.* **4** (1972) 199.

[2] V. Cirigliano *et al.*, *Rev. Mod. Phys.* **84** (2012) 399.

[3] C. Patrignani *et al.* (Particle Data Group), *Chin. Phys. C* **40** (2016) 100001.

[4] P. Lichard, *Phys. Rev. D* **55** (1997) 5385.

[5] V. Bernard, M. Oertel, E. Passemar and J. Stern, *Phys. Rev. D* **80** (2009) 034034.

[6] J.R. Batley *et al.* [NA48/2 Collaboration], *Eur. Phys. J. C* **52** (2007) 875.

[7] V. Fanti *et al.* [NA48/2 Collaboration], *Nucl. Instr. Methods A* **574** (2007) 433.

[8] C. Gatti, *Eur. Phys. J. C* **45** (2006) 417.

[9] M. Antonelli *et al.*, *Phys. Rep.* **494** (2010) 197 and references [362-368] therein.

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