# Search for CP violation in the decay of tagged $\overline{K}^0$ and $K^0$ to $\pi^0\pi^0\pi^0$

A. Angelopoulos, A. Apostolakis, E. Aslanides, G. Backenstoss, O. Behnke, A. Benelli, V. Bertin, F. Blanc, P. Bloch, P. Carlson, et al.

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# Search for CP violation in the decay of tagged $\overline{\mathrm{K}}^0$ and $\mathrm{K}^0$ to $\pi^0\pi^0\pi^0$

*CPLEAR Collaboration*

A. Angelopoulos[1], A. Apostolakis[1], E. Aslanides[11], G. Backenstoss[2], P. Bargassa[13], O. Behnke[17], A. Benelli[2], V. Bertin[11], F. Blanc[7], P. Bloch[4], P. Carlson[15], M. Carroll[9], E. Cawley[9], M.B. Chertok[3], M. Danielsson[15], M. Dejardin[14], J. Derre[14], A. Ealet[11], C. Eleftheriadis[16], L. Faravel[7], W. Fetscher[17], M. Fidecaro[4], A. Filipčič[10], D. Francis[3], J. Fry[9], E. Gabathuler[9], R. Gamet[9], H.-J. Gerber[17], A. Go[4], A. Haselden[9], P.J. Hayman[9], F. Henry-Couannier[11], R.W. Hollander[6], K. Jon-And[15], P.-R. Kettle[13], P. Kokkas[4], R. Kreuger[6], R. Le Gac[11], F. Leimgruber[2], I. Mandić[10], N. Manthos[8], G. Marel[14], M. Mikuž[10], J. Miller[3], F. Montanet[11], A. Muller[14], T. Nakada[13], B. Pagels[17], I. Papadopoulos[16], P. Pavlopoulos[2], G. Polivka[2], R. Rickenbach[2], B.L. Roberts[3], T. Ruf[4], M. Schäfer[17], L.A. Schaller[7], T. Schietinger[2], A. Schopper[4], L. Tauscher[2], C. Thibault[12], F. Touchard[11], C. Touramanis[9], C.W.E. Van Eijk[6], S. Vlachos[2], P. Weber[17], O. Wigger[13], M. Wolter[17], D. Zavrtanik[10] and D. Zimmerman[3]

## Abstract

The CPLEAR experiment measured the eigentime-dependent asymmetry in the rates of initially tagged $\overline{\mathrm{K}}^0$ and $\mathrm{K}^0$ decaying to $\pi^0\pi^0\pi^0$ in order to study the interference between the CP-violating $\mathrm{K_S}$ and the CP-conserving $\mathrm{K_L}$ decay amplitudes. Without assuming CPT invariance, we obtain for the CP-violation parameter $\eta_{000}$ the values $\mathrm{Re}(\eta_{000}) = 0.18 \pm 0.14_{\mathrm{stat.}} \pm 0.06_{\mathrm{syst.}}$ and $\mathrm{Im}(\eta_{000}) = 0.15 \pm 0.20_{\mathrm{stat.}} \pm 0.03_{\mathrm{syst.}}$. Requiring $\mathrm{Re}(\eta_{000})$ to be equal to $\mathrm{Re}(\epsilon)$ we obtain $\mathrm{Im}(\eta_{000}) = -0.05 \pm 0.12_{\mathrm{stat.}} \pm 0.05_{\mathrm{syst.}}$. The corresponding upper limit for the branching ratio of the $\mathrm{K_S} \to \pi^0\pi^0\pi^0$ decay is deduced to be $B_{\mathrm{K_S}\to\pi^0\pi^0\pi^0} < 1.9 \times 10^{-5}$ at the 90% confidence level.

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1) University of Athens, Greece
2) University of Basle, Switzerland
3) Boston University, USA
4) CERN, Geneva, Switzerland
5) LIP and University of Coimbra, Portugal
6) Delft University of Technology, Netherlands
7) University of Fribourg, Switzerland
8) University of Ioannina, Greece
9) University of Liverpool, UK
10) J. Stefan Inst. and Phys. Dep., University of Ljubljana, Slovenia
11) CPPM, IN2P3-CNRS et Université d'Aix-Marseille II, France
12) CSNSM, IN2P3-CNRS, Orsay, France
13) Paul Scherrer Institut (PSI), Switzerland
14) CEA, DSM/DAPNIA, CE-Saclay, France
15) Royal Institute of Technology, Stockholm, Sweden
16) University of Thessaloniki, Greece
17) ETH-IPP Zürich, Switzerland

## 1 Introduction

The CPLEAR experiment at the Low Energy Antiproton Ring at CERN uses tagged $\overline{\mathrm{K}}^0$ and $\mathrm{K}^0$ to study CP, T and CPT symmetries in the neutral-kaon system. In this letter we present the measurement of CP-violation parameters obtained from the decay of initially tagged $\overline{\mathrm{K}}^0$ and $\mathrm{K}^0$ decaying to $\pi^0\pi^0\pi^0$. In a previous CPLEAR publication the measurement of the CP parameters of neutral kaons decaying to $\pi^+\pi^-\pi^0$ was reported [1]. In contrast to this final state, the $\pi^0\pi^0\pi^0$ state has a well-defined CP eigenvalue and the CP-conserving $\mathrm{K_S} \to \pi^0\pi^0\pi^0$ decay does not occur. The CP-violation parameter $\eta_{000}$ is defined as the ratio of $\mathrm{K_S}$ to $\mathrm{K_L}$ decay amplitudes: $\eta_{000} \equiv A(\mathrm{K_S} \to \pi^0\pi^0\pi^0)/A(\mathrm{K_L} \to \pi^0\pi^0\pi^0)$. If CPT invariance holds, then Re$(\eta_{000})$ is a measure of CP violation in the mixing of neutral kaons, and Im$(\eta_{000})$ is sensitive to a possible direct CP violation in the decay amplitudes. Furthermore, the CP-violation parameters of neutral kaons decaying to three pions provide an important experimental input to a test of CPT symmetry based on the Bell–Steinberger relation [2, 3].

## 2 Experimental method

The neutral kaons are produced in the annihilations $\overline{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}^0\mathrm{K}^+\pi^-$ and $\overline{\mathrm{p}}\mathrm{p} \to \mathrm{K}^0\mathrm{K}^-\pi^+$. Owing to strangeness conservation in the annihilation process the strangeness of the neutral kaon is determined on an event-by-event basis by identifying the simultaneously produced charged kaon (tagging). This technique allows the measurement of differences between the CP conjugate rates $R(\overline{\mathrm{K}}^0 \to \pi^0\pi^0\pi^0)(\tau)$ and $R(\mathrm{K}^0 \to \pi^0\pi^0\pi^0)(\tau)$ to be made through the eigentime-dependent rate asymmetry

$$A_{000}(\tau) \equiv \frac{R(\overline{\mathrm{K}}^0 \to \pi^0\pi^0\pi^0)(\tau) - R(\mathrm{K}^0 \to \pi^0\pi^0\pi^0)(\tau)}{R(\overline{\mathrm{K}}^0 \to \pi^0\pi^0\pi^0)(\tau) + R(\mathrm{K}^0 \to \pi^0\pi^0\pi^0)(\tau)} , \quad (1)$$

which is sensitive to the $\mathrm{K_S}$–$\mathrm{K_L}$ interference term. The CP-violation parameter $\eta_{000}$ is derived from the time dependence of this asymmetry:

$$A_{000}(\tau) = 2\mathrm{Re}(\epsilon) - 2[\mathrm{Re}(\eta_{000})\cos(\Delta m\tau) - \mathrm{Im}(\eta_{000})\sin(\Delta m\tau)]\mathrm{e}^{-\frac{1}{2}(1/\tau_\mathrm{S} - 1/\tau_\mathrm{L})\tau} , \quad (2)$$

where $\tau$ denotes the decay eigentime of the neutral kaon, $\tau_\mathrm{S}$ and $\tau_\mathrm{L}$ are the mean lives of $\mathrm{K_S}$ and $\mathrm{K_L}$ respectively, $\Delta m$ is the $\mathrm{K_L}$–$\mathrm{K_S}$ mass difference and $\epsilon$ describes the CP violation in $\overline{\mathrm{K}}^0$–$\mathrm{K}^0$ oscillations.

## 3 Detector description

A brief description of the CPLEAR detector is given here. More details can be found in Ref. [4]. Antiprotons of 200 MeV/$c$ are delivered by LEAR and are stopped inside a high-pressure, gaseous-hydrogen target at a rate of about $10^6$ per second. The cylindrical detector is placed inside a solenoid of 1 m radius and 3.6 m length, which provides a magnetic field of 0.44 T. Charged-particle tracks are detected by two proportional chambers, six drift chambers and two layers of streamer tubes. Fast kaon identification is provided by a threshold Cherenkov counter sandwiched between two scintillators which also provide ionization and time-of-flight measurements. An electromagnetic calorimeter made of 18 layers of lead converters and high-gain tubes is used for photon detection. Fast and efficient online data selection is achieved with a multi-level trigger system based on custom-made hardwired processors.

## 4 Event selection and reconstruction

The decay $\mathrm{K}^0(\overline{\mathrm{K}}^0) \to \pi^0\pi^0\pi^0 \to 6\gamma$ is selected by requiring two charged tracks that have been identified as a kaon and a pion, and six electromagnetic showers in the calorimeter [5]. In order to determine the neutral-kaon decay time, the position of the annihilation vertex and the four-momentum of the neutral kaon are calculated from the track parameters of the charged kaon and pion, whereas the decay vertex of the neutral kaon along its direction of flight is determined from the six photon showers measured in the calorimeter. The average energies of the least and most energetic photons are $\approx 40$ and $\approx 250$ MeV, respectively. The reconstruction of the showers is provided by the shower-pattern recognition algorithm described in Ref. [5]. To suppress photons generated by secondary interactions of charged tracks in the calorimeter, showers are only accepted if their conversion point is at least 50 or 25 cm from the charged-kaon or -pion track extrapolation into the calorimeter, respectively.

The neutral-kaon decay time is determined by a full geometrical and kinematical reconstruction of the annihilation $\overline{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}^0(\mathrm{K}^0)\mathrm{K}^\pm\pi^\mp$ and the neutral-particle cascade $\mathrm{K}^0 \to \pi^0\pi^0\pi^0 \to 6\gamma$ through a constrained fit. This fit requires energy and momentum conservation, the missing mass at the annihilation vertex to equal the $\mathrm{K}^0$ mass, and the $\gamma\gamma$ invariant masses of the three $\gamma\gamma$ pairs to equal the $\pi^0$ mass. The fit assumes that the six photons originate from a common point located on the flight direction of the neutral kaon, namely the unknown neutral-kaon decay vertex. As can be shown by simulation, the $\mathrm{K}^0$ momentum and the precise measurement of the photon conversion points contribute most of the information required to find the neutral-kaon decay vertex. The photon energies are used in the fit in order to find the correct association of the six photons to the three intermediate neutral pions. This is achieved by application of the constrained fit to all fifteen possible $\gamma\gamma$ pairings. The pairings with the lowest $\chi^2$ values are chosen. The directions of the showers are not used in the fit. Simulation also shows that the reconstructed neutral-kaon momentum is entirely determined by the charged-track information, and that the photons do not contribute to additional useful information. Therefore the $\chi^2$-probability provided by the fit can be expressed as the sum of two almost uncorrelated probabilities: one related to the reconstruction of the $\mathrm{K}^0$ missing mass determined by the charged particles ($\chi^2_{\mathrm{charged}}$), and one related to the reconstruction of the $\pi^0$ invariant masses determined by the six photons ($\chi^2_{\mathrm{neutral}}$). A cut of 10% on the $\chi^2_{\mathrm{neutral}}$-probability is used for event selection and for background reduction, but no cut is applied to the $\chi^2_{\mathrm{charged}}$-probability in order to allow for background studies with an unbiased missing-mass distribution.

The decay-time resolution obtained for signal events is determined from simulation. As can be seen from Fig. 1 the resolution depends slightly on the neutral-kaon decay time and varies from 4.2 to 4.8 $\tau_{\mathrm{S}}$ (RMS) between 0 and 20 $\tau_{\mathrm{S}}$.

The acceptance for reconstructing signal events as a function of the neutral-kaon decay time is obtained by simulation and is shown in Fig. 2a.

Figure 2b shows the decay-time distribution for simulated $\mathrm{K}^0(\overline{\mathrm{K}}^0) \to \pi^0\pi^0\pi^0$ events after full reconstruction. Note that, because of the finite decay-time resolution, the reconstructed decay time for signal events can become negative. Therefore, events populating the decay-time region below zero $\tau_{\mathrm{S}}$ also contribute to the decay-time asymmetry.

## 5 Signal and background determination

Sources of background are the kaonic annihilation channels $\overline{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}^0(\mathrm{K}^0)\mathrm{K}^\pm\pi^\mp + \pi^0$, the pionic annihilation channel $\overline{\mathrm{p}}\mathrm{p} \to \pi^+\pi^- + n\pi^0$ $(n \geq 0)$ with a charged pion mistaken for a charged kaon, and the neutral-kaon decay $\mathrm{K}^0 \to \pi^0\pi^0 \to 4\gamma$ with two additional photons that originate from the strong interaction or the decay of the accompanying charged particles in the calorimeter.

The number of $K^0(\overline{K}^0) \to \pi^0\pi^0\pi^0$ events and the contribution of background to the data are determined from the reconstructed decay-time distribution and from the $K^\pm\pi^\mp$ missing-mass spectrum, by fitting reference distributions for signal and background to the measured ones. The reference distributions are obtained from simulations of the signal and of the background with neutral-kaon decays. For the pionic-annihilation background these distributions are obtained from data by studying the energy-loss distribution of the charged particles in the inner scintillator of the particle-identification detector. The proportion of signal to background events in the data is determined from a simultaneous fit of the reference distributions to the measured missing-mass and decay-time distributions, leaving the number of events for each contribution as a free parameter in the fit.

Figures 3 and 4 show the measured missing-mass and decay-time distributions, respectively. The measured distributions are compared with the result of the fit. Also shown are the individual contributions of signal and background. The correlation coefficients between the signal and the different background contributions given by the fit vary between 0.04 and 0.32. Those for the background channels relative to each other vary between 0.02 and 0.68. The biggest correlation is observed between the backgrounds from pionic annihilations and from secondary interactions generating photons.

In the $K^\pm\pi^\mp$ missing-mass spectrum (Fig. 3) one can distinguish the signal events, that correspond to the neutral-kaon mass, from the kaonic-annihilation channels with an additional $\pi^0$, which populate the high-mass region, and from the pionic annihilations, which contribute to the low-mass region. In order to reject background, only events in the missing-mass square interval of 0.15 to 0.35 $\mathrm{GeV}^2/c^4$ are accepted. In the decay-time distribution (Fig. 4), most of the events at positive decay times are signal events, while events reconstructed at negative decay times are mainly background. In order to retain most of the signal events and to reject a significant amount of background, a decay-time interval of $-1$ to 20 $\tau_S$ is selected. The events $K^0(\overline{K}^0) \to \pi^0\pi^0\pi^0$ with an additional $\pi^0$ are treated as background, because the reconstruction of their decay time is affected by the presence of the additional $\pi^0$. Kaon decays that are accompanied by additional photons from secondary interactions are suppressed, by requesting that the minimal $\gamma\gamma$ invariant mass of all possible $\gamma\gamma$ combinations be larger than 12 MeV/$c^2$.

Table 1 summarizes the contributions of signal and background to the final data sample, in a missing-mass square interval of 0.15 to 0.35 $\mathrm{GeV}^2/c^4$ and a decay-time interval of $-1$ to 20 $\tau_S$.

## 6 Determination of $\eta_{000}$

The results reported here are based on all events collected by the CPLEAR experiment. Selecting the missing-mass square region of 0.15 to 0.35 $\mathrm{GeV}^2/c^4$, a total of 17'300 $K^0(\overline{K}^0) \to \pi^0\pi^0\pi^0$ events are reconstructed in the decay-time interval $-1$ to 20 $\tau_S$. The measured time-dependent decay-rate asymmetry is shown in Fig. 5a.

The relative efficiency $\xi$ for tagging $\overline{K}^0$ and $K^0$ in the experiment deviates from unity, since the charged particles used to determine the strangeness of the neutral kaon interact differently with the detector material depending on their charge and momentum. Since the theoretical asymmetry of Eq. (2) has a constant term of $2\mathrm{Re}(\epsilon)$, the total offset of the measured asymmetry in Fig. 5a is $(\alpha - 1)/(\alpha + 1)$, where $\alpha = \xi[1 + 4\mathrm{Re}(\epsilon)]$.

The values of $\mathrm{Re}(\eta_{000})$ and $\mathrm{Im}(\eta_{000})$ are extracted from a likelihood fit of the asymmetry given by Eq. (2) to the measured decay-rate asymmetry, taking into account the parametrized decay-time resolution as shown in Fig. 1, and the background contributions as listed in Table 1. The $\alpha$-value is left as a free parameter in the fit, assuming that the tagging efficiency is the same for all kaonic annihilation channels. The relative contribution of pionic background to the $K^0$

| Signal | Contribution [%] |
|---|---|
| $\overline{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}^0(\mathrm{K}^0)\mathrm{K}^{\pm}\pi^{\mp}$ ; $\overline{\mathrm{K}}^0(\mathrm{K}^0) \to \pi^0\pi^0\pi^0$ | $50.0 \pm 0.8$ |
| **Background** | **Contribution [%]** |
| $\overline{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}^0(\mathrm{K}^0)\mathrm{K}^{\pm}\pi^{\mp} + \pi^0$ ; $\overline{\mathrm{K}}^0(\mathrm{K}^0) \to \pi^0\pi^0\pi^0$ | $4.9 \pm 0.2$ |
| $\overline{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}^0(\mathrm{K}^0)\mathrm{K}^{\pm}\pi^{\mp} + \pi^0$ ; $\overline{\mathrm{K}}^0(\mathrm{K}^0) \to \pi^0\pi^0$ | $3.7 \pm 0.2$ |
| $\overline{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}^0(\mathrm{K}^0)\mathrm{K}^{\pm}\pi^{\mp} +$ secondary photons ; $\overline{\mathrm{K}}^0(\mathrm{K}^0) \to \pi^0\pi^0$ | $16.5 \pm 0.3$ |
| $\overline{\mathrm{p}}\mathrm{p} \to \pi^+\pi^- + n \cdot \pi^0$ $(n \geq 0)$ | $24.9 \pm 0.5$ |

Table 1: Contributions of signal and background to the final data sample in the decay time interval $-1$ to 20 $\tau_{\mathrm{S}}$ and within a missing-mass square interval of 0.15 to 0.35 GeV$^2/c^4$. The quoted errors are statistical.

and $\overline{\mathrm{K}}^0$ signal is determined from the study of the energy-loss distribution in the scintillator and is fixed to $1.18 \pm 0.02$. The values for the mass difference and the $\mathrm{K_S}$ mean life are fixed at $\Delta m = (530.7 \pm 1.3) \times 10^7\ \hbar\mathrm{s}^{-1}$, and $\tau_{\mathrm{S}} = (89.22 \pm 0.10)$ ps as determined in Ref. [6]; the value for the $\mathrm{K_L}$ mean life is fixed at $\tau_{\mathrm{L}} = (51.7 \pm 0.4)$ ns as given by Ref. [7]. The fit yields

$$\mathrm{Re}(\eta_{000}) = 0.18 \pm 0.14_{\text{stat.}}$$
$$\mathrm{Im}(\eta_{000}) = 0.15 \pm 0.20_{\text{stat.}}$$

with $\alpha = 1.10 \pm 0.03$, where the error is statistical. The result of the fit is shown as a solid line in Fig. 5a. The correlation coefficient between $\mathrm{Re}(\eta_{000})$ and $\mathrm{Im}(\eta_{000})$ given by the fit is 0.79. The correlations of $\alpha$ with $\mathrm{Re}(\eta_{000})$ and $\mathrm{Im}(\eta_{000})$ are $-0.09$ and $-0.56$, respectively.

## 7 Systematic uncertainties

The contributions to the systematic uncertainties in the determination of $\mathrm{Re}(\eta_{000})$ and $\mathrm{Im}(\eta_{000})$ are discussed below and are summarized in Table 2.

- *The resolution in reconstructing the neutral-kaon decay time.*
  Uncertainties in the reconstruction of the neutral-kaon decay time have been studied using simulation. To evaluate the systematic errors in the values of $\mathrm{Re}(\eta_{000})$ and $\mathrm{Im}(\eta_{000})$ the width of the resolution function has been increased by 10% compared to the one extracted from the simulation (see Fig. 1). Furthermore, possible deviations in the decay-time dependence of the resolution function from the simulation have been considered by fitting the asymmetry with a resolution function of 5 $\tau_{\mathrm{S}}$ (RMS) for all decay times.
  The effect of different parametrizations of the resolution function has been studied, and found to be negligible.
- *The amount of background contributing to the sum of $\mathrm{K}^0$ and $\overline{\mathrm{K}}^0$.*
  Systematic uncertainties in the amount of signal and background in the data were estimated by comparing the results from the simultaneous fit with the level of signal and background obtained from independent fits of the reference distributions to the measured missing-mass and decay-time distributions. The proportions of signal and background obtained from the different fits agree within better than 3%. The amount of pionic annihilations was also estimated from a study of the energy-loss distribution of the charged

| Source | $\Delta$Re$(\eta_{000})$ | $\Delta$Im$(\eta_{000})$ |
|---|---|---|
| $\overline{\mathrm{K}}^0$($\mathrm{K}^0$) decay-time resolution | 0.01 | 0.01 |
| Amount of background in $\mathrm{K}^0$+ $\overline{\mathrm{K}}^0$ | 0.02 | 0.02 |
| Difference in background contribution to $\mathrm{K}^0$ and $\overline{\mathrm{K}}^0$ | 0.05 | 0.01 |
| Regeneration | $\ll 0.01$ | $\ll 0.01$ |
| $\Delta m$ , $\tau_{\mathrm{S}}$ [6] and $\tau_{\mathrm{L}}$ [7] | $\ll 0.01$ | $\ll 0.01$ |
| **Total** | **0.06** | **0.03** |

Table 2: Contributions to the systematic errors on Re$(\eta_{000})$ and Im$(\eta_{000})$.

particles in the scintillators, and gives a value that is 7% smaller than the result of the fit. The systematic errors on Re$(\eta_{000})$ and Im$(\eta_{000})$ were determined by varying the amount of signal and background from kaon decays by $\pm 3\%$, and by reducing the pionic annihilations by 7% compared to the mean values given in Table 1, taking into account their correlations.

- *The relative contribution of background to the* $\mathrm{K}^0$ *and* $\overline{\mathrm{K}}^0$ *signal.*
  The relative contribution of background to the $\mathrm{K}^0$ and $\overline{\mathrm{K}}^0$ signal can be different from the relative tagging efficiency of $\mathrm{K}^0$ and $\overline{\mathrm{K}}^0$. The tagging efficiency as well as the relative contribution of each background channel has been determined from simulation for the kaon decays. The values are all compatible within better than 5% and in agreement, within statistical errors, with the $\alpha$-value resulting from the asymmetry fit. The relative contribution of pionic background to the $\mathrm{K}^0$ and $\overline{\mathrm{K}}^0$ signal is determined from the study of the energy-loss distribution in the scintillator and yields $1.18 \pm 0.02$. The systematic errors on Re$(\eta_{000})$ and Im$(\eta_{000})$ are evaluated by varying the relative contribution of background to $\mathrm{K}^0$ and to $\overline{\mathrm{K}}^0$ within ±5% for each background channel.
- *Uncertainties due to regeneration effects.*
  It was evaluated that, taking into account the regeneration amplitudes as measured by CPLEAR [8], the effect of neutral-kaon regeneration is negligible at short decay time where the asymmetry is maximal.
- *Uncertainties related to* $\Delta m$ *,* $\tau_{\mathrm{L}}$ *and* $\tau_{\mathrm{S}}$*.*
  The experimental uncertainties on the values of $\Delta m$ and $\tau_{\mathrm{S}}$ as determined in Ref. [6], and of $\tau_{\mathrm{L}}$ as given in Ref. [7], have a negligible influence on the results of the fit.

## 8 Final results and conclusions

Our final result from 17’300 reconstructed $\mathrm{K}^0(\overline{\mathrm{K}}^0) \to \pi^0\pi^0\pi^0$ events is,

$$\begin{aligned} \mathrm{Re}(\eta_{000}) &= 0.18 \pm 0.14_{\text{stat.}} \pm 0.06_{\text{syst.}} \\ \mathrm{Im}(\eta_{000}) &= 0.15 \pm 0.20_{\text{stat.}} \pm 0.03_{\text{syst.}} \,. \end{aligned}$$

These results are independent of any assumption on CPT invariance. This is the first determination of $\eta_{000}$ using the rate asymmetry of initially pure $\overline{\mathrm{K}}^0$ and $\mathrm{K}^0$ decaying to $\pi^0\pi^0\pi^0$. We have obtained an improved sensitivity for $\eta_{000}$ compared to the previous measurement [9], as shown in Fig. 5b.

By fixing Re$(\eta_{000})$ to $\mathrm{Re}(\epsilon) = 1.635 \times 10^{-3}$ [7] in the fit, we obtain

$$\mathrm{Im}(\eta_{000}) \;\; = \;\; -0.05 \pm 0.12_{\mathrm{stat.}} \pm 0.05_{\mathrm{syst.}} \; .$$

Using the definition of $\eta_{000}$ and $B_{\mathrm{K_L}\to\pi^0\pi^0\pi^0} = (21.12 \pm 0.27)\%$ from Ref. [7], an upper limit for the branching ratio of the $\mathrm{K_S} \to \pi^0\pi^0\pi^0$ decay is deduced to be

$$B_{\mathrm{K_S}\to\pi^0\pi^0\pi^0} < 1.9 \times 10^{-5}$$

at the 90% confidence level, which is an improvement by a factor of two compared to the measurements of Ref. [9].

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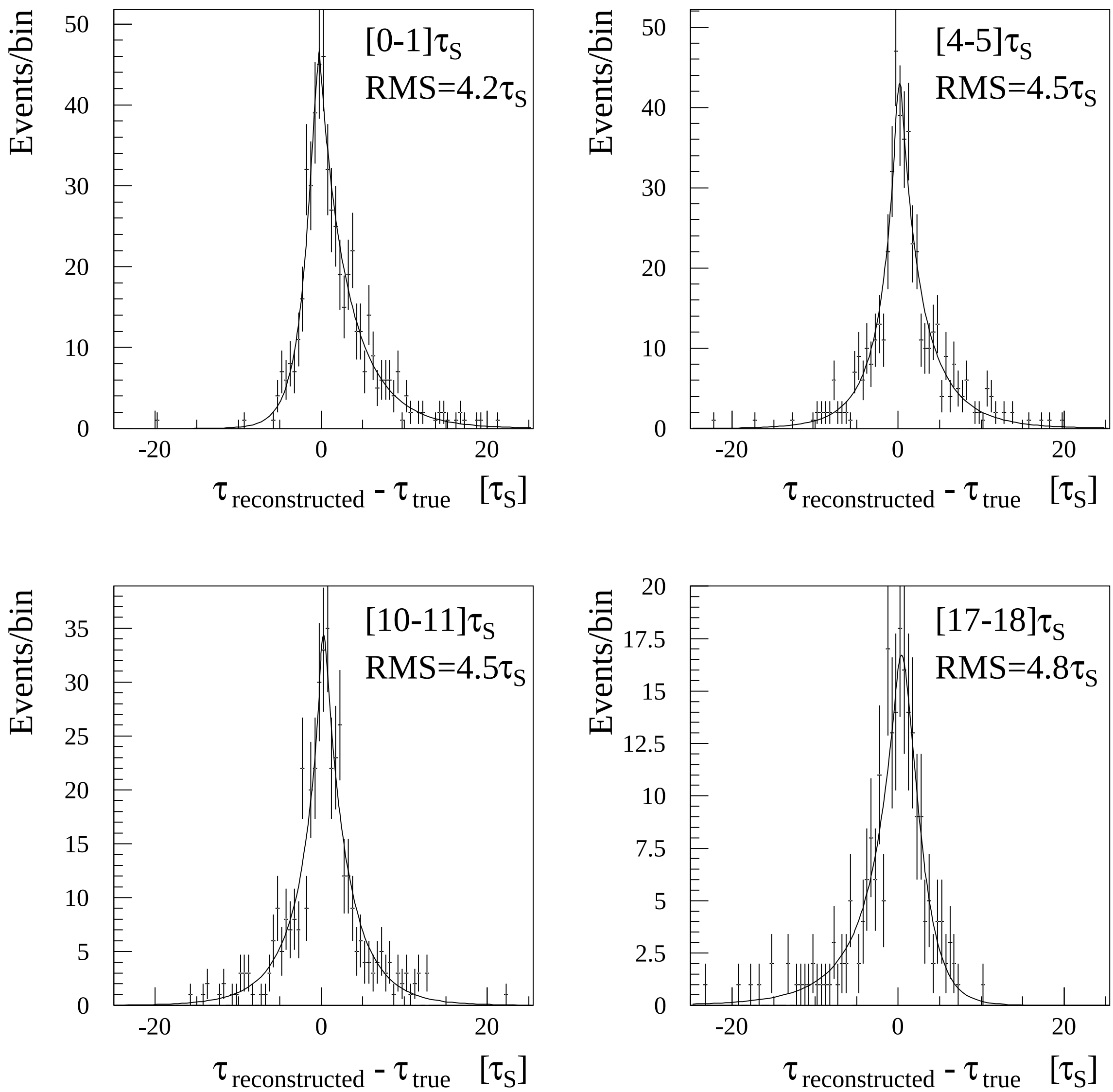


Figure 1: The decay-time resolution for four different decay-time regions as derived from simulation. The solid line shows the parametrization of the resolution function.

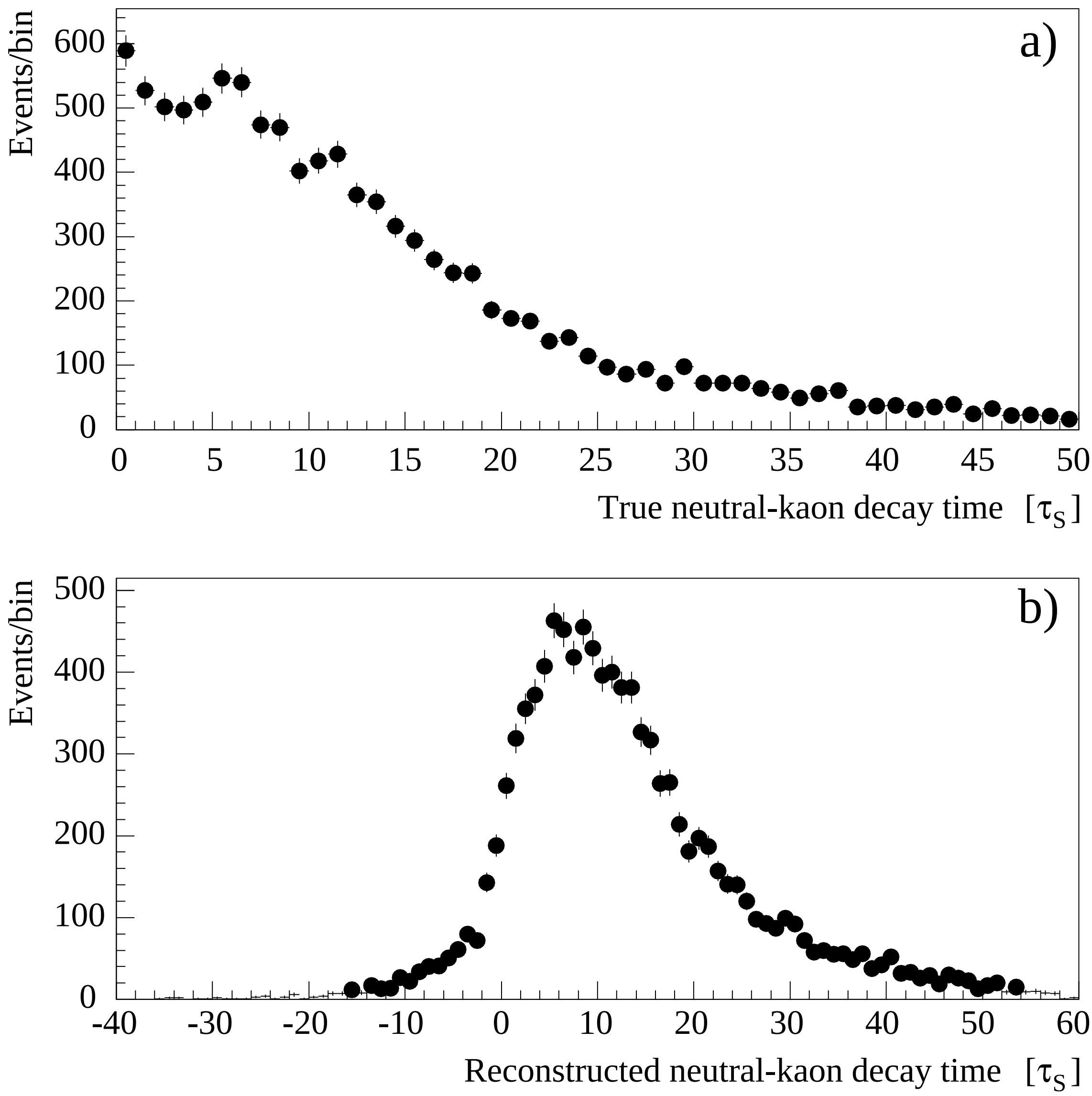


Figure 2: a) The acceptance for detection and reconstruction of $K^0(\overline{K}^0) \to \pi^0\pi^0\pi^0$ as a function of the true decay time, derived from simulation. b) The reconstructed decay time for $K^0(\overline{K}^0) \to \pi^0\pi^0\pi^0$, derived from simulation.

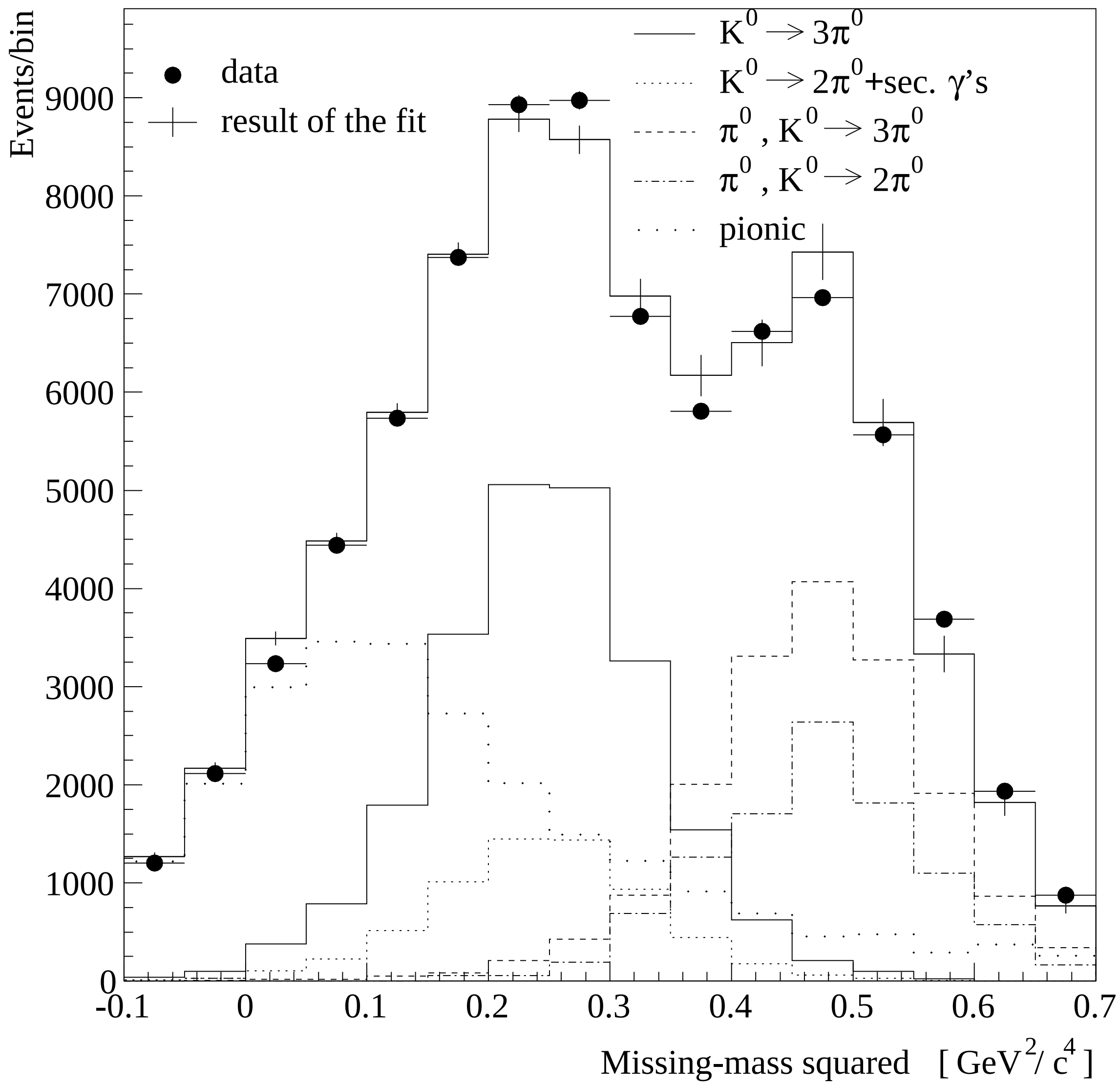


Figure 3: The measured missing-mass squared of $K^{\pm}\pi^{\mp}$ emerging from $\overline{p}p$ annihilation. Only events with a neutral kaon detected within a decay-time interval of $-1$ to 20 $\tau_S$ are retained. Overlayed are the signal and background contributions resulting from the fit (see text). One can distinguish the signal events, that correspond to the neutral-kaon mass, from the kaonic-annihilation channels with an additional $\pi^0$, which populate the high-mass region, and from the pionic annihilations, which contribute to the low-mass region.

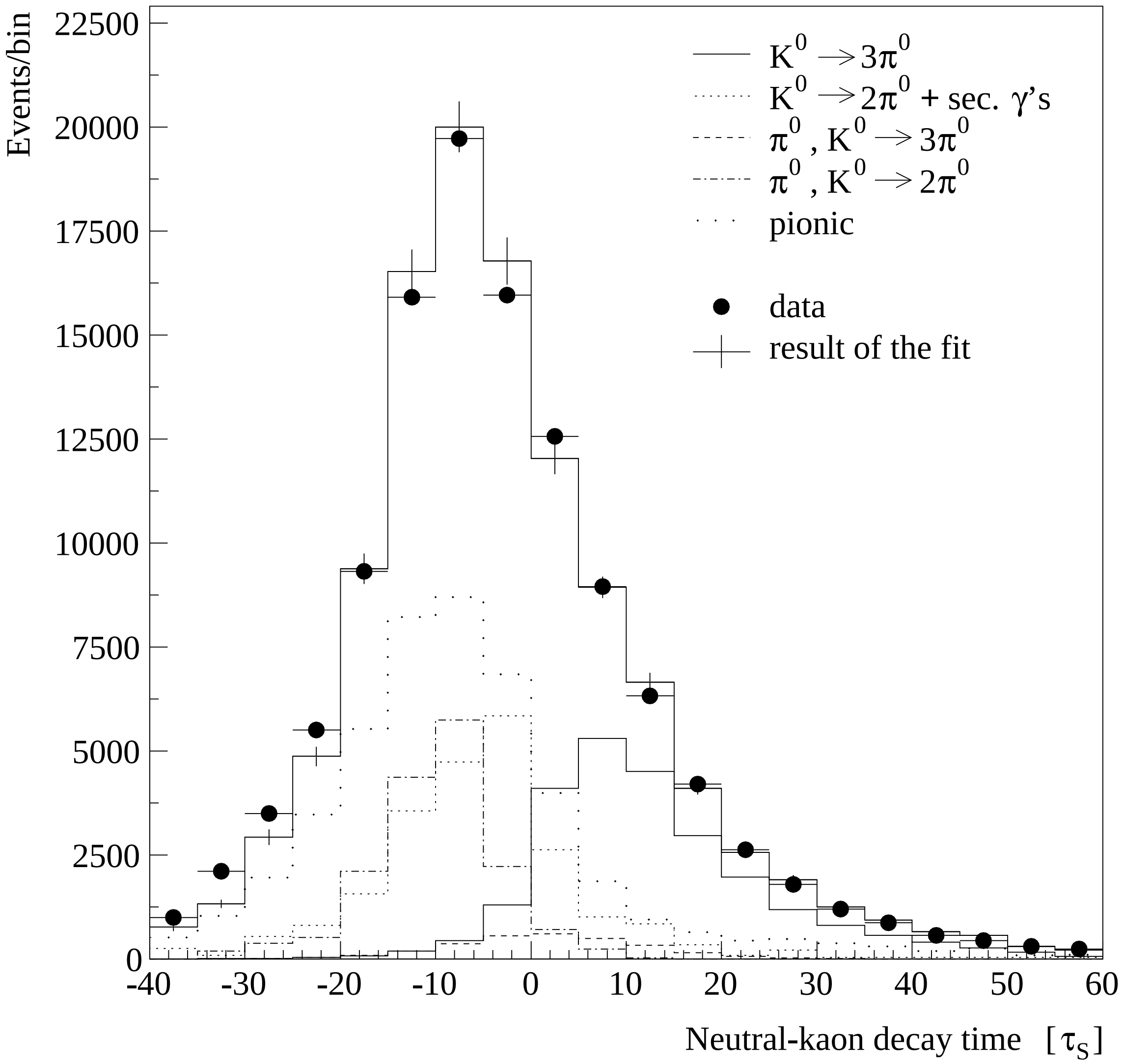


Figure 4: The measured neutral-kaon decay-time distribution in the missing-mass squared interval 0.15 to 0.35 $\mathrm{GeV}^2/c^4$. Overlayed are the signal and background contributions resulting from the fit (see text). At positive decay times most of the events are signal events, while events reconstructed at negative decay times are mainly background.

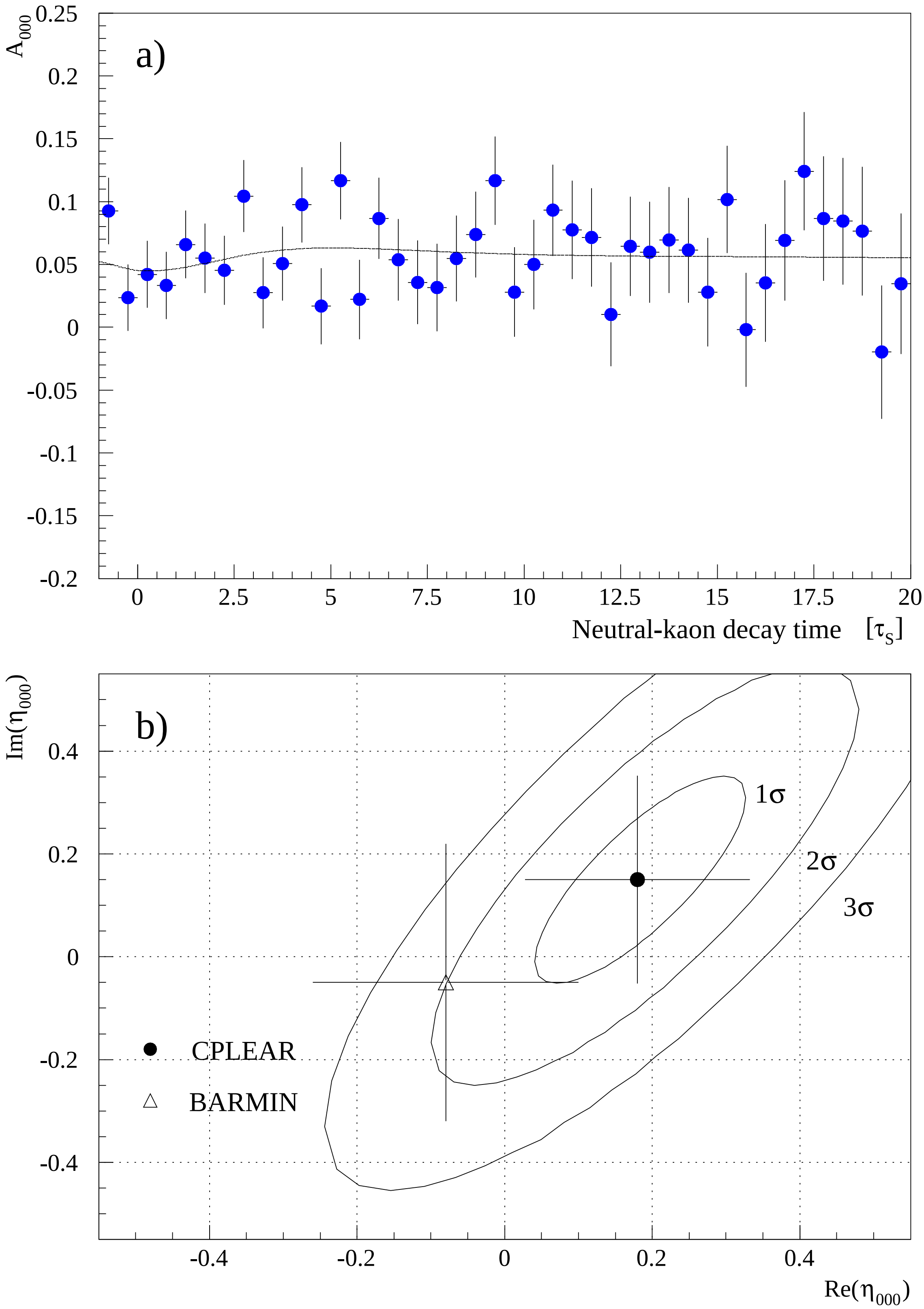


Figure 5: a) The measured time-dependent CP asymmetry between $-1$ and 20 $\tau_S$. The solid line shows the result of the fit of Eq. (2) to the data, taking into account the decay-time resolution, and the background contributions as listed in Table 1. b) The contour plot for $\mathrm{Re}(\eta_{000})$ and $\mathrm{Im}(\eta_{000})$ obtained in this analysis; the error bars represent the statistical and systematic uncertainties added in quadrature. For comparison, the result of Barmin et al. [9] is also shown; their error bars are statistical.