Model independent measurement of the leptonic kaon decay $K^\pm \to \mu^\pm \nu_\mu e^+ e^-$ and study of the $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ decay by the NA48/2 experiment

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Two recent results on rare kaon decays are presented, based on $\sim 2 \times 10^{11}$ $K^\pm$ decays recorded by the NA48/2 experiment at CERN SPS in 2003 and 2004. The branching ratio of the rare leptonic decay $K^\pm \to \mu^\pm \nu_\mu e^+ e^-$ has been measured in the region of large $e^+ e^-$ invariant mass $M_{ee} \geq 140\,\mathrm{MeV/c^2}$, where low energy QCD contributions become important and can be calculated in the framework of Chiral Perturbation Theory (ChPT). This branching ratio is measured to be $\mathrm{BR}(K^\pm \to \mu^\pm \nu_\mu e^+ e^- \mid M_{ee} \geq 140\,\mathrm{MeV/c^2}) = (7.8 \pm 0.2) \times 10^{-8}$. The $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ rare decay has been observed for the first time, with about 5000 candidates and a 5% background. The branching ratio in the full kinematic region is measured to be $\mathrm{BR}(K^\pm \to \pi^\pm \pi^0 e^+ e^-) = (4.22 \pm 0.15) \times 10^{-6}$, in good agreement with ChPT-based theoretical predictions.

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1. Introduction

Radiative kaon decays, although dominated by long-distance processes, contain information on short-distance physics which can be extracted with a detailed Dalitz plot analysis. In $K^{\pm} \to \mu^{\pm} \nu_{\mu} e^+ e^-$ and $K^{\pm} \to \pi^{\pm} \pi^0 e^+ e^-$ decays the virtual photon γ^* emitted in the decay and internally converting to an $e^+ e^-$ pair can be produced by two different mechanisms: Inner Bremsstrahlung (IB), where the γ^* is radiated by one of the charged particles in the initial or final state, and Direct Emission (DE), where the γ^* is emitted at the weak vertex of the intermediate state. The former is accurately predicted by QED, while the latter involves low-energy QCD contributions, which can be calculated in the framework of Chiral Perturbation Theory (ChPT). The resulting differential decay rate contains three terms: the dominant long-distance IB contribution, the DE component and their interference (INT). The kinematic region at large values of the $e^+ e^-$ invariant mass is particularly interesting, as in this region DE and INT significantly contribute to the differential decay rate. In this work we present the measurement of the branching ratio $\mathrm{BR}(K^{\pm} \to \mu^{\pm} \nu_{\mu} e^+ e^-)$ in the kinematic region $M_{ee} \geq 140 \, \mathrm{MeV/c^2}$ and the first observation of the $K^{\pm} \to \pi^{\pm} \pi^0 e^+ e^-$ decay.

2. The NA48/2 experiment

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]. Two simultaneous oppositely charged beams of (60 ± 3) GeV/c momentum were produced by 400 GeV/c protons from the CERN SPS impinging on a 40 cm long 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 $\Delta p/p = (1.0 \oplus 0.044p[\mathrm{GeV/c}])\%$. 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.

The energy and position of photons and electrons were precisely measured by a Liquid Krypton calorimeter (LKr), consisting of a $27X_0$ almost homogeneous ionization chamber with high-granularity tower read-out, providing a spatial resolution of about 1.5 mm and an energy resolutions $\Delta E/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 9\%/E[\mathrm{GeV}] \oplus 0.42\%$. The ratio E/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].

3. The $K^{\pm} \to \mu^{\pm} \nu_{\mu} e^+ e^-$ decay

The branching ratio of the radiative leptonic decay $K^{\pm} \to \mu^{\pm} \nu_{\mu} \gamma^* (\gamma^* \to e^+ e^-)$ in the full phase space is dominated by IB and is predicted[3] to be $\mathrm{BR}(K^{\pm} \to \mu^{\pm} \nu_{\mu} e^+ e^-) = 2.49 \times 10^{-5}$. However, at large values of the $e^+ e^-$ invariant mass the structure-dependent DE term gives an important contribution, which can be calculated unambiguously at next-to-leading order in ChPT. A calculation including ChPT form factors predicts[3] $\mathrm{BR}(K^{\pm} \to \mu^{\pm} \nu_{\mu} e^+ e^- | M_{ee} \geq 140 \, \mathrm{MeV/c^2}) = 8.51 \times 10^{-8}$.

The $K^{\pm} \to \mu^{\pm} \nu_{\mu} e^{+} e^{-}$ event selection is based on the reconstruction of a three-track vertex with a total charge $q_{\text{vtx}} = \pm 1$. Two of these tracks ($e^{\pm}$ candidates) are required to deposit all their energy in the LKr ($0.95 < E/p < 1.05$). The very few pions depositing a large fraction of their energy in the LKr are rejected using a linear discriminant variable based on the shower shape. The invariant mass of the two electrons M_{ee} is required to be larger than 140 MeV/c^2. The third track (muon candidate) is required to deposit only a small fraction of its energy in the LKr ($E/p < 0.2$) and to produce a signal in the MUV detector.

The decay $K^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$ is chosen as normalization for the $K^{\pm} \to \mu^{\pm} \nu_{\mu} e^{+} e^{-}$ branching ratio measurement because of its similar three-track topology. This leads to first order cancellation of systematic effects due to imperfections in the kaon beam description and to detector or trigger inefficiencies. The signal acceptance is determined with a Monte Carlo simulation using a generator based on [3] with all form factors computed up to O(p^4) in ChPT and the PHOTOS package to include radiative corrections. The acceptance of the $K^{\pm} \to \mu^{\pm} \nu_{\mu} e^{+} e^{-}$ decay mode ranges between 12% and 15% depending on M_{ee}.

The largest background to $K^{\pm} \to \mu^{\pm} \nu_{\mu} e^{+} e^{-}$ comes from kaon decays with a Dalitz-decaying π^0 ($\pi_D^0 \to e^+ e^- \gamma$) in the final state, i.e. $K^{\pm} \to \pi_D^0 \mu^{\pm} \nu_{\mu}$ and $K^{\pm} \to \pi^+ \pi_D^0$. These decays are almost completely suppressed by the choice of the kinematic region $M_{ee} \geq 140$ MeV/c$^2 > m_{\pi^0}$. Background from $K^{\pm} \to \pi^{\pm} e^+ e^-$ followed by a $\pi^{\pm} \to \mu^{\pm} \nu_{\mu}$ decay is suppressed by requiring the neutrino-muon invariant mass $M_{\mu\nu}$ to be larger than 170 MeV/c^2. The small background remaining after event selection is composed of decays with multiple pions in the final state misidentified as either muons or electrons. It has three components: $K^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$, $K^{\pm} \to \pi^+ \pi^- e^{\pm} \nu$ and $K^{\pm} \to \pi^+ \pi_D^0 \pi_D^0$. In the latter decay the condition $M_{ee} \geq 140$ MeV/c^2 may be satisfied by a combination of electrons from different π^0s. Background contamination from these decay modes is determined from data using "wrong-sign" events, i.e. events containing two same-sign electron candidates ($\mu^+ e^- e^-$ or $\mu^- e^+ e^+$). Figure 1(a) shows the squared missing mass distribution of the 1663 selected events (dots with error bars) together with the $54 \pm 10_{\text{stat}} \pm 5_{\text{syst}}$ estimated background (dark blue histogram). The distribution in the variable $z = (M_{ee}/M_K)^2$, shown in Fig.1(b), agrees with ChPT predictions[3]. More details about this analysis can be found in [4].

The branching ratio is computed in each z bin. The total number of kaon decays in the fiducial volume $(1.56 \pm 0.01) \times 10^{11}$ is derived from the number of normalization events. The total model-independent branching ratio is obtained as the sum over all z bins and results to be BR($K^{\pm} \to \mu^{\pm} \nu_{\mu} e^{+} e^{-} | M_{ee} \geq 140$ MeV/c^2)= $(7.84 \pm 0.21_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.04_{\text{ext}}) \times 10^{-8}$, in fair agreement with the ChPT-based theoretical prediction[3]. The 1.2% systematic error is dominated by the effect of radiative corrections on the signal acceptance and background contamination, while the external error is due to the uncertainty on BR($K^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$)[5].

4. 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, is expected to be dominated by IB. The branching ratios of the single components have been predicted[6] using as input the NA48/2 measurement of the $K^{\pm} \to \pi^{\pm} \pi^{0} \gamma$ decay[7].

The decay $K^{\pm} \to \pi^{\pm} \pi_D^0$ ($\pi_D^0 \to e^+ e^- \gamma$) is chosen as normalization mode in the measurement of the $K^{\pm} \to \pi^{\pm} \pi^{0} e^{+} e^{-}$ branching ratio because of its similar three-track topology, differing from
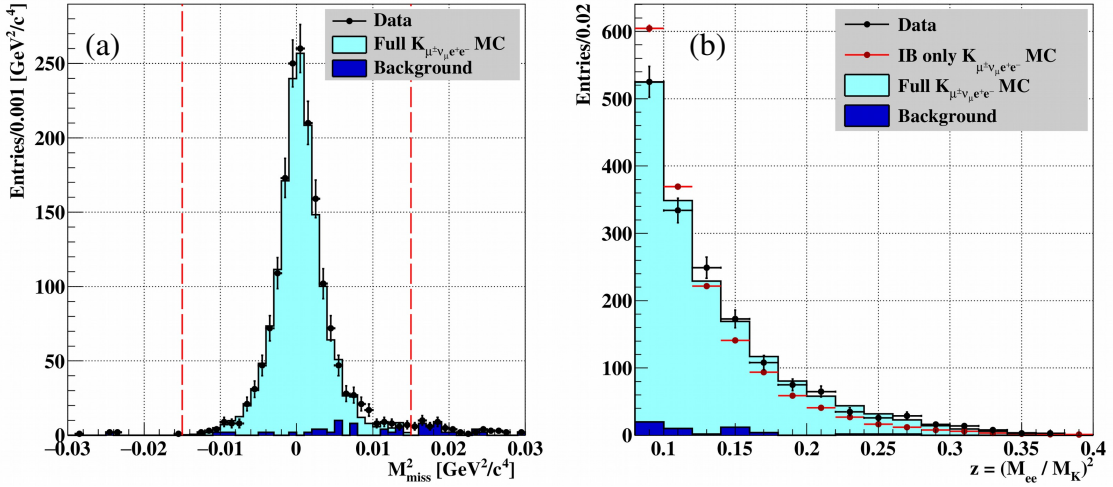
Figure 1: Distributions of $K^{\pm} \to \mu^{\pm}\nu_{\mu} e^{+}e^{-}$ candidate events (black dots with error bars) after final selection and of the evaluated background (dark blue histogram). Full MC simulation is shown with a light blue histogram. (a) Squared missing mass M_{miss}^2. Boundaries of the selected region are shown with vertical dashed lines. (b) $z = (M_{ee}/M_K)^2$. IB-only simulation is shown with red dots.

the signal by only one photon and satisfying similar kinematic constraints on the reconstructed π^0 and $K^{\pm}$ masses. Both signal and normalization candidates are selected among events having a three-track vertex with total charge $q_{\text{vtx}} = \pm 1$, i.e. with two same-sign tracks and one opposite-charge track. The three tracks times, measured using the HOD, are required to coincide within 5 ns. Isolated energy clusters without associated track depositing more than 2 GeV in the LKr, in time within 5 ns with the vertex time (mean of the three track times) are considered as photon candidates. The photon four-momenta are reconstructed assuming they originate from the 3-track vertex. In both (signal and normalization) selections, the mass of the reconstructed π^0 and $K^{\pm}$ are required to be within $\pm 15\,\text{MeV}/c^2$ and $\pm 45\,\text{MeV}/c^2$, respectively, from the corresponding nominal PDG masses[5]. Moreover, the total ($\pi^{\pm}\pi^0 e^{+}e^{-}$ or $\pi^{+}\pi_D^0$) 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 $K^{\pm} \to \pi^{\pm}\pi^0 e^{+}e^{-}$ candidate event are identified using kinematics. The single track with charge opposite to q_{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 $|M(\pi^0) - 0.42\,M(K) + 73.2\,\text{MeV}/c^2| < 6\,\text{MeV}/c^2$.

Two main sources of background affect the signal sample: $K^{\pm} \to \pi^{\pm}\pi^0\pi_D^0$ ($K_{3\pi D}$) when one of the photons escapes detection and $K^{\pm} \to \pi^{\pm}\pi_D^0$ ($K_{2\pi D}$) when an extra photon combines with a Dalitz photon to mimic a $\pi^0 \to \gamma\gamma$ decay. The former is suppressed by requiring the squared invariant mass of the $\pi^{\pm}\pi^0$ system to be greater than $0.12\,\text{GeV}^2/c^4$, the latter by requiring the invariant masses of both possible $ee\gamma$ combinations to be more than $7\,\text{MeV}/c^2$ away from the nominal π^0 mass.

Signal acceptance has been evaluated from Monte Carlo simulation of the different contributions (IB, DE, INT) generated according to [6], with radiative corrections included as implemented

in the PHOTOS package. The signal acceptance has been obtained from a weighted average of the single component acceptances, using as weights the relative contributions with respect to IB computed in [6].

The Branching Ratio of the $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ decay mode is obtained from the number of signal (5076) and normalization (16.8×10^6) events and their estimated background (289 ± 25 and 25517 ± 223, respectively). It results to be BR($K^\pm \to \pi^\pm \pi^0 e^+ e^-$)= $(4.22 \pm 0.06_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}} \pm 0.13_{\mathrm{ext}}) \times 10^{-6}$, where the external error is dominated by the uncertainty on the PDG branching ratio of the normalization mode. This measurement of the $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ branching ratio is in good agreement with theoretical predictions[6] of $4.10(4.19) \times 10^{-6}$ including (not including) Isospin breaking corrections. More details about this analysis can be found in [8].
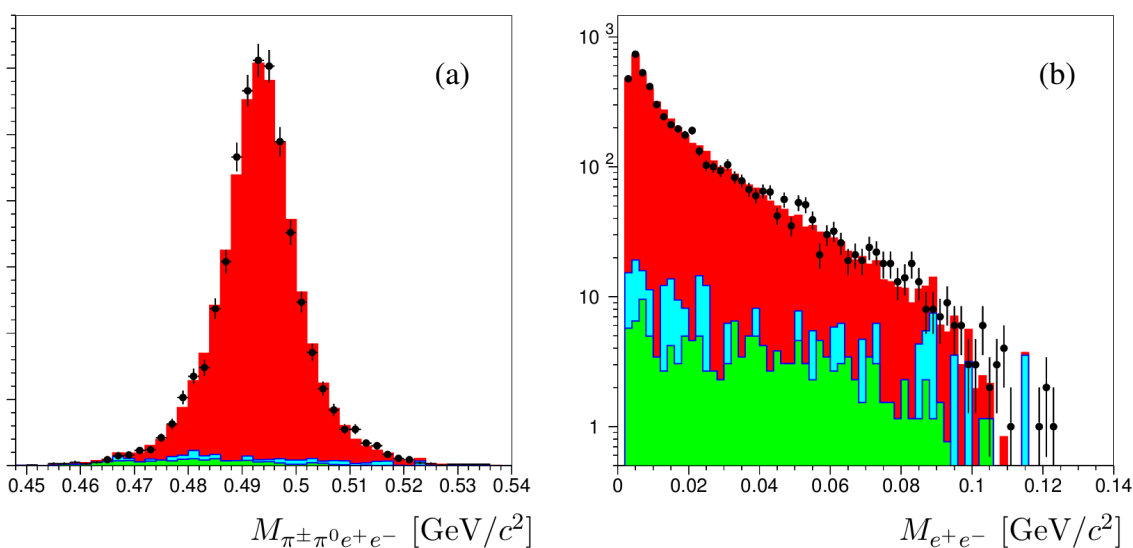
Figure 2: Signal candidates. (a) Reconstructed $\pi^\pm \pi^0 e^+ e^-$ invariant mass distribution. (b) Reconstructed $e^+ e^-$ invariant mass distribution. Full dots correspond to data candidates, stacked histograms are, from bottom to top, the expected $K_{3\pi D}$ and $K_{2\pi D}$ backgrounds and the signal IB simulation.

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