Precision measurements of kaon radiative decays at NA48/2

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Abstract. We report the most recent results of the NA48/2 experiment in charged kaon radiative decays. Using data collected during 2003 and 2004, precise measurements of the properties of $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$, $K^{\pm} \to \pi^{\pm}\gamma\gamma$, and $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$ decay modes have been obtained.

Keywords: Kaon, Radiative Decays, CP violation
PACS: 14.40.Df

INTRODUCTION

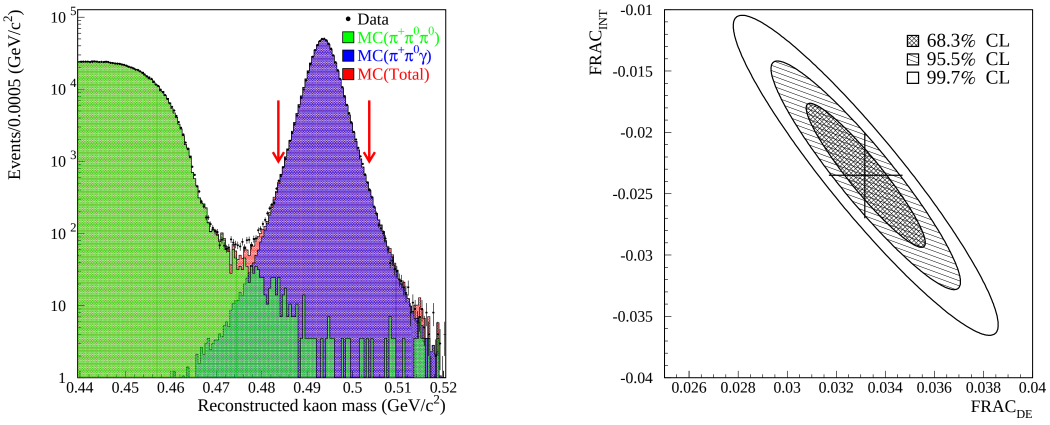
The NA48/2 experiment at CERN SPS has collected the world largest amount of charged kaon decays. During two data taking periods in 2003 and 2004, with about 60 days of effective running each, about $18{\cdot}10^{9}$ events were recorded in total. The main goal of NA48/2 was to search for direct CP violation in $K^{\pm}$ decays into three pions. However, given the high statistics achieved, many other physics topics were also covered in rare and radiative Kaon decays.

NA48/2 BEAM LINE AND DETECTOR

NA48/2 simultaneous K^{+} and K^{-} beams were produced by 400 GeV protons from the CERN SPS, impinging on a Be target. Kaons were deflected in a two stage front-end achromat to select a momentum band of 60 ± 3 GeV/c and then focused such that they converge at the beginning of the magnetic spectrometer. The most important detector components are the magnetic spectrometer, consisting of four drift chambers and a dipole magnet, and the quasi-homogeneous liquid Krypton calorimeter (LKr). The momentum of the charged particles and the energy of the photons are measured with a relative uncertainty of $\sim$1% at 20 GeV. A detailed description of the beam line and detector can be found in [1].

THE $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ DECAY

The decay channel $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ is one of the most interesting channels for studying the low energy structure of QCD, The total amplitude of the decay is the sum of two terms: the inner bremsstrahlung (IB) namely a $K^{\pm} \to \pi^{\pm}\pi^{0}$ decay with a photon emitted from the outgoing charged pion, and the direct emission (DE) in which the photon is emitted at the weak vertex. Using the Low theorem the branching ratio of the IB component can



(a) **(b)**

FIGURE 1. (a) Reconstructed kaon mass with MC background expectations for $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$. (b) Contour plot for DE and INT terms. The cross shows the 1σ statistical uncertainties on the projections.

be predicted using QED corrections. The IB component of the decay is suppressed by the ΔI = 1/2 rule, resulting in a relative enhancement of the DE contribution. Direct photon emission can occur through both electric and magnetic dipole transitions. The electric dipole transition can interfere with the IB amplitude giving rise to an interference term (INT), which can have CP violating contributions. The properties of the $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay can be conveniently described using the T^{*}_{π} , 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 $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ process can be written as [2][3]:

$$\frac{\partial^2\Gamma^{\pm}}{\partial T^{*}_{\pi}\partial W} = \frac{\partial^2\Gamma^{\pm}_{IB}}{\partial T^{*}_{\pi}\partial W}\left[1+2cos(\pm\phi+\delta^1_1-\delta^2_0)m^2_\pi m^2_K X_E W^2 + m^4_\pi m^4_K (X^2_E + X^2_M)W^4\right] \tag{1}$$

where ϕ is the CP violating phase, δ^I_l are the strong pion-pion rescattering phases, and X_E, X_M are normalized electric and magnetic amplitudes respectively. The different W dependence, the DE term is proportional to W^4 while the INT term to W^2, allows the extraction of the different decay components.

Previous experiments have measured DE and INT terms in the kinematical region of $55< T^{*}_{\pi} <90$ MeV, obtaining a value for the INT contribution compatible with zero. The values quoted in the Particle Data Group (PDG) tables have been obtained from fits where the INT term has been set to zero. Their current average is: $BR(DE) = (4.3 \pm 0.7)\cdot 10^{-6}$ [4].

From a sample about 600k $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay candidates the NA48/2 experiment has measured the relative amounts of DE and INT with respect to the internal bremsstrahlung (IB) contribution in this decay in the range 0< T^*_π <80 MeV. The relative background contamination has been kept to $< 10^{-4}$, see Fig. 1(a), and the rate of wrong solutions for the odd photon to $< 0.1\%$. Thanks to the implementation of an algorithm rejecting background from $K^\pm \to \pi^\pm\pi^0\pi^0$ decays, the cut on T^*_π could be released below the standard 55 MeV used by most of the previous experiments, gaining in sensitivity to both DE and INT contributions to the $K^\pm \to \pi^\pm\pi^0\gamma$ decay amplitude. In order to compare the NA48/2 results with those from previous experiments, the maximum likelihood fit of the selected sample has been first done setting INT term to zero. The bad value of the χ^2 computed on the residuals, 51/13 dof, demonstrate that the INT term cannot be neglected with such a high statistics data. Detail on the selection and fitting technique can be found in [5].

Using an extended maximum likelihood technique, comparing data and simulated W distribution including non vanishing INT term, the following fractions of DE and INT with respect to IB have been obtained [5]:

$$Frac_{DE}(0 < T^*_\pi < 80\,MeV) = BR_{DE}/BR_{IB} = (3.32 \pm 0.15_{stat} \pm 0.14_{sys}) \cdot 10^{-2} \quad (2)$$

$$Frac_{INT}(0 < T^*_\pi < 80\,MeV) = BR_{INT}/BR_{IB} = (-2.35 \pm 0.35_{stat} \pm 0.39_{sys}) \cdot 10^{-2} \quad (3)$$

This measurement constitutes the first observation of an interference term in $K^\pm \to \pi^\pm\pi^0\gamma$ decays. The contour plot in the DE INT plane, Fig. 1(b), shows the high correlation, $\rho = -0.93$, between the extracted fractions. The χ^2 computed on the residuals is 14.4/13 dof. From the above results using Eqn.1 the electric and magnetic contributions, can be calculated to be:
$X_E = (-24 \pm 4_{stat} \pm 4_{sys})\ GeV^{-4}$ and $X_M = (254 \pm 6_{stat} \pm 6_{sys})\ GeV^{-4}$
The magnetic part is compatible with pure chiral anomaly prediction $\sim 270\ GeV^{-4}$.

CP violation in $K^\pm \to \pi^\pm\pi^0\gamma$

Using a slightly modified event selection, two samples of 695kK^+ and 386k K^- have been reconstructed and used to set a limit on the CP violating asymmetry in the K^+ and K^- branching ratios. The simplest observable that can be measured is the difference in the decay rates of K^+ and K^- which can be expressed as the asymmetry on the total number of events A_N defined as:

$$A_N = \frac{N^+ - RN^-}{N^+ + RN^-} \quad (4)$$

where N^+, N^- are the number of K^+, K^- decays to $\pi^\pm\pi^0\gamma$ in the data sample, and R is the ratio of the number of K^+ to K^- in the beam. For the measurement of R the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay has been used as normalization. Using the full data sample a limit to A_N of less than $1.5 \cdot 10^{-3}$ at 90% confidence level has been set [5]. Another CP violation observable is the asymmetry in the distribution of the Dalitz plot variable W (A_W). A fit to the distribution using the same data sample gives: $A_W = (-0.6 \pm 1.0_{stat}) \cdot 10^{-3}$.The result is compatible with A_N value. We can conclude that no CP violation is present at the level of 10^{-3} in $K^\pm \to \pi^\pm\pi^0\gamma$ as expected by standard model predictions.

THE $K^{\pm} \to \pi^{\pm}\gamma\gamma$ DECAY

The contributions of the chiral lagrangian to this decay appear only at O(p^4) where only the $\Delta I = 1/2$ invariant amplitudes A(z) and C(z) with $z = M^2_{\gamma\gamma}/M^2_{\pi^{\pm}}$ are relevant [6].

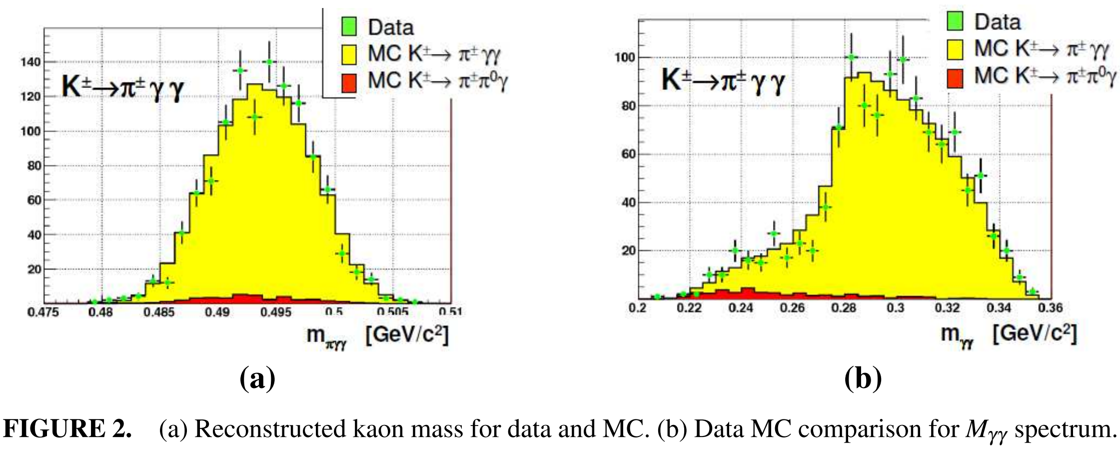
$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{M_K}{(8\pi)^3}\left[z^2\left(|A+B|^2+|C|^2\right)+\left(y^2-\frac{1}{4}\lambda(1,z,r_\pi^2)\right)^2\left(|B|^2+|D|^2\right)\right] \quad (5)$$

A(z,$\hat{c}$) contains the O(p^4) leading contribution of loop diagrams and the tree level counter terms absorbed in the unknown O(1) parameter called $\hat{c}$. The value of parameter $\hat{c}$ fixes the branching ratio and the $M_{\gamma\gamma}$ spectrum shape. The C terms, which accounts for $\sim$10% of the total amplitude, comes from the reducible anomaly contribution and can be calculated using the Wess Zumino Witten functional. O(p^6) studies [7] suggested that unitarity correction effects could increase the BR between 30%-40%, while vector meson exchange contributions would be negligible.

NA48/2 has analyzed about 20% of its 2003+2004 data sample, finding 1164 signal candidates (wrt 31 of previous E787 measurement [8]) with 3.3% background, mainly from $K^{\pm} \to \pi^{\pm}\pi^0\gamma$, Fig. 2 (a). Both signal and normalization channels $K^{\pm} \to \pi^{\pm}\pi^0$ 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 ($\sim$ 50%). The reconstructed spectrum of two photons invariant mass in the accessible kinematic region $M_{\gamma\gamma} > 0.2 GeV/c^2$ is presented in Fig. 2 (b), along with a MC expectation. The MC assumes ChPT O(p^6) distribution [7] with a realistic value of the parameter $\hat{c} = 2$ following experimental indication in [8]. The model dependent branching ratio of $K^{\pm} \to \pi^{\pm}\gamma\gamma$ has been measured using the same assumptions leading to the preliminary result:

$$BR(K^{\pm} \to \pi^{\pm}\gamma\gamma) = (1.07 \pm 0.04_{sta} \pm 0.08_{sys}) \cdot 10^{-6} \quad (6)$$

The result is compatible with the previous measurement obtained by E787 [8]. A model independent BR measurement is in preparation, together with the extraction of $\hat{c}$ from a fit to $M_{\gamma\gamma}$ spectrum.



(a) **(b)**

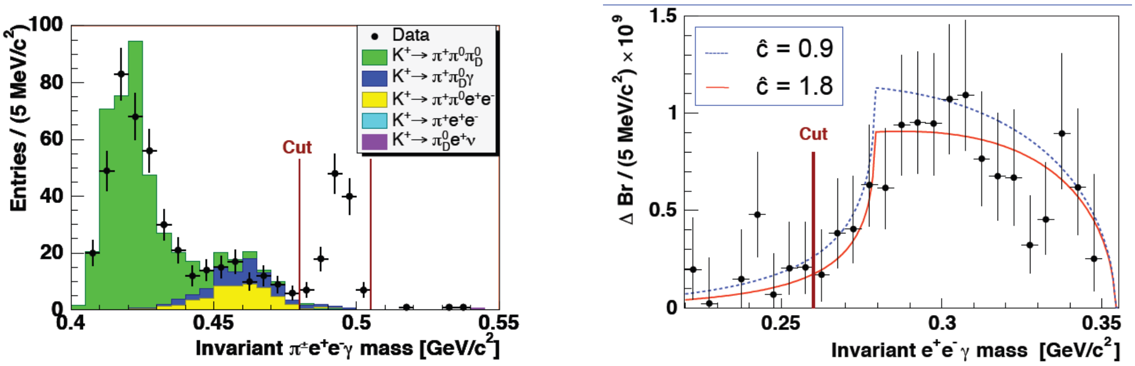
FIGURE 2. (a) Reconstructed kaon mass for data and MC. (b) Data MC comparison for $M_{\gamma\gamma}$ spectrum.

THE $K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$ DECAY

The physics of the decay $K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$ is similar to the one $K^{\pm} \to \pi^{\pm} \gamma\gamma$, with one of the photons internally converting into a pair of electrons. For this reason, in ChPT, the loop contribution is fixed up to the same free parameter $\hat{c}$ [9]. Using the full NA48/2 data sample 120 $K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$ decay candidates (with a total background of 6.1% estimated by MC) are found in the accessible kinematic region, $M_{ee\gamma} > 0.26\ GeV/c^2$, Fig. 3 (b). The rate is measured relatively to the $K^{\pm} \to \pi^{\pm} \pi^0_D$ channel, which has identical particle composition in the final state. This is the first observation of this decay mode. The reconstructed spectrum of $e^{+} e^{-} \gamma$ invariant mass is presented in Fig. 3, along with MC expectations for background contributions. The model-independent partial width in the accessible kinematic region ($M_{ee\gamma} >\ 0.26\ GeV/c^2$) is measured to be:

$$BR(M_{ee\gamma} > 0.26) = (1.19 \pm 0.12_{sta} \pm 0.04_{sys}) \cdot 10^{-8} \tag{7}$$

The ChPT parameter $\hat{c}$ was measured to be $\hat{c} = 0.90 \pm 0.45$ by fitting the $M_{ee\gamma}$ spectrum, Fig. 3 (b), assuming O(p^4) distribution in [9]. The result is compatible with the measurement obtained by E787 using $K^{\pm} \to \pi^{\pm} \gamma\gamma$ [8]. Details on the data analysis can be found in [10].



(a) **(b)**

FIGURE 3. (a) Data invariant $ee\gamma$ mass with MC background expectations. (b) Fit to the $M_{ee\gamma}$ spectrum.

REFERENCES

1. V. Fanti *et al.* [NA48 Collaboration], Nucl. Instrum. Meth. A **574**, 433 (2007).
2. N. Christ, Phys. Rev. **159**, 1292 (1967).
3. R. J. Abrams *et al.*, Phys. Rev. Lett. **29**, 1118 (1972).
4. C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).
5. J. R. Batley *et al.* [NA48/2 Collaboration], Eur. Phys. J. C **68**, 75 (2010)
6. G. Ecker, A. Pich and E. de Rafael, Nucl. Phys. B **303**, 665 (1988).
7. G. D'Ambrosio and J. Portoles, Phys. Lett. B **386**, 403 (1996)
8. P. Kitching *et al.* [E787 Collaboration], Phys. Rev. Lett. **79**, 4079 (1997)
9. F. Gabbiani, Phys. Rev. D **59**, 094022 (1999)
10. J. R. Batley *et al.* [NA48/2 Collaboration], Phys. Lett. B **659**, 493 (2008)