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# Recent QCD results from NA48/2

To cite this article: Gianluca Lamanna and for theNA48/2 Collaboration 2019 J. Phys.: Conf. Ser. 1137 012009

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# Recent QCD results from NA48/2

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#### Abstract.

In 2003 and 2004, the NA48/2 experiment collected an unprecedented statistics of charged kaon decays to measure the CP violation in three pions. An additional extensive physics program has been carried out. In particular, it was possible to verify the predictions of low energy QCD in several processes, with high precision. In this paper we present the precise measurement of the charged kaon semileptonic form factors (FF) and the first observation of the  $K^+ \rightarrow \pi^+ \pi^0 e^+ e^$ decay. The semileptonic FF are measured on the sample collected in 2004 in a dedicated minimum bias run, to overcome the limitation imposed by the 3 pions triggers, while the first observation of the  $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$  decay is based on the full sample of data collected in two vears.

#### 1. The NA48/2 Experiment

The NA48/2 experiment beam line has been designed to measure the CP violating charged asymmetry through the study of the Dalitz Plot in the  $K \to 3\pi$  decay [1]. Simultaneous positive and negative kaons beams are produced in the same beryllium target by impinging 400 GeV protons from the CERN/SPS accelerator. The momentum range of  $(60 \pm 3)$  GeV/c is selected, for both beams, in the first "achromat" and a complex system of magnets allows to have superimposed and focused beams  $\sim 200$  m downstream, at the end of the  $\sim 100$  m long decay region, where  $K^+$  and  $K^-$  decays are registered simultaneously with the same detectors. The detector, based on the NA48 setup, apart some minor changes, is discussed in details in [2]. A spectrometer, housed in a helium vessel located just after the vacuum tank, thanks to a thin Kevlar window, is composed by four drift chambers (DCH) and a dipole magnet. The

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Spectrometer allows to measure the charged kaon decay products momentum with a resolution of  $\sigma_p/p = (1.02 \oplus 0.044 \ p)\%$  where p is in GeV/c. The photon detection is performed by a quasi-homogeneous liquid Krypton calorimeter (LKr), with a depth of 27  $X_0$ . The LKr has a resolution of  $\sigma(E)/E = 0.032/\sqrt{(E)} \oplus 0.09/E \oplus 0.0042$ ) with E in GeV. Other detectors, for particle identification and trigger purpose, complete the setup. The data taking took place in 2003-2004 collecting a total of about  $3 \times 10^9 \ K^{\pm} \to \pi^{\pm} \pi^{\pm} \pi^{\mp}$ , about  $9 \times 10^7 \ K^{\pm} \to \pi^{\pm} \pi^0 \pi^0$  and other decays for rare processes studies. The normal trigger configuration was optimized for both three charged pions and two neutral pions and a single charged pion. In 2004, in 52 hours of data taking with a dedicated minimum bias trigger (requiring one track and  $E_{LKr} > 10 \ GeV$ ), NA48/2 efficiently collected semileptonic decays used for the analysis presented in this paper.

# 2. The $K^{\pm} \rightarrow e^{\pm} \pi^0 \nu$ and $K^{\pm} \rightarrow \mu^{\pm} \pi^0 \nu$ form factors

The decay width of both  $K_{e3}$   $(K^{\pm} \to e^{\pm} \pi^0 \nu)$  and  $K_{\mu3}$   $(K^{\pm} \to \mu^{\pm} \pi^0 \nu)$ ,  $K_{l3}$  in general, can be described in the Dalitz plot as a function of the lepton and pion energies in kaon rest frame  $E_l^*$  and  $E_{\pi}^*$ , with the density defined by:

$$\frac{d^2\Gamma_0(K_l)}{dE_l^* dE_\pi^*} = N(Af_+^2(t) + Bf_+(t)f_-(t) + Cf_-^2(t))$$

where N is a normalization factor and dimensionless  $f_{\pm}(t)$  are the so called vector form factors, described as a function of the squared four-momentum transferred to the lepton system,  $t = (P_K - P_\pi)^2 = (m_K^2 + m_\pi^2 - 2m_K E_\pi)$ . Commonly the so called scalar form factor,  $f_0(t)$ , is defined so that  $f_-(t) = \frac{(f_+(t) - f_0(t))(m_K^2 - m_\pi^2)}{t}$  and  $f_+(0) = f_-(0)$ . There are several parametrization in literature for the scalar  $(f_0(t))$  and vector  $(f_+(t))$  form factors. In this work we used the following three:

• Quadratic expansion (a.k.a. Taylor expansion): is the most used and simplest. The slopes and curvatures are defined by the fit parameters  $\lambda'_{+}$ ,  $\lambda''_{+}$  and  $\lambda_0$  [3]:

$$f_{+}(t) = 1 + \lambda'_{+}(\frac{t}{m_{\pi}^{2}}) + \frac{1}{2}\lambda''_{+}(\frac{t}{m_{\pi}^{2}})^{2}$$
$$f_{0}(t) = 1 + \lambda_{0}(\frac{t}{m_{\pi}^{2}})$$

• Pole parametrization: a single resonance is assumed to be relevant in the expansion and the corresponding pole mass  $M_{V,S}$  are the only free parameters in the fit [4]:

$$f_+(t) = \frac{M_V^2}{M_V^2 - t}$$
$$f_0(t) = \frac{M_S^2}{M_S^2 - t}$$

• Dispersive approach: two dispersive functions are introduced, G(t) and H(t), and the C and  $\Lambda_{+}$  parameters are used in the fit [5]:

$$f_{+}(t) = exp((\Lambda_{+} + H(t)(\frac{t}{m_{\pi}^{2}}))$$
$$f_{0}(t) = (ln(C) - G(t))(\frac{t}{M_{K}^{2} - M_{\pi}^{2}})$$



Figure 1. Joint Quadratic expansion fit for  $K_{l3}$  comparison between previous experiments and this work (black ellipse) (figure colored online).

#### 2.1. $K_{l3}$ events selection

One single good track in the DCHs in time with at least two LKr clusters, is the starting point for both  $K_{e3}$  and  $K_{\mu3}$  selections. In addition, the good reconstructed charged vertex obtained assuming the beam direction, defined on run by run basis with a  $K^{\pm} \to 3\pi^{\pm}$  sample, is required to be in the decay region. A cut for the track momentum  $p > 5 \ GeV$  is used in the electron selection while  $p > 10 \ GeV$  for the muons ensure a proper efficiency in the MUV detector. The PID is done by requiring and E/p > 0.9 (where E is the energy deposited in the LKr and p is the momentum measured by the spectrometer) for the electrons and no signal in time in the MUV. Conversely the muons are identified asking for an associated hit in time in the MUV and E/p < 0.9. For both channels, the background contribution has been evaluated by Monte Carlo. The most significant backgrounds, in the  $K_{e3}$ , come from the  $K^{\pm} \to \pi^{\pm}\pi^{0}$  and  $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ , in which the pion is misidentified as an electron. A cut on the reconstructed transverse momentum of the neutrino,  $P_t(\nu) > 0.03 \ GeV/c$ , helps in reducing the background contribution at level of 0.027%. The  $K^{\pm} \to \pi^{\pm}\pi^{0}$  and the  $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$  are also the main backgrounds for the  $K_{\mu3}$  channel, due to  $\pi^{\pm} \to \mu^{\pm}\nu$  decay in flight. The final contamination is maintained at level of 0.0264%, by cutting in both  $m(\pi^{\pm}\pi^{0})$  and  $m(\mu^{\pm}\nu)$ .

## 2.2. Preliminary results on $K_{l3}$ form factors

In the final sample  $4.28 \times 10^6 K_{e3}$  and  $2.91 \times 10^6 K_{\mu3}$  are selected. The form factors are extracted by performing an events-weighting in 5  $MeV \times 5 MeV$  cells in the Dalitz plot of  $E_l^*$  vs  $E_{\pi^0}^*$ , computed in the kaon rest frame. In table 1 the results of the three parametrizations for the form factors (see sect.2) are reported. The  $\chi^2/ndf$  for the fits are: 1004.6/1073 for quadratic, 1001.1/1074 for Pole and 998.3/1074 for dispersive fits.

# 3. The $K^{\pm} \rightarrow \pi^{\pm} \pi^0 e^+ e^-$ first observation

The  $K^{\pm} \to \pi^{\pm} \pi^0 e^+ e^-$  is obtained by the internal conversion of the  $\gamma$  in the decay  $K^{\pm} \to \pi^{\pm} \pi^0 \gamma^*$ . The  $\gamma^*$  is radiated in the weak vertex through two different mechanisms: IB (Inner Bremsstrahlung), in which the virtual photon is radiated either in the initial or in the final state by the charged meson (either kaon or pion) and DE (Direct Emission) where the gamma is produced directly at the weak vertex. As a consequence there are three contributions to the differential decay rate: the IB (pure electric E), the DE (both electric E and magnetic M parts) and their interference. The measurement of the IB, DE and interference terms in  $K^{\pm} \to \pi^{\pm} \pi^0 \gamma$ 





**Figure 2.**  $M_{e^+e^-}$  distribution for signal events.

**Figure 3.**  $M_{e^+e^-}$  distribution for  $\pi^+\pi^0_D$  events used as normalization.

[6] allows to predict [7] the Branching Ratio (BR) of the  $K^{\pm} \to \pi^{\pm} \pi^{0} e^{+} e^{-}$  and then to test the theoretical prediction of Chiral Perturbation Theory (ChPT).

3.1. The 
$$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$$
 selection

Three well reconstructed tracks are selected in DCH and CHOD acceptance. The tracks momentum must be in the range  $(2 - 60) \ GeV/c$  and the distances between the tracks at the first DCH, is required to be greater than 2 cm in order to reject photon conversions. The three tracks must point to the same vertex lying on the nominal beam direction. Differently

## Table 1. Fit Results.

Quadratic	$\lambda_{+}^{'} (10^{-3})$	$\lambda_{+}^{''} (10^{-3})$	$\lambda_0 \; (10^{-3})$
$K_{\mu 3}$	$23.32 \pm 3.08_{stat} \pm 3.50_{syst}$	$2.14 \pm 1.06_{stat} \pm 0.96_{syst}$	$14.33 \pm 1.11_{stat} \pm 1.25_{syst}$
$\frac{K_{e3}}{K_{l3}}$	$23.52 \pm 0.78_{stat} \pm 1.29_{syst} 23.35 \pm 0.75_{stat} \pm 1.23_{syst}$	$\begin{array}{c} 1.60 \pm 0.30_{stat} \pm 0.39_{syst} \\ 1.73 \pm 0.29_{stat} \pm 0.41_{syst} \end{array}$	$14.90 \pm 0.55_{stat} \pm 0.80_{syst}$
Pole	$M_V (MeV/c^2)$	$M_S \ (MeV/c^2)$	
$K_{\mu 3}$	$879.1 \pm 8.1_{stat} \pm 13.5_{syst}$	$1196.4 \pm 18.1_{stat} \pm 28.8_{syst}$	
$\frac{K_{e3}}{K_{l3}}$	$\begin{array}{c} 896.8 \pm 3.4_{stat} \pm 7.6_{syst} \\ 894.3 \pm 3.2_{stat} \pm 5.4_{syst} \end{array}$	$1185.5 \pm 16.6_{stat} \pm 35.5_{syst}$	
Dispersive/	$\Lambda_{+}(10^{-3})$	$ln[C] (10^{-3})$	
$K_{\mu 3}$	$23.55 \pm 0.50_{stat} \pm 0.97_{syst}$	$186.68 \pm 5.12_{stat} \pm 9.23_{syst}$	
$K_{e3}$ $K_{l3}$	$22.54 \pm 0.20_{stat} \pm 0.62_{syst}$ $22.67 \pm 0.18_{stat} \pm 0.55_{syst}$	$189.12 \pm 4.91_{stat} \pm 11.09_{syst}$	

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with respect to the  $K_{e3}$  FF selection, no E/p cut is applied to select the electrons in order to increase the signal acceptance. The closed kinematics, by assuming the electron mass for two tracks, is the only condition required for the electron identification. The LKr is used exclusively to measure position and energy of the gammas, to reconstruct the  $\pi^0$  mass. The final sample is selected by applying cut on kaon  $(|M_K - M_K(PDG)| < 45 \ MeV/c^2)$  and neutral pion  $(|M_{\pi^0} - M_{\pi^0}(PDG)| < 15 \ MeV/c^2)$  masses. Since the total kaons flux is unknown a normalization channel is selected together with the signal. The  $K^{\pm} \to \pi^{\pm}\pi^0_D$  with  $\pi^0_D \to e^+e^-\gamma$ is considered as normalization since the similar topologies and trigger efficiency.

#### 3.2. Branching ratio result

In 2003 and 2004 data taking we used  $1.7 \times 10^{11}$  kaon decays (both  $K^+$  and  $K^-$ ). In this sample we selected a total of 5076  $K^{\pm} \to \pi^{\pm} \pi^0 e^+ e^-$  (fig.2) with an estimated background of 289 events from  $K^{\pm} \to \pi^{\pm} \pi^0_D$  and  $K^{\pm} \to \pi^{\pm} \pi^0 \pi^0_D$ . As a preliminary result we measured:

$$BR(K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}) = (4.22 \pm 0.06_{stat} \pm 0.04_{syst} \pm 0.13_{ext}) \times 10^{-6}$$

The main contribution on the total error comes from the uncertainty on the branching ratio of  $K^{\pm} \rightarrow \pi^{\pm} \pi_D^0$  used as normalization. Other contributions to the systematics error are due to trigger efficiency and radiative effects. The result is fully compatible with the ChPT prediction within the experimental uncertainty [7]:

$$BR(K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-})_{IB} = 4.19 \times 10^{-6}$$

#### 4. Conclusions

The  $K_{l3}^{\pm}$  form factors are important for the best determination of  $|V_{us}|^2$ . The measurement is performed by NA48/2 experiment on the basis of 2004 run data. The result has the smallest error for what concern  $K_{e3}^{\pm}$  and it is at the same level of precision with respect to previous measurements for what concern  $K_{\mu3}^{\pm}$ , this gives the smallest uncertainty on the combined result on  $K_{l3}$  form factors. The first observation of the  $K^{\pm} \to \pi^{\pm} \pi^0 e^+ e^-$  is presented. The measured branching ratio is compatible with the prediction of the Chiral perturbation Theory. Both results presented here are preliminary, the papers are in preparation.

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