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Recent results on Kaon decays from NA48/2

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The first observation of the $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ rare decay by the NA48/2 experiment at CERN SPS is reported, based on $\sim 2 \times 10^{11}$ $K^{\pm}$ decays recorded in 2003-2004. From a sample of 4919 candidates with 4.9% background the branching ratio in the full kinematic region is measured to be $\mathrm{BR}(K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}) = (4.24 \pm 0.14) \times 10^{-6}$.
The study of the kinematic space shows evidence for a structure dependent contribution in agreement with predictions based on Chiral Perturbation Theory. The CP-violating asymmetry between $K^{+} \to \pi^{+}\pi^{0}e^{+}e^{-}$ and $K^{-} \to \pi^{-}\pi^{0}e^{+}e^{-}$ decay rates has been measured, providing an upper limit $|A_{\mathrm{CP}}| < 4.82 \times 10^{-2}$ at 90% CL.
The NA48/2 combined measurement of the charged kaon semileptonic form factors, based on 4.4 million $K^{\pm} \to \pi^{0}e^{\pm}\nu_{e}$ and 2.3 million $K^{\pm} \to \pi^{0}\mu^{\pm}\nu_{\mu}$ events collected in 2004, is presented. This result represents the most precise form factor measurement from a combined $K^{\pm}_{l3}$ analysis.

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1. 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 [1]. It used two simultaneous oppositely charged beams of 60 GeV/c momentum produced by 400 GeV/c primary CERN SPS protons impinging on a beryllium 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 ~ 150 ps time resolution.

Photons and electrons were precisely measured by a a Liquid Krypton electromagnetic calorimeter (LKr), consisting of a $27X_0$ 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 [2].

2. The $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay

The $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay, never observed so far, proceeds through virtual photon emission followed by internal conversion into an electron-positron pair, i.e. $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma^{*} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$. The virtual photon can be produced by two different mechanisms: Inner Bremsstrahlung (IB) where the virtual photon γ^{*} is emitted by the charged mesons in the initial or final state, and Direct Emission (DE) where the γ^{*} is radiated off at the weak vertex.
The differential decay rate of this decay consists of three terms: the dominant IB contribution, the DE component (electric E and magnetic M parts) and their interference. The IB-M and E-M interference terms are P-odd and cancel upon angular integration in the total rate.

There are few theoretical studies [3, 4, 5] investigating this decay mode. The authors of [4] predicted, using as input the NA48/2 measurements of the $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay [6], the branching fractions of IB, DE and INT components of the $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ decay. In a recent revised work [5] they re-evaluated the interference term using more realistic inputs based on additional experimental results and fewer theoretical assumptions.

The $K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ branching fraction is measured relative to the normalization decay $K^{\pm} \to \pi^{\pm}\pi^{0}$, collected concurrently with the same trigger logic. In the signal sample, the π^{0} is identified through the dominant $\pi^{0} \to \gamma\gamma$ mode ($\pi^{0}_{\gamma\gamma}$). In the normalization sample, the π^{0} is identified through the $\pi^{0} \to e^{+}e^{-}\gamma$ Dalitz mode (π^{0}_{D}).

Both signal and normalization candidates are selected among events having a three-track vertex with total charge ± 1. The photon four-momenta are reconstructed assuming they originate from the three-track vertex. In both (signal and normalization) selections, the mass of the reconstructed π^0 and $K^\pm$ are required to be within ± 15 MeV/c^2 and ± 45 MeV/c^2, respectively, from the corresponding nominal PDG masses [7]. Moreover, the total ($\pi^\pm\pi^0e^+e^-$ or $\pi^+\pi^0_D$) reconstructed momentum and the position of the 3-track vertex are required to be compatible with the beam momentum and trajectory. The charged pion and the electrons in each $K^\pm \to \pi^\pm\pi^0e^+e^-$ candidate event are identified using kinematics. The single track with charge opposite to $q_{\rm vtx}$ is assigned the electron mass, then the remaining electron-pion ambiguity for the two same-sign tracks is solved by testing both mass hypotheses (m_e, m_π) and (m_π, m_e) and selecting events within a band defined as |M(π^0) - 0.42 M(K) + 73.2 MeV/c^2| < 6 MeV/c^2.

Cuts on the $\pi^\pm\pi^0$ and $ee\gamma$ invariant masses are applied to suppress background from $K^\pm \to \pi^\pm\pi^0\pi^0_D$ ($K_{3\pi D}$) and $K^\pm \to \pi^\pm\pi^0_D$ ($K_{2\pi D}$) decays. Signal acceptance has been evaluated from Monte Carlo simulation. More details about this analysis can be found in [8].

Samples of 4919 signal candidates and 16.3×10^6 $K_{2\pi D}$ candidates have been selected from a subset of 1.7×10^{11} Kaon candidates recorded in 2003-2004. Background contamination estimated from Monte Carlo simulatied samples amounts to $(4.9 \pm 0.4)\%$ in the signal mode and to 0.11% in the normalization mode. The reconstructed $\gamma\gamma$ and $\pi^\pm\pi^0e^+e^-$ mass distributions for the selected signal candidates are shown in Fig. 1.

The Branching Ratio of the $K^\pm \to \pi^\pm\pi^0e^+e^-$ decay mode is obtained from the number of signal and normalization events and their estimated background. It results to be BR($K^\pm \to \pi^\pm\pi^0e^+e^-$)= $(4.24 \pm 0.06_{\rm stat} \pm 0.03_{\rm syst} \pm 0.13_{\rm ext}) \times 10^{-6}$, where the statistical error is dominated by the signal statistics, the systematic error by the radiative effects and the external error by the π^0_D branching ratio uncertainty.

This measurement of the $K^\pm \to \pi^\pm\pi^0e^+e^-$ branching ratio is consistent with theoretical predictions [4, 5] BR($K^\pm \to \pi^\pm\pi^0e^+e^-$)= 4.183×10^{-6} for IB only, BR($K^\pm \to \pi^\pm\pi^0e^+e^-$)= 4.229×10^{-6} when including all DE and INT terms, although none of the above predictions includes radiative or isospin breaking effects.

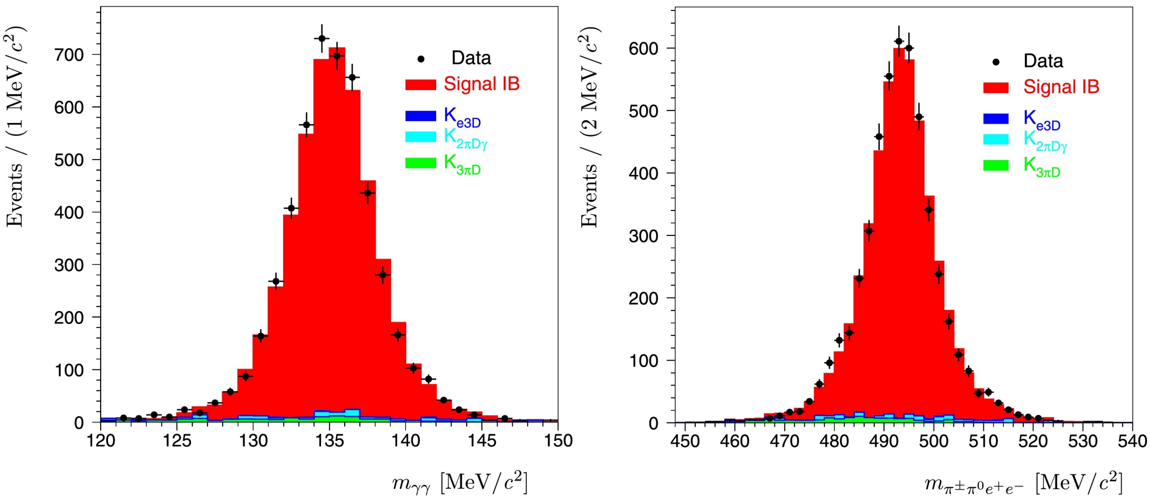

Figure 1: Signal candidates. Left: reconstructed $\gamma\gamma$ mass. Right: reconstructed $\pi^\pm\pi^0e^+e^-$ mass. Full dots correspond to data candidates, stacked histograms are, from bottom to top, the expected backgrounds and IB signal (red) estimated from simulation.

A study of the event distribution in the kinematic space allows to determine the ratio between

DE(M) and IB contributions to the decay, $M/IB = 0.0114 \pm 0.0043_{\rm stat}$, consistent with the predicted value from [4], $0.0141 \pm 0.0014_{\rm ext}$. The measurement of both K^+ and K^- decay rates allows to constrain the CP-violating asymmetry $A_{\rm CP} = [\Gamma(K^+ \to \pi^+\pi^0 e^+e^-) - \Gamma(K^- \to \pi^-\pi^0 e^+e^-)]/[\Gamma(K^+ \to \pi^+\pi^0 e^+e^-) + \Gamma(K^- \to \pi^-\pi^0 e^+e^-)]$, resulting in an upper limit $|A_{\rm CP}| < 4.82 \times 10^{-2}$ at 90% CL. More details about these analyses can be found in [8], together with measurements of other P- and CP- violating asymmetries involving the event distribution in the kinematic space.

3. Measurement of the $K^\pm \to \pi^0 e^\pm \nu$ (K_{e3}) and $K^\pm \to \pi^0 \mu^\pm \nu$ ($K_{\mu 3}$) form factors

The K_{l3} ($l = e, \mu$) 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 $Z_{\rm v}$ 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 [7].

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 $E_{\rm LKr}/p > 0.9$ are identified as electrons or positrons, while muon identification is based on the MUV. The decay vertex transverse position $(X_{\rm v}, Y_{\rm v})$ is defined by back-extrapolating the track at $z = Z_{\rm v}$. A wide $Z_{\rm v}$-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 [9] are applied to the K_{e3} selection to reduce dependence on the beam shape details and to $K_{\mu 3}$ selection to suppress $K_{2\pi}$ and $K_{3\pi}$ backgrounds.

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 4.4 million K_{e3} and 2.3 million $K_{\mu 3}$ events, are shown in Figure 2.

Background contamination is estimated from Monte Carlo simulated samples of several $K^\pm$ decay modes and results very small, $< 0.1\%$ in K_{e3}, $\sim 0.2\%$ in $K_{\mu 3}$.

Three different parametrizations are used to describe the $K^\pm_{l3}$ form factors dependence on the $l\nu$ invariant mass squared: a Taylor expansion [7], a parametrization assuming vector and scalar pole masses M_V and M_S [10, 11] and a more physical dispersive parametrization [12]. The corresponding parameters are determined by minimising a proper χ^2 estimator [9]. 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. The resulting form factors parameters λ''_+, λ'_+, λ'_0 of the Taylor expansion parametrization [7] and their correlations are shown in Figure 3 for the joint $K^\pm_{l3}$ analysis 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. More details about this analysis, as well as the complete set of results, are reported in [9].

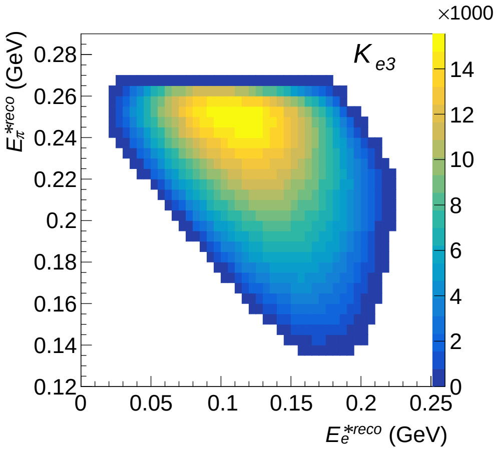

Figure 2: Dalitz plot distribution (in 5 MeV×5 MeV cells) of K_{e3} (left) and $K_{\mu 3}$ (right) selected events. E_{π}^{*reco} and E_{l}^{*reco} ($l = e, \mu$) are the pion and charged lepton energies in the Kaon rest frame.

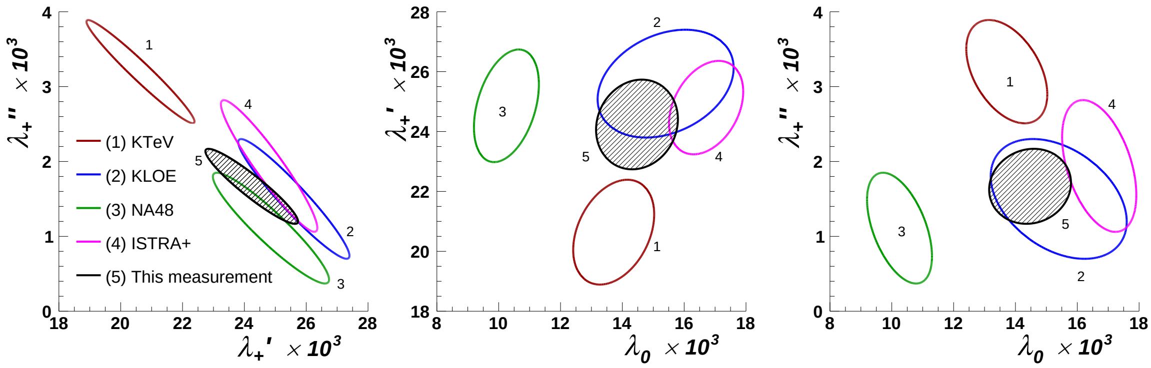

Figure 3: Correlation plots (1σ contours) of $K_{l3}^{\pm}$ form factors parameters (Quadratic parametrization) from $K_{e3} + K_{\mu 3}$ joint analysis. NA48/2 results are shown, together with those of previous experiments.

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