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Model independent measurement of the leptonic kaon decay $K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}e^{+}e^{-}$ with the NA48/2 experiment

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A measurement of the branching ratio of the rare leptonic kaon decay $K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}e^{+}e^{-}$ is presented using data collected by the NA48/2 experiment in 2003 and 2004. The measurement is performed in the region $M_{ee} > 140$ MeV/c^2. In this particular region low energy QCD contributions become important and can be calculated in the framework of Chiral Perturbation Theory (ChPT). From a total number of 1.56×10^{11} recorded kaon decays, the branching ratio is measured to be $\mathscr{B}\left(K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}e^{+}e^{-}|M_{ee} > 140\, MeV/c^2\right) = (7.8 \pm 0.2) \times 10^{-8}$.

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1. Motivation

Radiative decays of K mesons can be used to test theories describing low energy Quantum Chromodynamics (QCD). Chiral Perturbation Theory (ChPT) is one of the successful frameworks for such calculations. This theory is an an effective field theory that describes QCD below the scale Λ of $\mathcal{O}(1\text{ GeV})$. The pseudo-scalar meson masses are below the cutoff scale and an expansion can be performed in terms of (p/Λ), called the chiral expansion. The Standard Model can be tested using radiative decays in next-to-leading order in the chiral expansion without any further assumptions. The radiative leptonic process $K^{\pm} \to \mu^{\pm}\nu_{\mu}\gamma^{*}(\gamma^{*} \to e^{+}e^{-})$ can proceed via two different types of diagrams presented in Figure 1. The phase space is dominated by Inner Bremsstrahlung from the final state muon, which is a pure QED process and its contribution to the branching ratio can be calculated exactly. The intriguing part of the phase space is the invariant mass of the $e^{+}e^{-}$ pair in the region $M_{ee} > 140$ MeV/c^2, where the ChPT form factors have an important contribution to the branching ratio. We use a MC generator based on [1] with all form factors computed up to $\mathcal{O}(p^4)$ in ChPT. Radiative corrections are included in the MC generation using the PHOTOS package. Figure 2 shows the differences between the generated distributions of the dimensionless variable $z = (M_{ee}/M_K)^2$ with pure IB simulation and one with added non-zero ChPT form factors. However, above $M_{ee} = 140$ MeV/c^2 the phase space is greatly reduced, therefore a large number of decayed kaons is needed in order to measure precisely the very small branching ratio.

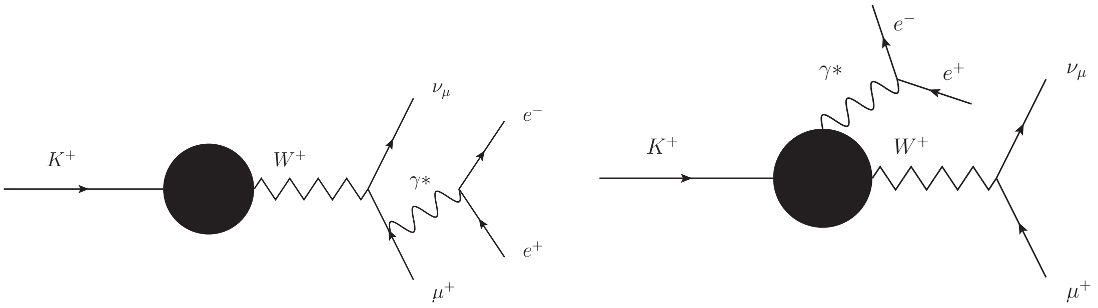

Figure 1: Feynman diagrams of the process $K^{\pm} \to \mu^{\pm}\nu_{\mu}e^{+}e^{-}$ proceeding via a W boson and a virtual photon. The left graph shows the contribution of the Inner Bremsstrahlung (IB) from the final state lepton (pure QED). The right shows the combined contribution from the virtual photon emitted from the initial state and the so called Structure Dependent (SD) radiation.

2. Experimental apparatus

The NA48/2 experiment at the CERN SPS was a multi-purpose $K^{\pm}$ experiment, whose main goal was the search for direct CP violation in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays [2]. Simultaneous and collinear K^{+} and K^{-} beams of the same momentum of (60 ± 3) GeV/c were produced by 400 GeV/c SPS primary protons impinging on a Beryllium target, and were steered into a 114 m long decay region, contained in a cylindrical vacuum tank. The downstream part of the vacuum tank was sealed by a convex Kevlar window, that separated the vacuum from helium at atmospheric pressure. Inside the helium vessel a magnetic spectrometer was installed,

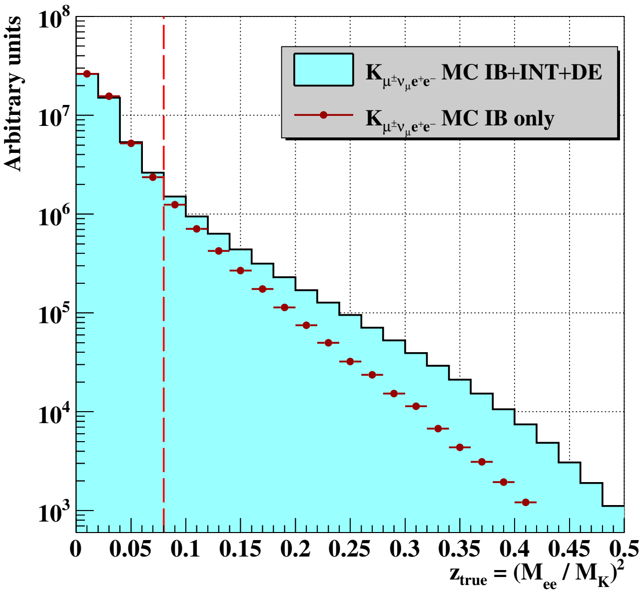

Figure 2: MC simulated true $z = (M_{ee}/M_K)^2$ distribution without any selection criteria applied. The data points correspond to a simulation with only IB term included in the matrix element. The shaded histogram corresponds to simulation with all of the ChPT form factors included according to [1]. The region of the measurement is to the right of the red dashed line.

which was formed of 4 drift chambers (DCHs) and a dipole magnet providing a horizontal momentum kick of p_t = 120 MeV/c. The spatial resolution of each DCH was $\sigma_x = \sigma_y = 90\ \mu$m. The nominal spectrometer momentum resolution was $\sigma_p/p = (1.02 \oplus 0.044p)$ % (p in GeV/c). The magnetic spectrometer was followed by a scintillating hodoscope (HOD) used to provide a fast time measurement of charged particles used in the trigger chain. The HOD consisted of a plane of horizontal and a plane of vertical strip-shaped counters. The HOD was followed by a quasi-homogeneous, 27 X_0 deep electromagnetic calorimeter filled with liquid krypton (LKr), which was used for photon detection and particle identification. The calorimeter had an energy resolution of $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ (E in GeV). The spatial resolution for isolated electromagnetic showers was $\sigma_x = \sigma_y = (0.42/\sqrt{E} \oplus 0.06)$ cm (E in GeV) for the transverse coordinates x and y and the single shower time resolution was $\sigma_t = 2.5$ ns$/\sqrt{E}$. The LKr was followed by a hadronic calorimeter (not used for the present measurement) and a muon detector (MUV). The MUV consisted of three planes made of plastic scintillator strips, read out by photomultipliers on both ends. Each plane was preceded by a 80 cm thick iron wall to provide absorption of hadrons. A more detailed detector description can be found in [3].

3. Analysis

The analysis of the mode $K^\pm \to \mu^\pm \nu_\mu e^+ e^- (K_{\mu\nu ee})$ is based on the reconstruction of a three-track vertex. Two of those tracks have to be identified as electrons using the LKr calorimeter and to have an invariant mass $M_{ee} > 140$ MeV/c^2. The third track has to be compatible with a muon, acting as a minimum ionising particle (MIP) in the LKr and leaving a signal in the MUV detector.

The mode $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ $(K_{3\pi})$ is chosen as normalization for the $K_{\mu\nu ee}$ branching ratio measurement, because the topologies of both decays are similar. This leads to first order cancellation of systematic effects due to possible imperfect kaon beam description or detector or trigger inefficiencies.

3.1 Event Selection

The $K_{\mu\nu ee}$ selection is characterized by the presence of three charged tracks and a missing momentum carried away by the undetected neutrino.The missing mass for such a mode is equivalent to a neutrino mass squared and should be zero for signal events. The phase space region of $M_{ee} > 140$ MeV/c^2 is experimentally clean, because decays with e^+e^- pairs coming from $K^{\pm} \to \pi^{\pm}\pi^{0}$ or $K^{\pm} \to \pi^{0}\mu^{\pm}\nu_{\mu}$ decay with a following $\pi^0 \to e^+e^-\gamma$ decay ($m_{\pi^0} = 135$ MeV/c^2) are fully suppressed.

The three tracks have to form a good vertex inside the 98 m long decay volume of the experiment and to have a total charge of $|Q| = \pm 1$. Each of the tracks has to pass through the geometrical acceptance of the Drift Chambers, HOD, LKr and MUV detector and to have momenta in the range between 3 and 50 GeV/c. The showers in the LKr produced by the charged tracks have to be isolated from each other by at least 20 cm to avoid overlapping showers. The total momentum of the three tracks has to be $p_{3track} < 66$ GeV/c in order to be consistent with the beam kaons. A cut is applied on the invariant mass of the muon – neutrino system of $M_{\mu\nu} > 170$ MeV/c^2, to suppress events coming from $K^{\pm} \to \pi^{\pm}e^{+}e^{-}$ followed by $\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$.

The particle identification is based on the LKr calorimeter and the MUV system. The ratio E/p of the energy deposited in the LKr divided by the total momentum distinguishes between muons, pions and electrons. The muon is required to leave only a small fraction of its energy in the LKr (E/p < 0.2) and to have a positive identification in the MUV detector. Electrons should leave all their energy in the LKr with an energy deposition shower shape different from the shape of hadronic showers produced by pions. To distinguish between genuine electrons and misidentified pions we require $0.95 < E/p < 1.05$ and use a linear discriminant variable, which makes use of the different shape and starting point of the created showers. This discriminant provides almost complete suppression of pions coming from $K_{3\pi}$ or $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu_{e}$ decays.

The NA48/2 detector recorded more than 10^{11} decayed kaons in the fiducial volume of the experiment, which makes it suitable for rare decay rate measurements as $K_{\mu\nu ee}$. The acceptance for this decay mode is M_{ee} dependent and of the order of $12-15\%$.

3.2 Background

After the full selection described in Section 3.1 only small fraction of background processes survives as shown in Figure 3. The remaining background is composed of decays with multiple pions in the final state misidentified as either muons or electrons. It has three components: $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu_{e}$ and $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$, followed by two Dalitz decays of the two π^0s ($e^+e^-\gamma$). The two electrons have to come from two different π^0 decays so the M_{ee} can be higher than 140 MeV/c^2. The background contamination coming from those modes can be studied directly in data using Wrong Sign (WS) selection. The WS selection is the same as the signal selection, but requiring two same-sign electrons/positrons and an opposite sign muon ($\mu^+e^-e^-$ or $\mu^-e^+e^+$).

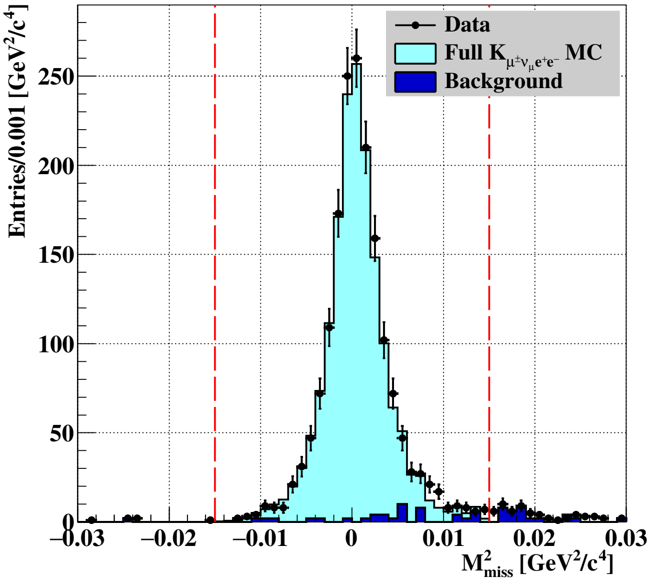

Figure 3: Missing mass squared distribution after the final selection. The selected region is indicated by the two dashed lines. The tail on the right is dominated mostly by background processes with several missing particles.

Those Lepton Flavor Violating modes do not exist in the SM, therefore the only surviving events come from processes constituting the background for the $K_{\mu\nu ee}$ selection. A scaling factor is applied to the WS selected data in order to take into account that the modes with three pions in the final state have two possibilities to enter the signal selection and only one to enter the WS selection.

4. Results

After the event selection, 1663 signal candidates are observed with an estimated background contamination of $54 \pm 10(stat) \pm 5(syst)$ events. The total number of kaons decayed in the fiducial volume of the experiment is $(1.56 \pm 0.01) \times 10^{11}$ as obtained from the number of normalisation events corrected for acceptance, trigger efficiency and branching ratio. The z spectrum shown in Figure 4 is compatible with the spectrum predicted by the ChPT. The branching ratio is computed for each of the z bins (15 bins in total) and shown on Figure 4. The results obtained in each bin are then summed to get the total branching ratio. This minimizes the effect of the z dependence of the signal acceptance. The total model-independent branching ratio in the phase space $M_{ee} \geq 140$ MeV/c^2 is $\mathscr{B}(K^\pm \to \mu^\pm \nu_\mu e^+ e^-) = (7.84 \pm 0.21(stat) \pm 0.08(syst) \pm 0.06(ext)) \times 10^{-8}$. Radiative corrections, not available in [1] have been included in the acceptance calculation using the PHOTOS package. The systematic uncertainty is 1.2 % and is dominated by the effect of radiative corrections on the signal acceptance and the background contamination. The external error is due to the uncertainty on the normalization channel branching ratio $\mathscr{B}(K^\pm \to \pi^\pm \pi^+ \pi^-)$[6].

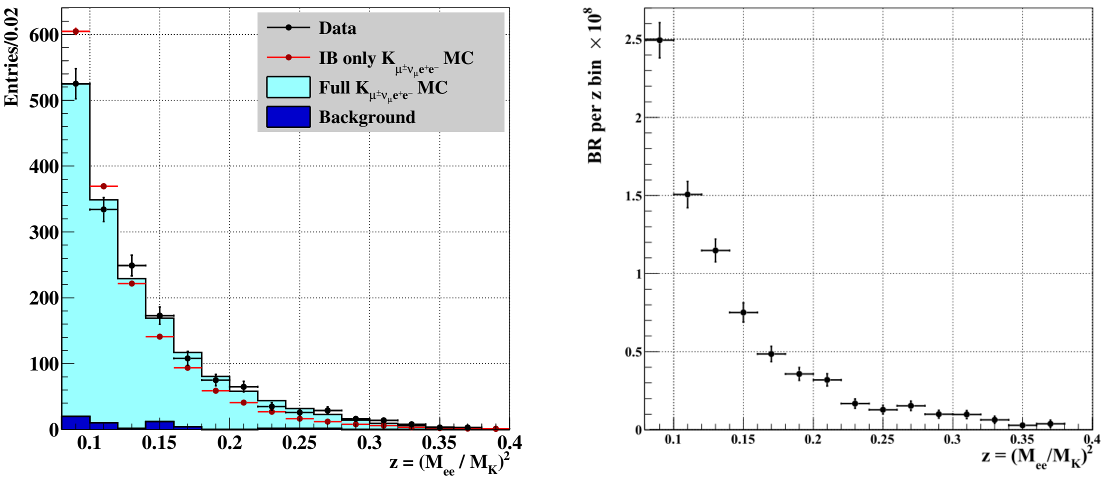

Figure 4: On the left: z distribution after the final selection. Data is presented with points with errorbars. The estimated background is shown in dark blue. With brighter shaded histogram is presented the signal MC, scaled to the total number of expected events after background subtraction. The signal MC with only IB contribution is shown with points without errorbars to demonstrate, that the shape predicted from ChPT is the one favored by the data; On the right: Branching ratio of the process $K^{\pm} \to \mu^{\pm}\nu_{\mu}e^{+}e^{-}$ calculated for each bin of the z distribution. The final result is the sum of the individual contributions in each bin.

5. Conclusions

The branching ratio of the $K^{\pm} \to \mu^{\pm}\nu_{\mu}e^{+}e^{-}$ decay mode has been measured with 3 % background contamination in the phase space region $M_{ee} > 140$ MeV/c^2. The achieved uncertainty is improved by a factor 1.5 with respect to the previous most precise measurement [4] and is statistically dominated. It is the first measurement of this mode where radiative corrections are included. The observed spectrum is in agreement with the predictions by ChPT [1]. The result is also compatible with previous measurements [4],[5].

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