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Precision measurement of kaon radiative decays at NA48

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Abstract

The 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. In the channel $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ more than a million reconstructed decays have lead to the precision measurement of both the direct photon emission and inner bremsstrahlung amplitudes, with their interference term being observed for the first time. In addition the CP violating asymmetry between K^{+} and K^{-} has been obtained to be less than 10^{-3} in this channel. We also report on the measurement of the branching fraction of the rare decay $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ using more than 1000 events from 20% of the full NA48/2 data set. From the spectrum of $\gamma\gamma$ mass the decay parameter $\hat{c}$ has been extracted with unprecedented precision. We measured in a model independent way the decay rate of the process $K^{\pm}\rightarrow\pi^{\pm}e^{+}e^{-}\gamma$, never observed before, using 120 events.

Keywords: Kaon; Radiative Decays; CP violation

1. Introduction

The analysis of strong interaction dynamics at low energy is one of the main issues studied using kaon decays and in particular radiative kaon decays offer a unique opportunity to study Chiral Perturbation theory (ChPT) in detail.

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 $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$, and decays with vanishing $O(p^{2})$ contribution to ChPT as in $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ and $K^{\pm}\rightarrow\pi^{\pm}e^{+}e^{-}\gamma$ 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 are studied experimentally.

2. NA48 experiment

The NA48 experiment [1] at CERN SPS has a long history in studying direct CP violation in the neutral and charged kaon. The NA48 detector con-

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sists of a magnetic spectrometer made of two sets of drift chambers before and after a dipole magnet providing a momentum resolution of about 1.4% for 20 GeV/c charged tracks, and a liquid krypton (LKr) electro-magnetic calorimeter with an energy resolution of about 1% for 20 GeV photons and electrons. The experiment uses collinear K^+ and K^- beams of mean momentum 60 GeV/c, recorded simultaneously to cancel systematic effects in CP violation measurements.

Aiming at charge asymmetry measurements, during 2003 and 2004, the NA48/2 experiment collected the world largest amount of charged kaon decays.

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.

3. The $K^\pm \to \pi^\pm\pi^0\gamma$ decays

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 the $K^\pm \to \pi^\pm\pi^0\gamma$ 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 straight forward way.

For the DE term, several studies within the framework of ChPT exist. At O(p4) ChPT, direct photon emission can occur through both electric (XE) and magnetic (XM) 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 instead 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. Therefore by measuring the INT term it is possible to disentangle the electric and magnetic amplitudes and to investigate possible CP violation in $K^\pm \to \pi^\pm\pi^0\gamma$.

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 release the cut on the kinetic energy of the pion, in the kaon rest frame (T^*_p), below the standard 55 MeV used by most of the previous experiments [2], reflecting into a gain in sensitivity to both DE and INT contributions to the decay amplitude. The remaining background was estimated with Monte Carlo 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}. For comparison, in previous measurements [2] the background percentage was at the level of 1% or more and the percentage of wrong solutions for the odd photon were always larger than 10%.

After applying all the cuts, about 600,000 $K^\pm \to \pi^\pm\pi^0\gamma$ events are selected, see Fig. 1.

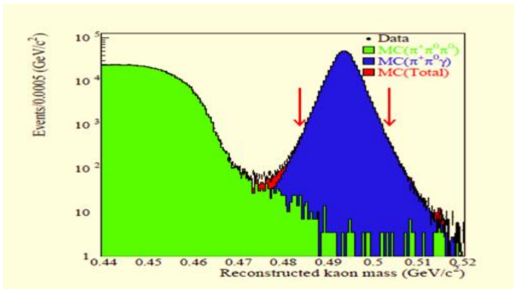

Fig. 1. Reconstructed kaon mass with MC background expectations for $K^\pm \to \pi^\pm\pi^0\gamma$.

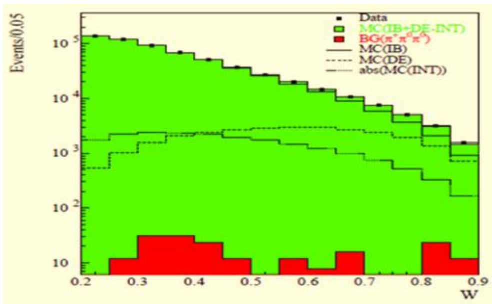

Fig. 2. Maximum-likelihood fit of the distribution of the Lorentz invariant variable W for $K^\pm \to \pi^\pm\pi^0\gamma$ events.

Since the different contributions have different W dependences, IB, DE and INT distributions can be extracted using an extended Maximum-Likelihood (ML) fit of the Monte Carlo W distributions of the single components to the data distribution (see Fig. 2). The relative contribution of every source is calculated in such a way that the difference between the number of events and the total number of simulated events in each bin is minimized.

The fit to the data is shown in Fig. 3a and yielded Frac(DE/IB)=$(3.32\pm0.15_{stat}\pm0.14_{syst})$% and Frac(INT /IB) = $(-2.35\pm0.35_{stat}\pm0.39_{syst})$% for $0<T^{\star}_{p}<80$ MeV, with a high correlation coefficient of −0.93 between the two fraction values (see Fig. 3b) [3].

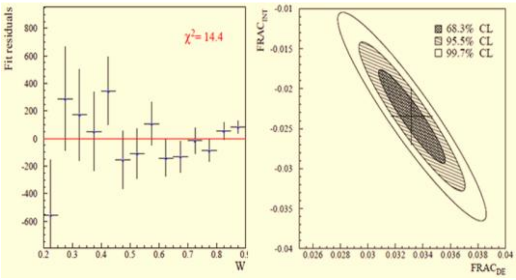

Fig. 3. (a): ML fit residuals, χ^2=14.4/13 d.o.f.;
(b): Contour plot for the DE and INT terms. The cross shows the 1σ statistical uncertainties on the projections.

From this, the electric and magnetic amplitudes can be extracted [3]: XE=$(-24\pm4_{stat}\ \pm4_{syst})$ GeV^{-4}; XM=$(254\pm6_{stat}\ \pm6_{syst})$ GeV^{-4} with the magnetic amplitude compatible with the pure chiral anomaly prediction of about 270 GeV^{-4}.

Previous experiments have measured DE and INT terms in the restricted kinematic region $55<T^{\star}_{p}<90$ MeV, obtaining a value for INT compatible with zero. The combined DE branching fraction, based on the world total of about 30,000 $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$ events, is Br(DE) = $(4.3\pm0.7)\times10^{-6}$ [2], with the assumption of no interference term. The statistics used by NA48/2 is more than one order of magnitude larger than the sum of all previous experiments.

NA48 measurement constitutes the first observation of an interference term in $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$ decays. To compare this result with previous experiments the ML fit has been repeated setting the INT term to zero. The bad value of the χ^2, equal to 51/13 d.o.f., demonstrates that the INT term cannot be neglected.

Finally for these decays we investigated also possible direct CP violation. 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.

Using the ratio R of K^{+} to K^{-} in the beam, determined using the $K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$ sample, and the number of K^{+} and K^{-} decays we define a simple asymmetry parameter in the total number of events.

Applying a slightly modified $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$ event selection, two samples of 695k K^{+} and 386k K^{-} were re-constructed 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.

Assuming instead 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 in good agreement with the one obtained with the previous method.

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

The NA48/2 measurement of the $K^{\pm}\to\pi^{\pm}\gamma\gamma$ branching ratio is a sensitive test of the O(p4) and O(p6) terms in chiral expansion since O(p2) terms vanish.

The leading contribution at O(p^4) is responsible for a cusp in the invariant $\gamma\gamma$ mass at twice the π^{+} mass (see Fig.4b) [4]..

The amplitude is known up to a parameter ĉ, which needs to be measured from experiment.

At O(p6), unitarity corrections [5] could alter the branching fraction by 30−40%, as shown in Fig.4a.

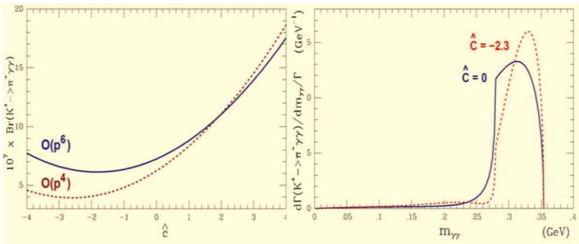

Fig. 4. (a): The leading contribution at O(p^4) is responsible for a cusp at $m_{\gamma\gamma} = m_{2\pi}$ (b): O(p6) unitarity corrections could halter the branching fraction by 30−40%.

Due to the similarity in topology to $K^{\pm}\to\pi^{\pm}\pi^{0}$ events which were trigger suppressed, the signal trigger efficiency was only about 40%. In total 1164 $K^{\pm}\to\pi^{\pm}\gamma\gamma$ candidates were selected out of about 20% of the complete data set, corresponding to about 40 times the previous world sample. The invariant $\pi^{\pm}\gamma\gamma$

and $\gamma\gamma$ mass distributions are shown in Fig. 5a and Fig. 5b, the latter exhibiting the expected cusp at twice the $\pi^{\pm}$ mass.

The value of the parameter ĉ fixes both the decay spectrum and the rate. The shape of the $m_{\gamma\gamma}$ distribution is well described by ChPT for certain parameters values and is the first observation of the cusp behaviour at $m_{2\pi}$ for such channel.

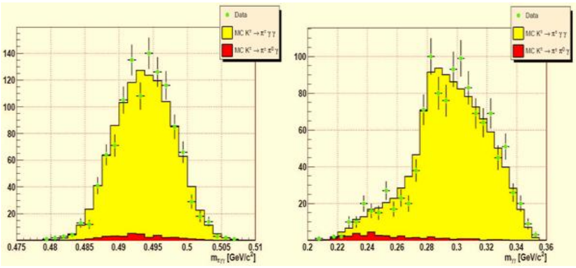

Fig. 5. (a): The reconstructed kaon mass for data and MC; (b): Data MC comparison for the $\gamma\gamma$ mass distribution, showing the expected cusp at twice the π mass.

Both decay spectrum and rate strongly depend on the single ĉ parameter. The shape of the $m_{\gamma\gamma}$ distribution is well described by ChPT for certain parameters values and this is the first observation of the cusp behaviour at $m_{2\pi}$ for such channel.

Obtaining the detector acceptance from a simulation using O(p6) ChPT [5] with ĉ = 2 [6], a preliminary, model-dependent branching fraction was obtained:
$Br(K^{\pm}\to\pi^{\pm}\gamma\,\gamma)_{\hat{c}=2,O(p6)} = (1.07 \pm 0.04_{stat} \pm 0.08_{syst})\times 10^{-6}$.

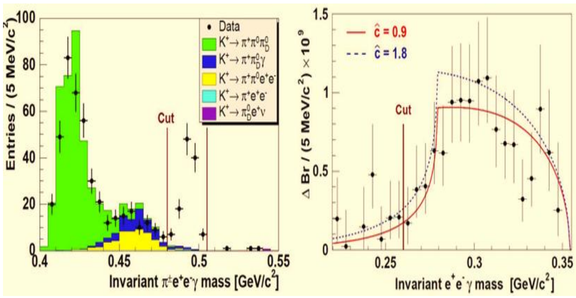

Fig. 6. (a) Invariant $\pi^{+}e^{+}e^{-}\gamma$ mass and MC background expectations; (b): Fit to the $e^{+}e^{-}\gamma$ mass.

The result is compatible with the previous measurement obtained by E787 [6]. The systematic uncertainty is dominated by the trigger efficiency. A model independent BR measurement and the extraction of the parameter ĉ from a fit to the $\gamma\gamma$ mass spectrum are in preparation.

5. $K^{\pm}\to\pi^{\pm} e^{+}e^{-}\gamma$

The physics of 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. For this reason, in ChPT, the loop contribution is fixed up to the same free parameter ĉ [7]. Using the full NA48/2 data set, 120 signal candidates with only 7.3 ± 1.7 background contamination were found in the region with the invariant $e^{+}e^{-}\gamma$ mass greater than 0.26 GeV/c^2 (see Fig. 6). 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 gave:
$Br(K^{\pm}\to\pi^{\pm}e^{+}e^{-}\gamma) = (1.19 \pm 0.12_{stat} \pm 0.04_{syst})\times 10^{-8}$ for $m_{ee\gamma}$>260 MeV/c^2.

A single-parameter fit to the $m_{ee\gamma}$ distribution above 260 MeV/c^2 gave a value ĉ = 0.90±0.45, assuming O(p4) distribution in [7]. The measurement is compatible with the result obtained by E787 using $K^{\pm}\to\pi^{\pm}\gamma\gamma$. Using the value obtained for ĉ, we extract $Br(K^{\pm}\to\pi^{\pm}e^{+}e^{-}\gamma) = (1.29 \pm 0.13_{exp} \pm 0.03_{\hat{c}\ syst})\times 10^{-8}$ where the last uncertainty reflects the model uncertainty for $m_{ee\gamma}$ below 260 MeV/c^2. More details on the analysis can be found in ref. [8].

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