Model independent measurement of the leptonic kaon decay $K^\pm \to e^+ e^-$

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Model independent measurement of the leptonic kaon decay $K^{\pm} \rightarrow \mu^{\pm} \nu_\mu e^+ e^-$

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Abstract. 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 1500 events of the very rare decay $K^{\pm} \rightarrow \mu^{\pm} \nu_\mu e^+ e^-$ 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
Quantum Chromodynamics (QCD), at low energies, is described by theories that can be tested using radiative decays of K mesons. Chiral Perturbation Theory (ChPT) is one of the frameworks available to describe QCD at low energy. In this theory QCD is an effective field theory with a cutoff scale $\Lambda$ of $\mathcal{O}(1 \text{ GeV})$, where for energies below the cutoff an expansion can be performed in $p/\Lambda$ (chiral expansion). The study of radiative kaon decays expressed in chiral expansion at next-to-leading order can so be used to test ChPT.

The present work is focused on the study of the leptonic decay $K^{\pm} \rightarrow \mu^{\pm} \nu_\mu e^+ e^-$ with data collected in 2003–2004 at the NA48/2 experiment at CERN.

Of particular interest is the kinematic region in which the invariant mass of the electron-positron pair is above the $\pi^0$ mass where the ChPT contribution increases the tree-level branching fraction by 70%. A precise description of the theoretical calculation of the branching fraction for the full phase space and for $M_{ee} \geq 140 \text{ MeV}/c^2$ can be found in Ref. [1].

The amplitude is dominated by the Inner Bremsstrahlung of the muon (IB) in the final state which is a purely Quantum Electrodynamical (QED) process and can be exactly calculated within the Standard Model (SM). Going to next-to-leading order, the impact of ChPT on the branching fraction becomes more and more important especially for large $M_{ee}$, the so-called Structure Dependent (SD) amplitude. In Figure 1 the Feynman diagrams of both the IB and SD contributions are shown. The Monte Carlo simulation used for the analysis is based on Ref. [1], which includes the form factors computed up to $\mathcal{O}(p^4)$ in ChPT and no radiative corrections. The phase space is expressed in terms of the dimensionless variable $z = (M_{ee}/M_K)^2$. For $z \geq 0.1$ a sizeable part of the amplitude originates from the SD contribution (Figure 2).

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Figure 1. The Feynman diagrams of $K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^-$ proceed via a $W$ boson and a virtual photon. The Inner Bremsstrahlung (IB) contribution from the muon in the final state (a) is a pure QED process, while the Structure Dependent (SD) contribution (b) is described in terms of ChPT.

Figure 2. Simulated $z = (M_{ee}/M_K)^2$ distribution before applying any selection criteria. The Monte Carlo simulation is produced according to [1]. Two types of simulation are show here: the red dots correspond to a simulation with only the IB contribution while the light-blue solid plot includes all the ChPT form factors contributions, providing an enhancement at large $z$. The analysis is performed in the phase space $z > 0.08$ which means $M_{ee} \geq 140$ MeV/$c^2$ (right region with respect to red dashed vertical line).

The first measurement of $BR(K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^- |M_{e+e} \geq 140$ MeV/$c^2$) = (12.3 ± 3.2)$^{-8}$ was performed at CERN in 1976 [2] with 14 observed events. With a more stringent cut on the phase space the E865 experiment at BNL in 2002 measured $BR(K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^- |M_{e+e} \geq$
Table 1. Theoretical prediction of $\mathcal{BR}(K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^-)$ [1].

|             | IB contribution | IB+SD contribution |
|-------------|-----------------|--------------------|
| Full phase space | $2.49 \times 10^{-5}$ | $22.49 \times 10^{-5}$ |
| $M_{e^-+e^-} \geq 140$ MeV/$c^2$ | $4.98 \times 10^{-8}$ | $8.51 \times 10^{-8}$ |

2. The NA48/2 apparatus and data taking conditions

The NA48/2 experiment was located in the north area (NA) of the CERN SPS accelerator facility and was a successor of the NA48 experiment with almost the same detector set up. The primary goal of NA48/2 was the search of direct CP violation in $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays [4] with about 100 days of effective data taking in 2003–2004. The experiment used 400 GeV/$c$ protons provided by the SPS which, hitting on a Beryllium target, produced a secondary hadronic beam. Thanks to a system of magnets and collimators only charged particles from a helium vessel at atmospheric pressure in which a magnetic spectrometer was located. The spectrometer consisted of four drift chambers (DCH) and a dipole magnet, placed between the second and the third chamber, which provided a horizontal momentum kick of $p_t = 120$ MeV/$c$ for charged particles. Each chamber had four different views and a spatial resolution of $\sigma_{x,y} = 90 \mu m$. The nominal momentum resolution of the spectrometer was $\sigma_p/p = (1.02 \pm 0.044 \%)/p$ where $p$ is given in GeV/$c$. A scintillating hodoscope (HOD) followed the spectrometer. It was divided in four quadrants by a horizontal and a vertical plane of strip-shaped counters. The HOD was used in the trigger chain to provide a fast time measurement for charged particles with a 150 ps time resolution. A quasi homogeneous electromagnetic calorimeter filled with liquid krypton (LKr) and a depth of 27$X_0$ was used both for photon detection and particle identification. It had an energy resolution of $\sigma_E/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ (E in GeV) corresponding to $\sigma_E/E = 0.94\%$ at 20 GeV. The particle identification was completed by a hadronic calorimeter and a muon veto system (MUV). The hadronic calorimeter consisted of alternated iron and scintillator planes, while the MUV of three plastic scintillator strips planes each of them preceded by a 80 cm iron wall. A more detailed description of the experiment can be found in Ref. [5].

3. Events selection

The $K^\pm \rightarrow \mu^\pm \nu_\mu e^+ e^-$ ($K_{\mu\nu e e}$) selection is based on the reconstruction of a three-track vertex. Two of the three tracks have to be identified as electron and positron while the other has to be compatible with a muon. The decay mode $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ ($K_{3\pi}$) has the same vertex topology and is used as a normalization channel for the $K_{\mu\nu e e}$ branching ratio measurement, leading to a first order cancellation of systematic effects. Using the $K_{3\pi}$ normalization channel, the total number of kaon decays in the fiducial volume is measured to be $N_K = (1.56 \pm 0.01) \times 10^{11}$. In the $K_{\mu\nu e e}$ selection the three tracks have to form a vertex of good quality inside the fiducial volume with a total charge of $Q = \pm 1$ corresponding to the kaon charge. Each track has to be
inside the geometrical acceptance of the detectors and has to have a momentum between 3 and 50 GeV/c. The total momentum of the three tracks is requested to be less than 66 GeV/c in order to be consistent with the momentum of the beam kaons.

The particle identification of the electron-positron pair is based on the ratio between the total energy measured in the calorimeter over the momentum measured by the spectrometer ($E/p$) which has to be within the range 0.95-1.05 and on a linear discriminant method based on the shower shape. The good $e/\pi$ separation of the discriminant provides an almost complete suppression of pions coming from $K_{3\pi}$ and $K^{\pm} \rightarrow \pi^{\pm} e^\pm \nu_e$ ($K_{e4}$) background decays, that can mimic the signal if they are not really identified as pions. The muon is required to behave like a minimum ionising particle in the LKr ($E/p < 0.2$) and to have an in-time coincidence in the MUV detector.

Two further cuts are applied to the $K_{\mu\nu e\nu}$ signal:

1. the invariant mass of the electron-positron is requested to be $M_{ee} \geq 140$ MeV/$c^2$ in order to reject decays with an $e^+e^-$ pair coming from a $\pi^0$ ($m_{\mu\nu} = 135$ MeV/$c^2$) like $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ or $K^\pm \rightarrow \pi^0 \mu^\pm \nu_\mu$ decays followed by $\pi^0 \rightarrow e^+e^-\gamma$.

2. the invariant mass of the muon and neutrino is required to be above 170 MeV/$c^2$ in order to reject background events coming from $K^\pm \rightarrow \pi^\pm e^+e^-\nu_\mu$ followed by $\pi^\pm \rightarrow \mu^\pm \nu_\mu$ decay. The cut decreases the signal acceptance by 11% but completely suppresses $K^\pm \rightarrow \pi^\pm e^+e^-$ events.

4. Background estimation

After the signal selection few irreducible background events remain in the signal region. The events contributing to this background arise from multiple pions in the final state, with one pion decaying into $\mu\nu$. Three different channels are contributing:

1. $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ ($K_{3\pi^0}$) decays with $\pi^\pm \rightarrow \mu^\pm \nu_\mu$ and both $\pi^0$ undergo Dalitz decays $\pi^0 \rightarrow e^+e^-\gamma$, with only two of the four electrons from different $\pi^0$'s being detected.

2. $K^\pm \rightarrow \pi^\pm \pi^+\pi^-$ ($K_{3\pi}$) decays where one pion decays into $\mu\nu$ and the other two are misidentified as electrons.

3. $K^\pm \rightarrow \pi^\pm \pi^- e^+\nu_e$ ($K_{e4}$) decays in which one of the pions is misidentified as electron and the other either misidentified as muon or decaying into $\mu\nu$.

The background estimation is performed using data by selecting events with same sign electrons, while all other requirements remain unchanged. Since the detector acceptances, trigger inefficiencies and misidentification probabilities do not depend on the electric charge the expected number of background events in the signal sample is equal to the observed number of events in the same sign sample multiplied by a corresponding combinatorial factor. For both $K_{3\pi^0}$ and $K_{3\pi}$ the combinatorial factor is 2, because there are two possibilities for having a opposite sign pair ($e^+ e^-$), while for $K_{e4}$ the corresponding factor is 1. Using this method the total number of observed background events is $N_{bgk} = 54 \pm 10$ (stat.) $\pm 5$ (syst.).

5. Results

After the selection 1663 signal candidates are observed with a background contamination of 3% and a signal acceptance varying between 12 and 15% depending on $M_{ee}$.

Figure 3 and 4 show the surviving events for both data and Monte Carlo simulation after applying the selection criteria.
Figure 3. Missing mass $M_{\text{miss}}^2 = (P_K - P_{\mu} - P_{e^+} - P_{e^-})^2$ after the full signal selection. The expected background contribution is represented by the dark-blue solid plot which dominates the right tail of the squared missing mass. The two dashed red vertical lines define the signal region.

Figure 4. Distribution of $z = (M_{ee}/M_K)^2$ for both data (black points) and Monte Carlo simulation (IB+SD solid, only IB red points). Data are in good agreement with the shape predicted by ChPT.
In order to properly account for the variation of the acceptance the branching ratio $\mathcal{BR}(K_{\mu ee})$ is measured in 15 different bins of $z$ as shown in Figure 5.

![Figure 5](image)

**Figure 5.** Branching ratio of the decay $K^\pm \rightarrow \mu^\pm \nu_\mu e^+e^-$ computed in 15 different bins of $z = (M_{ee}/M_K)^2$ in the interesting region $M_{ee} \geq 140$ MeV/$c^2$. The final result is the sum of each individual bin.

The total branching ratio is then the sum over all bins of $z$ and is obtained to be

$$\mathcal{BR}(K^\pm \rightarrow \mu^\pm \nu_\mu e^+e^- \mid M_{e^+e^-} \geq 140 \text{ MeV}/c^2) = (7.81 \pm 0.21(\text{stat.}) \pm 0.08(\text{syst.}) \pm 0.06(\text{ext.})) \times 10^{-8}$$

The relative systematic uncertainty is 1.2% and is dominated by the effect of the radiative corrections on the signal acceptance and the statistical uncertainty of the background estimation. The external error is due to the uncertainty on the $K_{3\pi}$ branching fraction. Table 2 summarizes all contributions to the total uncertainty.

### 6. Conclusion

A model independent measurement of the leptonic kaon decay $K^\pm \rightarrow \mu^\pm \nu_\mu e^+e^-$ has been presented, using data collected by the NA48/2 experiment in 2003–2004. A total number of 1663 events are observed in the signal region with an estimated background of 54 events. The branching ratio for the phase space of $M_{ee} \geq 140$ MeV/$c^2$ is measured to be

$$\mathcal{BR}(K^\pm \rightarrow \mu^\pm \nu_\mu e^+e^-) = (7.81 \pm 0.21(\text{stat.}) \pm 0.08(\text{syst.}) \pm 0.06(\text{ext.})) \times 10^{-8}.$$  

The measurement is statistically dominated and the total uncertainty is improved by a factor 1.5 with respect to the previous result [3]. For the first time also radiative corrections are included. The observed $z$ spectrum is in agreement with the shape predicted by ChPT [1].
Table 2. Contributions to the uncertainty on $\mathcal{B}\mathcal{R}(K^\pm \to \mu^\pm \nu_\mu e^+e^-)$. The list includes statistical, systematic and external sources.

| Source                              | $\Delta \mathcal{B}\mathcal{R}/\mathcal{B}\mathcal{R}[\times10^2]$ |
|-------------------------------------|---------------------------------------------------------------------|
| Data statistics                     | 2.54                                                                |
| Normalization channel statistics    | 0.02                                                                |
| Total statistical                   | 2.54                                                                |
| Radiative corrections               | 0.70                                                                |
| Background statistics               | 0.62                                                                |
| Trigger efficiency                  | 0.54                                                                |
| Background systematic               | 0.30                                                                |
| Muon ID efficiency                  | 0.13                                                                |
| Signal channel acceptance           | 0.12                                                                |
| Electron ID uncertainty             | 0.04                                                                |
| Normalization channel acceptance    | 0.03                                                                |
| Total systematic                    | 1.15                                                                |
| External uncertainty $\mathcal{B}\mathcal{R}(K_{3\pi})$ | 0.72                                                                |
| Total uncertainty                   | 2.88                                                                |

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