CP Violation results from the NA48 experiments

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Abstract.
The main goal of the NA48 experiments at the CERN SPS has been the search for direct CP violation (CPV) in neutral and charged kaon decays. In this paper selected results on CPV from the NA48 and NA48/2 experiments are presented. The direct CPV parameter $Re(\varepsilon'/\varepsilon)$ has been measured by NA48 from the decay rates of neutral kaons into two pions. In the charged kaon sector, NA48/2 has measured the asymmetry A_g of the linear slope parameter g in the Dalitz plot of $K^{\pm} \to 3\pi$ decays. Thanks to the high statistics collected in 2003 and 2004, further CPV studies were performed in several kaon decays. Results on CPV studies in $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$, $K^{\pm} \to \pi^{\pm}e^{+}e^{-}$ and $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ decays will be presented, as well as in the $K_S \to \pi^{+}\pi^{-}e^{+}e^{-}$ decay.

1. Introduction

The investigation of CP violation is of fundamental importance in particle physics as it addresses basic questions related to the observed matter-antimatter asymmetry in the Universe. CP violation was discovered in $K^0 \to \pi\pi$ decays in 1964 [1]. Still, kaons remain a privileged observatory for the study of the phenomenon. All three types of CP violation are observed in neutral kaons. The small asymmetry between the $K^0 \to \overline{K^0}$ and $\overline{K^0} \to K^0$ transition rates accounts for the indirect CP violation, measured with the parameter $Re(\varepsilon)$. Direct CP violation, represented by the parameter $Re(\varepsilon')$, occurs in the K^0 decays into two pions and is related to the phase difference of the two amplitudes with different $\pi\pi$ isospin values (I=0, I=2). The violation of CP symmetry takes also place in the interference between decays with and without mixing. In the Standard Model, CP violation is naturally accommodated by an irreducible complex phase in the CKM matrix, in the case of three quark families. Only direct CP violation occurs in charged kaons since mixing is not allowed.

The NA48 Collaboration has carried out over the last decade an extensive experimental programme at CERN dedicated to the study of CP violation (and rare processes) in both neutral and charged kaon decays. NA48, and its successors, was a fixed target experiment at SPS CERN. The main components were a magnetic spectrometer to measure charged particle momenta and an electromagnetic calorimeter based on liquid krypton for the measurement of electromagnetic showers. More detailed information about the detector components and performance can be found in [2].

[1] on behalf of the NA48 and NA48/2 Collaborations

2. Highlights from the past

2.1. Measurement of $Re(\varepsilon'/\varepsilon)$

$Re(\varepsilon'/\varepsilon)$ is determined from the double ratio of the two pion decay rates of K_L and K_S:

$$R = \frac{\Gamma(K_L \to \pi^0\pi^0) \cdot \Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0) \cdot \Gamma(K_L \to \pi^+\pi^-)} \approx 1 - 6Re(\varepsilon'/\varepsilon)$$

The NA48 experiment was designed to exploit cancellations of systematic effects contributing symmetrically to different components of the double ratio. The four decay modes were collected simultaneously in the same decay region, minimising sensitivity to intensity variations, detection efficiency and accidental effects. K_L and K_S acceptances become similar and approximately cancel in the ratio, despite of the large lifetime difference, by weighting K_L decays with a function of the proper time. Small differences between K_L and K_S beam intensity variations are eliminated by weighting K_S events by the K_L/K_S intensity ratio. High resolution detectors were used to achieve an efficient background rejection. A detailed description of the analysis method and event selection can be found in [3]. Data were collected in 1997, 1998-1999 and 2001. Taking into account the correlation of the systematic uncertainty between results from different periods of data taking, the combined final result is $Re(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \cdot 10^{-4}$ showing a clean evidence of direct CP violation in the neutral kaon system.

2.2. Measurement of charged asymmetry

Complementary with ε'/ε, the CP observable in the charged kaon sector is the asymmetry

$$A_g = (g^+ - g^-)/(g^+ + g^-) \approx \Delta g/2g$$

of the linear slope parameter g (g^+ refers to K^+, g^- to K^-). Since there is no mixing in the decays of charged kaons, any non-zero value of A_g would reflect evidence for direct CPV. SM predictions for the charge asymmetry lay in the range $10^{-6} - 10^{-5}$, while theoretical calculations involving processes beyond the SM do not exclude substantial enhancements of A_g. The goal of NA48/2 was to measure A_g with an accuracy of few 10^{-4}. From the data samples collected in 2003 and 2004, 3.11×10^9 $K^\pm \to \pi^\pm\pi^+\pi^-$ and 9.13×10^7 $K^\pm \to \pi^\pm\pi^0\pi^0$ were selected. The results for the asymmetries [4] are

$$A_g^c = (-1.5 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.1_{syst}) \times 10^{-4} = (-1.5 \pm 2.1) \times 10^{-4}$$

$$A_g^n = (1.8 \pm 1.7_{stat} \pm 0.9_{syst}) \times 10^{-4} = (1.8 \pm 1.8) \times 10^{-4}.$$

The results are compatible with the SM predictions, i.e. no evidence for direct CP violation at the order of 10^{-4} has been found. Due to the high precision achieved, the result can be used to constrain extensions of the SM predicting enhancements of the CP violating effects.

3. Recent results

3.1. 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 for studying the low energy structure of QCD. The total amplitude of the decay is the sum of two terms: the inner bremsstrahlung (IB), with a photon emitted from the outgoing charged pion, and the direct emission (DE) in which the photon is emitted at the weak vertex. The IB component of the decay is suppressed by the $\Delta I = 1/2$ 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^* 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 defined as: $W^2 = (P_K \cdot P_\gamma)(P_\pi \cdot P_\gamma)/(m_K \cdot m_\gamma)^2$ where P_K, P_π and P_γ are the 4-momenta of the kaon, the charged pion and the radiative photon respectively. Using these variables, the differential rate for the process $K^\pm \to \pi^\pm\pi^0\gamma$ can be written as [5],[6]:

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

where ϕ is the CP violating phase, δ_l^I are the strong pion-pion rescattering phases, and X_E and X_M are the 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. 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 the range $0 < T_\pi^* < 80$ MeV. The relative background contamination has been kept to $< 10^{-4}$ and the rate of wrong solutions for the odd photon to $< 0.1\%$. Thanks to the implementation of an algorithm to reject 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. 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 [7]:

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

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

This measurement constitutes the first observation of an interference term in $K^\pm \to \pi^\pm\pi^0\gamma$ decays. From the above results, the electric and magnetic contributions can be extracted: $X_E = (-24 \pm 4_{stat} \pm 4_{syst})\ GeV^{-4}$ and $X_M = (254 \pm 6_{stat} \pm 6_{syst})\ GeV^{-4}$. This result is compatible with the hypothesis that the chiral anomaly, that predicts $X_M \sim 270\ GeV^{-4}$ [8], is the only source of magnetic amplitudes in the Direct Emission term, and indicates that factorization models cannot provide an appropriate description of DE and INT in the $K^\pm \to \pi^\pm\pi^0\gamma$ decay.

3.1.1. CP Violation in $K^\pm \to \pi^\pm\pi^0\gamma$ decays. The $K^\pm \to \pi^\pm\pi^0\gamma$ decay with direct photon emission is not suppressed by the $\Delta I = 1/2$ rule, therefore it is a good decay to search for CP Violation. Using a slightly modified event selection, two samples of 695k K^+ 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:

$$A_N = \frac{N^+ - RN^-}{N^+ + RN^-}$$

where N^+ and N^- are the number of K^+ and 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. Using the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay as normalization, a measurement of $R = 1.7998\ \ 0.0004$ has been performed with a high accuracy of $\delta R/R \sim 10^{-4}$. Using the full data sample, the measured asymmetry is

$$A_N = (0.0 \pm 1.0_{stat} \pm 0.6_{syst}) \cdot 10^{-3}$$

From the above value a limit for the rate asymmetry of $|A_N| < 1.5 \cdot 10^{-3}$ at 90% confidence level has been set [7]. 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 $A_W = (-0.6 \pm 1_{stat}) \cdot 10^{-3}$. The result is compatible with the A_N value. We can conclude that no CP violation is present at the level of 10^{-3} in $K^\pm \to \pi^\pm\pi^0\gamma$ decay, as expected by the Standard Model predictions.

3.2. The $K^\pm \to \pi^\pm e^+e^-$ decay

The flavour-changing neutral current decays $K^\pm \to \pi^\pm l^+l^-$ ($l = e, \mu$), induced at the one-loop level in the Standard Model (SM), are well suited to explore its structure and, possibly, its extensions. The rates of these transitions are dominated by the long-distance contributions involving one photon exchange. They have been described in the framework of Chiral Perturbation Theory (ChPT) [9] in terms of a vector interaction form factor determined by experimental measurements.

The dynamics of the $K^\pm \to \pi^\pm e^+e^-$ decay, highly suppressed by the GIM mechanism, is completely specified by the invariant function $W(z)$, where $z = (M_{ee}/M_K)^2$ is a kinematic variable. Several models have been developed predicting the form factors that characterize the decay rate and the dilepton invariant mass distribution. In the present analysis the following parameterizations of the form factors are considered:

- Linear: $W(z) = G_F M_K^2 f_0(1 + \delta z)$, with free normalization and slope (f_0 and δ).
- Next-to-Leading Order ChPT [10]: $W(z) = G_F M_K^2(a_+ + b_+ z) + W^{\pi\pi}(z)$ with free parameters (a_+, b_+) and an explicitly calculated pion loop term $W^{\pi\pi}(z)$.
- Combined framework of ChPT and large-N_c QCD [11]: the form factor is parameterized as $W(z) \equiv W(\tilde{w}, \beta, z)$, with free parameters $(\tilde{w}, \beta)$.
- A ChPT parameterization [12] involving meson form factors $W(z) = W(M_a, M_\rho, z)$, with meson masses (M_a, M_ρ) treated as free parameters.

The aim of the analysis is to extract the form factor parameters in the framework of each of the above models and to measure the corresponding BR's in the full kinematic range and, in addition, a model-independent BR in the visible kinematic range ($z > 0.08$).

The $K^\pm \to \pi^\pm e^+e^-$ rate is measured relatively to $K^\pm \to \pi^\pm\pi^0_D$ (with $\pi^0_D \to e^+e^-\gamma$). Since the two decays have the same charged particles in the final state, common selection criteria have been used, resulting in cancelation of particle ID inefficiencies at first order. At the end of the selection, based on the reconstruction of three-track events, a total of 7146 $K^\pm \to \pi^\pm e^+e^-$ candidates with 0.6% background are found in the signal region. The reconstructed $(\pi^\pm e^+e^-)$ invariant mass spectrum is shown in Fig. 1.

The computed values of $d\Gamma_{\pi ee}/dz$ as a function of z are shown in Fig. 2 with the results of the fits to the four considered models; the measured parameters and the corresponding BR's are reported in Table 1.

Fits to all the four models are of reasonable quality, however the linear form-factor model leads to the best χ^2 (see Fig. 2). The size of the data sample is insufficient to distinguish between the models. The BR in the full kinematic range, which includes an uncertainty due to extrapolation into the inaccessible region $z < 0.08$, is

$$BR = (3.11 \pm 0.04_{stat} \pm 0.05_{syst} \pm 0.08_{ext} \pm 0.07_{mod}) \times 10^{-7}$$

$$BR(K^\pm \to \pi^\pm e^+e^-) = (3.11 \pm 0.12) \times 10^{-7}$$

This result is in fair agreement with previous measurements. In particular, comparison to the most precise BNL E865 result [13], using the same external input, and taking into account correlation of external uncertainties between the two analyses, shows a 1.6 σ level of agreement.

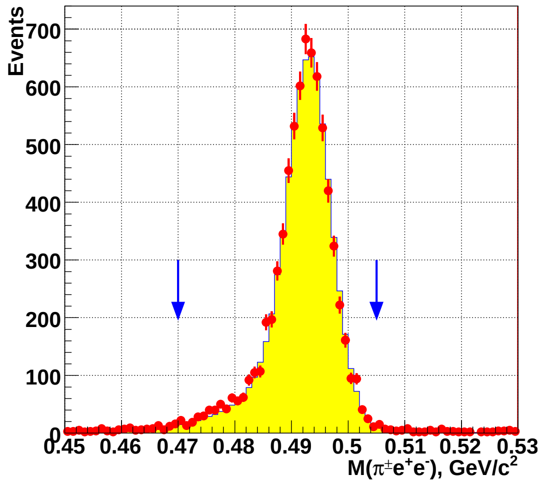

Figure 1. Reconstructed spectrum of $(\pi^{\pm}e^{+}e^{-})$ invariant mass: data (dots) and MC simulation (filled area).

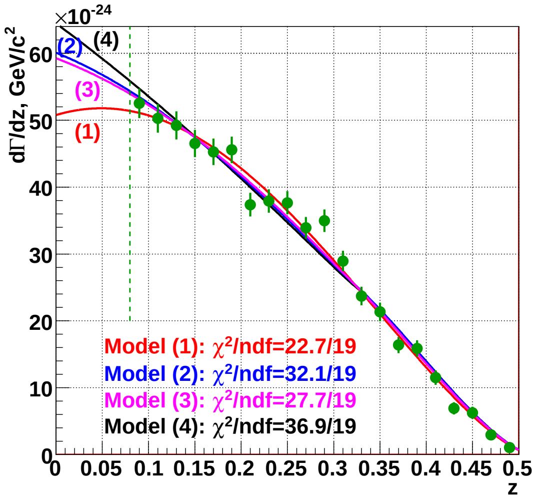

Figure 2. The computed $d\Gamma_{\pi ee}/dz$ and the results of the fits according to the four considered models.

Table 1. Results of fits to the four models and the Model-Independent BR($z > 0.08$).

Model(1)												
$\lvert f_0\rvert =$	0.531	$\pm$	$0.012_{\rm stat.}$	$\pm$	$0.008_{\rm syst.}$	$\pm$	$0.007_{\rm ext.}$	$=$	0.531	$\pm$	0.016
$\delta =$	2.32	$\pm$	$0.15_{\rm stat.}$	$\pm$	$0.09_{\rm syst.}$	$\pm$	$0.00_{\rm ext.}$	$=$	2.32	$\pm$	0.18
$\mathrm{BR}_1 \times 10^7 =$	3.05	$\pm$	$0.04_{\rm stat.}$	$\pm$	$0.05_{\rm syst.}$	$\pm$	$0.08_{\rm ext.}$	$=$	3.05	$\pm$	0.10
Model(2)												
$a_+ =$	-0.578	$\pm$	$0.012_{\rm stat.}$	$\pm$	$0.008_{\rm syst.}$	$\pm$	$0.007_{\rm ext.}$	$=$	-0.578	$\pm$	0.016
$b_+ =$	-0.779	$\pm$	$0.053_{\rm stat.}$	$\pm$	$0.036_{\rm syst.}$	$\pm$	$0.017_{\rm ext.}$	$=$	-0.779	$\pm$	0.066
$\mathrm{BR}_2 \times 10^7 =$	3.14	$\pm$	$0.04_{\rm stat.}$	$\pm$	$0.05_{\rm syst.}$	$\pm$	$0.08_{\rm ext.}$	$=$	3.14	$\pm$	0.10
Model(3)												
$\tilde{w} =$	0.057	$\pm$	$0.005_{\rm stat.}$	$\pm$	$0.004_{\rm syst.}$	$\pm$	$0.001_{\rm ext.}$	$=$	0.057	$\pm$	0.007
$\beta =$	3.45	$\pm$	$0.24_{\rm stat.}$	$\pm$	$0.17_{\rm syst.}$	$\pm$	$0.05_{\rm ext.}$	$=$	3.45	$\pm$	0.30
$\mathrm{BR}_2 \times 10^7 =$	3.13	$\pm$	$0.04_{\rm stat.}$	$\pm$	$0.05_{\rm syst.}$	$\pm$	$0.08_{\rm ext.}$	$=$	3.13	$\pm$	0.10
Model(4)												
$M_a/\mathrm{GeV} =$	0.974	$\pm$	$0.030_{\rm stat.}$	$\pm$	$0.019_{\rm syst.}$	$\pm$	$0.002_{\rm ext.}$	$=$	0.974	$\pm$	0.035
$M_\rho/\mathrm{GeV} =$	0.716	$\pm$	$0.011_{\rm stat.}$	$\pm$	$0.007_{\rm syst.}$	$\pm$	$0.002_{\rm ext.}$	$=$	0.716	$\pm$	0.014
$\mathrm{BR}_3 \times 10^7 =$	3.18	$\pm$	$0.04_{\rm stat.}$	$\pm$	$0.05_{\rm syst.}$	$\pm$	$0.08_{\rm ext.}$	$=$	3.18	$\pm$	0.10
$\mathrm{BR}_{\rm MI} \times 10^7 =$	2.28	$\pm$	$0.03_{\rm stat.}$	$\pm$	$0.04_{\rm syst.}$	$\pm$	$0.06_{\rm ext.}$	$=$	2.28	$\pm$	0.08

Measurements of the decay parameters and BR's were performed separately for K^+ and K^- decays. In particular, the branching fractions in the full kinematic range and their statistical uncertainties were measured to be $BR^+ = (2.99 \pm 0.05_{stat}) \times 10^{-7}$, $BR^- = (3.13 \pm 0.08_{stat}) \times 10^{-7}$. This allows to perform a first measurement of the direct CP violating asymmetry of K^+ and K^- decay rates in the full kinematic range. Considering only the uncorrelated systematic uncertainties (those due to background subtraction) between K^+ and K^- samples, we found

$$\Delta(K^{\pm}_{\pi ee}) = \frac{BR^+ - BR^-}{BR^+ + BR^-} = (-2.2 \pm 1.5_{stat} \pm 0.6_{syst}) \times 10^{-2}$$

The other systematic uncertainties are correlated between the K^+ and K^- samples, and thus cancel in $\Delta(K^\pm_{\pi ee})$. A conservative limit for the charge asymmetry of $|\Delta(K^\pm_{\pi ee})| < 2.1 \times 10^{-2}$ at 90% CL can be deduced from the above value. This result is compatible with CP conservation, however the achieved precision is far from the Standard Model expectation $\Delta(K^\pm_{\pi ee}) \sim 10^{-5}$ [10] and even the SUSY upper limt $\Delta(K^\pm_{\pi ee}) \sim 10^{-3}$ [14],[15] for the CP violating asymmetry. The complete description of the study of the $K^\pm \to \pi^\pm e^+ e^-$ decay can be found in [16].

3.3. The $K^\pm \to \pi^\pm \mu^+ \mu^-$ decay

The $K^\pm \to \pi^\pm \mu^+ \mu^-$ rate is measured relative to the abundant $K^\pm \to \pi^\pm \pi^+ \pi^-$ normalization channel. The two samples are collected concurrently using the same trigger logic. The fact that the μ and π masses are close ($m_\mu / m_\pi = 0.76$) results in similar topologies of the signal and normalization final states. This leads to first order cancellation of the systematic effects induced by imperfect kaon beam description, local detector inefficiencies and trigger inefficiency. The reconstructed $\pi^\pm \mu^+ \mu^-$ invariant mass spectrum is shown in Fig. 3; the number of $K^\pm \to \pi^\pm \mu^+ \mu^-$ candidates in the signal region is $N_{\pi\mu\mu} = 3120$. Similarly to the $K^\pm \to \pi^\pm e^+ e^-$ decay, the $K^\pm \to \pi^\pm \mu^+ \mu^-$ decay is described as proceeding via single virtual photon exchange, resulting in a spectrum of the $z = (M_{\mu\mu}/M_K)^2$ kinematic variable sensitive to the form factor $W(z)$. In order to extract the form factors that characterize the decay rate and the dilepton invariant mass distribution, the same four models considered in the case of the $K^\pm \to \pi^\pm e^+ e^-$ decay were used. In Fig. 4 the fit to one of the models (the linear one) is shown.

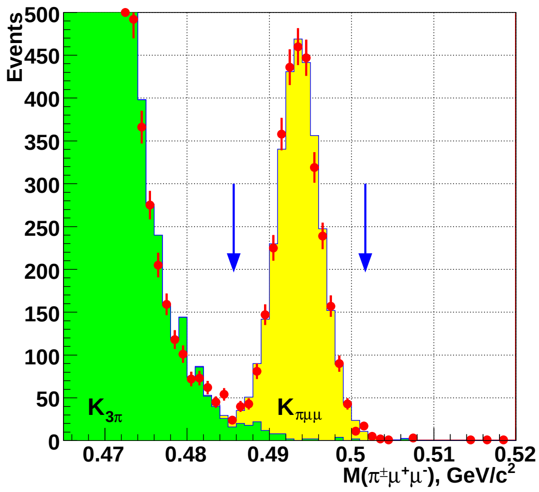

Figure 3. Reconstructed spectrum of $(\pi^\pm \mu^+ \mu^-)$ invariant mass: data (dots) and $K_{\pi\mu\mu}$ MC simulation and $K_{3\pi}$ background estimate(filled areas).

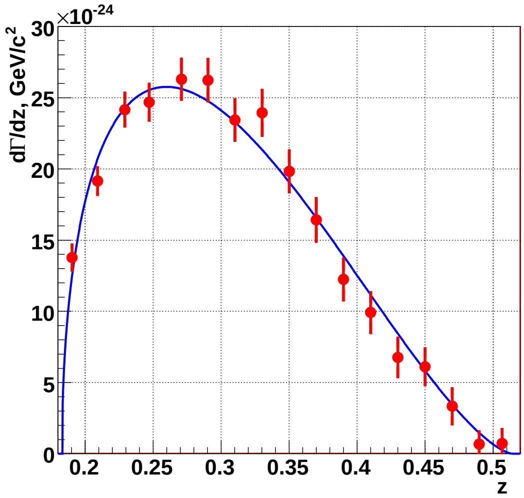

Figure 4. The reconstructed $d\Gamma_{\pi\mu\mu}/dz$ spectrum fitted to a linear form factor.

The measured model parameters and the model independent BR are reported in Table 2. The precision of our BR measurement represents a factor of ~ 3 improvement with respect to the most precise earlier measurement [17]. Each of the form factor models provides a reasonable fit to the data, but the statistical precision is insufficient to distinguish between the models.

The model-independent branching ratios measured separately for K^+ and K^- decays are

$$BR^+ = (9.70 \pm 0.26) \times 10^{-8}, \qquad BR^- = (9.49 \pm 0.35) \times 10^{-8}$$

where the quoted uncertainties are statistical only. Neglecting the systematic uncertainties of BR^+ and BR^- (which are small compared to the statistical uncertainties, and mostly common

Table 2. Results of fits to the four models and the Model-Independent Branching Ratio.

Model(1)										
$\lvert f_0\rvert =$	0.470	$\pm$	$0.039_{\rm stat.}$	$\pm$	$0.006_{\rm syst.}$	$\pm$	$0.002_{\rm ext.}$	$=$	0.470	$\pm$ 0.040
$\delta =$	3.11	$\pm$	$0.56_{\rm stat.}$	$\pm$	$0.11_{\rm syst.}$				3.11	$\pm$ 0.57
Model(2)										
$a_+ =$	-0.575	$\pm$	$0.038_{\rm stat.}$	$\pm$	$0.006_{\rm syst.}$	$\pm$	$0.002_{\rm ext.}$	$=$	-0.575	$\pm$ 0.039
$b_+ =$	-0.813	$\pm$	$0.142_{\rm stat.}$	$\pm$	$0.028_{\rm syst.}$	$\pm$	$0.013_{\rm ext.}$	$=$	-0.813	$\pm$ 0.145
Model(3)										
$\tilde{w} =$	0.064	$\pm$	$0.014_{\rm stat.}$	$\pm$	$0.003_{\rm syst.}$				0.064	$\pm$ 0.014
$\beta =$	3.77	$\pm$	$0.61_{\rm stat.}$	$\pm$	$0.12_{\rm syst.}$	$\pm$	$0.02_{\rm ext.}$	$=$	3.7	$\pm$ 0.62
Model(4)										
$M_a/{\rm GeV} =$	0.993	$\pm$	$0.083_{\rm stat.}$	$\pm$	$0.016_{\rm syst.}$	$\pm$	$0.001_{\rm ext.}$	$=$	0.993	$\pm$ 0.085
$M_\rho/{\rm GeV} =$	0.721	$\pm$	$0.027_{\rm stat.}$	$\pm$	$0.005_{\rm syst.}$	$\pm$	$0.001_{\rm ext.}$	$=$	0.721	$\pm$ 0.028
${\rm BR_{MI}} \times 10^8 =$	9.62	$\pm$	$0.21_{\rm stat.}$	$\pm$	$0.11_{\rm syst.}$	$\pm$	$0.07_{\rm ext.}$	$=$	9.62	$\pm$ 0.25

to the K^+ and K^- measurements), and the possible charge asymmetry of $K_{3\pi}$ decay rates which is experimentally compatible with zero within 2×10^{-3} precision, we measure the charge asymmetry to be $\Delta(K^{\pm}_{\pi\mu\mu}) = (1.1 \pm 2.3) \times 10^{-2}$. This is a factor of ~ 5 improvement in precision with respect to the only previous measurement [18], and is compatible with CP conservation. A limit for the charge asymmetry of $|\Delta(K^{\pm}_{\pi\mu\mu}| < 2.9 \times 10^{-2}$ at 90% CL can be deduced from the above value. The experimental precision is far from the SM expectation $\Delta(K^{\pm}_{\pi\mu\mu}) \sim 10^{-4}$ [10] and even the SUSY upper limit $\Delta(K^{\pm}_{\pi\mu\mu}) \sim 10^{-3}$ [14],[15]for the CP violating asymmetry.

The forward-backward asymmetry has been measured to be $A_{FB} = (-2.4 \pm 1.8) \times 10^{-2}$, where the error is dominated by the statistical uncertainty. It corresponds to an upper limit of $|A_{FB}| < 2.3 \times 10^{-2}$ at 90 % CL. The achieved precision does not reach the upper limits for the SM contribution via the two-photon intermediate state $K^{\pm} \to \pi^{\pm}\gamma^*\gamma^* \to \pi^{\pm}\mu^+\mu^-$ [19] and MSSM contribution [20], which are both of the order of 10^{-3}. The complete description of the study of the $K^{\pm} \to \pi^{\pm}\mu^+\mu^-$ decay can be found in [21].

3.4. The $K_S \to \pi^+\pi^-e^+e^-$ decay

In 2002, the NA48 experiment carried out a high intensity K_S program aiming to measure rare K_S and hyperon decays (NA48/1). Studies of the $K_S \to \pi^+\pi^-e^+e^-$ decay have recently been completed. This decay provides a testing ground for a CP non-invariance. Unlike the $K_L \to \pi^+\pi^-e^+e^-$ decay in which the CP=+1 inner bremsstrahlung (IB) process competes with the CP=-1 direct emission (DE) M1 term, the decay amplitude of $K_S \to \pi^+\pi^-e^+e^-$ is expected to be dominated by the CP-even inner bremsstrahlung transition. Therefore, the CP violating asymmetry, defined as

$$A_\phi = \frac{N_{\pi\pi ee}(\sin\phi\cos\phi > 0) - N_{\pi\pi ee}(\sin\phi\cos\phi < 0)}{N_{\pi\pi ee}(\sin\phi\cos\phi > 0) + N_{\pi\pi ee}(\sin\phi\cos\phi < 0)}$$

where ϕ is the angle between the $\pi^+\pi^-$ and the e^+e^- decay planes in the kaon center of mass, is expected to be 0.

In total 22966 $K_S \to \pi^+\pi^-e^+e^-$ candidates, with a background of 103 events were selected. The BR ratio was measured with respect to the $K_L \to \pi^+\pi^-\pi^0_D$ decay. Using the existing values for $K^{\pm} \to \pi^+\pi^-\pi^0$ and $\pi^0 \to e^+e^-\gamma$ BR's [22], we found [23]

$$BR = (4.93 \pm 0.14) \times 10^{-5}$$

Other parameters of the decay were measured, in particular the CP-violating asymmetry. The normalized differential decay rate dependence on $\sin\phi\cos\phi$ is shown in Fig. 5.

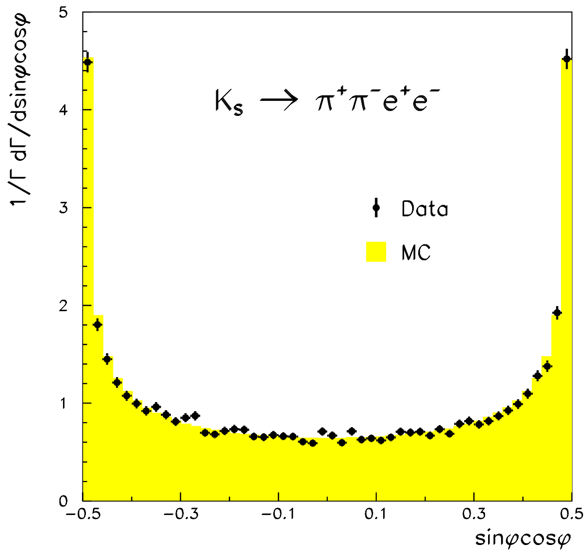

Figure 5. The $K_S \rightarrow \pi^+\pi^-e^+e^-$ normalized differential decay rate in the $\sin\varphi\cos\varphi$ variable.

The corresponding asymmetry parameter was found to be $A_\phi = (-0.4 \pm 0.7_{stat} \pm 0.4_{syst})\%$, consistent with zero, from which a limit of $A_\phi < 1.5\%$ at 90% CL can be set. No evidence for a CP-violating contribution in $K_S \rightarrow \pi^+\pi^-e^+e^-$ was observed.

References

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