New measurement of the $K^+ \to \pi^+\mu^+\mu^-$ decay at NA62

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A preliminary result of a new measurement of the $K^+ \to \pi^+\mu^+\mu^-$ form factor parameters and branching fraction using the NA62 Run 1 data set collected in the years 2016 – 2018 is presented. From the observed sample of 28011 $K^+ \to \pi^+\mu^+\mu^-$ event candidates with negligible background contamination, the form factor parameters $a_+ = -0.592 \pm 0.013_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.001_{\text{ext}}$ and $b_+ = -0.699 \pm 0.046_{\text{stat}} \pm 0.035_{\text{syst}} \pm 0.003_{\text{ext}}$, and the branching fraction $\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-) = (9.27 \pm 0.07_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.04_{\text{ext}}) \times 10^{-8}$ are obtained.

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1. Introduction

Extensive work [1–3] has been done towards the theoretical understanding of the flavour-changing neutral current (FCNC) $K^\pm \to \pi^\pm \ell^+ \ell^-$ decays. Studies of these processes contribute [4] to the body of experimental tests of lepton flavour universality (LFU), e.g. [5, 6].

Dominant contributions to the $K^\pm \to \pi^\pm \ell^+ \ell^-$ decays are mediated by the virtual photon exchange $K^\pm \to \pi^\pm \gamma^* \to \pi^\pm \ell^+ \ell^-$ and involve long-distance hadronic effects. The differential decay width, expressed in terms of the Dalitz variables $z = m^2_{\mu^+\mu^-}/M^2_K$ and $x = m^2_{\pi^+\mu^+}/M^2_K$, where m_{ij} is an invariant mass of an (i, j) particle pair, reads [2, 3]

$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}z\mathrm{d}x} = \frac{\alpha^2 M_K}{8\pi(4\pi)^4}\left[(2x+z-2-2r^2_\mu)(-2x-z+2r^2_\pi+2r^2_\mu)+z(z-2-2r^2_\pi)\right]|W(z)|^2\left[1+\delta(z,x)\right],$$
(1)

where $r_i = M_i/M_K$, $\delta(z,x)$ accounts for the radiative effects [7], and $W(z)$ is a form factor describing the dynamics of the decay. For the purposes of this analysis, we use the NLO chiral perturbation theory parametrization of $W(z)$ introduced in [2]

$$W(z) = G_F M^2_K(a_+ + b_+ z) + W^{\pi\pi}(z),$$
(2)

with free real parameters a_+ and b_+, and a complex function $W^{\pi\pi}(z)$ describing the contribution from a three-pion intermediate state with a $\pi^+\pi^- \to \gamma^*$ transition.

The goal of the presented analysis is to extract the two form factor parameters a_+ and b_+ from a fit to data for the muon mode and compute the model-dependent $K^+ \to \pi^+\mu^+\mu^-$ ($K_{\pi\mu\mu}$) branching fraction by integrating Eq. 1.

2. Experimental Setup

The NA62 is a kaon experiment at CERN SPS with the main aim of making a precise measurement of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$. The detector setup and performance are discussed in detail in [8]. The most relevant subsystems for the presented analysis (shown in Fig. 1) are: KTAG (kaon tagger), STRAW (downstream spectrometer), CHOD (charged particle hodoscope), LKr (electromagnetic calorimeter), and MUV3 (muon detector).
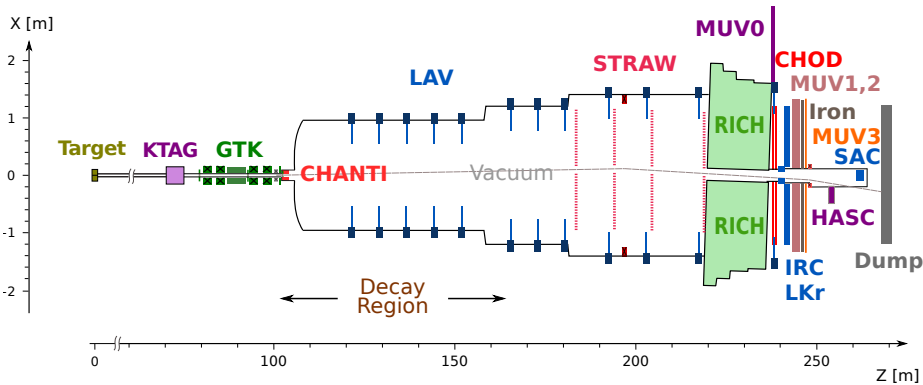

Figure 1: Schematic view of the NA62 detector setup [8].

3. Event Selections

The $K_{\pi\mu\mu}$ decay analysis is performed on the NA62 Run 1 data set. The sample corresponds to $N_K = 6.8 \times 10^{12}$ kaon decays inside the $Z \in [108, 180]$ m region. The measurement of the $K_{\pi\mu\mu}$ form factor parameters is normalized to the abundant and kinematically similar charged kaon decay into three pions, $K^+ \to \pi^+\pi^+\pi^-$ ($K_{3\pi}$), with branching fraction $\mathcal{B}(K_{3\pi}) \simeq 5.58\%$ [9]. This choice allows for minimal differences between the signal and normalization event selections, thus reducing both complexity of the analysis as well as the impact of certain systematic effects.

The NA62 trigger system consists of both hardware (L0) [10] and software (L1) stages. The normalization sample is collected with a "multitrack" trigger, while the signal sample is selected from data passing a "di-muon" trigger, differing from the multitrack trigger primarily in the additional L0 requirement of two in-time MUV3 signals. Both trigger streams are about 90% efficient.

3.1 Common Part of Signal and Normalization Event Selections

The event selection starts by building three-track vertices from STRAW tracks reconstructed in an event. Vertex charge, fit χ^2, position, momentum, and time requirements are then imposed to select one good three-track vertex. Further background reduction is achieved by requiring that no other in-time three-track vertex shares a STRAW track with the previously chosen vertex.

Next, at least one good reconstructed kaon candidate in KTAG in time (6 ns) with both the vertex time t_{vertex} and the trigger time t_{trigger} is required. The event selections proceed by imposing quality requirements on the three STRAW tracks forming the chosen vertex. These include geometric acceptance cuts, track-fit quality and momentum cuts, timing requirements, and track separation at the first STRAW chamber and the LKr front plane.

3.2 Signal Event Selection

In addition to the common selection conditions, the signal event selection employs particle identification criteria, background-reducing kinematic cuts, and a final cut on the invariant mass. The mutually exclusive particle identification criteria for pions and muons are:

1. a track is identified as a pion if $E_{\text{LKr}}/p_{\text{track}} < 0.9c$ (where E_{LKr} is the energy of a cluster associated to the track, and p_{track} is the track momentum magnitude), and there are no signals in MUV3 tiles geometrically compatible with the track within 10 ns from t_{vertex},

2. a track is identified as a muon if $E_{\text{LKr}}/p_{\text{track}} < 0.2c$ and there is a signal in a MUV3 tile geometrically compatible with the track and within 5 ns from t_{vertex} and t_{trigger}.

Exactly one π^+ track and a $\mu^\pm$ pair of tracks are required for the chosen good vertex. Further reduction of the dominant $K_{3\pi}$ background is achieved by kinematic cuts on the muon momenta and a cut on the extrapolated π^+ position in the plane of the last collimator ($Z = 101.3$ m).

Final cut on the invariant mass of the vertex tracks, $|m(\pi^+\mu^+\mu^-) - M_K| < 8$ MeV/c^2 (Fig. 2, left), results in a sample of 28011 $K_{\pi\mu\mu}$ signal event candidates in data. The background contamination is estimated using Monte Carlo (MC) and reads $N_{\text{bckg}} = 12.5 \pm 1.7_{\text{stat}} \pm 12.5_{\text{syst}}$ events, dominated by $K_{3\pi}$. The signal selection acceptance evaluated with $K_{\pi\mu\mu}$ MC is 9.40%.

3.3 Normalization Event Selection

The normalization event selection employs three additional cuts on top of the common selection criteria summarized in subsection 3.1. The first two are meant to further symmetrize the signal and normalization selections by imposing requirements on a randomly chosen positive track (see subsection 3.2):

1. positive π^+ identification is enforced,

2. cut on the track position at the last collimator plane is applied.

Final requirement of the normalization event selection is a cut on the invariant mass of the three vertex tracks assuming charged pion masses, $|m(\pi^+\pi^+\pi^-) - M_K| < 8\,\text{MeV}/c^2$ (Fig. 2, centre). A total number $N(3\pi) = 2.78 \times 10^8$ of $K_{3\pi}$ data event candidates pass the normalization event selection, with 0.3% contamination from the radiative decay $K^+ \to \pi^+\pi^+\pi^-\gamma$. The normalization event selection acceptance for $K_{3\pi}$ MC events is 7.11%.
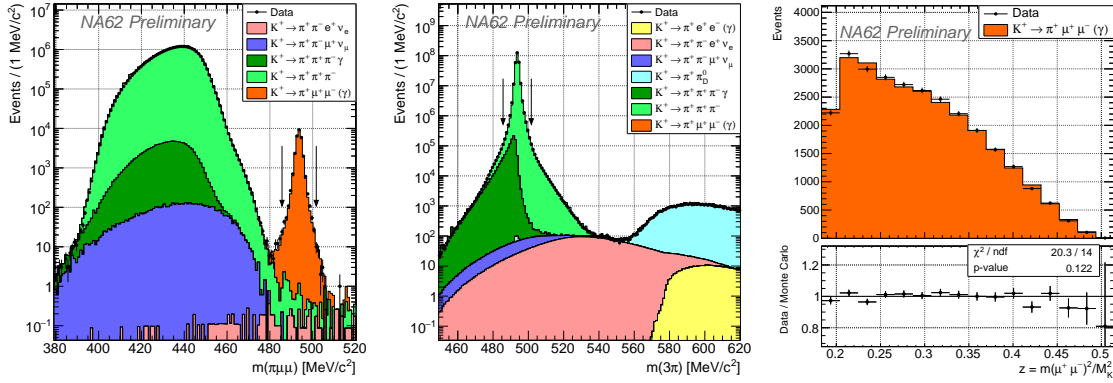

Figure 2: Left: $m(\pi^+\mu^+\mu^-)$ of events passing the signal event selection. **Centre:** $m(3\pi)$ of events passing the normalization event selection. Black arrows indicate final cuts applied to select the normalization and signal event samples. **Right:** z spectrum of the selected $K_{\pi\mu\mu}$ signal candidate events with MC events reweighted to best fit the data (see section 4 for details).
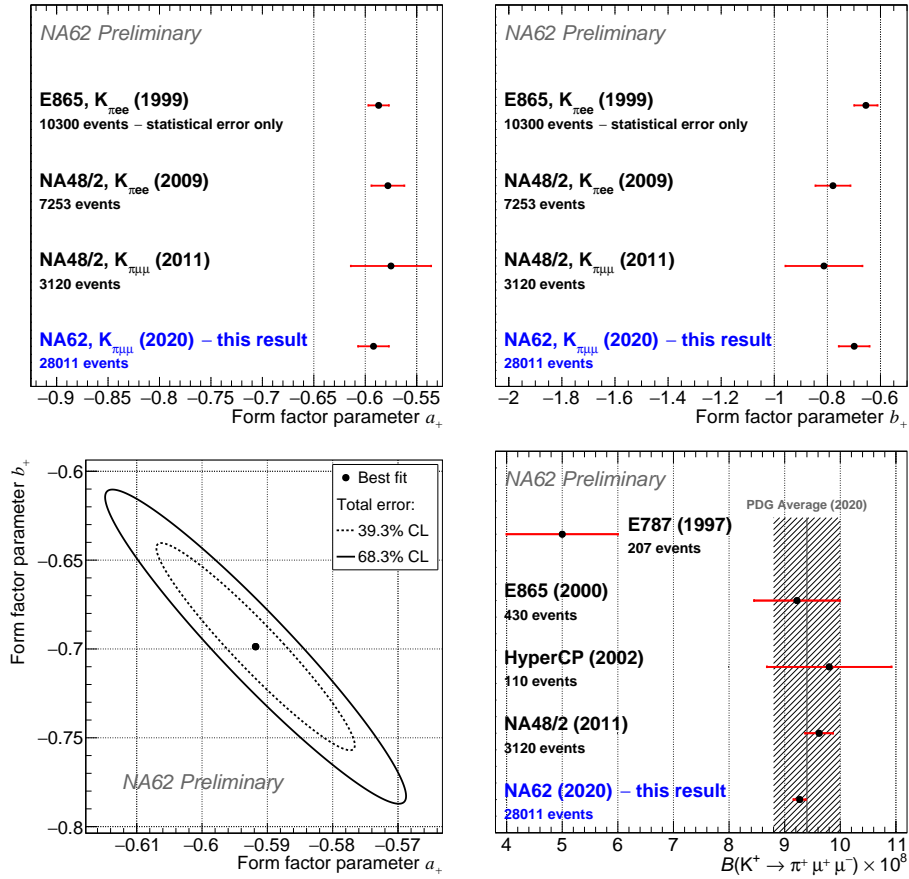
4. Results

The form factor parameters a_+ and b_+ (Eq. 2) are fitted using a technique involving reweighting the MC z spectrum (Fig. 2, right) and minimization of a $\chi^2(a, b)$ function. The fitted values of a_+ and b_+, and the resulting $\mathcal{B}(K_{\pi\mu\mu})$ are shown together with the full error budget in Table 1 and Fig. 3. The best fit leads to $\chi^2/\text{ndf} = 20.3/14$, corresponding to a p-value = 0.122.

A second local minimum of the $\chi^2(a, b)$ function ($\chi^2/\text{ndf} = 30.7/14$ and a p-value = 0.006) lies in the first quadrant of the a_+, b_+-plane: $a_+ = 0.368 \pm 0.013_{\text{stat}}$ and $b_+ = 2.045 \pm 0.046_{\text{stat}}$, and appears to be disfavoured when only statistical errors are considered.

The form factor parameters obtained in this analysis are compatible with previous measurements in both muon and electron modes (Fig. 3) and thus no departure from LFU is observed.

	a_+	b_+	$\mathcal{B}(K_{\pi\mu\mu}) \times 10^8$
Best fit	-0.592	-0.699	9.27
Errors	δa_+	δb_+	$\delta\mathcal{B}(K_{\pi\mu\mu}) \times 10^8$
Statistical	0.013	0.046	0.07
Systematic			
Reconstruction efficiency	0.005	0.026	0.06
Beam and pileup simulation	0.005	0.024	0.05
Trigger efficiency	0.001	0.005	0.04
Background	—	0.001	0.01
Total systematic	0.007	0.035	0.08
External			
PDG error in $\mathcal{B}(K_{3\pi})$	0.001	0.003	0.04
Total	0.015	0.058	0.11

Table 1: Best fit and error budget summary.

Figure 3: Top: Current and previous [11–13] measurements of form factor parameters a_+ and b_+ in both muon and electron modes. **Bottom-left:** Position of the best-fit point in the a_+, b_+-plane and two CL contours. **Bottom-right:** Current and previous [13–16] measurements of $\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-)$.

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