NEW AND RECENT RESULTS FROM NA48/2

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Recent results from the NA48/2 experiment are presented. The most precise measurement of the charged kaon semileptonic form factors has been obtained from 4.28 million $K^{\pm}_{e3}$ and 2.91 million $K^{\pm}_{\mu 3}$ events collected in 2004. A sample of 1663 events of the very rare decay $K^{\pm} \to \mu^{\pm}\nu e^{+}e^{-}$ has been collected in the region $M_{ee} > 140$ MeV/c^2 with negligible background. The measured model independent decay rate is in agreement with ChPT predictions. The branching ratio of the $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay, never observed so far, has been obtained from a sample of 5000 candidates, in agreement with ChPT predictions.

1 The NA48/2 beam and detector

The NA48/2 detector and beam have been described in details earlier[1,2]. Two simultaneous K^+ and K^- beams were 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) were selected by a system of magnets and collimators. Both beams of ≈ 1 cm width had similar paths within the decay volume contained in a 114 m long vacuum tank.

Charged decay products were measured by a magnetic spectrometer consisting of four drift chambers (DCH) and a dipole magnet located between the second and third chamber. The spatial resolution of each chamber was $\sim$90 μm, and the momentum resolution was $\sigma_p/p = (1.02 \oplus 0.044 \cdot p)\%$ (momentum p in Gev/c). The spectrometer was followed by a scintillator hodoscope (HOD) with a time resolution of $\sim$150 ps, whose signals were used to trigger the readout of events with at least one charged track

A Liquid Krypton calorimeter (LKr), located behind the hodoscope, was used to measure the position and energy of electrons and photons. It is an approximately homogeneous ionization chamber with an active volume of 7 m^3 of liquid krypton, 27 X_0 deep, segmented transversally into projective cells, 2×2 cm^2 each. The transverse position of isolated showers was measured

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with a spatial resolution $\sigma_x = \sigma_y = (0.42/\sqrt{E} \oplus 0.06)$ cm. Energy resolution for photons and electrons was $\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (energy E in GeV).

The muon system MUV, consisting of three scintillator planes and 80 cm thick iron walls, was used for muon identification. An aluminium beam pipe of 16 cm outer diameter and 1.1 mm thickness was traversing the centres of all the detector components, providing the path in vacuum for undecayed beam particles and for muons generated in the beam $\pi^{\pm}$ decays.

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

The $K_{l3}(l = \mu, e)$ differential rate as a function of the lepton and pion energies in the kaon rest frame (Dalitz plot) may be parameterised[3] in terms of the vector $f_+(t)$ and scalar $f_0(t)$ form factors function of $t = (P_K - P_\pi)^2$. In the K_{e3} decay, the scalar form factor terms become negligible due to the small electron mass. The K_{l3} form factors participate to the determination of the $|V_{us}|$ CKM matrix element[4] trough the phase space integrals of the differential rates.

Three K_{l3} form factor parameterizations were used: Quadratic[5] ($f_+(t) = 1 + \lambda'_+ t/m_\pi^2 + \frac{1}{2}\lambda''_+(t/m_\pi^2)^2$, $f_0(t) = 1 + \lambda'_0 t/m_\pi^2$), Pole[6] ($f_+(t) = \frac{M_V^2}{(M_V^2 - t)}$, $f_0(t) = \frac{M_S^2}{(M_S^2 - t)}$) and Dispersive[7] ($f_+(t) = \exp\left(\frac{(\Lambda_+ + H(t))t}{m_\pi^2}\right)$, $f_0(t) = \exp\left(\frac{(ln[C] - G(t))t}{(m_K^2 - m_\pi^2)}\right)$). The external functions $H(t), G(t)$ of the Dispersive parameterization depend on five extra parameters, that are fixed with some precision from other experimental data and theoretical considerations[7].

An event is considered as a K_{l3} candidate, if there is at least 2 LKr clusters consistent with photons of reconstructed energy above 3 GeV, and the sum of their energies is above 15 GeV, ensuring high trigger efficiency. The decay vertex longitudinal position Z_n is reconstructed from the photon energies and positions at LKr under the assumption that they are produced in the decay of a π^0 of PDG mass value[5].

At least one charged track is required with a minimum momentum of 5 GeV/c (10 GeV/c) for the $K_{e3}(K_{\mu3})$ selection. Electron identification is based on the E_{LKr}/P_{DCH} ratio, where E_{LKr} is the LKr energy deposit associated with the charged track, and P_{DCH} is its momentum measured by the spectrometer. Tracks with $E_{LKr}/P_{DCH} > 0.9$ are identified as electrons (positrons), while the muon identification is based on MUV information. The transverse position of the decay vertex is defined by the track coordinates at Z_n. A wide Z_n-dependent cut is applied to the distance between the vertex and the beam axis (< 11 cm) to include most events produced in the decay of a 3% additional beam halo component.

The kaon momentum P_K is computed under the assumptions of the kaon line of flight along the beam axis and a massless missing neutrino. From the two possible P_K solutions, the one closest to the beam momentum central value is chosen. Samples of 4.28 million K_{e3} (2.91 million $K_{\mu3}$) events with less than 1 per mille ($\sim$2 per mille) background have been selected from the NA48/2 data recorded in 2004 during a four-day long data taking period with reduced beam momentum spread, low intensity and using a minimum bias trigger.

Monte Carlo (MC) K_{l3} samples have been simulated using the KLOE generator[8] ensuring a proper implementation of radiative effects. The K_{l3} form factor results are obtained by minimization of a χ^2 estimator defined as the sum of contributions $\frac{(D_{i,j} - MC_{i,j})^2}{(\delta D_{i,j})^2 + (\delta MC_{i,j})^2}$ over bins(i, j) of the Dalitz plot with at least 20 data 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 as obtained from reweighting the MC events for the current iteration parameter values; $\delta D_{i,j}$ and $\delta MC_{i,j}$ are the corresponding errors on $D_{i,j}$ and $MC_{i,j}$. The fit is performed separately for the K_{e3} and $K_{\mu3}$ Dalitz plots or jointly by extending the summation over both Dalitz plots and using a common set of fit parameters.

The joint K_{l3} analysis form factor results are shown in Table 1 (in MeV/c^2 for the Pole parameters and in unit of 10^{-3} for the others). 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 errors contributions considered are related to the kaon beam simulation, LKr calibration, background, trigger efficiency, acceptance, radiative correction as well as to the external uncertainty introduced by the extra fixed parameters of the Dispersive parameterization. The measured form factors represent the most precise current result of a combined K_{l3} analysis.

Table 1: Form factor results from the joint K_{l3} analysis (m_V and m_S in MeV/c^2, others are multiplied by 10^3)

	λ'_+	λ''_+	λ_0	m_V	m_S	Λ_+	$ln[C]$
Central values	23.35	1.73	14.90	894.3	1185.5	22.67	189.12
Stat. error	0.75	0.29	0.55	3.2	16.6	0.18	4.91
Syst. error	1.23	0.41	0.80	5.4	35.5	0.55	11.09
Total error	1.44	0.50	0.97	6.3	39.2	0.58	12.13
χ^2/NDF	1004.6/1073			1001.1/1074		998.3/1074	

3 Study of the $K^\pm \to \mu^\pm \nu e^+ e^-$ decay

The radiative leptonic decay $K^\pm \to \mu^\pm \nu \gamma^* (\gamma^* \to e^+e^-)$ proceeds via two different mechanisms. The main contribution is the Inner Bremsstrahlung (IB) from the final state muon, that can be calculated from QED. The virtual γ^* can also be radiated off at the weak vertex of the intermediate state. This Structure Dependent (SD) contribution depends on form factors that can be calculated in the framework of ChPT and becomes dominant at large M_{ee} values.

The analysis is based on the reconstruction of three-track vertices. One of the tracks is required to be identified as a muon according to LKr and MUV information, while the two others are to be identified as an electron and a positron using LKr and DCH. The abundant $K^\pm \to \pi^\pm\pi^+\pi^-$ ($K_{3\pi}$) decay is used as normalization. Reconstructed momenta of selected tracks are required to be in the range (3–50) GeV/c, and the total vertex momentum to be < 66 GeV/c. The requirement $M_{ee} > 140$ MeV/c^2 suppresses background from decays including a π^0 Dalitz decay to $e^+e^-\gamma$, while requiring the muon-neutrino invariant mass $M_{\mu\nu} > 170$ MeV/c^2 suppresses background from $K^\pm \to \pi^\pm e^+e^-$ followed by $\pi^\pm \to \mu^\pm\nu$ decay.

The residual background comes from $K^\pm \to \pi^\pm\pi^+\pi^-$ and $K^\pm \to \pi^+\pi^- e^\pm\nu$ decays with pion decay and/or misidentification and from $K^\pm \to \pi^\pm\pi^0\pi^0$ followed by the Dalitz decay of both neutral pions. The total background is evaluated from the selected Wrong Sign events (containing a reconstructed same sign e^+e^+ or e^-e^- pair), coming from the above sources with a scaling factor defined by the possible charge combinations.

A sample of 1663 signal candidates is selected with an estimated background of 54 ± 11 events in an exposure to 1.56×10^{11} kaon decays in 2003–2004. The spectrum of the variable $z = (M_{ee}/M_K)^2$ shown in Fig.1-left is compatible with the prediction of ChPT[9]. The partial branching ratio is computed in each bin of z and includes radiative corrections as implemented using the PHOTOS package. The sum of these contributions represent a model-independent branching ratio for $M_{ee} > 140$ MeV/c^2 : $BR(K^\pm \to \mu^\pm\nu e^+e^-) = (7.84 \pm 0.21_{stat} \pm 0.08_{syst} \pm 0.06_{ext})\times 10^{-8}$. The systematic uncertainty is dominated by the contributions related to radiative corrections and background while the external error is due to the normalization branching ratio uncertainty[5].

4 First observation of the $K^\pm \to \pi^+\pi^0 e^+e^-$ decay

This mode proceeds through similar mechanisms, $K^\pm \to \pi^+\pi^0\gamma^*(\gamma^* \to e^+e^-)$, as the previous one and has not been observed so far. The signal events are selected concurrently with the normalization events ($K^\pm \to \pi^\pm\pi^0$ followed by π^0_D). Both signal and normalization candidates are reconstructed from three-track vertices with track reconstructed momenta in the range (2–60) GeV/c. Photon candidates are LKr clusters with energy above 2 GeV, not associated to a

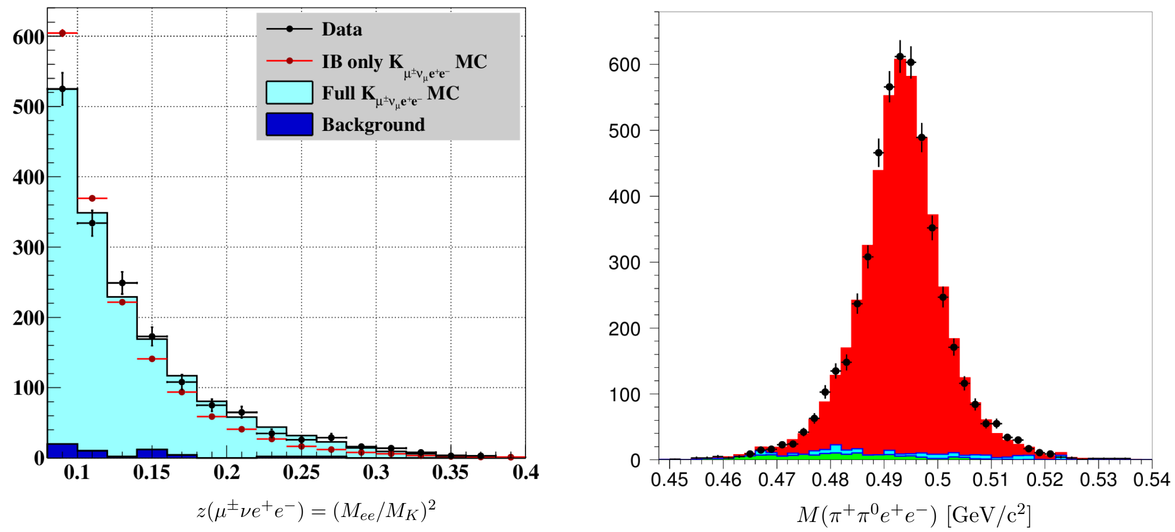

Figure 1 – Left: z distributions of $K^\pm \to \mu^\pm\nu e^+e^-$ events from data, simulation (IB only and full ChPT model[9]) and background contamination. Right: reconstructed kaon mass for $K^\pm \to \pi^+\pi^0e^+e^-$ decays (full dots – data, stacked histograms, from bottom to top – $K_{3\pi}$ and $K_{2\pi}$ backgrounds and signal IB simulation).

track and in time with the vertex tracks.

The two-photon invariant mass of a signal events (γe^+e^- of a normalization events) is required to be within ±15 MeV/c^2 from the π^0 PDG mass[5], and the reconstructed kaon mass to be within ±45 MeV/c^2 from the $K^\pm$ PDG mass. The total momentum is required to be in the range (54-66) GeV/c. The correlation between the reconstructed π^0 and kaon masses defines a kinematic constraint $|M_{\pi^0} - 0.42M_K + 73.2| < 6$ MeV/c^2 allowing particle identification without using E_{LKr}/P_{DCH} requirements, therefore increasing acceptance of low momentum tracks.

The two main background sources are $K^\pm \to \pi^\pm\pi^0\pi^0_D$ (with a lost photon) and $K^\pm \to \pi^\pm\pi^0_D$ (with an extra photon). The first background is additionally suppressed by requiring the squared invariant mass of the $\pi^\pm\pi^0$ system to be larger than 0.12 GeV^2/c^4. To reject further the second background source, both possible invariant masses $M_{ee\gamma}$ are required to be more than 7 MeV/c^2 away from the π^0 PDG mass. The 0.15% background to normalization is due to $K^\pm \to \mu^\pm\nu\pi^0_D$ and $K^\pm \to e^\pm\nu\pi^0_D$ misreconstructed events where the pion mass is assigned to the lepton.

A sample of 5076 signal candidates have been selected from an exposure to 1.7×10^{11} kaon decays in 2003–2004. The background contamination estimated from simulation is about 5.7%. The preliminary result is $BR(K^\pm \to \pi^+\pi^0e^+e^-) = (4.22 \pm 0.06_{stat} \pm 0.04_{syst} \pm 0.13_{ext}) \times 10^{-6}$, where the systematic error includes uncertainties related to acceptances, trigger efficiencies and radiative corrections. The external error is due to the normalization mode branching ratio uncertainty[5]. The obtained result is in agreement with the theoretical prediction[10] of 4.10×10^{-6} (obtained including isospin corrections but without radiative corrections).

References

1. V. Fanti *et al*, *Nucl. Instrum. Methods* A **574**, 433 (2007).
2. J.R. Batley *et al*, Eur. Phys. J. C **52**, 875 (2007).
3. L.M. Chounet, J.M. Gaillard, M.K. Gaillard, Phys.Rept. **4**, 199 (1972).
4. V. Cirigliano *et al*, Rev. Mod. Phys. **84**, 399 (2012)
5. C. Patrignani *et al* (Particle Data Group), Chin.Phys. C **40**, 100001 (2016).
6. P. Lichard, *Phys. Rev.* D **55**, 5385 (1997).
7. V. Bernard, M. Oertel, E. Passemar, J. Stern, *Phys. Rev.* D **80**, 034034 (2009).
8. C. Gatti, Eur.Phys.J. C **45**, 417 (2006).
9. J. Bijnens, G. Ecker, J. Gasser, *Nucl. Phys.* B **396**, 81 (1993).
10. L. Cappiello, O. Cata, G. D'Ambrosio, D. Gao, Eur. Phys. J. C **72**, 1872 (2012).