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Measurement of the CP Violation Parameter η_{+-} using tagged K^0 and $\overline{K}^0$

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Abstract

The CP violation parameter η_{+-} is determined through the eigentime–dependent asymmetry in the rates of initially tagged K^0 and $\overline{K}^0$ decaying to $\pi^+\pi^-$. The obtained values are $|\eta_{+-}| = (2.312 \pm 0.043_{\rm stat.} \pm 0.030_{\rm syst.} \pm 0.011_{\tau_S}) \times 10^{-3}$ and $\phi_{+-} = 42.7^\circ \pm 0.9^\circ_{\rm stat.} \pm 0.6^\circ_{\rm syst.} \pm 0.9^\circ_{\Delta m}$ with $\Delta m = (527.4 \pm 2.9) \times 10^7 \hbar\,{\rm s}^{-1}$ measured in the same experiment using the semileptonic decay channel.

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1 Introduction

Thirty years after the discovery of CP violation in the neutral kaon decays, systematic and precise studies of discrete symmetries in the neutral kaon system are still of great interest and may reveal physics beyond the Standard Model. For example, a comparison of the phase ϕ_{+-} with the superweak phase $\phi_{\rm SW}$ provides the most sensitive test of CPT invariance [1]. Such tests probe interactions at very high energy scales [2], and are one of the main objectives of recent and planned experiments [3–7].

The magnitude and phase of the CP violation parameter η_{+-} are obtained by measuring the interference between $\rm K_L$ and $\rm K_S$ decay amplitudes into two charged pions. In the CPLEAR experiment this interference is directly measured using the asymmetry between the rates of $\rm K^0$ and $\rm \overline{K}^0$ decays. In contrast to other interference experiments [3–6] the initial strangeness of the neutral kaon is known event by event using this approach [8]. In this paper we present a new precise measurement of $|\eta_{+-}|$ and ϕ_{+-} from data collected up to mid 1994.

2 Overview of the method

The CPLEAR experiment uses initially pure $\rm K^0$ and $\rm \overline{K}^0$ states produced concurrently in the annihilation channels $(\rm p\overline{p})_{rest} \to K^0K^-\pi^+$ and $(\rm p\overline{p})_{rest} \to \overline{K}^0K^+\pi^-$, each with a branching ratio of $\approx 0.2\%$. The strangeness of the neutral kaon is tagged by the charge sign of the accompanying kaon. The rates for initially pure $\rm K^0$ and $\rm \overline{K}^0$ decaying into the $\pi^+\pi^-$ final state, $R(\tau)$ and $\overline{R}(\tau)$ respectively, can be expressed as a function of the decay eigentime τ by:

$$\begin{matrix} R(\tau) \\ \overline{R}(\tau) \end{matrix} \propto \frac{1 \mp 2\mathrm{Re}(\varepsilon)}{2} \left[e^{-\tau/\tau_{\rm S}} + |\eta_{+-}|^2 e^{-\tau/\tau_{\rm L}} \pm 2|\eta_{+-}| e^{-\frac{1}{2}(\tau/\tau_{\rm L} + \tau/\tau_{\rm S})} \cos(\Delta m \tau - \phi_{+-}) \right], \qquad (1)$$

where Δm is the $\rm K_L$–$\rm K_S$ mass difference, $\tau_{\rm L}(\tau_{\rm S})$ is the $\rm K_L(K_S)$ mean life and ε describes CP violation in the kaon mixing matrix. Since $R(\tau)$ and $\overline{R}(\tau)$ are the decay rates of CP conjugate processes, any difference between the two is a sign of CP violation. In Fig. 1 the decay rates for $\rm K^0$ and $\rm \overline{K}^0$ measured by our experiment are shown separately, demonstrating the expected CP violation effect.

The $\rm K_L$–$\rm K_S$ interference term in Eq. 1 is isolated by forming the asymmetry of the observed number of $\rm K^0$ and $\rm \overline{K}^0$ decays to $\pi^+\pi^-$, $N(\tau)$ and $\overline{N}(\tau)$, as a function of the

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decay time:

$$A_{+-}(\tau) = \frac{\overline{N}(\tau) - \alpha N(\tau)}{\overline{N}(\tau) + \alpha N(\tau)} = -2\frac{|\eta_{+-}|e^{\frac{1}{2}(\tau/\tau_{\rm S}-\tau/\tau_{\rm L})}\cos(\Delta m\tau - \phi_{+-})}{1+|\eta_{+-}|^2 e^{(\tau/\tau_{\rm S}-\tau/\tau_{\rm L})}}. \quad (2)$$

The acceptances common to $\rm K^0$ and $\rm \overline{K}^0$ cancel in the asymmetry, thus reducing the systematic uncertainties. The normalization factor α includes the tagging efficiency ξ of $\rm \overline{K}^0$ relative to $\rm K^0$, $\alpha \simeq [1 + 4{\rm Re}(\varepsilon)] \times \xi$, and is determined from the data together with the CP violation parameters $|\eta_{+-}|$ and ϕ_{+-}.

3 The detector

The CPLEAR experiment uses an intense 200 MeV/c antiproton beam ($\approx 10^6\,\overline{\rm p}$/s) from the Low Energy Antiproton Ring (LEAR) at CERN. A detailed description of the detector can be found elsewhere [9] and only a brief outline is presented here. Viewed from the centre to the outside, the detector consists of a spherical gaseous hydrogen target (16 bar pressure and 7 cm radius), cylindrical tracking devices (two proportional, six drift chambers and two streamer tube layers), a threshold Čerenkov counter sandwiched between two layers of scintillator to provide charged particle identification (Čerenkov light, time of flight and energy loss), and an electromagnetic calorimeter (18 layers of lead converters and streamer tubes). All components are situated in a 0.44 T solenoid (1 m radius $\times$ 3.6 m length). A fast background rejection is achieved online by a multilevel trigger system.

4 Data analysis

First results based on the data sample taken in 1990, when only the early stages of the trigger were operational, have already been published [10]. Since 1992 the full CPLEAR trigger including reconstruction of charged tracks and particle identification has been operational, accepting events over all the available decay time region. In the analysis, the desired $\rm p\overline{p}$ annihilations followed by the decay of a neutral kaon into two charged pions are selected by demanding events with four tracks and zero total charge. A good reconstruction quality is required for each track and vertex. The transverse momentum of the charged kaon has to be greater than 350 MeV/c. In addition to online and offline event selections, a kinematical and geometrical fit with nine constraints is imposed on the events. These constraints require conservation of energy and momentum, the missing mass at the annihilation vertex to be equal to the $\rm K^0$ mass, the intersections of two track helices at the annihilation and decay vertices, respectively, and the $\rm K^0$ momentum to be colinear with the line joining the two vertices. The fit improves the signal–to–background ratio and the decay–time resolution. A simulation study of the detector shows this resolution varying from 4 ps to 10 ps as a function of the neutral kaon decay radius. The simulation also yields the acceptance for the signal and residual background events as a function of the decay time. The only remaining background source consists of semileptonic decays, which are further reduced by using electron identification [9]. Figure 2 shows the sum of the decay–time distributions of $\rm K^0$'s and $\rm \overline{K}^0$'s in which the $\rm K_S$–$\rm K_L$ interference cancels. A fit of the expected kaon decay rate and the background shape (Fig. 2, open circles) yields a value for the $\rm K_S$ mean life in agreement (within 1%) with the world average value [1]. The background level obtained with this fit is in good agreement with Monte Carlo calculations based on known branching ratios. A total of 1.6×10^7 $\rm K^0(\overline{K}^0) \to \pi^+\pi^-$ events remain after background subtraction (only a fraction of the data with decays below

$1\,\tau_S$ has been analysed since these decays do not contribute to the statistical significance of the final results).

5 Normalization of K^0 and $\overline{K}^0$ rates

The detection efficiency of the neutral kaon decay vertex cancels in the asymmetry (Eq. 2), since the kinematics is identical for K^0 and $\overline{K}^0$ decays to $\pi^+\pi^-$. However, the detection efficiency of $(K^+\pi^-)$ and $(K^-\pi^+)$ pairs, used to tag K^0 and $\overline{K}^0$ respectively, differs due to the geometrical imperfections of the detector and strong interactions of kaons and pions with the detector material (mainly in the scintillator and Čerenkov counters).

In order to eliminate geometrical biases causing a different detection efficiency for particles with opposite curvature sign, the magnetic field polarity is frequently reversed (approximately three times per day). Figure 3 shows the ratios between the numbers of tagged $\overline{K}^0$ and K^0 events corresponding to the same curvature sign of the associated charged kaon as a function of its momentum. The momentum dependence of these ratios, which are free from geometrical biases, is only due to strong interactions and therefore the ratios are the same for the two curvature signs. Since we average the detection efficiency over the $K\pi$ phase space configuration accepted in each decay time interval, the relative tagging efficiency between K^0 and $\overline{K}^0$ varies when the $K\pi$ configuration changes with the decay time. The radius–dependent decay acceptance, as well as the limited fiducial volume together with the correlation of the neutral kaon momentum with the $K\pi$ configuration lead to this effect. To take this variation into account, each event is weighted with the tagging efficiency corresponding to its $K\pi$ kinematics. The weights are measured at low decay times. Applying this correction changes the value of ϕ_{+-} by 0.2° while $|\eta_{+-}|$ remains the same with the systematic uncertainty given in Table 1.

After this procedure, the value of the normalization factor α, introduced in Eq. 2, is expected to be one. To accommodate possible residual effects and to include the correlations between α and the CP–violation parameters, the value of α is left free in the fit of Eq. 2 to the data, where it is determined with a precision of 6×10^{-4}.

6 Regeneration

The effect of coherent regeneration on the K^0 and $\overline{K}^0$ rates, mainly caused by the interference of the inherent K_S amplitude of the neutral kaon with the K_S amplitude regenerated by scattering in the detector material, needs to be considered. In the absence of experimental data for the difference between the forward scattering amplitudes of K^0 and $\overline{K}^0$ in the momentum region of the present experiment ($< 800\,\mathrm{MeV}/c$), we have used the values calculated recently by Eberhard and Uchiyama [11]. The values used for hydrogen as input to their calculation on heavy nuclei are consistent with others [12], from which we estimate an average uncertainty smaller than 13% on the magnitude and 9° on the phase for hydrogen and for heavy nuclei [13]. We have corrected our data on an event–by–event basis depending on the measured momentum of the neutral kaon as well as on the detector materials traversed (see [13]). The values for ϕ_{+-} and $|\eta_{+-}|$ do not change by more than $\pm\,0.6^0$ and $\pm 0.02 \cdot 10^{-3}$ respectively, when the magnitude and phase of the scattering amplitudes are varied within our estimated uncertainties. Diffractive regeneration and absorption are found to be negligible in our experimental set–up.

7 Fit of the asymmetry and final results

Equation 2 folded with the decay time resolution is fitted to the asymmetry shown in Fig. 4 with $|\eta_{+-}|$, ϕ_{+-} and α as free parameters. The values of ϕ_{+-} and $|\eta_{+-}|$ obtained by the fit, together with their dependence on Δm (in units of $\hbar\,\mathrm{s}^{-1}$) and τ_S (in units of ps), are:

$$
\begin{aligned}
|\eta_{+-}| &= (2.312 \pm 0.043 - 0.001[\Delta m - 527.4] + 0.091[\tau_\mathrm{S} - 89.26]) \times 10^{-3} &(3)\\
\phi_{+-} &= 42.7 \pm 0.9^\circ + 0.316[\Delta m - 527.4]^\circ + 0.30[\tau_\mathrm{S} - 89.26]^\circ, &(4)
\end{aligned}
$$

where we used $\Delta m = (527.4 \pm 2.9) \times 10^7 \hbar\,\mathrm{s}^{-1}$ measured recently by the CPLEAR collaboration using semileptonic decays [14] and $\tau_\mathrm{S} = (89.26 \pm 0.12)\,\mathrm{ps}$ [1]. The correlation coefficient between ϕ_{+-} and $|\eta_{+-}|$ given by the fit is 12%. Floating Δm in the fit gives $\Delta m = (529.5 \pm 6.7) \times 10^7 \hbar\,\mathrm{s}^{-1}$, in good agreement with the value used. By changing the background level, the decay time resolution, the regeneration amplitude, Δm and τ_S within their estimated uncertainties we derive the systematic errors shown in Table 1. Our results are:

$$
\begin{aligned}
|\eta_{+-}| &= (2.312 \pm 0.043_{\mathrm{stat.}} \pm 0.030_{\mathrm{syst.}} \pm 0.011_{\tau_\mathrm{S}}) \times 10^{-3} &(5)\\
\phi_{+-} &= 42.7^\circ \pm 0.9^\circ_{\mathrm{stat.}} \pm 0.6^\circ_{\mathrm{syst.}} \pm 0.9^\circ_{\Delta m}\ . &(6)
\end{aligned}
$$

Using the PDG [1] value of $\Delta m = (533.3 \pm 2.7) \times 10^7 \hbar\,\mathrm{s}^{-1}$, we find $|\eta_{+-}| = 2.311 \times 10^{-3}$ and $\phi_{+-} = 44.5^\circ$. The errors remain the same except for the error on ϕ_{+-} resulting from the uncertainty of Δm which reduces to 0.8°. The value of ϕ_{+-} obtained with our value of Δm agrees well with the superweak phase computed with the same Δm and $\Delta\Gamma$ from [1]:

$$
\phi_{\mathrm{SW}} = \tan^{-1}\frac{2\Delta m}{\Delta\Gamma} = 43.30^\circ \pm 0.16^\circ, \qquad (7)
$$

being consistent with CPT symmetry. Our systematic errors result mainly from the present uncertainty on the difference between the forward scattering amplitudes of K^0 and $\overline{\mathrm{K}}^0$ and the uncertainty on the value of Δm.

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Table 1: Systematic errors of the presented ϕ_{+-} and $|\eta_{+-}|$ values

Source	ϕ_{+-}	$\lvert\eta_{+-}\rvert\ \times 10^3$
Background level	0.05^0	0.02
Decay time resolution	0.10^0	0.01
Normalization procedure	0.05^0	0.005
Regeneration	0.60^0	0.02
Total syst.	$\mathbf{0.61^0}$	**0.030**
$\sigma(\Delta m)$	0.92^0	0.003
$\sigma(\tau_S)$	0.04^0	0.011

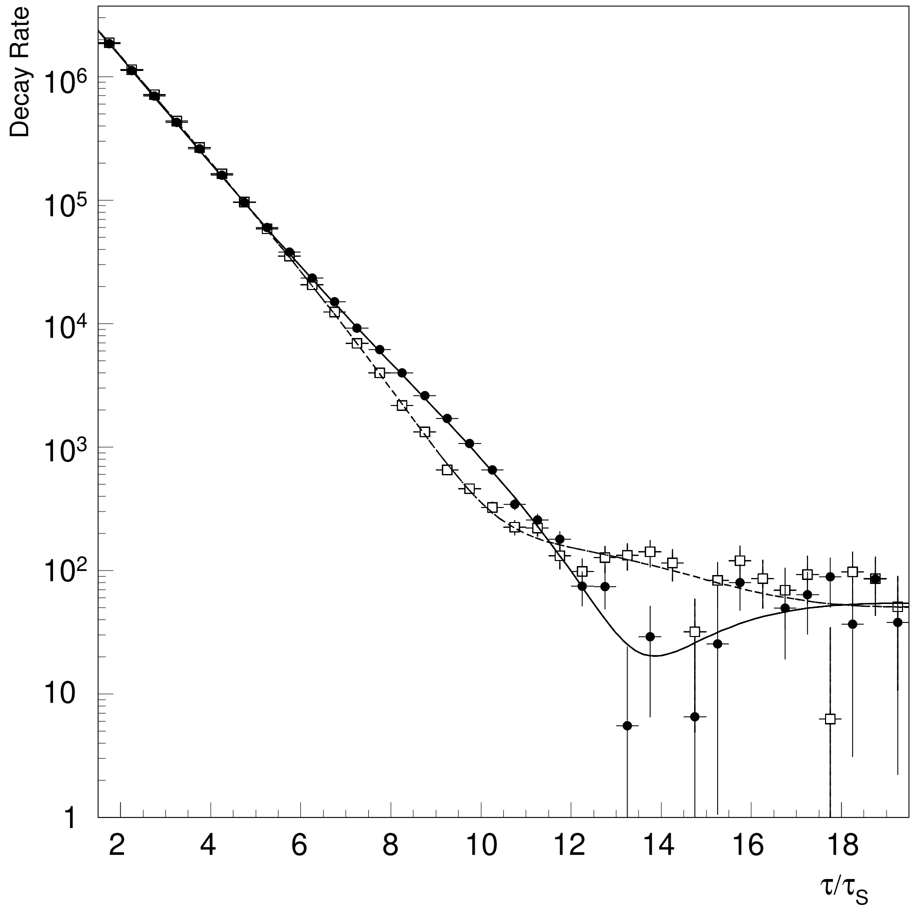

Figure 1: Acceptance corrected decay rate of $K^0(\square)$ and $\overline{K}^0(\bullet)$ into $\pi^+\pi^-$. The lines are the expected rates (Eq. 1) when the PDG–94 values are used for Δm, Γ_S, Γ_L and η_{+-}. Only the data accumulated with the full trigger are shown (see section 4).

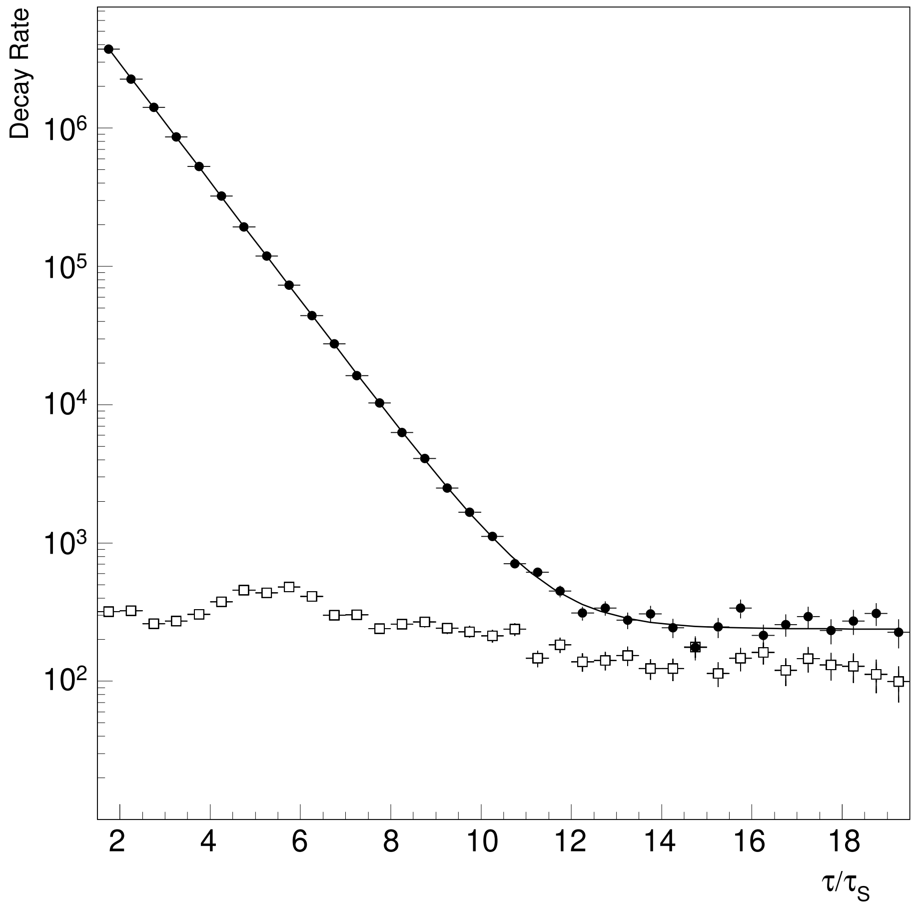

Figure 2: Sum of K^0 and $\overline{K}^0$ decay rates (●) (normalized and corrected for $K \rightarrow \pi^+\pi^-$ acceptance). The solid line is a fit with two exponential functions for K_S and K_L, and the background distribution (□) obtained from a simulation.

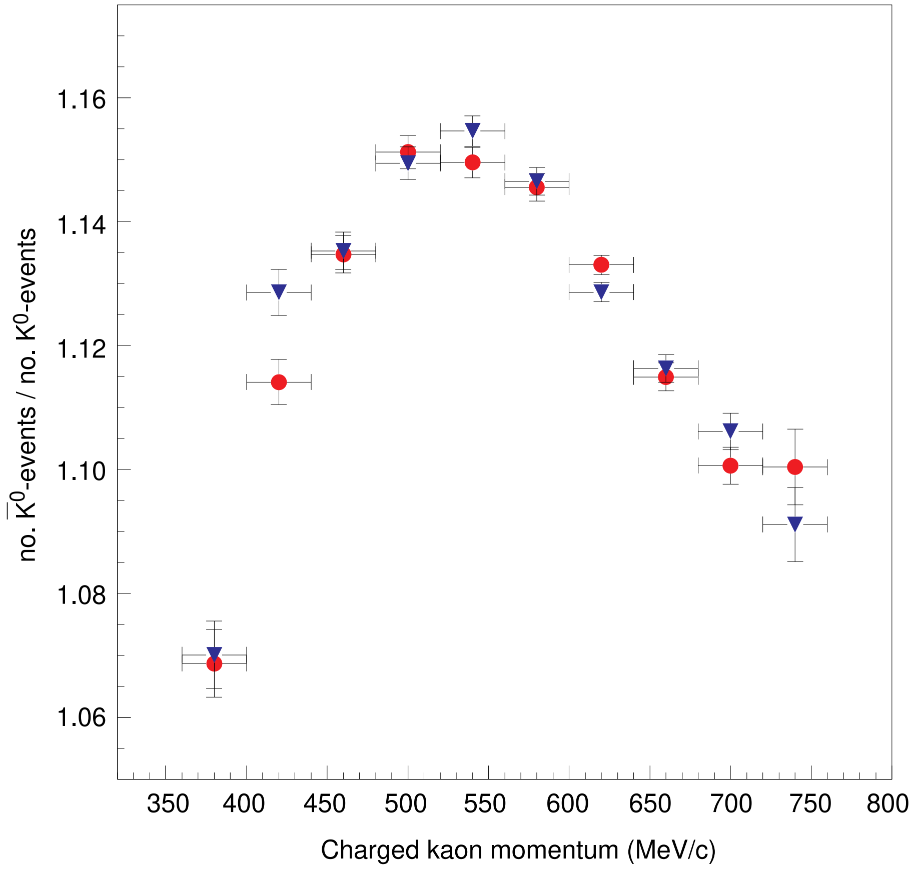

Figure 3: Ratios of $\overline{K}^0/K^0$ events as a function of the charged kaon momentum for positive (●) and negative (▼) curvatures. The momentum dependence, resulting from different strong interactions of $K^-\pi^+$ and $K^+\pi^-$ pairs used to tag the neutral kaon, is the same for both curvatures.

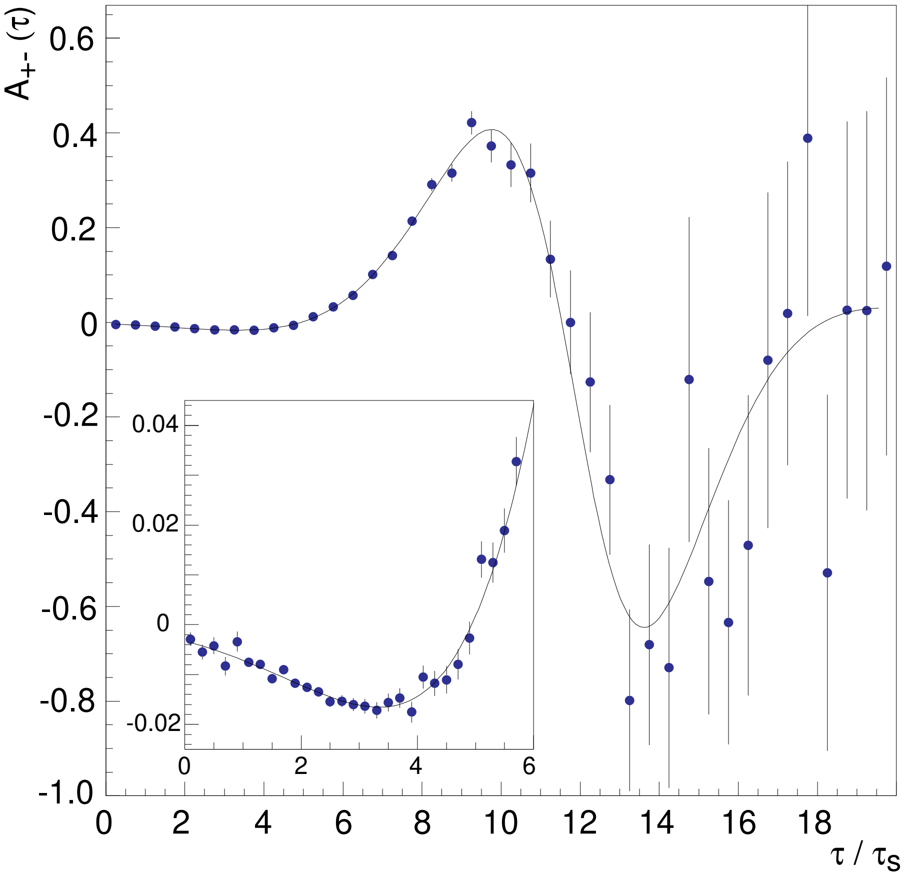

Figure 4: Decay rate asymmetry as a function of the decay eigentime. The solid line is the result of our fit. The inset displays the data at short decay times with a refined binning. Only part of the data below $1\,\tau_S$ was analyzed (see section 4).