Studies of the decay $K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-$ at NA48

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The NA48/2 experiment reports the first observation of about 2000 candidates of the rare decay $K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-$, with a background contamination below 3%. The preliminary branching ratio in the full kinematic region is: $\mathscr{B}(K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-) = (4.06 \pm 0.17) \cdot 10^{-6}$ by analyzing the data collected in 2003.

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1. The NA48/2 experiment

The NA48/2 experiment at the CERN SPS collected a large sample of charged kaon ($K^\pm$) decays during the 2003-04 data taking period. The experiment was designed for charge asymmetry measurements in $K^\pm$ decays to three pions, using simultaneous K^+ and K^- beams produced by a primary beam of 400 GeV/c protons from CERN SPS, impinging on a 40 cm-long beryllium target. Secondary beams with central momenta of (60 ± 3) GeV/c (r.m.s.) which followed a common beam axis were used; they were selected by two systems of dipole magnets with zero total deflection (each of them forming an *achromat*), focusing quadrupoles, muon sweepers, and collimators. The kaon beam, which contained $\sim 2.3 \times 10^6$ K^+ and $\sim 1.3 \times 10^6$ K^- per pulse with a duration of 4.5 s, decayed in a fiducial volume contained in a 114 m-long cylindrical vacuum tank. Both beams followed the same path in the decay region: their axes coincided within 1 mm, while the transverse size of the beams was about 1 cm. The fraction of beam kaons decaying in the vacuum tank at nominal momentum was about 22%. The momenta of charged decay products were measured by a magnetic spectrometer, housed in a tank filled with helium at nearly atmospheric pressure, placed after the decay volume and separated from the vacuum tank by a thin ($\sim 0.4\% X_0$) Kevlar composite window. An aluminium beam pipe, 1.1 mm-thick and with an outer radius of 8 cm, passing through the spectrometer centre (and all the following detectors), allowed the undecayed beam particles and the muon halo from beam pion decays to continue their path in vacuum. The spectrometer consisted of four octagonal drift chambers (DCHs) with a radial extension of 1.35 m, each composed of four staggered double planes of sense wires, located upstream (DCH1–2) and downstream (DCH3–4) of a large aperture dipole magnet. The magnet provided a transverse momentum kick $\Delta p = 120$ MeV/c to charged particles in the horizontal plane. The spatial resolution of each DCH was $\sigma x = \sigma y = 90$ μm and the momentum resolution achieved in the spectrometer was $\sigma p/p = (1.02 \oplus 0.044 \cdot p)\%$ (p *expressed in* GeV/c). A charged hodoscope (CHOD), consisting of two planes of plastic scintillators segmented into vertical and horizontal strip-shaped counters (128 in total), producing fast trigger signals and providing precise time measurements of charged particles, was placed after the spectrometer. The CHOD surface was logically subdivided into 2×4 non-overlapping square regions. The achieved time resolution was ~ 150 ps. Further downstream there was a liquid krypton electromagnetic calorimeter (LKr), an almost homogeneous ionization chamber with an active volume of 7 m^3 of liquid krypton, $27 X_0$ deep, transversally segmented into 13248 projective cells, $\sim 2 \times 2$ cm^2, and with no longitudinal segmentation. The energies of electrons and photons were measured with a resolution $\sigma E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E *expressed in* GeV) and the transverse position of isolated showers was measured with a spatial resolution $\sigma x = \sigma y = (0.42/\sqrt{E} \oplus 0.06)$ cm. An iron/scintillator hadronic calorimeter and muon detector were located further downstream. A dedicated two-level trigger was used to collect three-track decays with a very high efficiency. A more detailed description of the NA48 detector can be found in [1].

2. First observation of $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ decay

The $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ decay proceeds through virtual photon exchange which undergoes internal conversion into electron-positron pair, i.e. $K^\pm \to \pi^\pm \pi^0 \gamma^* \to \pi^\pm \pi^0 e^+ e^-$. The γ^* is produced

by two different mechanisms: Inner Bremsstrahlung (IB), where the γ^* is emitted by one of the charged mesons in the initial or final state, and Direct Emission (DE) where γ^* is radiated off at the weak vertex of the intermediate state. As a consequence of these processes, the differential decay width consists of three terms: the dominant long-distance IB contribution (pure electric), the DE component (electric E and magnetic M) and the interference between them[2]. The interference term collects the different contributions, IB-E, IB-M and E-M. For this reason, the $\pi^{\pm}\pi^0 e^+ e^-$ decay offers interesting short and long distance parity-violating observables. In the $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ mode, the interference consists only of the IB-E term[3], because the remaining (E-M) interferences are P-violating, and cancel out upon angular integration. There are few theoretical publications related to the $K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-$ decay [2][4][5]. Recently, authors of [2] where able to predict, on the basis of the NA48/2 measurement of the magnetic and electric terms in $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ [6], the branching ratio of the single components. No experimental observation has so far been reported.

2.1 Selection and background estimations

$K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-$ event candidates are reconstructed from three charged tracks and two photons pointing to a common vertex in the fiducial decay volume. The particle identification is based on the energy deposition in LKr (E), associated or not to a charged track momentum (p) measured in the spectrometer. The charged track is identified as an electron/positron if its E/p ratio is greater than 0.85, and as a charged pion if the E/p ratio is lower than 0.85. Two isolated energy clusters without associated tracks in the LKr are identified as the two candidate photons from the π^0 decay. Their invariant mass is required to be within ± 10 MeV/c^2 from the nominal PDG[7] π^0 mass. The reconstructed invariant mass of the $\pi^{\pm}\pi^0 e^+ e^-$ system is required to be within ± 10 MeV/c^2 from the nominal PDG[7] $K^{\pm}$ mass. Two main sources of background give contribution to the signal final state: $K^{\pm} \to \pi^{\pm}\pi^0\pi^0_D$ ($K_{3\pi D}$) when one of the photons is lost, and $K^{\pm} \to \pi^{\pm}\pi^0_D(\gamma)$ ($K_{2\pi D}$), where π^0_D denotes the π^0 Dalitz decay $\pi^0 \to e^+ e^-\gamma$. The suppression of the $K_{3\pi D}$ background events is obtained by requiring the squared invariant mass of the $\pi^+\pi^0$ system to be greater than 120 MeV^2/c^4, exploiting the presence of three particles with almost the same mass in the final state. In order to reject $K_{2\pi D}$ background contaminations, both the invariant masses $M_{ee\gamma_{1,2}}$ are required to be more than 7 MeV/c^2 away from the nominal mass of the neutral pion. Analyzing the 2003 data, a sample of 1916 signal candidates has been selected with a background contamination below 3%. In particular, MC simulations predict a contribution of (26 ± 5.1) candidates from $K_{2\pi D}$ and (30 ± 5.5) from $K_{3\pi D}$ events. The normalization mode ($K_{2\pi D}$) is recorded concurrently with the signal mode , using the same trigger logic. A common event reconstruction is used to cancel systematic effects such as particle identification and trigger inefficiencies. The selection of the normalization mode $K_{2\pi D}$ uses the same set of requirements as the signal selection except for the π^0 reconstruction and background suppression. The neutral pion is reconstructed by requiring only one γ-candidate cluster and computing its invariant mass with the electron and positron pair. The only background source for the normalization channel is the $K_{\mu 3D}$ mode ($K^{\pm} \to \mu^+\nu\pi^0_D$). In the whole 2003 data sample, 6.715 million $K_{2\pi D}$ candidates have been selected with a background contamination smaller than 0.1%.

2.2 Branching ratio measurement

The total Branching Ratio of $K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-$ is obtained by the expression:

$$\mathscr{B}(K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-) = \frac{N_S - N_B}{N_N}\frac{A_N \varepsilon_N}{A_S \varepsilon_S}\mathscr{B}(N) \tag{2.1}$$

where $N_{S,B,N}$ are the number of signal (1916), background (55.8±7.4) and $K_{2\pi D}$ events. $A_{S,N}$ $\varepsilon_{S,N}$ are the acceptances and trigger efficiencies of the signal and normalization modes. The branching ratio of the normalization mode $\mathscr{B}(N) = (2.425 \pm 0.076) \cdot 10^{-3}$ is obtained from the PDG[7] world average. The trigger efficiencies (ε), very similar ($\sim$98%) for signal and normalization mode, are measured on data using control samples. The signal acceptances, the normalization and the background channels are computed using GEANT3-based[8] MC simulations, which include the full detector and material description, stray magnetic fields, beam line geometry and local detector imperfections. The MC simulation for the different $K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-$ contributions IB, DE, and
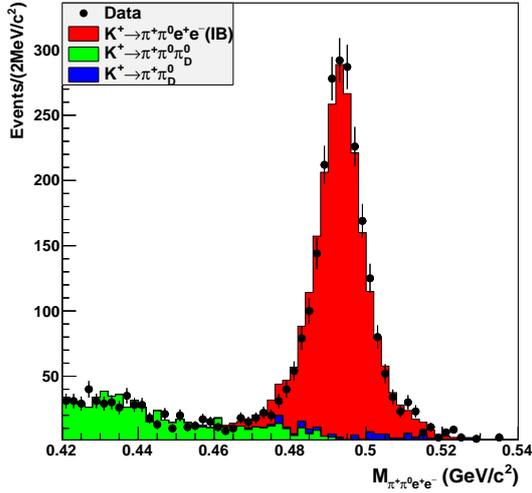

Figure 1: Reconstructed $\pi^{\pm}\pi^0 e^+ e^-$ invariant mass distributions of the data and simulated background samples.
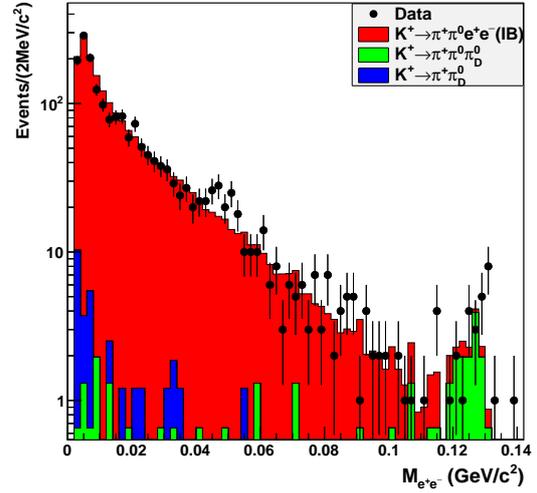

Figure 2: Reconstructed $e^+ e^-$ invariant mass distributions of the data and simulated background samples.

the electric interference have been generated separately according to the theoretical description given in [2], neglecting the magnetic interference in the present preliminary result. Due to limited statistics of the data sample, the extraction of the DE and the electric interference is not possible in this analysis. The signal acceptance has been obtained from a weighted average of the single component acceptances, using as weights the relative fractions computed in [2] on the basis of the measurement of magnetic and electric terms of $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ in [6]:

$$A_S = \frac{A_{IB} + A_{DE} \cdot Frac_{DE} + A_{INT} \cdot Frac_{INT}}{1 + Frac_{DE} + Frac_{INT}} \tag{2.2}$$

To take into account the E,M measurement uncertainties [6], the weights entering the total signal acceptance were varied accordingly, resulting in a $\sim$ 1% relative change quoted as the systematic

uncertainty due to the acceptance modeling. As radiative corrections to the $K^{\pm} \rightarrow \pi^{\pm}\pi^0 e^+ e^-$ mode are not computed in [2], the NA48/2 signal MC simulation included the following effects: the classical Coulomb attraction/repulsion between charged particles and the real photon(s) emission as implemented in the PHOTOS package. The preliminary result for the total branching ratio is:

$$\mathscr{B}(K^{\pm} \rightarrow \pi^{\pm}\pi^0 e^+ e^-) = (4.06 \pm 0.10_{stat.} \pm 0.06_{syst.} \pm 0.13_{ext.}) \cdot 10^{-6} \tag{2.3}$$

where systematic errors include uncertainties on acceptance, particle identification, trigger efficiencies and radiative corrections. The uncertainty on the BR of the normalisation mode branching ratio uncertainty is the dominant error in the present measurement obtained with an overall precision of about 3%. The comparison with theoretical expectations is presented in Figure 3. The small-dashed blue line represents the theoretical prediction with no isospin-breaking correction published in [2]. The big, dashed blue line shows the expected branching ratio corrected for isospin-breaking (private communication from the authors of [2]). The experimental value of the $\mathscr{B}(K^{\pm} \rightarrow \pi^{\pm}\pi^0 e^+ e^-)$ is in very good agreement with the theoretical predictions (within one standard deviation). The
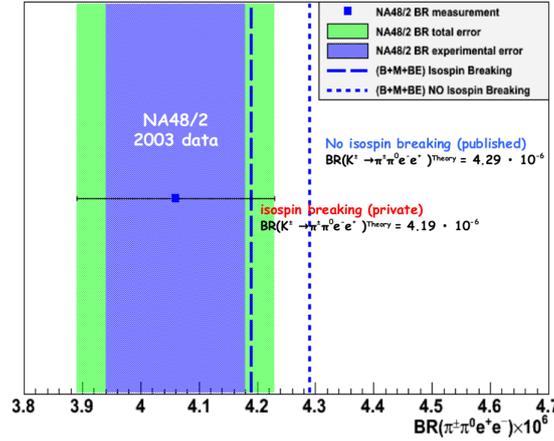

Figure 3: The $K^{\pm} \rightarrow \pi^{\pm}\pi^0 e^+ e^-$ preliminary branching ratio is plotted with its experimental error (shaded blue band) and its total error (shaded green band).

NA48/2 data sample analyzed has no sensitivity to the DE and INT contributions to the M_{ee} spectrum within the current statistics (see Figure 2). It will be difficult to perform a full Dalitz plot analysis without a proper description of the radiative effects, particularly relevant in a final state with two electron/positrons.

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