NEW RESULTS ON KAON DECAYS FROM NA48

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New measurements of $K_{\rm L}$ and $K_{\rm S}$ decays from the NA48 experiment are presented. From data taken in the year 2001, the value of the K_{e3} charge asymmetry has been determined to $\delta_L(e) = (3.317 \pm 0.070_{\rm stat} \pm 0.072_{\rm syst}) \times 10^{-3}$. From a special high-intensity $K_{\rm S}$ run period performed in 2000, NA48 has found a limit of 1.4×10^{-6} on the $K_{\rm S} \to 3\pi^0$ branching ratio and measured the parameter η_{000}. The same data sample also leads to the first observation of the rare decay $K_{\rm S} \to \pi^0\gamma\gamma$. All results are still preliminary.

1 Introduction

The NA48 experiment has originally been designed to precisely measure direct CP violation in the decay of neutral kaons to two pions. It is a typical fixed target experiment: Neutral kaons and hyperons are produced by protons interacting with two targets and decay in a roughly 100 m long decay region (Fig. 1). One target (*far target*) is located 126 m before the begin of the decay region, a distance large enough that all $K_{\rm S}$ mesons and neutral hyperons have decayed before reaching the final collimator. The other target (*near target*) is located only 6 m before the decay region. Decays observed from this target therefore are predominantly $K_{\rm S}$ and and neutral hyperon (Λ, Ξ^0) decays, but may also be $K_{\rm L}$ decays. In both neutral beams charged particles are deflected from the beam line by sweeping magnets. During the CP violation measurement, both targets were used simultaneously, producing two almost collinear beams of neutral kaons.

Apart from the CP violation measurement, several special run periods have been performed for investigations in rare $K_{\rm L}$, $K_{\rm S}$, and neutral hyperon decays. In the year 2000, when due to an accident the drift chambers were not operational, the run period was split into two halves. The first half with a pure $K_{\rm L}$ beam from the far target was used for systematic investigations of the ϵ'/ϵ measurement and for normalization purposes of the subsequently performed high intensity run using the near target. Data from this latter period, taken in the second half of the 2000 run period, have been used for the $K_{\rm S} \to 3\pi^0$ and $K_{\rm S} \to \pi^0\gamma\gamma$ measurements reported here.

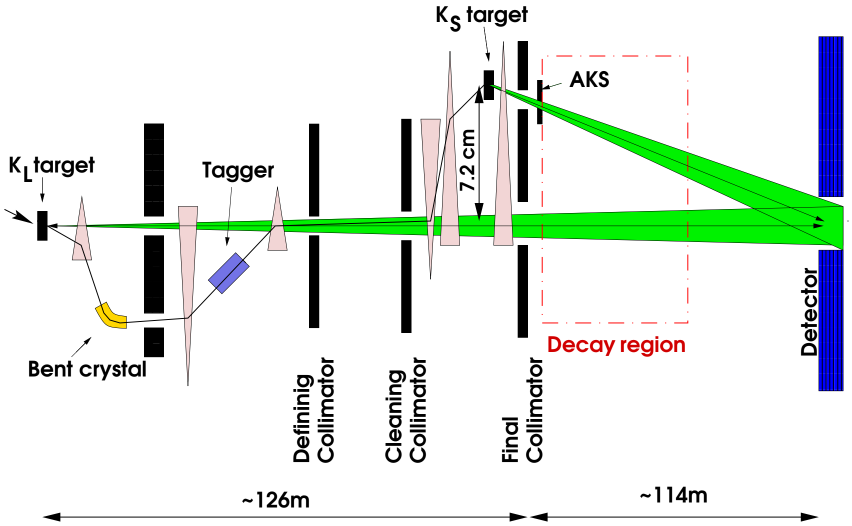

Figure 1: Beam line of the NA48 experiment.

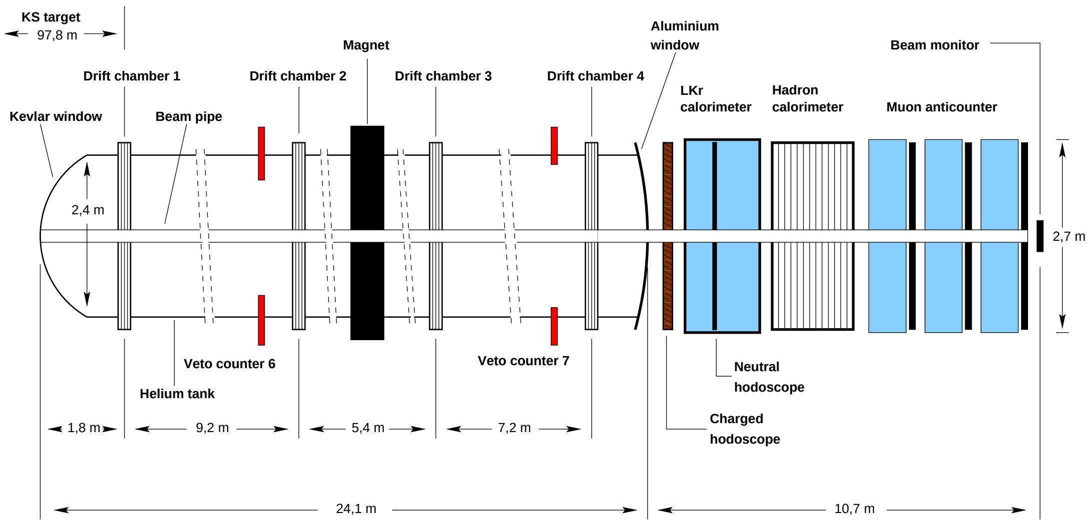

Figure 2: Side view of the NA48 detector.

The NA48 detector is shown in Fig. 2. Its main components are a liquid-krypton electromagnetic calorimeter (LKr) and a magnetic spectrometer consisting out of two sets of drift chambers both before and after a dipole magnet and embedded in a helium tank. The calorimeter has an energy resolution of $\Delta E/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 90\ \mathrm{MeV}/E \oplus 0.42\%$ and allows for the precision measurements of neutral decays described below.

For the analyses described here, the magnetic spectrometer only is relevant for the K_{e3} charge asymmetry measurement. In the 2000 run period it was replaced by a vacuum tank to minimize multiple scattering.

2 Measurement of the K_{e3} Charge Asymmetry

The charge asymmetry in semileptonic K_{L} decays is an important observable for CP violation. For $K_{\mathrm{L}} \to \pi e \nu$ (K_{e3}) decays it is defined as

$$\delta_L(e) \;=\; \frac{\Gamma(K_{\mathrm{L}} \to \pi^- e^+ \nu) - \Gamma(K_{\mathrm{L}} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{\mathrm{L}} \to \pi^- e^+ \nu) + \Gamma(K_{\mathrm{L}} \to \pi^+ e^- \bar{\nu})}$$

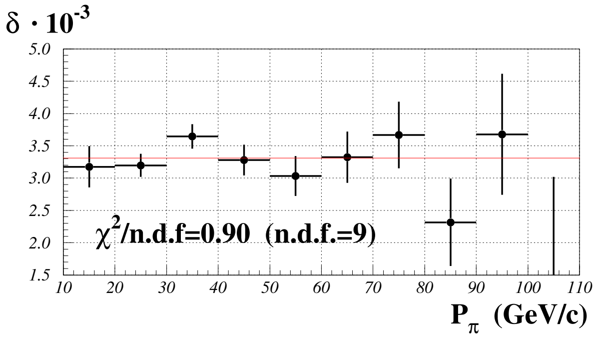

Figure 3: Fit results for $\delta_L(e)$ in bins of the pion momentum.

	Correction in 10^{-5}
Trigger	$+26.2 \pm 6.0$
Punch through	-1.4 ± 3.5
Pion ID	-17.1 ± 2.4
Acceptance	± 0.5
Background	± 0.5
Total	$+7.7 \pm 7.2$

Table 1: Corrections and systematic uncertainties on $\delta_L(e)$.

and equals to $2 \times \mathrm{Re}(\epsilon)$ in case of CPT symmetry. Very accurate measurements of the charge asymmetry have already be performed in the 1970's. However, the most precise value comes from a recent measurement of KTeV which yields $\delta_L(e) = (3.322 \pm 0.058 \pm 0.047) \times 10^{-3}$ [2].

In the run period of 2001, alongside the $\pi\pi$ events used for the final ϵ'/ϵ measurement, the NA48 experiment has collected about 2×10^8 K_{e3} events in a special trigger stream. During the data taking, the sign of the magnet current was swapped several times to reduce systematics. All backgrounds have been estimated to be negligible. The main systematic uncertainties arise from asymmetries in the energy deposition of the differently charged pions in the LKr calorimeter. This results in asymmetries in the efficiency of the total-energy trigger and in the pion identification when comparing the LKr-measured energy with the momentum measured in the spectrometer. Both these effects are strongly momentum dependent. They are corrected for by the use of data from control triggers and from well-known control samples as $K_{\mathrm{L}} \to \pi^+\pi^-\pi^0$ or $K_{\mathrm{S}} \to \pi^+\pi^-$. After the correction, no momentum dependency of the result can be seen (Fig. 3).

A summary of the applied corrections and the systematic uncertainties is given in Tab. 1. After the corrections, the (preliminary) result on the charge asymmetry is

$$\delta_L(e) \;=\; (3.317 \pm 0.070_{\mathrm{stat}} \pm 0.072_{\mathrm{syst}}) \times 10^{-3},$$

in very good agreement with the KTeV result quoted above.

3 Search for the CP violating Decay $K_{\mathrm{S}} \to 3\pi^0$ and Measurement of η_{000}

The decay $K_{\mathrm{S}} \to 3\pi^0$ is purely CP violating in complete analogy, but with reversed CP values, to $K_{\mathrm{L}} \to \pi^0\pi^0$. The amplitude ratio compared to the corresponding K_{L} decay is expected to be

$$\eta_{000} \;\equiv\; \frac{A(K_{\mathrm{S}} \to 3\pi^0)}{A(K_{\mathrm{L}} \to 3\pi^0)} \;=\; \epsilon + i\,\frac{\mathrm{Im}(A_1)}{\mathrm{Re}(A_1)}.$$

While the real part is fixed by CPT conservation the imaginary part depends on the isospin 1 amplitude A_1 and may differ from $\mathrm{Im}(\epsilon)$. Experimentally, $K_{\mathrm{S}} \to 3\pi^0$ has never been observed. The parameter η_{000} has been measured to $\mathrm{Re}(\eta_{000}) = 0.18 \pm 0.15$ and $\mathrm{Im}(\eta_{000}) = 0.15 \pm 0.20$ by CPLEAR [3]. In addition, the SND experiment has set a limit on the branching fraction of 1.4×10^{-5} at 90% confidence level [4].

In NA48 K_{L} and K_{S} mesons are produced in equal amounts at the target. The dependence of the $K^0/\overline{K^0} \to 3\pi^0$ intensity as function of proper time therefore is given by

$$I_{3\pi^0}(t) \propto \underbrace{e^{-\Gamma_L t}}_{K_{\mathrm{L}}\text{ decay}} + \underbrace{|\eta_{000}|^2\, e^{-\Gamma_S t}}_{K_{\mathrm{S}}\text{ decay}} + \underbrace{2\,D(p)\,(\mathrm{Re}(\eta_{000})\cos\Delta m t - \mathrm{Im}(\eta_{000})\sin\Delta m t)\; e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)\,t}}_{K_{\mathrm{L}}\text{-}K_{\mathrm{S}}\text{ interference}}$$

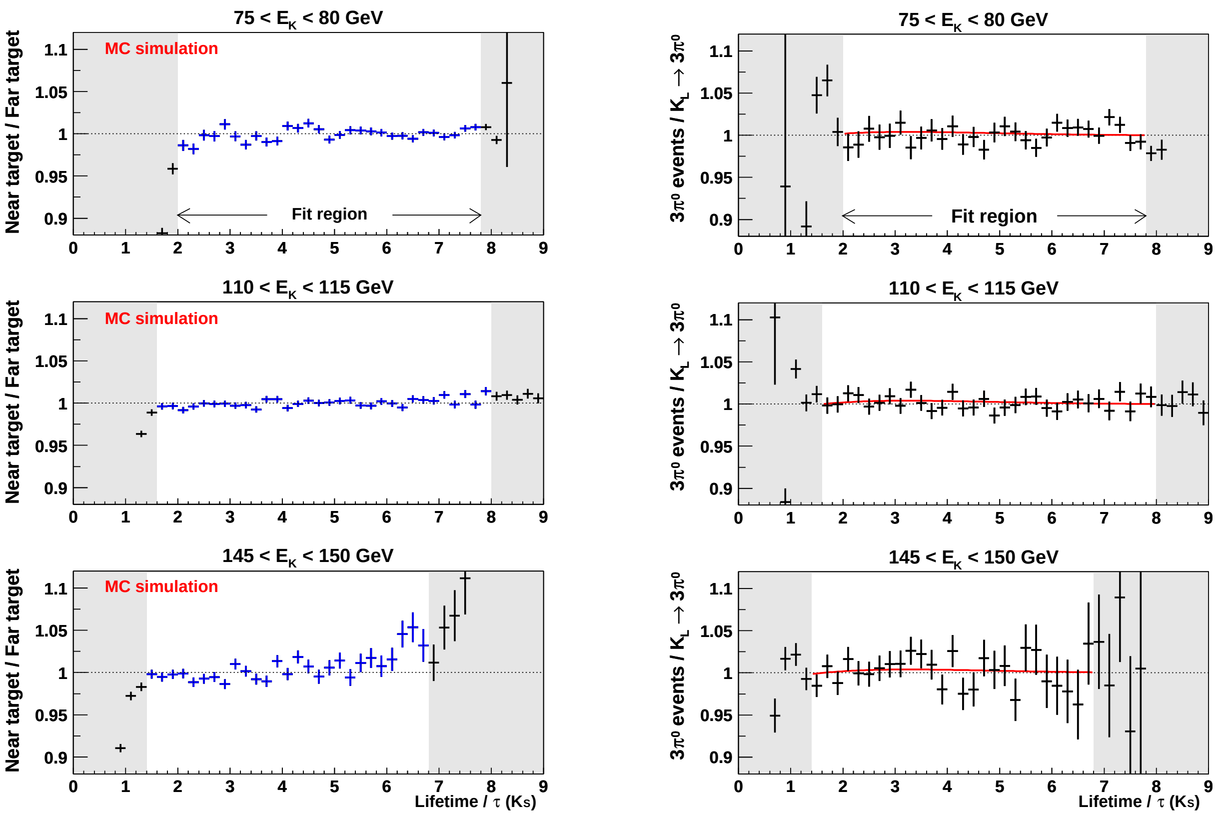

Figure 4: Ratios of $3\pi^0$ events for different energy bins. Left: $K_{\rm L} \to 3\pi^0$ Monte Carlo simulation from near and far target. Right: Near-target data normalized to geometry-corrected far-target $K_{\rm L} \to 3\pi^0$ data.

with the momentum dependent dilution $D(p) = (N(K^0) - N(\overline{K^0})/(N(K^0) - N(\overline{K^0})$. In NA48, this production asymmetry is on average about 0.35 with an almost linear dependency from the kaon momentum. While it is hopeless to observe the pure $K_{\rm S}$ contribution above the $K_{\rm L}$ decay, the $K_{\rm L}K_{\rm S}$ interference is suppressed by only the first order in η_{000}.

For the η_{000} measurement data from the 2000 near-target run period were used. From these data about 6.5×10^6 $3\pi^0$ events were selected with practically negligible background. To be as independent from Monte Carlo simulation as possible data from the far-target run period of the same year were used for normalization to $K_{\rm L} \to 3\pi^0$. In this way, due to the almost identical geometry of near- and far-target beams, only residual effects had to be corrected for by Monte Carlo simulation (see Fig. 4 left). To also be independent of the correct modeling of the different kaon energy spectra in the simulation, the fit to the proper time distribution of the $3\pi^0$ events was performed in bins of energy, leaving all normalizations free in the fit. The fit result is $\mathrm{Re}(\eta_{000}) = -0.026 \pm 0.010$ and $\mathrm{Im}(\eta_{000}) = -0.034 \pm 0.010$ with a correlation coefficient of 0.8. The systematic uncertainties are dominated by uncertainties in the detector acceptance, the accidental activity, and the $K^0\overline{K^0}$ dilution (see Tab. 2). The complete result, which is still preliminary, then is

$$\mathrm{Re}(\eta_{000}) = -0.026 \pm 0.010_{\rm stat} \pm 0.005_{\rm syst} \quad \text{and} \quad \mathrm{Im}(\eta_{000}) = -0.034 \pm 0.010_{\rm stat} \pm 0.011_{\rm syst}.$$

The corresponding confidence limits are shown in Fig. 5. The result is consistent with 0 with roughly 5% probability. Turning this result into an upper limit on the branching fraction, we get

$$\mathrm{Br(K_S \to 3\pi^0) < 1.4 \times 10^{-6}} \quad \text{at 90\% CL},$$

which is one order of magnitude below the previous best limit.

	Re(η_{000})	Im(η_{000})
Acceptance	± 0.003	± 0.008
Accidental activity	± 0.001	± 0.006
Energy scale	± 0.001	± 0.001
$K^0\overline{K^0}$ dilution	± 0.003	± 0.004
Fit	± 0.001	± 0.002
Total:	± 0.005	± 0.011

Table 2: Systematic uncertainties on η_{000}.

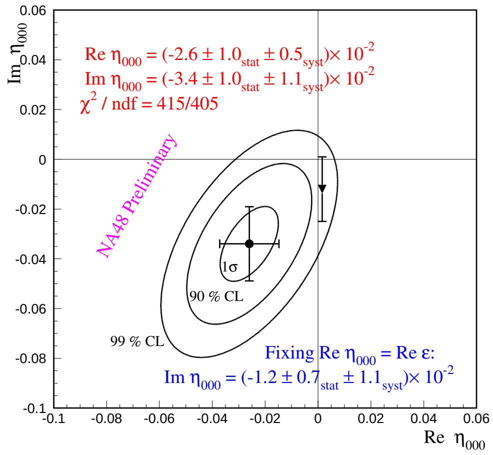

Figure 5: Fit result for η_{000} (preliminary).

Assuming CPT conservation, which fixes Re(η_{000}) to Re(ϵ) $= 1.6 \times 10^{-3}$, we receive

$$\mathrm{Im}(\eta_{000})|_{\mathrm{Re}(\eta_{000})=\mathrm{Re}(\epsilon)} = -0.012 \pm 0.007_{\mathrm{stat}} \pm 0.011_{\mathrm{syst}}$$

and $\mathrm{Br}(\mathrm{K_S} \to 3\pi^0)|_{\mathrm{Re}(\eta_{000})=\mathrm{Re}(\epsilon)} < 3.0 \times 10^{-7}$ at 90% CL.

Finally, this result improves the limit on CPT violation via the Bell-Steinberger relation. Using unitarity, this relation connects the CPT violating phase δ with the CP violating amplitudes of the various K_L and K_S decays [5]. So far, the limiting quantity has been the precision of η_{000}. This new result, added to the measurements of the other η parameters [6,7,8], improves the accuracy on Im(δ) by about 40% to Im(δ) $= (-1.2 \pm 3.0) \times 10^{-5}$, now limited by the knowledge of η_{+-}. Assuming CPT conservation in the decay, this can be converted to a new limit on the $K^0\overline{K^0}$ mass difference of $m_{K^0} - m_{\overline{K^0}} = (-1.7 \pm 4.2) \times 10^{-19}$ GeV$/c^2$.

4 First Observation of the Decay $K_\mathrm{S} \to \pi^0\gamma\gamma$

The decay $K_\mathrm{S} \to \pi^0\gamma\gamma$ has been investigated by using Chiral Perturbation Theory (ChPT) [9]. A comparison of the predicted spectra with pure phase space is shown in Fig. 6 for $z \equiv q^2/m_K^2 = m^2_{\gamma_3\gamma_4}/m_K^2 > 0.2$ far away from the pion pole. The branching fraction is predicted to $\mathrm{Br}(K_\mathrm{S} \to \pi^0\gamma\gamma)|_{z>0.2} = 3.8 \times 10^{-8}$. Experimentally, the decay $K_\mathrm{S} \to \pi^0\gamma\gamma$ had not yet been observed. The best limit has been set only recently by NA48, using data from a test run in 1999 [10].

The new NA48 analysis uses the data from the high-intensity near-target run period of the year 2000. After applying all selection criteria 31 signal candidates remain. Although great care has been taken to suppress all sources of background, the selected sample still contains estimated 13.6 ± 2.7 background events. They consist mostly of accidental beam activity (7.4 ± 2.4 events), which was estimated using time sidebands. Other large sources are irreducible but well-known $K_\mathrm{L} \to \pi^0\gamma\gamma$ events and misidentified $K_\mathrm{S} \to \pi^0\pi^0_{\mathrm{Dalitz}}$ decays. The distribution in Fig. 7 shows the reconstructed invariant π^0 mass of the selected events together with fitted signal and background expectations.

For computing the branching fraction the signal sample is normalized to $K_\mathrm{S} \to \pi^0\pi^0$ decays. The result is

$$\mathrm{Br}(K_\mathrm{S} \to \pi^0\gamma\gamma)|_{z>0.2} = (4.9 \pm 1.6_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}}) \times 10^{-8}.$$

The systematic error is dominated by uncertainties in the background subtraction. The probability of a background fluctuation has been estimated to be less than 9×10^{-4}. The result is compatible with the prediction quoted above. However, the statistics are still too low to conclude from the $m_{\gamma_3\gamma_4}$ spectrum to the structure of the weak vertex (Fig. 8).

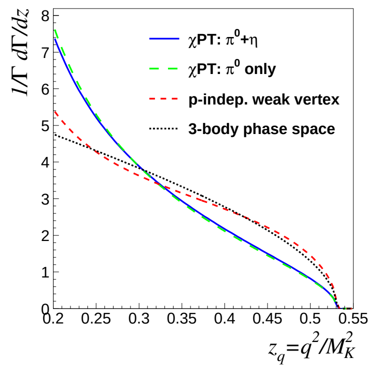

Figure 6: Theoretical predictions for $z = q^2/m_K^2$ in $K_S \to \pi^0\gamma\gamma$ from 3-body phase space and ChPT.

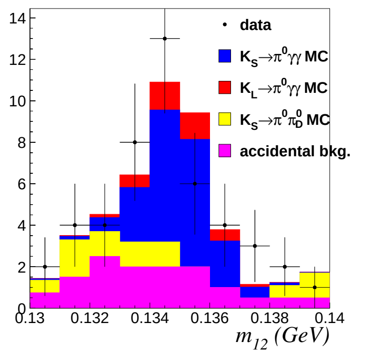

Figure 7: Invariant $m_{\gamma_1\gamma_2}$ mass for the selected $K_S \to \pi^0\gamma\gamma$ candidates with estimated background.

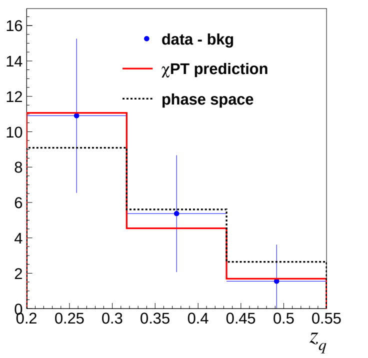

Figure 8: Measured $z = q^2/m_K^2$ for the fitted $K_S \to \pi^0\gamma\gamma$ signal and predictions.

5 A Look into the Future

After having finished the ϵ'/ϵ program, the NA48 collaboration performs two further programs: For the NA48/1 experiment [11] the whole 2002 run period was devoted for investigations of rare K_S and neutral hyperon decays with a high-intensity K_S beam. Among many other interests, the prime goals of this run are the measurement of the rare decay $K_S \to \pi^0 e^+ e^-$, which determines the indirectly CP violating amplitude of $K_L \to \pi^0 e^+ e^-$, and the precision measurement of Ξ^0 beta decays. A first look into the 2002 data shows more than 9000 $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ candidates over very little background. Also a first signal of the so far unobserved channel $\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu$ is seen.

In the year 2003 and possibly 2004 the experiment NA48/2 [12] will investigate $K^\pm$ decays. For this experiment the beam line is greatly modified and a beam spectrometer for $K^\pm$ momentum determination is added. In total, about 3×10^{11} $K^\pm$ decays are expected in 2003 in the fiducial volume. The main goal of this experiment is the search for CP violation in the slope of $K^\pm \to \pi^+\pi^-\pi^\pm$ Dalitz plot, which might be as as large as 10^{-4}. Other goals of the NA48/2 experiment are the measurement of the quark condensate $\langle 0|q\bar{q}|0\rangle$ in K_{e4} decays ($K^+ \to \pi^+\pi^- e^+\nu_e$), an absolute measurement of $\mathrm{Br}(K^+ \to \pi^0 e^+ \nu_e)$ for determination of V_{us}, and many investigations of rare K^+ decays such as $K^+ \to \pi^+\gamma\gamma$ or $K^+ \to l^+ l^- l^+ \nu_l$.

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