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Recent results from precision measurements at the NA62 experiment

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Recent results on precision mesaurements from the NA62 experiment at CERN are presented. Precision measurements are performed on data collected in 2017–2018 for the decays $K^+ \to \pi^0 e^+ \nu\gamma$, $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+\gamma\gamma$ with significant improvements compared to previous experiments.

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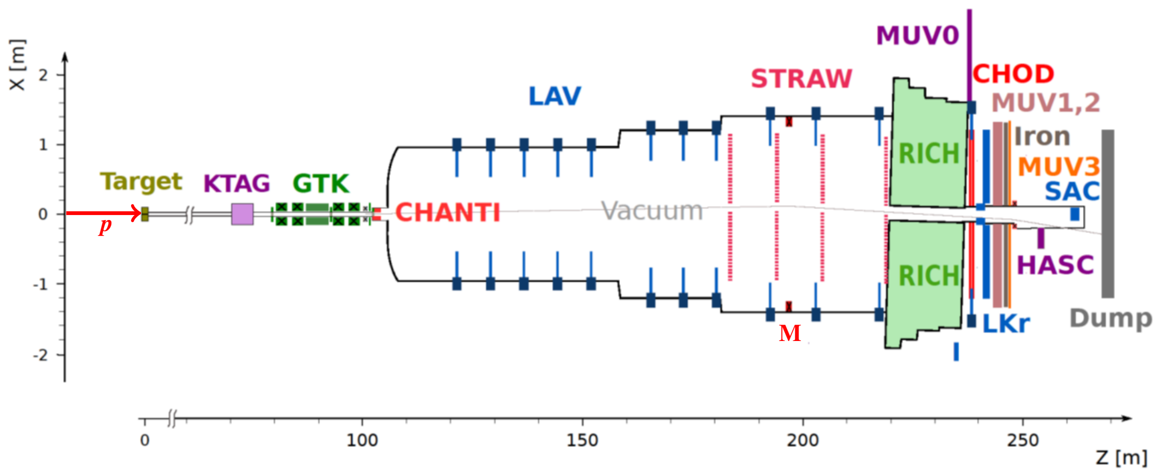
1. The NA62 experiment

Tha NA62 experiment at CERN is a fixed-target experiment designed to measure the branching fraction of the $K^+ \to \pi^+ \nu \bar{\nu}$ very rare decay[1]. Its experimental layout is described in [2] and schematically shown in Figure 1.

An unseparated 75 GeV/c hadron beam containing $\pi^+(70\%)$, $p(24\%)$ and $K^+(6\%)$ is produced by a 400 GeV/c proton beam from the CERN Super Proton Synchrotron impinging on a beryllium target. Kaons in this secondary beam are identified by a differential Čerenkov counter (KTAG); trajectories and momenta of all beam particles are measured by a Si-pixel beam spectrometer (GTK), which is followed by an evacuated fiducial volume. Trajectories and momenta of charged particles from K^+ decays are reconstructed with a spectrometer consisting of a dipole magnet (M) and four tracking chambers made of STRAW tubes. Particle identification is provided by a Ring Imaging Cherenkov (RICH) detector, a liquid kripton (LKr) electromagnetic calorimeter, a hadron calorimeter and muon detectors (MUV). Large (LAV) and small angle (IRC, SAC) photon detectors are included to veto photons outside the LKr acceptance.

Thanks to auxiliary trigger lines [3, 4], the NA62 physics program includes most of the K^+ decay channels and the possibility of precisely measuring decays as $K^+ \to \pi^0 e^+ \nu \gamma$, $K^+ \to \pi^+ \mu^+ \mu^+$ and $K^+ \to \pi^+ \gamma \gamma$.

Figure 1: Layout of the NA62 experiment at CERN SPS.



2. The $K^+ \to \pi^0 e^+ \nu \gamma$ decay

The $K^+ \to \pi^0 e^+ \nu \gamma$ ($K_{e3\gamma}$) decay is defined as as subset of the inclusive decays $K^+ \to \pi^0 e^+ \nu(\gamma)$ (K_{e3}) defined by requiring a minimum value of the energy E_γ of the radiative photon and a range of angles $\theta_{e\gamma}$ between the photon and the positron in the Kaon rest frame. Three different phase space regions are considered: S_1 ($E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10°$), S_2 ($E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20°$) and S_3 ($E_\gamma > 10$ MeV, $0.6 < \cos\theta_{e\gamma} < 0.9$). The ratio of the branching fractions of the radiative decay $K_{e3\gamma}$ to the inclusive decay K_{e3} is expressed as:

$$R_j = \frac{\mathrm{BR}(K^+ \to \pi^0 e^+ \nu\gamma \,|\, \text{phase space region } S_j)}{\mathrm{BR}(K^+ \to \pi^0 e^+ \nu(\gamma))} \tag{1}$$

The experimental study of the $K_{e3\gamma}$ decay allows a precise test of Chiral Perturbation Theory (ChPT). In this approach, the $K_{e3\gamma}$ decay is described by inner bremsstrahlung (IB) and structure-dependent (SD) processes, and their interference. Theoretical calculations of the ratios R_j at different orders of approximation of radiative effects are given in [5–8].

T-violating contributions to the $K_{e3\gamma}$ decay can be studied by measuring the T-odd observable ξ and the corresponding T-asymmetry A_ξ , defined as:

$$\xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{(M_K \cdot c)^3} \quad , \quad A_\xi = \frac{N_+ - N_-}{N_+ + N_-} \tag{2}$$

where $\vec{p}_\gamma$, $\vec{p}_e$ and $\vec{p}_\pi$ are the three-momentum of the corresponding particle in the kaon rest frame and $N^+(N^-)$ is the number of events with positive (negative) values of ξ.

Values of A_ξ predicted by theoretical calculations within the Standard Model (SM) and beyond [6, 8–10] fall in the range $[-10^{-4}, -10^{-5}]$ with the only exception of one SM extension[10] predicting -2.5×10^{-3}.

In the NA62 analysis of this decay, a sample of 1.3×10^5 $K_{e3\gamma}$ candidate events with less than 1% background contamination has been selected from data collected in 2017-2018, together with a large K_{e3} normalization sample of 6.6×10^7 candidate events with 0.016% background contamination. The details of the analysis and the results are described in [11].

The results of NA62 measurements of the branching ratio R_j and the T-asymmetry $A_{\xi j}$ in the three phase space regions S_j are presented in Table 1, together with ChPT-based theoretical predictions and results of previous experiments [12–14].

Table 1: R_j and $A_{\xi j}$ expectations from ChPT $O(p^6)$ calculations [7, 9] and measurements from ISTRA+ [12], OKA [13, 14] and NA62 [11] experiments, with statistical and systematic uncertainties quoted separately.

	ChPT $O(p^6)$	ISTRA+	OKA	NA62
$R_1 \times 10^2$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.715 \pm 0.005 \pm 0.010$
$R_2 \times 10^2$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.609 \pm 0.003 \pm 0.006$
$R_3 \times 10^2$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.533 \pm 0.003 \pm 0.004$
$A_{\xi 1} \times 10^3$			$-0.1 \pm 3.9 \pm 1.7$	$-1.2 \pm 2.8 \pm 1.9$
$A_{\xi 2} \times 10^3$	-0.059		$-4.4 \pm 7.9 \pm 1.9$	$-3.4 \pm 4.3 \pm 3.0$
$A_{\xi 3} \times 10^3$		15 ± 21	$7.0 \pm 8.1 \pm 1.5$	$-9.1 \pm 5.1 \pm 3.5$

The ratios measured by NA62 are at least a factor two more precise than previous experiments. Their relative uncertainties are below 1%, comparable with the precision of most precise theoretical calculations. The T-asymmetry values, measured with improved precision, are consistent with no asymmetry; their uncertainties are still two orders of magnitude larger than theoretical predictions.

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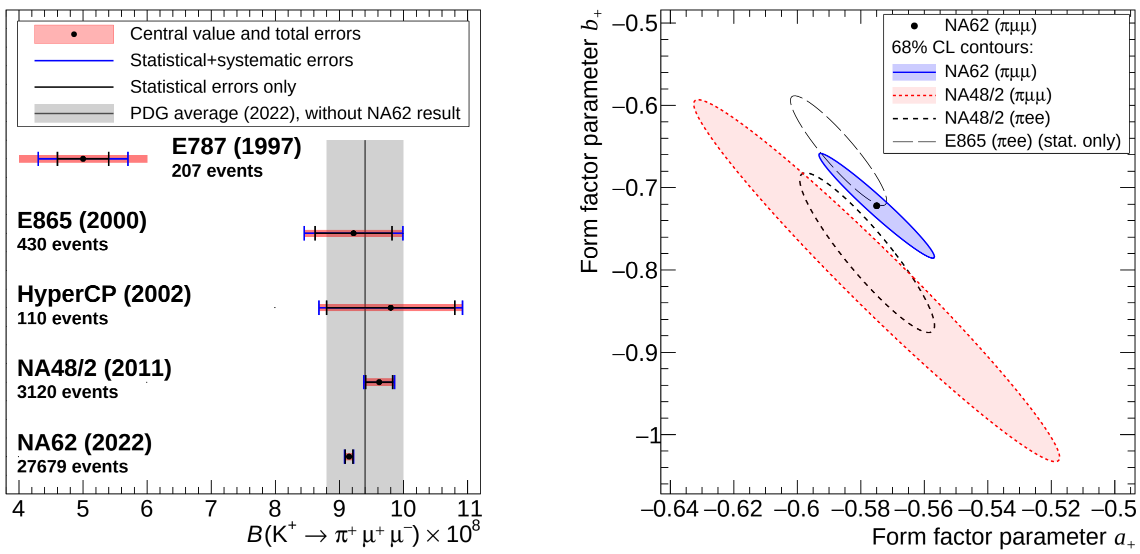
3. The $K^+ \to \pi^+\mu^+\mu^-$ decay

The differential decay width of the $K^+ \to \pi^+\mu^+\mu^-$ decay as a function of the normalized di-muon invariant mass squared $z = m^2(\mu^+\mu^-)/m_K^2$ is parametrized in ChPT by two real parameters a_+ and b_+ [15, 16]. The values of these parameters are expected to be the same in $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+e^+e^-$ decays due to lepton universality.

In the NA62 analysis of this decay, a sample of 2.8×10^4 $K^+ \to \pi^+\mu^+\mu^-$ candidate events has been selected from data collected in 2017-2018, with less than 0.1% background. The signal sample is subdivided in 50 equipopulated bins of z and the differential decay rate $\mathrm{d}\Gamma/\mathrm{d}z$ is evaluated in each z bin. From the integration of $\mathrm{d}\Gamma/\mathrm{d}z$, the model-independent measurement of the branching fraction $\mathrm{BR}(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}$ is obtained with a precision improved by a factor of three compared to previous experiments. A χ^2 fit is performed on $\mathrm{d}\Gamma/\mathrm{d}z$ to determine the parameter values $a_+ = -0.575 \pm 0.013$, $b_+ = -0.722 \pm 0.043$. Uncertainties on a_+, b_+ and the branching fraction are dominated by the statistics of the selected signal sample. The details of the analysis and the results are described in [17].

The results of NA62 measurements of the $K^+ \to \pi^+\mu^+\mu^-$ branching fraction and the form factor parameters a_+ and b_+ are shown in Figure 2 together with those of previous experiments. The present measurement is the first to employ inclusive radiative corrections [18, 19] in the simulation of the signal channel. The form factor parameters are consistent with those measured by previous experiments on this decay and on the $K^+ \to \pi^+e^+e^-$ decay, in agreement with lepton flavour universality.

Figure 2: Comparison of NA62 results with previous experiments. Left: the $K^+ \to \pi^+\mu^+\mu^-$ branching fraction, with the PDG [20] average shown as a shaded band. Right: 68% CL contours in the (a_+, b_+) plane for the muon and electron modes.



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4. The $K^+ \to \pi^+\gamma\gamma$ decay

The $K^+ \to \pi^+\gamma\gamma$ decay is dominated by long-distance effects. Its branching fraction and $\gamma\gamma$ invariant mass spectrum are described in ChPT as a function of several low energy parameters determined from other kaon decays, plus one, named $\hat{c}$, specific of this decay mode [21].

In the NA62 analysis of this decay, a sample of about 4×10^3 signal candidates has been selected from data collected in 2017-2018, with a background contamination smaller than 10%. Details of this anlaysis have been presented for the first time in September 2022 [22] and a paper with the final result [23] has recently been submitted for publication.

The differential decay width of the $K^+ \to \pi^+\gamma\gamma$ decay is measured as a function of the normalized $\gamma\gamma$ invariant mass squared $z = m^2_{\gamma\gamma}/m^2_K$, computed from the reconstructed K^+ and π^+ four-momenta as $z = (P_K - P_\pi)^2/m^2_K$. The $\hat{c}$ parameter is then extracted from the spectrum using the $O(p^6)$ ChPT description, obtaining $\hat{c} = 1.144 \pm 0.069_{\text{stat}} \pm 0.034_{\text{syst}}$. The background is estimated from simulations and validated with data in control regions. The branching fraction is also measured using the $K^+ \to \pi^+\pi^-$ decay as normalization channel, obtaining the final result $\text{BR}(K^+ \to \pi^+\gamma\gamma) = (9.61 \pm 0.15_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-7}$. The NA62 results are consistent with previous measurements and much more precise.

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