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Precision measurement of kaon radiative decays in NA48/2

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Kaon decays are an excellent laboratory to test low energy strong interaction perturbative theories. Recent results on radiative $K^{\pm}$ decays from CERN NA48/2 experiment are presented. From data collected during 2003 and 2004 about 600k $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay candidates have been selected leading to the measurement of the direct emission (DE) and interference (INT) terms, with the interference term being observed for the first time. In addition the CP violating asymmetry between K^{+} and K^{-} has been determined to be less than 1.5×10^{-3} at 90% c.l. in this channel. We also report on the preliminary measurement of the branching fraction of the rare decay $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ using more than 1000 events from 40% of the full NA48/2 data set. The decay rate of the process $K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma$, never observed before, was measured in a model independent way using 120 events. From the spectrum of the $e^{+}e^{-}\gamma$ invariant mass the decay parameter $\hat{c}$ has been extracted with unprecedented precision.

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1. Introduction

The analysis of strong interaction dynamics at low energy is one of the main issues studied using kaon decays.

Radiative kaon decays offer a unique opportunity to study Chiral Perturbation theory (ChPT): in radiative kaon decays the only physical states that appear are pseudoscalar mesons, photons and leptons and the characteristic momenta involved are small compared to the natural scale of chiral symmetry breaking. In particular decays with direct photon emission like $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$, and decays with vanishing $O(p^2)$ contribution to ChPT as in $K^{\pm} \to \pi^{\pm}\gamma\gamma$ and $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ where precise predictions are made in terms of a few coupling constants, are of theoretical interest. Since intrinsic CP violation in charge asymmetries are predicted, various possible test of CP non-invariance can be studied experimentally.

2. The NA48/2 experiment

The NA48/2 experiment took data in 2003 and 2004 at the CERN SPS. The beamline of the NA48/2 experiment was specifically designed to measure charge asymmetries in $K^{\pm} \to \pi^{\pm}\pi\pi$ decays [1]. Two simultaneous K^{+} and K^{-} beams are produced by 400 GeV/c protons on a beryllium target. Particles with a central momentum of (60 ± 3) GeV/c are selected in a charge-symmetric way by a system of dipoles forming an achromat with zero total deflection, focusing quadrupoles, muon sweepers and collimators. With 7×10^{11} protons per burst the positive (negative) beam flux at the entrance of the decay volume is $3.8 \times 10^{7} (2.5 \times 10^{7})$ particles per pulse, of which 5.7% are K^{+} and 4.9% are K^{-}.

A detailed description of the NA48 detector can be found in [2]. The charged decay products are measured by a magnetic spectrometer consisting of two sets of drift chambers before and after a dipole magnet providing a momentum resolution $\sigma_p/p = (1.02 \oplus 0.044p)\%$ (p in GeV/c). The spectrometer is followed by a hodoscope consisting of two planes of plastic scintillators segmented into horizontal and vertical strips and arranged in four quadrants. A quasi-homogeneous liquid Krypton calorimeter (LKr), 27 X_0 deep, is used to reconstruct γ and electron showers with an energy resolution $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ (E in GeV).

A 3-track trigger was used to collect kaon decays into three charged particles, while a 1-track trigger required a minimum invariant mass of the neutral decay particles to exclude the much more frequent $K^{\pm} \to \pi^{\pm}\pi^{0}$ and $K^{\pm} \to \mu^{\pm}\nu_{\mu}$ decays. In total, 18 billions of reconstructed decays were recorded allowing precision measurements of rare charged kaon decays: this is the world largest amount of charged kaon decays.

3. The $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay

The decay $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ is one of the most interesting channels to study the low energy structure of QCD. The total amplitude of this decay is the sum of two terms: inner bremsstrahlung (IB), with the photon being emitted from the outgoing charged pion, and direct emission (DE), where the photon is emitted from the weak vertex.

The IB component, suppressed by the $\Delta I = 1/2$ rule, can be predicted from QED corrections to BR($K^{\pm} \to \pi^{\pm}\pi^{0}$) in a straightforward way.

For the DE term, several studies within the framework of ChPT exist. At $O(p^4)$ ChPT, direct photon emission can occur through both electric (X_E) and magnetic (X_M) dipole transitions. The magnetic part is the sum of a reducible amplitude, that can be calculated using the Wess-Zumino-Witten (WZW) functional, and a direct amplitude, which size is expected to be small. For the electric dipole transition no definite prediction exists.

The electric dipole transition can interfere with the IB term giving rise to an interference term (INT) with possible CP violating contributions. An experimental measurement of both DE and INT terms allows the determination of both the electric and magnetic amplitudes and to investigate possible CP violation.

The properties of the $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay can be conveniently described using the T_{π}^{*} and W variables, where T_{π}^{*} is the kinetic energy of the charged pion in the kaon rest frame and W is a Lorentz invariant variable given by: $W^2 = (P_K \cdot P_\gamma)(P_\pi \cdot P_\gamma)/(m_K \cdot m_\pi)^2$. Here P_K, P_π, P_γ are the 4-momenta of the kaon, the charged pion and the radiative photon. Values of W can vary within the range $0 < W < 1$. Using these variables, the differential rate for the process can be written as [3,4]:

$$\frac{\partial^2\Gamma^{\pm}}{\partial T_{\pi}^{*}\partial W} = \frac{\partial^2\Gamma_{IB}^{\pm}}{\partial T_{\pi}^{*}\partial W}[1 + 2cos(\pm\phi + \delta_1^1 - \delta_0^2) \times m_\pi^2 m_K^2 (X_E) W^2 + m_\pi^4 m_K^4 (X_E^2 + X_M^2) W^4]$$

where $\partial^2\Gamma_{IB}^{\pm}/\partial T_{\pi}^{*}\partial W$ is the differential rate for the IB component, ϕ is the CP violating phase, δ_l^I are the strong pion-pion rescattering phases, and X_E, X_M are normalized electric and magnetic amplitudes respectively. The different W dependence allows the extraction of the different decay components.

Previous experiments have measured DE and INT terms in the restricted kinematic region $55 < T_{\pi}^{*} < 90$ MeV, obtaining a value for INT compatible with zero. The combined DE branching fraction, based on the world total sample of about 30,000 $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ events and with the assumption of no interference term, is BR(DE) = $(4.3 \pm 0.7) \times 10^{-6}$ [5]. The statistics used by NA48/2 is more than one order of magnitude larger than the sum of all previous experiments.

A strong suppression of $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ background events, based on the excellent performance of the LKr calorimeter, was implemented. This allowed to use a less stringent cut on the kinetic energy of the pion in the kaon rest frame T_{π}^{*}, below the standard 55 MeV used by most of the previous experiments, reflecting into a gain in sensitivity to both DE and INT contributions to the decay amplitude. The remaining background was estimated with Monte Carlo (MC) simulated events to be less than 1% of the DE contribution and the mistagging probability of the radiated photon, from Monte Carlo data, to be less than 10^{-3}. After applying all the cuts, about 600,000 $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ events were selected, see Fig. 1. The IB, DE and INT contributions have been extracted performing a fit to the data sample. Given the different W dependence (see Fig. 2) the IB, DE and INT components can be extracted using an extended Maximum-Likelihood (ML) fit of the Monte Carlo W distributions of the single components to the data distributions.

The fit to the data [6], shown in Fig. 3, yielded $Frac(DE/IB) = (3.32 \pm 0.15_{stat} \pm 0.14_{syst})\%$ and $Frac(INT/IB) = (-2.35 \pm 0.35_{stat} \pm 0.39_{syst})\%$ for $0 < T_{\pi}^{*} < 80$ MeV, with a high correlation coefficient of -0.93 between the two fraction values (see Fig. 4).

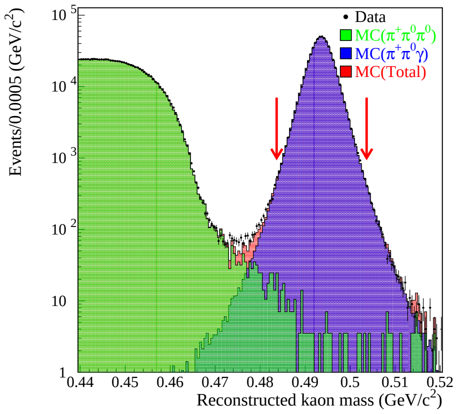

Figure 1: Reconstructed kaon mass distribution for $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ events with MC background expectations.

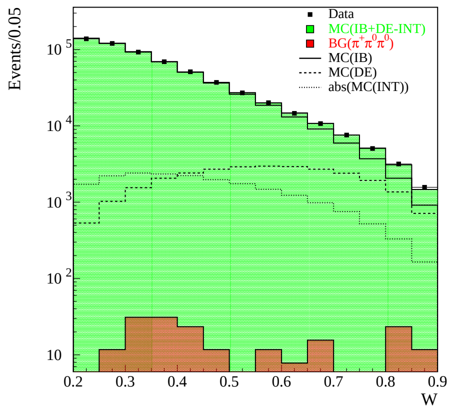

Figure 2: Maximum-Likelihood fit of the distribution of the Lorentz invariant variable W for $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ events.

The NA48/2 measurement constitutes the first observation of a non zero interference term in $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decays. From this, the electric and magnetic dipole amplitudes can be extracted: $X_E = (-24 \pm 4_{stat} \pm 4_{syst})$ GeV^{-4} and $X_M = (254 \pm 6_{stat} \pm 6_{syst})$ GeV^{-4} with the magnetic amplitude compatible with the pure chiral anomaly prediction of about 270 GeV^{-4}. In order to compare this result with those from previous experiments, the ML fit has been redone setting the INT term to zero, and the result for DE extrapolated to $55 < T^{*}_{\pi} < 90$ MeV. The bad value of the $\chi^2 = 51/13$ demonstrates that the INT term cannot be neglected.

Finally we investigated also possible direct CP violation in this channel. CP violation will manifest in a decay rate asymmetry of K^{+} and K^{-} and/or in different W distributions for K^{+} and K^{-}, due to a non vanishing phase in the differential decay rate. The asymmetry parameter in the total number of events is $A_N = (N_{+} - RN_{-})/(N_{+} + RN_{-})$ where N_{+}, N_{-} are the number of K^{+} and K^{-} decays in the data sample and R is the ratio of K^{+} and K^{-} in the beam, determined using the $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ sample. Applying a slightly modified event selection, two samples of 695k K^{+} and 386k K^{-} were reconstructed and used to set a limit on the CP violating asymmetry in the K^{+} and K^{-} branching ratios of less than 1.5×10^{-3} at 90% confidence level. Assuming the INT term to be at the origin of possible CP violation, another observable is the asymmetry in the distribution of the Dalitz variable W for K^{+} and K^{-}. The resulting limit is compatible with the result A_N of the overall charge asymmetry.

4. The rare $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay

The $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay is of high interest in ChPT, since tree-level contributions at $O(p^2)$ vanish, providing high sensitivity to $O(p^4)$ and $O(p^6)$ terms in chiral expansion. The leading contribution at $O(p^4)$ is responsible for a cusp in the invariant $\gamma\gamma$ mass at twice the $\pi^{\pm}$ mass (see Fig. 6) [7]. Pole and tadpole diagrams contribute to the amplitude [8]. At $O(p^6)$ unitarity

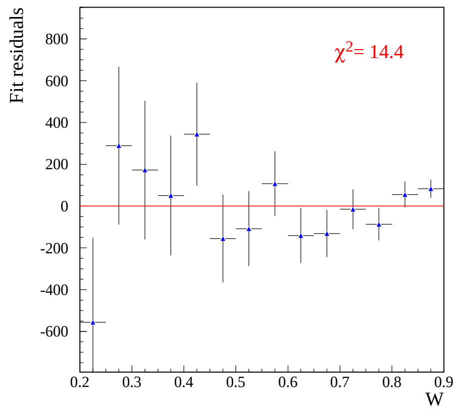

Figure 3: Fit residuals of data wrt the simulated decay components weighted according to the Maximum-likelihood fit results.

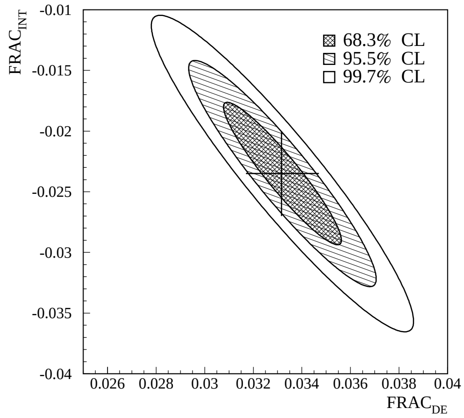

Figure 4: Contour plot for DE and INT terms. The cross shows the 1σ statistical uncertainties of the projections.

corrections [9] could alter the branching fraction by $30-40\%$, as shown in Fig. 5. The amplitude is known up to a parameter $\hat{c}$, which needs to be measured experimentally.

Both signal and normalization channel $K^{\pm} \to \pi^{\pm}\pi^{0}$ were collected through a trigger intended to collect $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays, therefore suffered from a very low trigger efficiency of about 40%. In total 1164 $K^{\pm} \to \pi^{\pm}\gamma\gamma$ candidates were selected from approximately 40% of the complete data set, corresponding to about 40 times the previous world sample. The background contribution, mainly from $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ events, was determined from Monte Carlo simulation to be 3.3%. The invariant $\pi^{\pm}\gamma\gamma$ and $\gamma\gamma$ mass distributions are shown in Fig. 7 and Fig. 8, the latter exhibiting the expected cusp at twice the $\pi^{\pm}$ mass: this is the first observation of the cusp behaviour at $m_{2\pi}$ for this channel.

The value of the parameter $\hat{c}$ fixes both the decay spectrum and the rate; the shape of the $m_{\gamma\gamma}$ distribution is well described by ChPT for certain parameter values. Obtaining the detector acceptance from a simulation using $O(p^6)$ ChPT [9] with $\hat{c} = 2$ [10], a preliminary model-dependent branching fraction was obtained: $BR(K^{\pm} \to \pi^{\pm}\gamma\gamma)_{\hat{c}=2,O(p^6)} = (1.07 \pm 0.04_{stat} \pm 0.08_{syst}) \times 10^{-6}$, where the systematic uncertainty is dominated by the trigger efficiency. The result is compatible with the previous measurement obtained by E787 [10]. A model independent BR measurement and the extraction of the parameter $\hat{c}$ from a fit to the $\gamma\gamma$ mass spectrum are in preparation.

5. First observation of the $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ decay

The decay $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ is similar to the one of $K^{\pm} \to \pi^{\pm}\gamma\gamma$ with one photon internally converting into a pair of electrons. The lowest order terms are of $O(p^4)$, where predominantly loop diagrams contribute to the amplitude [7]. In ChPT the loop contribution is fixed up to a free parameter $\hat{c}$, which is a function of several strong and weak coupling constants and expected to be of $O(1)$ [9]. The predicted branching ratios for $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ lie in the range between $0.9-1.7 \times 10^{-8}$, for values of $|\hat{c}| < 2$ [11].

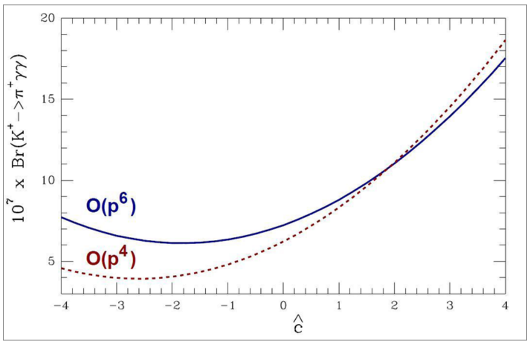

Figure 5: BR($K^{\pm} \to \pi^{\pm}\gamma\gamma$) as a function of the $\hat{c}$ amplitude. $O(p^6)$ unitarity corrections could increase the expected BR.

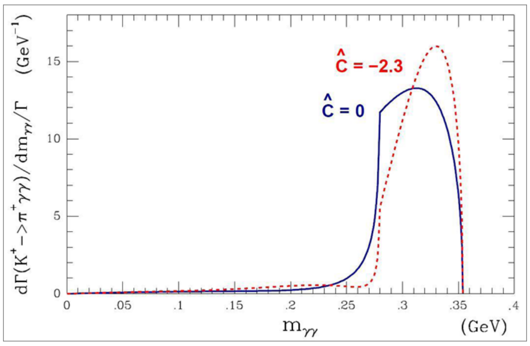

Figure 6: $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay: $m_{\gamma\gamma}$ spectra for two different values of $\hat{c}$.

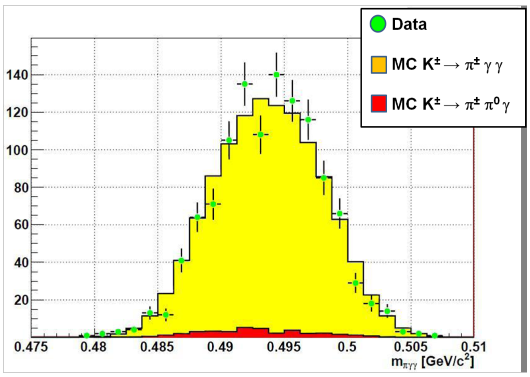

Figure 7: $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay: reconstructed kaon mass for data and MC expectations for signal and background.

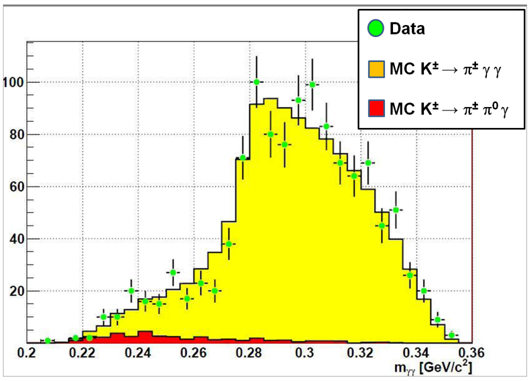

Figure 8: $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay: $m_{\gamma\gamma}$ distribution for data and MC expectations: the expected cusp at twice the π mass is visible.

Using the full NA48/2 data set, 120 signal candidates with 7.3 ± 1.7 estimated background events have been selected in the accessible region with invariant mass $m_{ee\gamma} > 260$ MeV/c^2 (see Fig. 9). This is the first observation of this rare decay.

The background contribution below the signal peak is mainly due to $K^{\pm} \to \pi^{\pm}\pi^0_D\gamma$ decay. The abundant decay $K^{\pm} \to \pi^{\pm}\pi^0_D$ with $\pi^0_D \to e^+e^-\gamma$ was used as normalization. The branching fraction was computed in bins of $m_{ee\gamma}$, thus being independent of any assumption on the $m_{ee\gamma}$ distribution. Integrating over the single bins in the accessible region $m_{ee\gamma} > 260$ MeV/c^2 gave: $BR(K^{\pm} \to \pi^{\pm}e^+e^-\gamma) = (1.19 \pm 0.12_{stat} \pm 0.04_{syst}) \times 10^{-8}$.

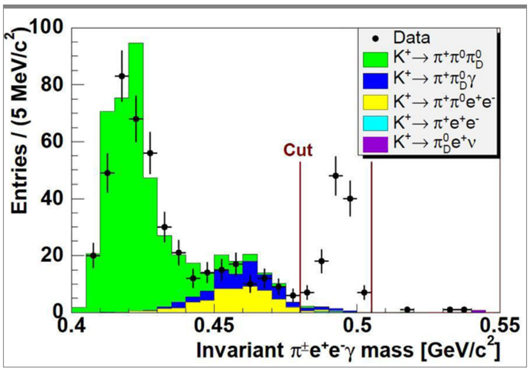

Figure 9: $K^\pm \to \pi^\pm e^+e^-\gamma$ decay: invariant $\pi^\pm e^+e^-\gamma$ mass for selected signal candidates and background expectations. Vertical lines indicate the accepted region for the BR measurement.

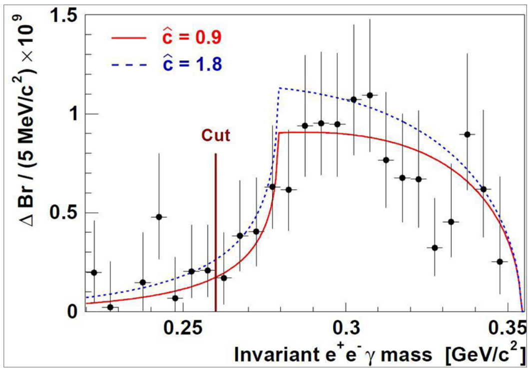

Figure 10: Branching fractions as a function of the $e^+e^-\gamma$ mass. The curves are the predicted spectra for our best fit value of $\hat{c}$ (red) and the previously found value from BNL (blue).

A single-parameter fit to the $m_{ee\gamma}$ distribution above 260 MeV/c^2 (see Fig. 10) gave a value $\hat{c} = 0.90 \pm 0.45$, assuming $O(p^4)$ distribution as in Ref. [11]. More details on the analysis can be found in Ref. [12]. The measurement is compatible with the result obtained by E787 using $K^\pm \to \pi^\pm\gamma\gamma$ [10]. Using our measured value for $\hat{c}$ and Ref. [11] we computed the differential branching fraction for $m_{ee\gamma} < 260$ MeV/c^2 and added it to our measured result. We then obtained for the total branching fraction $BR(K^\pm \to \pi^\pm e^+e^-\gamma) = (1.29 \pm 0.13_{exp} \pm 0.03_{\hat{c}}) \times 10^{-8}$ where the last uncertainty reflects the model uncertainty for $m_{ee\gamma}$ below 260 MeV/c^2.

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