Chiral Perturbation Theory from Charged Kaon Decays at NA48/2

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Chiral Perturbation Theory, as a low-energy effective field theory of strong interactions, is a very useful tool to study the interactions of kaons. The NA48/2 experiment, whose primary goal was the measurement of direct CP violation in the decays of charged kaons, has however collected enough statistics to check the ChPT predictions for several decay modes of charged kaons.

1. Introduction

During 2003 and 2004, NA48/2 has collected at the CERN SPS the world largest amount of charged kaon decays, with the main goal to search for direct CP violation in the decay of $K^{\pm}$ into three pions. However the collected statistics allowed the collaboration to study many other physics topics. In the following, results about measurements of ChPT parameters will be presented.

2. Chiral Perturbation Theory

Chiral Perturbation Theory [1] is the effective quantum field theory for hadronic interactions below the breaking scale of the chiral symmetry ($\approx$ 1 GeV). At these energies, the spectrum of the theory is simple and it consists only of the octet of light pseudoscalar mesons π, K and η. ChPT is now a mature technique able to provide high precision predictions for the mesonic sector, for instance in K decays.

3. The NA48/2 experiment

Simultaneous K^{+} and K^{-} beams were produced by 400 GeV/c protons from the CERN SPS. Kaons were deflected in a front-end achromat to select a momentum band of 60 ± 3 GeV/c and then focused such that they converge about 200 m downstream at the beginning of the detector. A description of the detector can be found in [2]. The most important subdetectors used in these analyses are the magnetic spectrometer (four chambers and a dipole magnet) and the quasi-homogeneous liquid krypton calorimeter, which both allow the measurement of the momentum of charged particles and of the energy of the photons with a relative uncertainity of 1% at 20 GeV. The very good performances of the liquid krypton calorimeter have been very useful in reducing the background levels in all the analyses described here.

4. Experimental results

4.1. $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$

In the $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay, two different processes are responsible for the origin of the photon: either it is Inner Bremsstralhung (IB), produced by a final state radiation of the $\pi^{\pm}$ or it is Direct Emission (DE) in the decay itself. The IB component has been measured already in the seventies [3], achieving a good agreement with QED predictions. The DE component, consisting of magnetic and electric transition, it is very difficult to observe, due to the dominant IB contribution. The magnetic part can be evaluated using the Wess-Zumino-Witten functional, but the electric part has not been predicted in a definite way. The electric contribution is interesting as it interferes with the IB amplitude and therefore can be distinguished from the magnetic part.

DE, IB and the interference term INT can be distinguished kinematically using the variable W defined as [4]:

$$W^2 = \frac{(P_K^* \cdot P_\gamma^*)(P_\pi^* \cdot P_\gamma^*)}{(m_K m_\pi)^2}$$

Integrating the decay rate over T_π^*, the pion energy in the kaon rest frame, one can obtain an expression which separates the various components with different powers of W:

$$\frac{d\Gamma^\pm}{dW} \approx (\frac{d\Gamma^\pm}{dW})_{IB}[1 + 2(\frac{m_\pi}{m_K})^2 W^2 |E| cos((\delta_1 - \delta_0) \pm \phi) + (\frac{m_\pi}{m_K})^4 W^4 (|E|^2 + |M|^2)]$$

Previous measurements used a cut on T_π^* in the range 55-90 MeV to keep at a low level the backgrounds due to the K$^\pm$ decays with a π^0. The region with $T_\pi^* < 55$ MeV is indeed rich of DE and INT events. Thanks to the excellent energy and space resolution of the LKr calorimeter, the NA48/2 analysis has selected events in the region $0 < T_\pi^* < 80 MeV$, the upper limit being chosen because of trigger reasons. In Fig. 1 the kaon mass spectrum for the data is compared with the MC simulation for the signal and the background. A total of 220 Kevents is shown in the plot. The extraction of the fractions of DE and INT is done with a likelihood function which takes into account the different W distributions of the 3 components. The fit used 124K events in the range $0.2 < W < 0.9$ and the results for the DE and INT fractions wrt IB are:

$$Frac(DE) = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\%$$
$$Frac(INT) = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\%$$

This is the first measurement of a non-zero interference term in the K$^\pm \to \pi^\pm \pi^0 \gamma$ decay. Fig.2 shows the high correlation of the two contributions.

4.2. K$^\pm \to \pi^\pm \gamma\gamma$

The decay K$^\pm \to \pi^\pm\gamma\gamma$ has no tree O(p^2) contribution; the leading contribution is at order O(p^4) with an undetermined constant ĉ of order 1 [5](Fig. 3). O(p^6) corrections to the branching ratio are expected to be around 30-40 %. Different models give a branching ratio of about $7 \cdot 10^{-7}$. The E787 experiment at BNL observed this decay for the first time [6], with 5.1 ± 3.3 events in the range 100 MeV/c $< P_\pi <$ 180 MeV/c and a branching ratio of $(6.0 \pm 1.5_{st} \pm 0.7_{sy}) \cdot 10^{-7}$. NA48/2 has analyzed about 40% of its data, finding 1164 events with 3.3% background. This

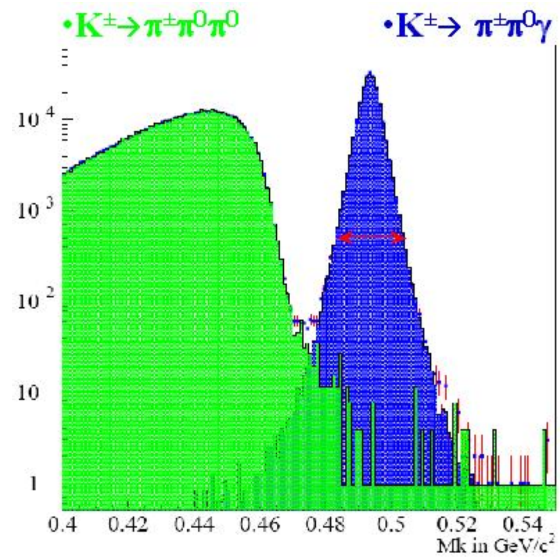

Figure 1. K$^\pm \to \pi^\pm \pi^0 \gamma$: *$M_K$ spectrum Data-MC comparison*

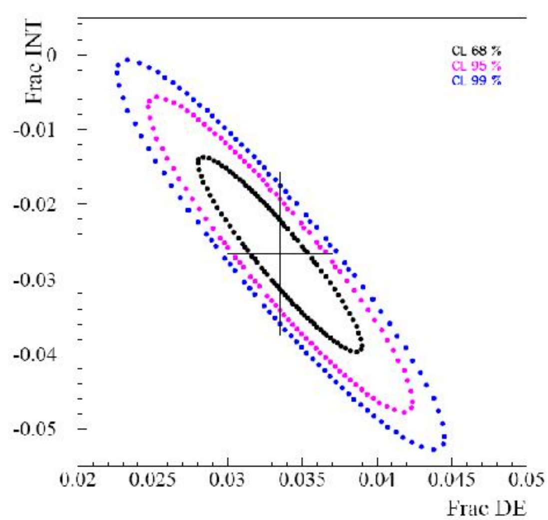

Figure 2. K$^\pm \to \pi^\pm \pi^0 \gamma$: *contour plot for DE and INT components*

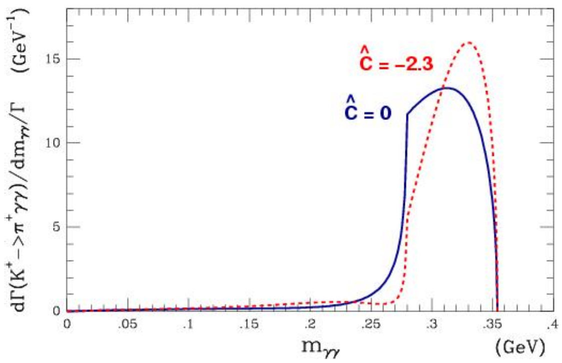

Figure 3. K$^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$: *theoretical predictions of the $m_{\gamma\gamma}$ distribution for two different values of $\hat{c}$*

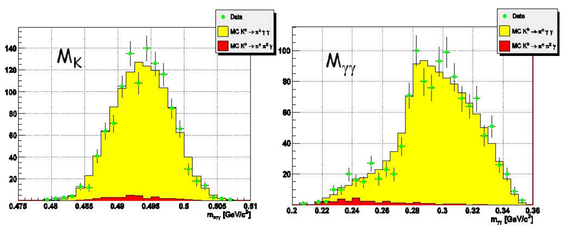

Figure 4. K$^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$: *theoretical predictions of the $m_{\gamma\gamma}$ distribution for two different values of $\hat{c}$*

is 40 time more statistics than previous experiments. These data and the normalization channel (K$^{\pm} \rightarrow \pi^{\pm}\pi^{0}$) are collected with the same trigger (mainly energy deposition in the calorimeter) which however suffered from a low efficiency ($\approx$ 50%), corrected with an elaborate analysis. Fig. 4 shows the distribution of the M$_{\gamma\gamma}$ invariant mass for the candidates.

The model dependent branching ratio has been measured, assuming the O(p^6) prediction from [7] and using ĉ=2 (based on the result from [6]). The preliminary result is BR(K$^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$) = $(1.07 \pm 0.04_{stat} \pm 0.08_{syst}) \cdot 10^{-6}$. The analysis is progressing toward the goals of the measurement of the model independent BR measurement and of the extraction of ĉ from a fit to M$_{\gamma\gamma}$ and to the BR.

4.3. K$^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma$

This decay is similar to K$^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ with one photon internally converting in one pair of electrons. A first guess for the BR is $\approx \alpha \cdot BR$(K$^{\pm} \rightarrow$

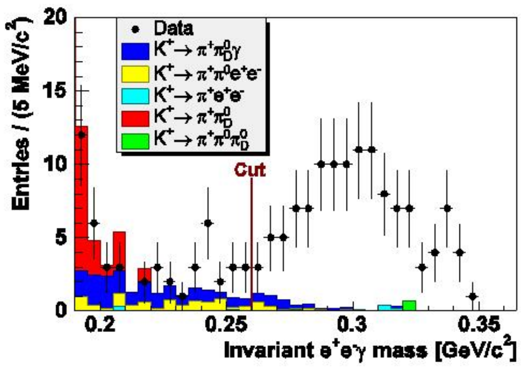

Figure 5. K$^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma$: *invariant mass of the candidates. Crosses are signal and histograms the backgrounds*

$\pi^{\pm}\gamma\gamma$). Theoretical computation ([8]) gives a value of $(0.9 - 1.6) \cdot 10^{-8}$. NA48/2, using the full 2003 and 2004 sample, has reported [9] the first observation of this decay with 120 candidates and 7.3 ± 1.7 estimated background events. The events have been selected in the region with $M_{\gamma ee} > 0.26\ GeV/c^2$ invariant mass (Fig. 5). Using K$^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D}$ as normalization channel, the model independent branching ratio has been determined as $BR = (1.19 \pm 0.12_{stat} \pm 0.04_{syst}) \cdot 10^{-8}$ for $M_{\gamma ee} > 0.26\ GeV/c^2$. Assuming the O(p^6) prediction [8], the ĉ parameter has been found to be ĉ = 0.90 ± 0.45.

4.4. K$^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}$

This decay, described by ChPT [10], is supposed to proceed through one photon exchange resulting, for the $z = (M_{ee}/M_K)^2$ kinematic variable, in a spectrum sensitive to a form factor $W(z)$. The NA48/2 analysis has considered the following parametrizations factors in the amplitude

- Linear: $W(z) = G_F M_K^2 f_0(1 + \delta z)$
- Next-to-leading order ChPT [11]: $W(z) = G_F M_K^2(a_+ + b_+ z) + W^{\pi\pi}(z)$ with the free parameters (a_+, b_+) and an explicitly computed pion loop term $W^{\pi\pi}(z)$
- The Dubna version of the ChPT parametrization involving meson form factors: $W(z) = W(M_a, M_\rho, z)$[12].

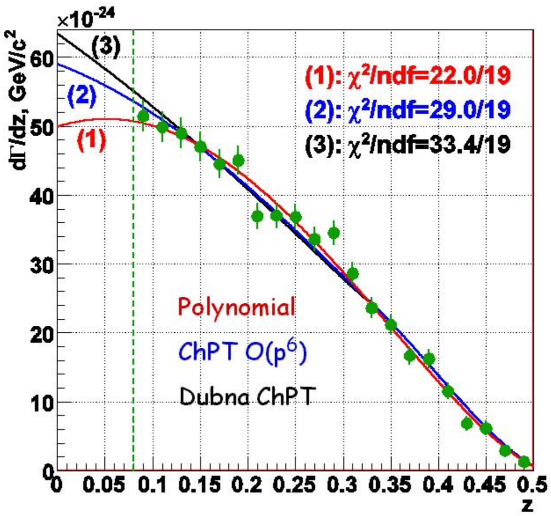

Figure 6. K$^{\pm} \to \pi^{\pm} e^{+} e^{-}$: *differential decay rate and different fit results from the models considered.*

The goal of the analysis is the extraction of the form factor parameters for the models listed above and the computation of the corresponding branching ratios BR_1, BR_2, BR_3.

With the cut $z > 0.08$, 7103 signal events has been selected with a background of 56 events. The normalization channel is K$^{\pm} \to \pi^{\pm}\pi^{0}{}_{D}$. Fig. 6 shows the results of the fits to the z distribution for the three models considered. Table 1 summarizes the results of the fits and the computations of the model-dependent and model-independent branching ratios.

A previous result from E865 at BNL [13] ($\approx$ 10000 events with 1.2% background) have been used to fit a_+, b_- finding $a_+ = -0.587 \pm 0.010, b_+ = -0.655 \pm 0.044$ and a branching ratio of $(2.94 \pm 0.05_{st} \pm 0.13_{sy} \pm 0.05_{model}) \cdot 10^{-7}$.

δ	$2.35 \pm 0.15_{stat} \pm 0.09_{syst} \pm 0.00_{ext}$
f_0	$0.532 \pm 0.012_{stat} \pm 0.008_{syst} \pm 0.007_{ext}$
BR_1	$3.02 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext}$
a_+	$-0.579 \pm 0.012_{stat} \pm 0.008_{syst} \pm 0.007_{ext}$
b_+	$-0.798 \pm 0.053_{stat} \pm 0.037_{syst} \pm 0.017_{ext}$
BR_2	$3.02 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext}$
M_a	$0.965 \pm 0.028_{stat} \pm 0.018_{syst} \pm 0.002_{ext}$
M_ρ	$0.711 \pm 0.010_{stat} \pm 0.007_{syst} \pm 0.002_{ext}$
BR_3	$3.15 \pm 0.04_{stat} \pm 0.04_{syst} \pm 0.08_{ext}$
BR_{mi}	$2.26 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.06_{ext}$

Table 1
Results of the fits to the three models and the model independent BR. The branching ratios are in units of 10^{-7}

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