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The analysis of $\mathrm{K}^0(\overline{\mathrm{K}^0}) \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ events

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Abstract

For the first time in the CPLEAR experiment, the analysis of the run periods P17-P25 shows an indication of CP violation in the decay $\mathrm{K}^0(\overline{\mathrm{K}^0}) \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$, where all emitted photons are detected by the electromagnetic calorimeter. The observed CP violating asymmetry is dampened due to a $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime resolution of 0.7 τ_S (FWHM). A fit to the asymmetry $A_{oo}(t)$ yields the preliminary result $\Phi_{00} = (53.6 \pm 9.6)^o$ (stat). The background is estimated to be $(0.141 \pm 0.005)\%$.

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1 Introduction

This report is aimed to give a complete overview of the present analysis of $K^0(\overline{K^0}) \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma$ events recorded by the CPLEAR detector. Our analysis is based on a full event reconstruction, which requires, that all four emitted photons are detected by the electromagnetic calorimeter. Data of the run periods P17-P25 are used for the analysis.

First we summarize shortly the selection of $K^\mp\pi^\pm K^0(\overline{K^0})$ events and photons. Then the full event reconstruction using a kinematical and geometrical constraint fit is described. The obtained $K^0(\overline{K^0})$ lifetime distribution at this analysis level allows two immediate observations: The data contain a considerable amount of background and the $K^0(\overline{K^0}) \rightarrow \pi^0\pi^0$ decay rates are smeared due to the limited precision of the $K^0(\overline{K^0})$ lifetime reconstruction. Techniques and methods to suppress the background and to improve the lifetime resolution are presented. Especially the improvement of the lifetime resolution is shown to be essential to observe the CP violating interference in the asymmetry $A_{00}(t)$.

The finally obtained $K^0(\overline{K^0}) \rightarrow \pi^0\pi^0$ data sample, which consists of 768k events, is used to calculate the asymmetry $A_{00}(t)$. There is a strong indication, that the asymmetry shows indeed CP violation, despite large statistical errors. The phase Φ_{00} of the CP violating parameter η_{00} is extracted from the asymmetry.

It must be noted, that so far no systematical effects have been studied.

2 Analysis

The analysis chain to select golden $K^0(\overline{K^0}) \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma$ events is the following:

- Golden $\overline{p}p \rightarrow K^\mp\pi^\pm K^0(\overline{K^0})$ events are enriched by cuts on the two primary tracks (e.g. track quality, 1c-fit on the $K^0(\overline{K^0})$ missing mass, particle identification).
- Events with four photons are selected by investigating the showers in the electromagnetic calorimeter (e.g. track association, shower multiplicity, shower quality).
- A full event reconstruction is performed by using a kinematical and geometrical constraint fit (6c-fit). The algorithm provides the $K^0(\overline{K^0})$ decay vertex.
- Background is suppressed by cuts on the probability and the kinematical variables of the 6c-fit.
- The $K^0(\overline{K^0})$ lifetime resolution of the 6c-fit is improved by some dedicated algorithms ('New Loop Method', use of photon shower directions).

The next sections explain these different analysis steps in more detail. Some technical aspects concerning the data processing and the generation of Monte Carlo events are summarized in appendix A.

2.1 Selection of $K^\mp\pi^\pm K^0(\overline{K^0})$ events

The two opposite charged primary tracks have to fulfill the conditions listed below to be accepted as $K^\mp\pi^\pm K^0(\overline{K^0})$ candidates:

• # PC and DC transversal hits	≥ 4
• # PC and DC longitudinal hits	≥ 2
• Annihilation vertex r-component	[0,2.5] cm
• Annihilation vertex z-component	[-6.0,6.0] cm
• # kaon candidates (S·$\overline{\mathrm{C}}$·S)	$\equiv 1$
• Kaon momentum	[400,800] MeV/c
• Pion momentum	[75,550] MeV/c
• Kaon S_1 response	$(dE/dx) \geq 2.0$ MeV/cm
	$(dE/dx) \geq (dE/dx)_{expected} - 2.0 \cdot \sigma_{kaonband}$
• Kaon-pion TOF difference	$(\Delta t^{K\pi}_{measured} - \Delta t^{K\pi}_{expected}) \geq -0.65\ ns$
• Pion S_1 response	$(dE/dx) \leq (dE/dx)_{expected} + 1.75 \cdot \sigma_{pionband}$,
	if $(\Delta t^{K\pi}_{measured} - \Delta t^{K\pi}_{expected})$
	$\leq (0.005 \cdot p_\pi/(\mathrm{MeV/c}) - 2.375)$ ns
• Probability of $\mathrm{K}^0(\overline{\mathrm{K}^0})$ missing mass 1c-fit	≥ 0.1
• $\mathrm{K}^0(\overline{\mathrm{K}^0})$ momentum of 1c-fit	≥ 400 MeV/c

The cuts on (dE/dx) and the TOF information of the kaon and the pion candidates are important to suppress especially the $(\overline{\mathrm{p}}\mathrm{p})_{rest} \to \pi^+\pi^- + n \cdot \pi^0$ background and, to a lower extend, the $(\overline{\mathrm{p}}\mathrm{p})_{rest} \to \mathrm{K}^+\mathrm{K}^- + \pi^0\pi^0$ contamination to the golden events. Rejecting events with a $\mathrm{K}^0(\overline{\mathrm{K}^0})$ momentum below 400 MeV/c improves the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime resolution.

2.2 Identification of photons

The result of the calorimeter shower pattern recognition and the extrapolation of the tracks to the calorimeter are used to identify four photons. We apply the following criteria:

- Number of neutral showers is equal to 4 or equal to 5. A shower is per definition a neutral shower, if its distance to the calorimeter extrapolation of the kaon (pion) track is greater than 50.0 cm (25.0 cm).
- Number of neutral showers without missing z-component is equal to 4.
- No neutral shower overlaps in the transversal projection with another neutral or track associated shower (no W-ambiguities). Overlapping showers in the longitudinal projection (U- and V-ambiguities) are accepted.
- Number of wire hits of a neutral shower in at least two layers of the calorimeter is greater equal than 3.

Photons converting in the PID's are accepted, since no significant effect on the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime resolution is observed.

2.3 Full event reconstruction

The reconstruction of the $K^0(\overline{K^0})$ decay vertex is done in two steps: First the $K^0(\overline{K^0})$ decay vertex is estimated through the 'Decay Length Variation Method' and then a 6c-fit fit is applied to reconstruct the vertex with better resolution [1].

Decay Length Variation Method: For a given $K^0(\overline{K^0})$ decay length one can calculate the photon energies (and hence the $\gamma\gamma$ invariant masses), using the $K^0(\overline{K^0})$ momentum of the 1c-fit and the photon impact points measured in the calorimeter. Due to the fact, that the photons emerge from π^0 decays, a scan over an interval of hypothetical $K^0(\overline{K^0})$ decay length values can be performed to search for the minimum of

$$\mathcal{N}(\lambda) = \Big(m_{\pi^0} - m_{12}(\lambda)\Big)^2 + \Big(m_{\pi^0} - m_{34}(\lambda)\Big)^2$$

where $m_{12}(\lambda)$ and $m_{34}(\lambda)$ denote the $\gamma\gamma$ invariant masses at the decay length λ. The $K^0(\overline{K^0})$ decay length determined by the minimum of $\mathcal{N}(\lambda)$ is a good estimate for the true $K^0(\overline{K^0})$ decay length. This procedure is repeated for all three possible pairings of the four photons, giving for each $\gamma\gamma$ pairing a separate decay length estimate. Events, which do not pass this algorithm (about 25 %), are considered as background events and are rejected.

6c-fit: A 6c-fit is at present the basic tool to reconstruct the $K^0(\overline{K^0})$ decay vertex. It uses as observables the annihilation vertex, both track momenta, the photon impact points and the photon energies. The $K^0(\overline{K^0})$ decay length is the only unknown. The 7 constraints are listed below:

Energy-momentum conservation:

1.	$2m_{\mathrm{p}} - E_{\mathrm{K}^-} - E_{\pi^+}$	$=$	$\sum_{i=1}^{4} E_{\gamma_i}$
2.-4.	$-\vec{p}_{\mathrm{K}^-} - \vec{p}_{\pi^+}$	$=$	$\sum_{i=1}^{4} \vec{p}_{\gamma_i}$

Mass constraints:

5.	$(2m_{\mathrm{p}} - E_{\mathrm{K}^-} - E_{\pi^+})^2 - (\vec{p}_{\mathrm{K}^-} + \vec{p}_{\pi^+})^2$	$=$	$m^2_{\mathrm{K}^0}$
6.-7.	m_{π^0}	$=$	$m_{\gamma\gamma}$

Again the cfit is applied for each possible $\gamma\gamma$ pairing separately, using as start value for the unknown $K^0(\overline{K^0})$ decay length the estimate of the previously executed Decay Length Variation Method. From the three solutions of the 6c-fit the one with the highest χ^2 probability is chosen for the further analysis.

In fig. (1) the obtained $K^0(\overline{K^0}) \to \pi^0\pi^0$ lifetime distribution is shown, after applying a cut on the χ^2 probability of the 6c-fit $(prob(\chi^2_{6c}) \geq 0.1)$[1]. The distribution is not efficiency corrected. The figure shows also the currently known background contributions,

[1]The figure shows only P24 and P25 data, since a cut to reject background events was already applied during the production of our pre-P24 data.

which, obtained from a Monte Carlo simulation and properly added up, agree at positive lifetimes well with the measured distribution. One also observes, that the slope of the reconstructed lifetime distribution differs significantly from the slope of the expected $K_S^0 \to \pi^0\pi^0$ lifetime distribution, which is due to the limited lifetime resolution of the 6c-fit. This finite resolution is also shifting $K^0(\overline{K^0}) \to \pi^0\pi^0$ events towards negative lifetimes.

2.4 Background

The 6c-fit is effective against all possible background contributions, because it is testing, whether the measured observables fit to the $K^0(\overline{K^0}) \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ hypothesis. Another background suppression is achieved by investigating the phase space distributions of the desired events and possible background events. When the 6c-fit has chosen a $\gamma\gamma$ pairing with the $\gamma\gamma$ invariant masses (m_{12}, m_{34}), then the $\gamma\gamma$ invariant masses (m_{13}, m_{24}) and (m_{14}, m_{23}) can also be calculated. We observe, that these phase space variables are suited to distinguish between $K^0(\overline{K^0}) \to \pi^0\pi^0$ events and background [2].

Wrong $\gamma\gamma$ pairing: For Monte Carlo events the 6c-fit chooses in about 9 % of all cases a wrong $\gamma\gamma$ pairing. Although these events are not real background events, they must be rejected due to their poorly reconstructed $K^0(\overline{K^0})$ lifetime, see fig. (1). For this reason a simple neural network, named Q2NN, was trained on Monte Carlo data to distinguish between correctly and wrongly paired photons. As input it uses the $\gamma\gamma$ invariant masses m_{13}, m_{24}, m_{14} and m_{23}. The output is a real number between 0 and 1 corresponding to the wrongly and correctly paired photons. Fig. (2) shows that the Q2NN output separates very well the two event classes.

$K^0(\overline{K^0}) \to \pi^0\pi^0\pi^0$: This channel can contribute to the background if only four of the six π^0 decay photons are detected in the calorimeter. Fig. (1) shows for Monte Carlo events, that this background populates the high lifetime region and becomes the dominant background at lifetimes greater than 10 τ_S. In analogy to the $\gamma\gamma$ pairing problem, a neural network was trained (Q3NN). The network output is shown in fig. (3) for $K^0(\overline{K^0}) \to \pi^0\pi^0\pi^0$ events and $K^0(\overline{K^0}) \to \pi^0\pi^0$ events with correctly and wrongly paired photons. It can be seen, that a cut, reducing the $\pi^0\pi^0\pi^0$ background, rejects at the same time $K^0(\overline{K^0}) \to \pi^0\pi^0$ events with wrongly paired photons, making the mentioned Q2NN neural network at present unnecessary. The chosen cut on the Q3NN output of 0.525 reduces the $K^0(\overline{K^0}) \to \pi^0\pi^0$ events with wrongly paired photons by a factor of 160 and the $K^0(\overline{K^0}) \to \pi^0\pi^0\pi^0$ background by a factor of 4. The efficiency for good events is about 74 %.

Ghost photons: It can happen, that one photon of the $K^0(\overline{K^0}) \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ decay chain is not detected and that instead an additional spurious neutral shower in the electromagnetic calorimeter ('ghost photon') simulates a golden four photon event [3], obviously with a poorly reconstructed $K^0(\overline{K^0})$ lifetime, fig. (1). This event class is also suppressed by the Q3NN cut, fig. (3). The reduction factor is 6.

$(\overline{p}p)_{rest} \to K^+K^- + \pi^0\pi^0$: This background channel is negligible, fig. (1).

$(\overline{p}p)_{rest} \to K^\mp\pi^\pm K^0(\overline{K^0}) + \pi^0$: This background is also negligible, fig. (1).

The annihilation background $(\overline{\mathrm{p}}\mathrm{p})_{rest} \to \pi^+\pi^- + n \cdot \pi^0$ has not been studied so far, since the Monte Carlo generation of this channel is too CPU time intensive. Furthermore the evaluation of this background from minimal bias data suffers from large systematical uncertainties.

2.5 Lifetime resolution

The observation of CP violation in the time-dependant asymmetry $A_{00}(t)$ requires a certain precision in reconstructing the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime. This is demonstrated by calculating the asymmetry from the theoretical expressions for the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ decay rates and from the lifetime resolution of the 6c-fit given by our full Monte Carlo (CPGEANT), fig. (4). Fig. (5) shows, that hardly the CP violating interference is visible in the asymmetry. Responsible for this dampening of the asymmetry are the tails in the lifetime resolution between 1 and 7 τ_S. Although the contribution of such tail events to the total event statistics is small, their influence on the interference region between K^0_S and K^0_L is drastically amplified by the exponentially falling K^0_S decay curve. So it is absolutely crucial for our analysis to improve the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime resolution. The 6c-fit used to reconstruct the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime suffers from two imperfections:

- The χ^2_{6c} contour has in some cases more than one minimum. However, the standard constraint fit procedure is a local method and hence unable to find all minima.
- The 7 constraint equations are highly non-linear. Thus the error for the reconstructed lifetime, calculated from the second derivative of the χ^2_{6c} contour, is very unreliable.

Therefore global methods were developed to overcome these 6c-fit drawbacks and to improve the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime resolution [4].

Loop Method: The Loop Method is based on the observation, that the tails in the lifetime resolution are correlated to a great extend with the resolution of the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ flight direction. Therefore for each kinematically allowed $\mathrm{K}^0(\overline{\mathrm{K}^0})$ flight direction a hypothetical $\mathrm{K}^0(\overline{\mathrm{K}^0})$ decay vertex is calculated. All these vertices form a curve in the 3-dimensional space. We observe, that the curve is a closed loop. Then by weighting each loop point with its probability according to the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ momentum covariance matrix, an expectation value for the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime and its standard deviation can be calculated. This method is sensitive to possible lifetime ambiguities on the loop. If there exists no ambiguity, then nevertheless a good lifetime error is calculated locally. Fig. (4) shows the effect on the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime resolution, if one cuts on the lifetime error of the Loop Method ($\sigma_\tau^{Loop} \leq 0.5\ \tau_S$). Compared to the 6c-fit, the central resolution is clearly improved and the tails are suppressed. The calculated asymmetry in fig. (5) shows therefore a significant amplitude enhancement.

New Loop Method: The Loop Method suffers from the lack of not using all detector observables. Especially the error on the absolute value of the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ momentum is not taken into account. Therefore the Loop Method was generalized and another method was developed, named the New Loop Method. In analogy to the Loop Method, an expectation value for the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime and a lifetime error is calculated.

When choosing a cut on the lifetime error, one has to find the best compromise between the improvement of the lifetime resolution and the loss of $K^0(\overline{K^0}) \to \pi^0\pi^0$ events. This problem is illustrated in fig. (6) for the significance of Φ_{00}. The optimal cut on the lifetime error is given by the minimum of the solid line ($\sigma_\tau^{NewLoop} \leq 1.1\ \tau_S$). Compared to the Loop Method (dotted line) one expects therefore a gain in the significance on Φ_{00} of about 12%[2].

Fig. (4) shows the improvement of the lifetime resolution after applying a cut on the lifetime error of the New Loop Method. Note, that compared to the Loop Method, not so much the suppression of tails was achieved, rather than the enrichment of events in the central part of the resolution distribution. The effect on the calculated asymmetry is shown in fig. (5).

Use of photon shower directions: The photon impact points and the photon shower directions can be used to estimate together with the $K^0(\overline{K^0})$ momentum of the 1c-fit the $K^0(\overline{K^0})$ lifetime [5]. Similar to the Decay Length Variation Method of section (2.3), a decay length scan along the $K^0(\overline{K^0})$ flight direction is done to minimize:

$$\chi^2_{angle}(\lambda) = \sum_{i=1}^{4}\left(\frac{\Theta^i_{measured} - \Theta^i(\lambda)}{\sigma^i_\Theta}\right)^2 + \sum_{i=1}^{4}\left(\frac{\Phi^i_{measured} - \Phi^i(\lambda)}{\sigma^i_\Phi}\right)^2$$

Θ^i and Φ^i are the measured angles of the shower direction parametrization and σ^i_Θ and σ^i_Φ their errors. $\Theta^i(\lambda)$ and $\Phi^i(\lambda)$ denote the calculated angles at the $K^0(\overline{K^0})$ decay length λ. The $K^0(\overline{K^0})$ lifetime τ^{angle} of this method and its lifetime error σ_τ^{angle} are used to calculate the quantity:

$$p^{angle} = \frac{\tau^{6c} - \tau^{angle}}{\sigma_\tau^{angle}}$$

where τ^{6c} is the lifetime resulting from the 6c-fit. If the lifetime of an event is badly determined by the 6c-fit, resulting in a shift to higher lifetimes, then p^{angle} is greater than zero. Fig. (7) illustrates this fact by the comparison of simulated $K^0_S \to \pi^0\pi^0$ and $K^0_L \to \pi^0\pi^0$ events for reconstructed 6c-fit lifetimes greater than 7.0 τ_S. In this lifetime region the K^0_S sample is dominated by events with a poorly reconstructed 6c-fit lifetime. We see, that as expected, the K^0_S events are clearly shifted to positive values of p^{angle}, in contrast to the K^0_L events.

We use the cut values $p^{angle} \leq 1$ and $prob(\chi^2_{angle}(\lambda_{6c}) \geq 0.01$ (λ_{6c} denotes the reconstructed $K^0(\overline{K^0})$ decay length of the 6c-fit). The fig. (4) shows the improvement in the lifetime resolution and fig. (5) illustrates the effect on the calculated asymmetry.

In addition, the quantity p^{angle} helps to reject $K^0(\overline{K^0}) \to \pi^0\pi^0\pi^0$ background events, since such events are shifted by the application of the 6c-fit to the region of higher lifetimes, see section (2.4). A rejection is also expected for any non-golden background originating from the $\overline{p}p$ annihilation, e.g. $(\overline{p}p)_{rest} \to \pi^+\pi^- + n \cdot \pi^0$. Further studies have to verify this assumption.

[2]The curves in fig. (6) take already the cuts on the photon shower directions into account. These cuts will be discussed under the following item.

The final Monte Carlo $K^0(\overline{K^0})$ lifetime resolution has a width of 0.7 τ_S (FWHM) and is shown in fig. (8). The parametrization of the distribution with the sum of two Gauss functions gives $\sigma_1 = 0.36\ \tau_S$ and $\sigma_2 = 1.18\ \tau_S$. The contribution of the smaller Gauss peak is 56 %. It must be emphasized, that this parametrization is not used for the fit of the experimental lifetime distribution and the asymmetry. Instead the histogram shown in fig. (8) is used.

2.6 Statistics

The following table summarizes the cut statistics:

Analysis level	# events [kev]
MINRAW/NFS456 production	27700
NFSPROD production	7000
6c-fit and $prob(\chi^2_{6c})$	1940
Q3NN	1234
New Loop Method	942
Photon shower directions	768

Here the number of events after the cut on the photon shower directions is the size of the final event sample used to analyse the $K^0(\overline{K^0}) \to \pi^0\pi^0$ asymmetry. The number of events per CPLEAR run period is:

Run period	# events [kev]	# events/tape
$\leq$ P23	255	46
P24	309	30
P25	204	28

The number of events per tape changed between the run periods P23 and P24 due to a relaxation of the 4-track trigger condition, resulting in a decrease of the ratio of 2-track to 4-track events per tape.

3 Preliminary results

3.1 Lifetime

The finally obtained $K^0(\overline{K^0})$ lifetime distribution is shown in fig. (9). A clear progress is observed compared to the lifetime distribution after the 6c-fit, fig. (1). The background is suppressed to a great extend and the data curve follows much closer the expected $K^0_S \to \pi^0\pi^0$ rate, which is a clear sign of the improvement of the lifetime resolution.

The Monte Carlo simulation matches the data points at positive lifetimes quite well. The background $K^0_L \to \pi^0\pi^0\pi^0$ takes over the signal at lifetimes greater than 9 τ_S. At negative lifetimes below -2 τ_S the Monte Carlo simulation does not fully agree with the observed lifetime distribution. We have indications, that only a part of this discrepancy may be explained with the pionic annihilation background $(\overline{p}p)_{rest} \to \pi^+\pi^- + n\cdot\pi^0$, which is not included in the Monte Carlo simulation. Integrating the estimated background sources over the interval [-5,20] τ_S the following contributions are obtained relative to the desired channel:

Background channel	Contribution [%]
$K_L^0 \to \pi^0\pi^0\pi^0$	(0.117 ± 0.009) (stat.)
$(\overline{p}p)_{rest} \to K^{\mp}\pi^{\pm}K^0(\overline{K^0}) + \pi^0$	(0.023 ± 0.008) (stat.)
$(\overline{p}p)_{rest} \to K^+K^- + \pi^0\pi^0$	—
$K_S^0 \to \pi^0\pi^0$ bad pairing	(0.035 ± 0.012) (stat.)
$K_S^0 \to \pi^0\pi^0$ ghosts	(0.677 ± 0.053) (stat.)

The contributions from the second and third process are not shown in fig. (9) as they are negligible. It must be pointed out again, that the contributions from the bad $\gamma\gamma$ pairing and ghost photons are not background, but events from $K^0(\overline{K^0}) \to \pi^0\pi^0$ decays with a poor lifetime resolution.

A fit to the $K^0(\overline{K^0})$ lifetime distribution is shown in fig. (10). The fit function is an exponential convoluted with the Monte Carlo lifetime resolution and with an acceptance correction. The acceptance is also taken from the Monte Carlo simulation. It is overlayed in fig. (10). The acceptance decreases from 0 to 10 τ_s only about 10 %, while above it drops more steeply. Background is included in the fit with a free normalization, while the shape is taken from the dominating $K_L^0 \to \pi^0\pi^0\pi^0$ channel. The fit to the lifetime on the interval $[1, 20]\ \tau_S$ yields the following results:

Fit quality	χ^2/nfd	=	203/187
K_S^0 lifetime		=	$(1.008 \pm 0.002)\ \tau_S$ (stat.)
Background in [-5,20] τ_S		=	(0.141 ± 0.005) % (stat.)

The fitted slope shows again the consistency with reconstructing dominantly $K_s \to \pi^0\pi^0$ events and indicates the correctness of the Monte Carlo lifetime resolution and the acceptance. The fitted background level is consistent with the one obtained from the simulation.

3.2 Asymmetry

The lifetime dependant asymmetry of the K^0 and $\overline{K^0}$ rates into $\pi^0\pi^0$ is shown in fig. (11). It is a 'raw asymmetry', which means, that the $K^0(\overline{K^0})$ rates have not been corrected for their different normalization:

$$A_{00}(t) = \frac{N(\overline{K^0} \to \pi^o\pi^o)(t) - N(K^0 \to \pi^o\pi^o)(t)}{N(\overline{K^0} \to \pi^o\pi^o)(t) + N(K^0 \to \pi^o\pi^o)(t)}$$

$N(K^0 \to \pi^o\pi^o)(t)$ and $N(\overline{K^0} \to \pi^o\pi^o)(t)$ denote the measured time dependant decay rates of K^0 and $\overline{K^0}$ into $\pi^0\pi^0$. The asymmetry is expected to follow

$$A_{00}(t) \quad = \quad \frac{\alpha\, r(\overline{K^0} \to \pi^o\pi^o)(t) - r(K^0 \to \pi^o\pi^o)(t) + (\alpha - 1)b(t)}{\alpha\, r(\overline{K^0} \to \pi^o\pi^o)(t) + r(K^0 \to \pi^o\pi^o)(t) + (\alpha + 1)b(t)} \tag{1}$$

with

$$r\left(K^0(\overline{K^0}) \to \pi^o\pi^o\right)(t) = \int_{-\infty}^{+\infty} R\left(K^0(\overline{K^0}) \to \pi^o\pi^o\right)(t - t')f(t')\,dt'$$

and

$$R\left(K^0(\overline{\mathrm{K}^0}) \to \pi^o\pi^o\right)(t) \;=\; \left(1 \mp 2Re(\varepsilon)\right) \cdot \left(e^{-t/\tau_S} + |\eta_{oo}|^2 e^{-t/\tau_L} \pm 2|\eta_{oo}|\cos(\Delta m t - \Phi_{oo}) e^{-\frac{1}{2}(1/\tau_S + 1/\tau_L)t}\right)$$

Here the expressions for the theoretical $\mathrm{K}^0(\overline{\mathrm{K}^0})$ decay rates $R(K^0 \to \pi^o\pi^o)(t)$ and $R(\overline{\mathrm{K}^0} \to \pi^o\pi^o)(t)$ are convoluted with a response function $f(t)$, which describes the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime resolution.

The variable $b(t)$ is the parametrization of the time dependant background. The background is assumed to be identical for K^0 and $\overline{\mathrm{K}^0}$. In case of a countable $(\overline{\mathrm{p}}\mathrm{p})_{rest} \to \pi^+\pi^- + n\cdot\pi^0$ contamination to our data, this assumption has to be verified.

α denotes the $\overline{\mathrm{K}^0}$-K^0-flux ratio. It is assumed to be lifetime independent. Fig. (12) shows this ratio as a function of the $\mathrm{K}^0(\overline{\mathrm{K}^0})$ momentum for events in the lifetime interval $[0,4]\,\tau_S$. It is not corrected for CP violation, since the CP violation in this lifetime interval is small. The flatness of the distribution is consistent with the assumption of a lifetime independent $\overline{\mathrm{K}^0}$-K^0-flux ratio.

For fitting the asymmetry, the lifetime resolution of the Monte Carlo simulation, fig. (8), is used. The background level has been extracted from the lifetime distribution and has been fixed according to the preceeding lifetime fit. $|\eta_{oo}|$ has been fixed at the value from the Particle Data Group [6]. We obtain the following fit results:

Fit quality	χ^2/ndf	=	22/18
Phase of η_{00}	Φ_{00}	=	$(53.6 \pm 9.6)^0$ (stat.)
Normalization	α	=	1.1565 ± 0.0029 (stat.)

The fit shows, that the asymmetry observed in the data, fig.(11), and the one from the calculation with the simulated $\mathrm{K}^0(\overline{\mathrm{K}^0})$ lifetime resolution, fig.(5), agree very well.

If the parameter $|\eta_{oo}|$ is not fixed in the asymmetry fit, we obtain the results $|\eta_{oo}| = (2.58 \pm 0.50) \times 10^{-3}$, $\Phi_{00} = (54.0 \pm 8.9)^0$ and $\alpha = 1.1588 \pm 0.0050$.

Another way of representing the asymmetry is the 'reduced asymmetry' in which the oscillating part is isolated. For this the measured K^0 and $\overline{\mathrm{K}^0}$ decay rates first have to be correctly normalized, so that in the asymmetry formula (1) α can be replaced by 1. Then the asymmetry is transformed by the equation:

$$A_{00}^{red}(t) = \left(A_{00}(t) - 2Re(\epsilon)\right) e^{-\frac{1}{2}(1/\tau_S + 1/\tau_L)t}$$

This reduced asymmetry is shown in fig. (13). The overlayed curve is the fit to the asymmetry $A_{00}(t)$, on which the same transformation was applied.

4 Conclusions and outlook

For the first time in the CPLEAR experiment, the time dependant asymmetry $A_{00}(t)$ is observed in the analysis of $\mathrm{K}^0(\overline{\mathrm{K}^0}) \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ events. The fundamental analysis tools used are a 6c-fit for reconstructing the $\mathrm{K}^0(\overline{\mathrm{K}^0}) \to \pi^0\pi^0$ decay vertex, a phase space cut on the $\gamma\gamma$ invariant masses to reject wrongly paired photons and to suppress background

(Q3NN-cut), and two algorithms (New Loop Method, use of the photon shower directions) to improve the $K^0(\overline{K^0})$ lifetime resolution. The asymmetry found in the data of the run periods P17-P25 agrees well with the expectation from the known CP violation and the simulated $K^0(\overline{K^0})$ lifetime resolution. The phase Φ_{00} of the CP violating parameter η_{00} is measured with a precision of about 10^o. The precision is mainly limited by the obtainable statistics and the $K^0(\overline{K^0}) \to \pi^0\pi^0$ lifetime resolution. A further suppression of background would not improve the precision on Φ_{00} significantly.

To confirm the obtained results, an extended analysis of systematics is foreseen for the next future. It will be focused on how the uncertainties in the background, the $\overline{K^0}/K^0$ normalization and the lifetime resolution can affect the measurement of ϕ_{00}. Beyond this we will work on the following points:

- Background: The discrepancy between our data and the Monte Carlo simulation in the $K^0(\overline{K^0})$ lifetime distribution at negative lifetimes is possibly explained by an unknown background, which has to be identified. In addition, the annihilation background $(\overline{p}p)_{rest} \to \pi^+\pi^- + n \cdot \pi^0$ has to be investigated.

- Cut optimization: It seems to be possible to recover a fraction of the $K^0(\overline{K^0}) \to \pi^0\pi^0$ events, which are rejected by the present analysis, e.g. 're-pairing' of events with a wrong $\gamma\gamma$ pairing with the help of the Q2NN neural network.

- Lifetime resolution: Any further improvement of the $K^0(\overline{K^0})$ lifetime resolution will enhance the observable asymmetry and lead to a better determination of ϕ_{00}.

We can estimate on the basis of our present analysis the obtainable precision for Φ_{00} by the end of 1995. If one assumes for the statistics an increase by a factor of 4, then the error on ϕ_{00} scales down from 9.6^o to 4.8^0. With a perfect lifetime resolution this number would scale further down to 2.8^0.

A Data processing and generation of Monte Carlo events

RAW-tapes of the run periods P17-P25 are filtered and processed in three stages to obtain the present $K^0(\overline{K^0}) \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ sample:

MINRAW/NFS456 production: This is the well-known official CPLEAR data processing at the production sites of the CPLEAR collaboration. For the NFS group 2-track events are selected. Soft cuts are applied on the tracks and the photon multiplicity.

NFSPROD production: A full event and $K^0(\overline{K^0})$ decay vertex reconstruction is done on the ETHZ workstation cluster locally at CERN. An event needs about 0.08 sec CPU time on a DEC 3000-300, which is equivalent to 615 h CPU time for the whole production of 2.7×10^7 MINRAW/NFS456 events.

Ntuple production: At present, the final ntuple production needs for each event another 0.5 sec CPU time due to the New Loop Method, see section (2.5). Therefore the 3.4 million surviving events at this production level correspond to 525 h CPU time!

The statistics of the available **Monte Carlo** events at the ntuple production level is small:

Monte Carlo channel	# events [kev]
$K^0_S \to \pi^0\pi^0$	186.2
$K^0_L \to \pi^0\pi^0$	31.0
$K^0_L \to \pi^0\pi^0\pi^0$	11.6
$(\overline{p}p)_{rest} \to K^\mp\pi^\pm K^0(\overline{K^0}) + \pi^0$	0.9
$(\overline{p}p)_{rest} \to K^+K^- + \pi^0\pi^0$	1.2

Here the generation of the events cost 270 h CPU time on the CSF farm and 1900 h CPU time on the ETHZ cluster. The interesting background channel $(\overline{p}p)_{rest} \to \pi^+\pi^- + n \cdot \pi^0$ could not be generated so far due to its tremendous need of CPU time.

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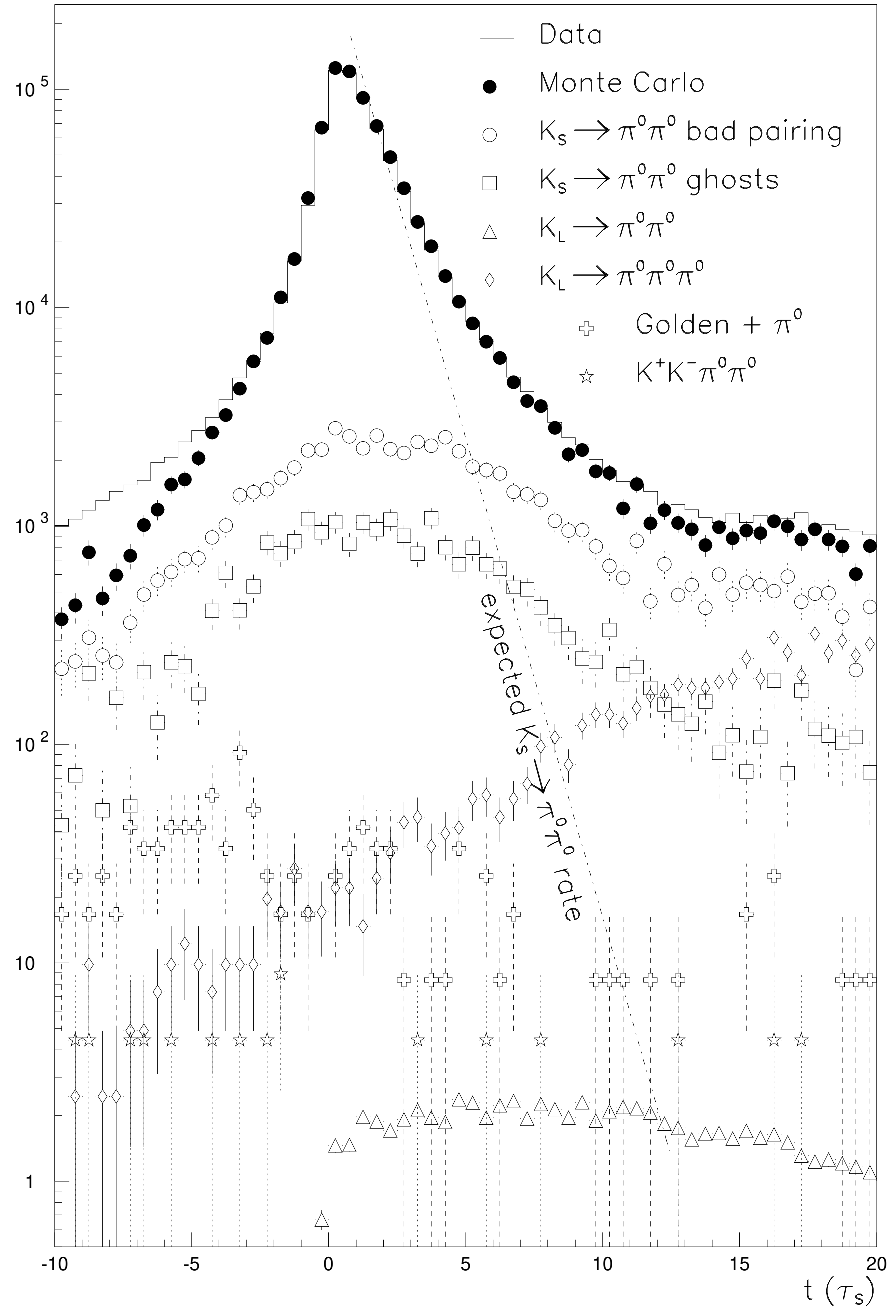

Figure 1: The $K^0(\overline{K^0}) \rightarrow \pi^0\pi^0$ lifetime distribution after the 6c-fit for data and Monte Carlo events.

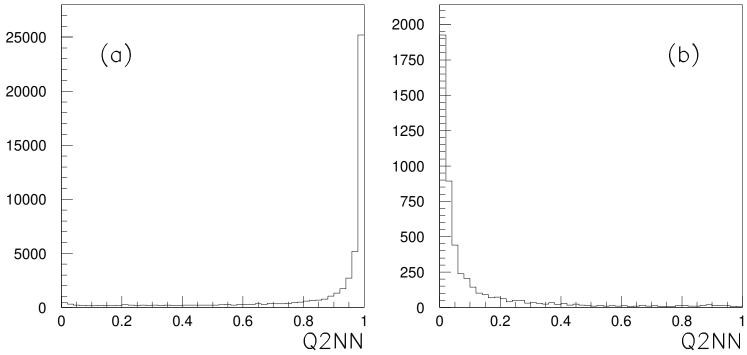

Figure 2: The output of the Q2NN neural network for $K^0(\overline{K^0}) \to \pi^0\pi^0$ Monte Carlo events with (a) correctly and (b) wrongly paired photons.

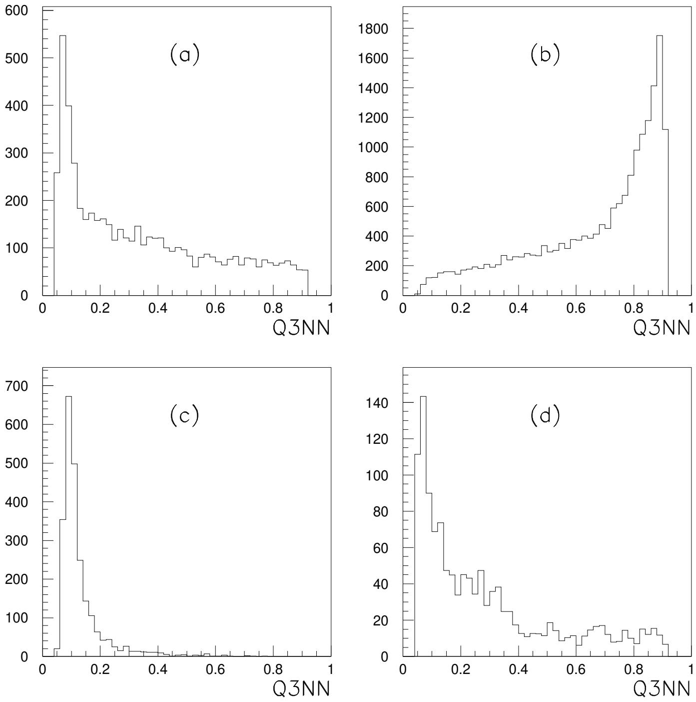

Figure 3: The Q3NN neural network output for Monte Carlo events: (a) $K^0(\overline{K^0}) \to \pi^0\pi^0\pi^0$ and $K^0(\overline{K^0}) \to \pi^0\pi^0$ with (b) correctly paired photons or (c) wrongly paired photons or (d) a ghost photon.

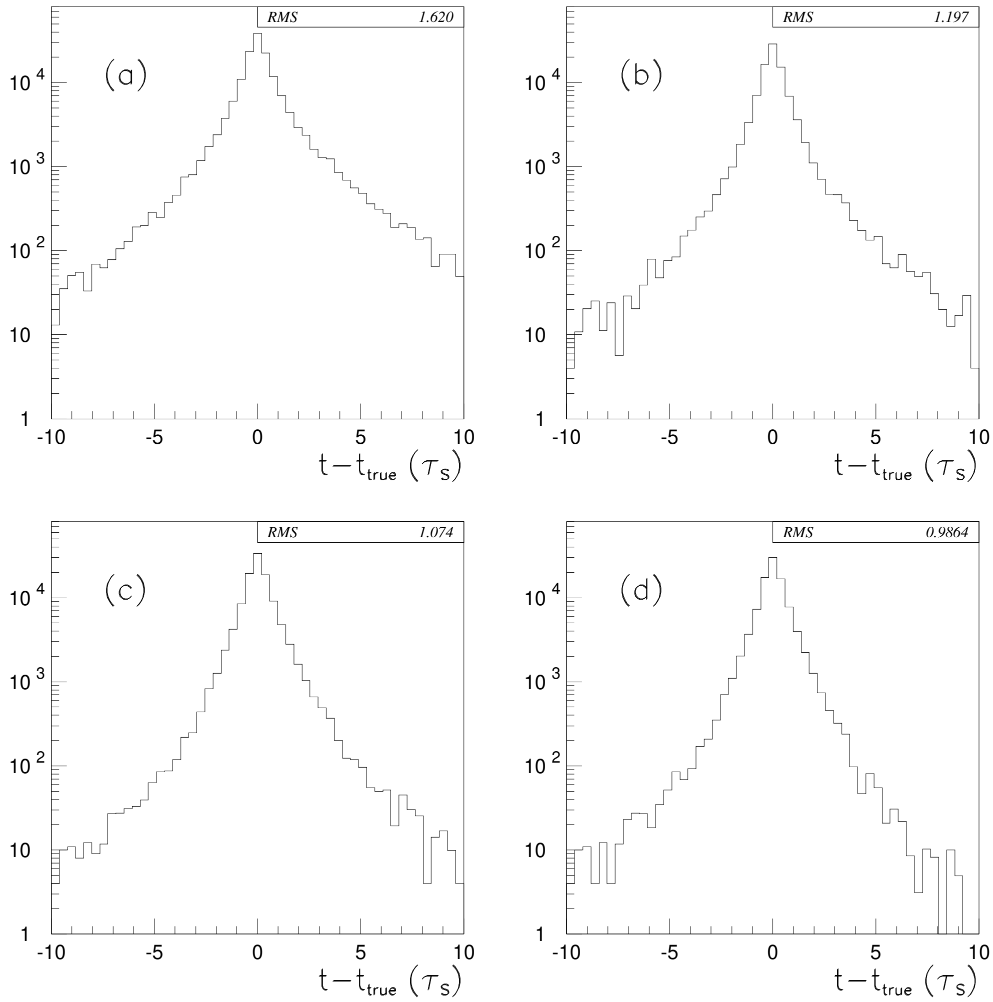

Figure 4: The Monte Carlo $K^0(\overline{K^0})$ lifetime resolution after (a) the 6c-fit, (b) the Loop Method, (c) the New Loop Method and (d) the cut on the photon shower directions.

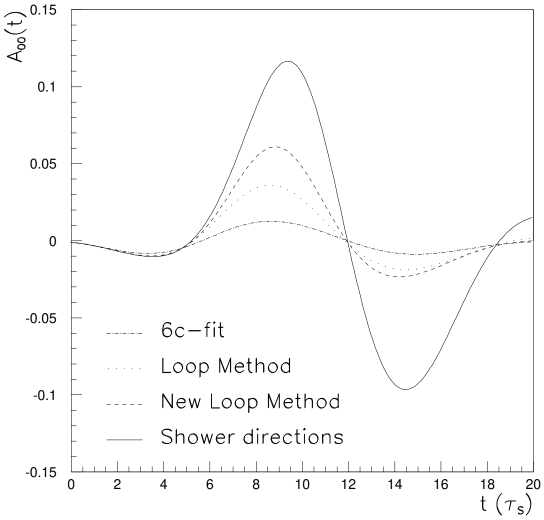

Figure 5: A calculated asymmetry using the Monte Carlo $K^0(\overline{K^0})$ lifetime resolution after the 6c-fit, the Loop Method, the New Loop Method and the cut on the photon shower directions. Background is not taken into account.

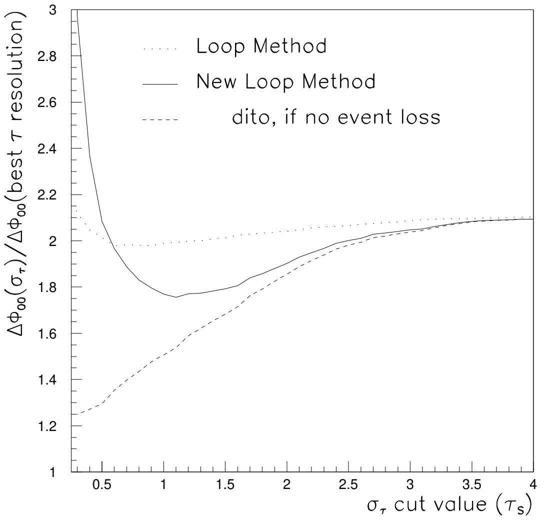

Figure 6: The significance on Φ_{00} as a function of the lifetime error of the Loop Method and the New Loop Method.

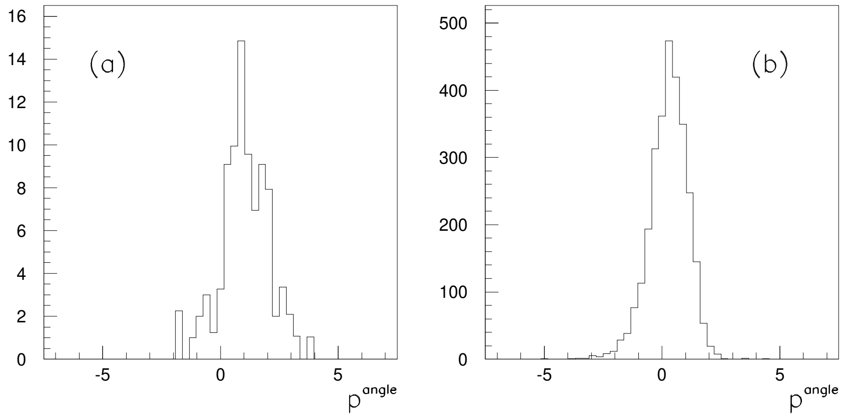

Figure 7: The quantity p^{angle} for (a) $\mathrm{K_S^0} \to \pi^0\pi^0$ and for (b) $\mathrm{K_L^0} \to \pi^0\pi^0$ Monte Carlo events with reconstructed lifetimes after the 6c-fit greater than 7.0 τ_S

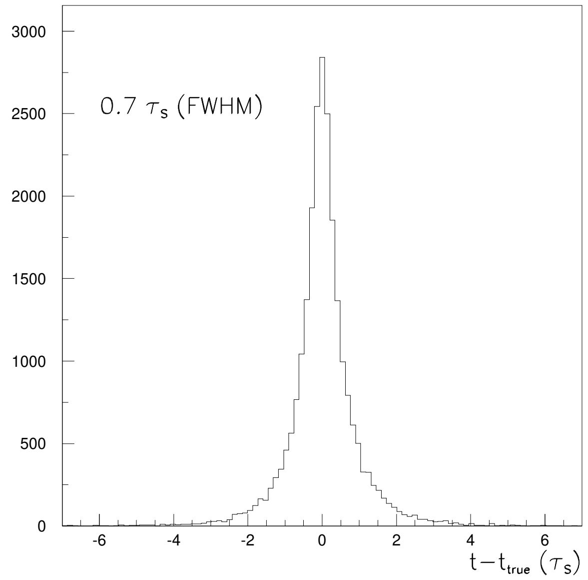

Figure 8: The Monte Carlo $\mathrm{K^0}(\overline{\mathrm{K^0}})$ lifetime resolution. Fig. (4,d) shows the same distribution on a logarithmic scale.

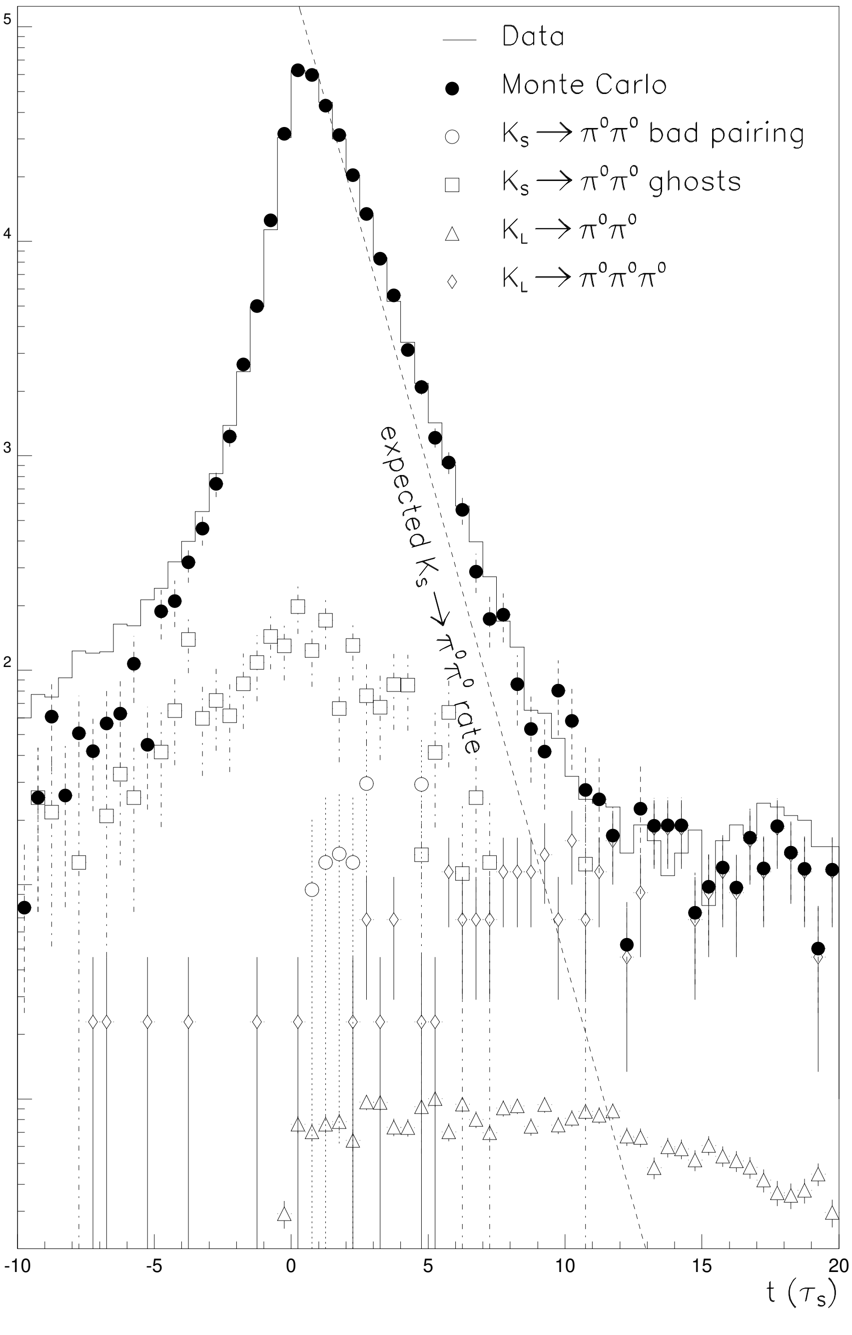

Figure 9: The $K^0(\overline{K^0}) \rightarrow \pi^0\pi^0$ lifetime distribution for data and Monte Carlo events after the 6c-fit, the Q3NN cut, the New Loop Method and the cut on the photon shower directions.

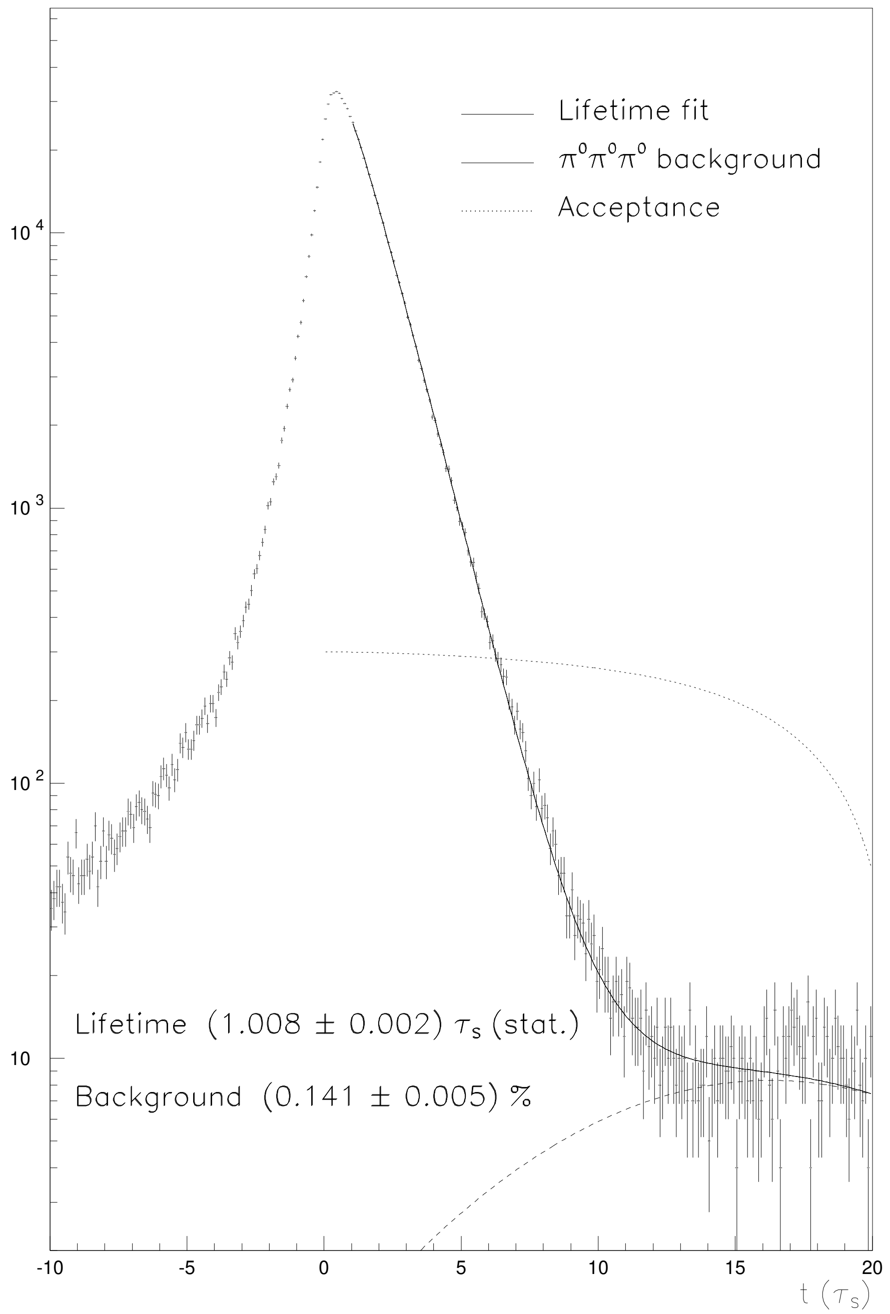

Figure 10: The $K^0(\overline{K^0}) \rightarrow \pi^0\pi^0$ lifetime distribution. The solid line is a fit with an exponential convoluted with the Monte Carlo lifetime resolution and taking the $K^0(\overline{K^0}) \rightarrow \pi^0\pi^0\pi^0$ background shape into account.

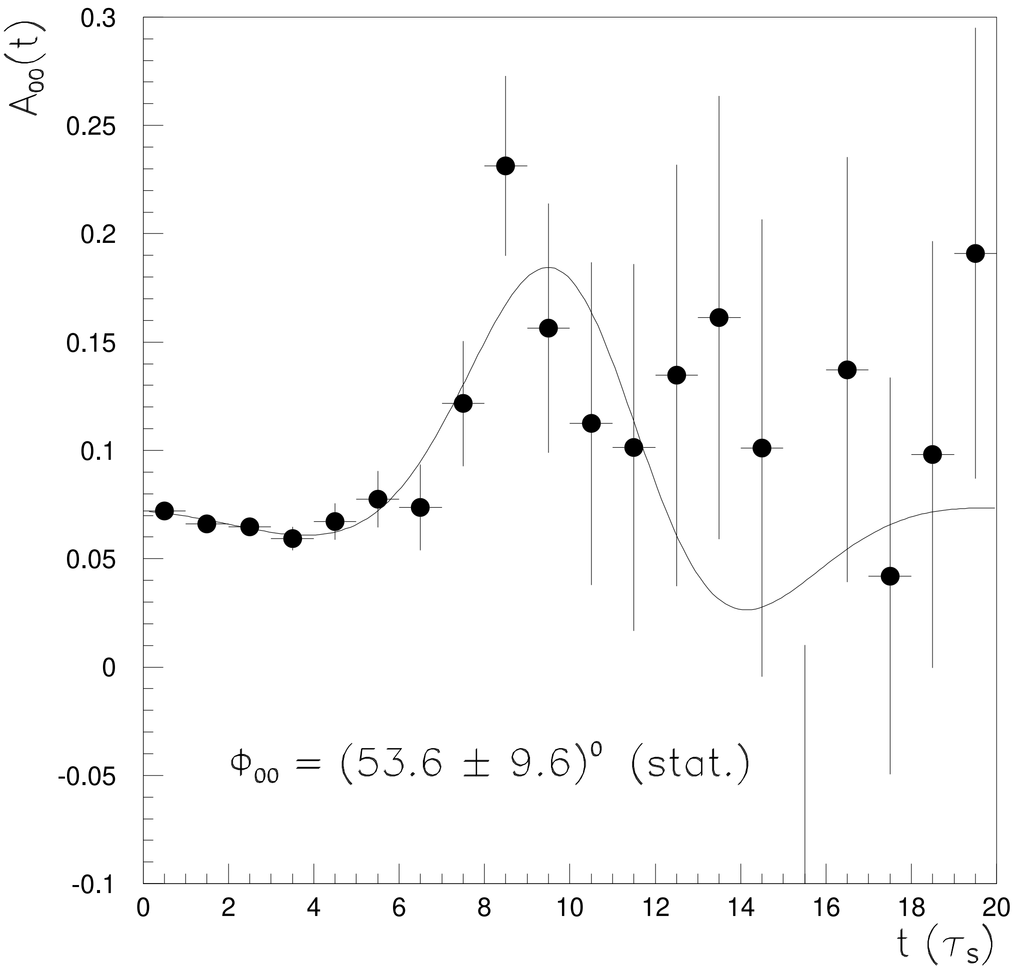

Figure 11: The asymmetry $A_{00}(t)$. The solid line is a fit with the phenomenological expression for the asymmetry convoluted with the Monte Carlo lifetime resolution and taking the $K^0(\overline{K^0}) \rightarrow \pi^0\pi^0\pi^0$ background into account.

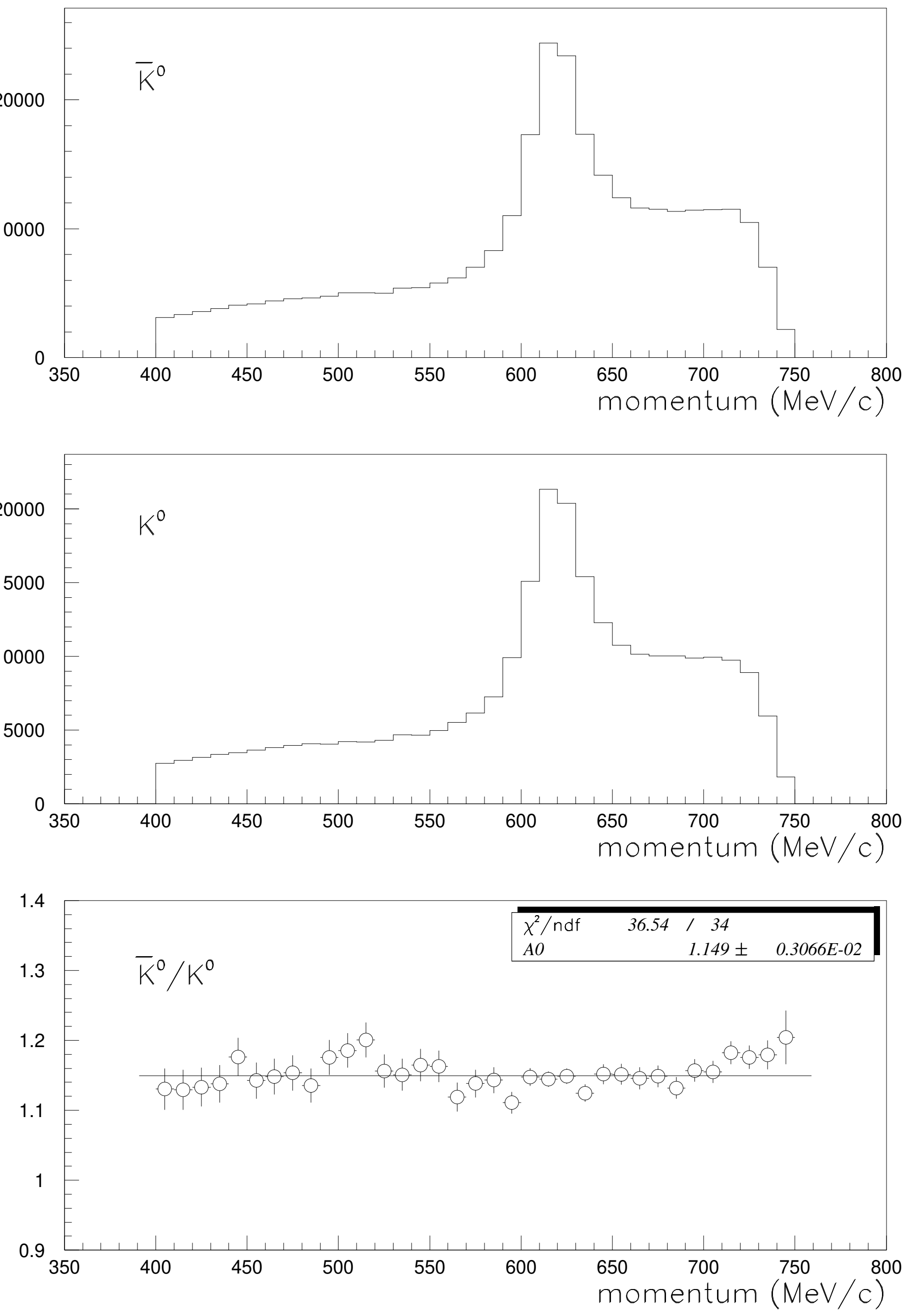

Figure 12: The $\overline{K^0}$ and the K^0 momentum distribution and the $\overline{K^0}$-K^0ratio as a function of the $\overline{K^0}(K^0)$ momentum for events in the $\overline{K^0}(K^0)$ lifetime interval [0,4] τ_S. No correction for CP violation was applied.

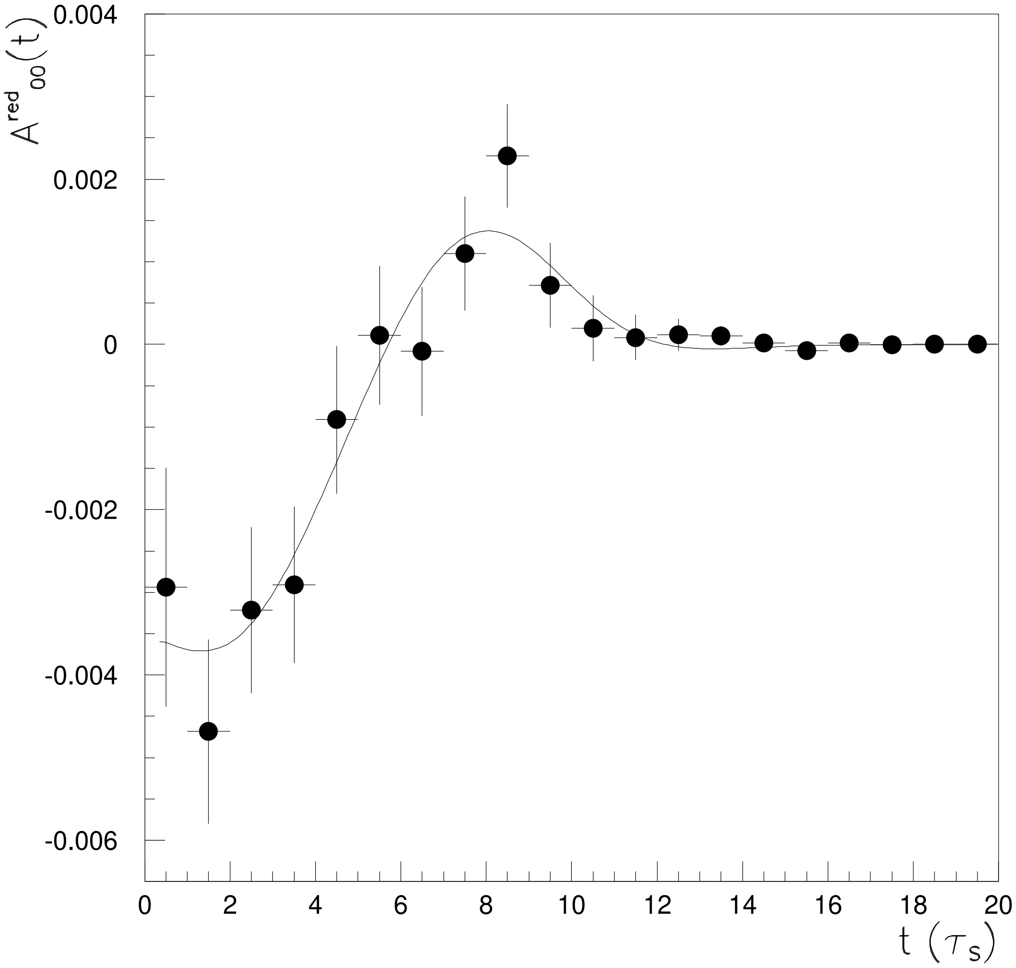

Figure 13: The reduced asymmetry $A^{red}_{00}(t)$.