

Search for \mathcal{CP} Violation in the Decay $\tau^- \rightarrow \pi^- K_s^0 (\geq 0 \pi^0) \nu_\tau$

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Abstract

We report a search for CP violation in the decay $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$ using a dataset of 437 million τ lepton pairs, corresponding to an integrated luminosity of 476 fb^{-1} , collected with the *BABAR* detector at the PEP-II asymmetric energy e^+e^- storage rings. The CP -violating decay-rate asymmetry is determined to be $(-0.45 \pm 0.24 \pm 0.11)\%$, approximately three standard deviations from the Standard Model prediction of $(0.33 \pm 0.01)\%$.

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1 CP violation has been observed only in the K and B meson systems. However, Bigi and Sanda predict that, in the Standard Model (SM), the decay of the τ lepton to final states containing a K^0 meson will also have a non-zero decay-rate asymmetry due to CP violation in the kaon sector. The decay-rate asymmetry

12 decay products in $\tau^- \rightarrow \pi^- K_S^0 \nu_\tau$ decays [3], or by the CLEO collaboration [4].

13 This paper presents a measurement of A_Q using $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$ and charge conjugate decays. The analysis uses data recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings operated at center-of-mass (CM) energies of 10.58 GeV and 10.54 GeV at the SLAC National Accelerator Laboratory. The *BABAR* detector is described in detail in Ref. [5]. In particular, charged kaons and pions are differentiated by ionization (dE/dx) measurements in the drift chamber in combination with an internally reflecting Cherenkov detector, with identification efficiency greater than 90% for pions and kaons with momenta above 1.5 GeV/c in the laboratory frame [6]. The probability of identify-

14 15 16 17 18 19 20 21 22 23 24 25 26

is predicted to be $(0.33 \pm 0.01)\%$ [1]. Significant deviation from the SM value could be evidence for new physics. No evidence for CP violation has been found in related studies by *BABAR* in $D^+ \rightarrow K_S^0 \pi^+$ decays [2], by the Belle collaboration in a study of the angular distribution of the

ing a pion as a charged kaon is less than 2%. An electromagnetic calorimeter made of cesium iodide crystals provides energy measurements for electrons and photons, whereas an instrumented flux return detector identifies muons [7]. For momenta above $1\text{ GeV}/c$ in the laboratory frame, electrons and muons are identified with efficiencies of approximately 92% and 70%, respectively. Based on an integrated luminosity of 476 fb^{-1} , the data sample contains approximately 875 million τ leptons.

Simulated event samples are used to estimate the purity of the data sample. The production of τ pairs is simulated with the KK2F Monte Carlo (MC) event generator [8]. Subsequent decays of the τ lepton, continuum $q\bar{q}$ events (where $q = u, d, s, c$), and final-state radiative effects are modeled with Tauola [9], JETSET [10], and PHOTOS [11], respectively. Passage of the particles through the detector is simulated by GEANT [12].

The τ pairs are produced back-to-back in the e^+e^- CM frame. As a result, the decay products of the two τ leptons can be separated from each other by dividing the event into two hemispheres – the “signal” hemisphere and the “tag” hemisphere – using the event thrust axis [13]. The event thrust axis is calculated using two charged particles, the K_S^0 candidate and all photon candidates in the entire event. We select events with one charged particle and a $K_S^0 \rightarrow \pi^+ \pi^-$ candidate reconstructed in the signal hemisphere, and exactly one oppositely charged particle in the tag hemisphere. The tracks, excluding those from the K_S^0 , must originate from the beam spot. The components of momentum transverse to the e^- beam axis for each of these latter two charged particles must be greater than $0.1\text{ GeV}/c$ in the laboratory frame. The event is rejected if the charged particle in the signal hemisphere is identified as a charged kaon. K_S^0 candidates are defined as a pair of oppositely charged pion candidates with invariant mass between 0.488 and $0.508\text{ GeV}/c^2$; furthermore, the distance between the beam spot and the $\pi^+ \pi^-$ vertex must be at least three times its uncertainty. To reduce backgrounds from non- τ -pair events, we require that the momentum of the charged particle in the tag hemisphere be less than $4\text{ GeV}/c$ in the CM frame and be identified as an electron (e -tag) or a muon (μ -tag). To reduce backgrounds from Bhabha, $\mu^+ \mu^-$, and $q\bar{q}$ events, we require the magnitude of the event thrust to be between 0.92 and 0.99 .

Backgrounds from $q\bar{q}$ events are further reduced by rejecting events in which the invariant mass M_{rec} of the charged particle (assumed to be a pion), the K_S^0 candidate, and up to three π^0 candidates, all in the signal hemisphere, is greater than $1.8\text{ GeV}/c^2$ (see Fig. 1). If more than three π^0 candidates are reconstructed in the signal hemisphere, the three with invariant mass closest to the world-average π^0 mass [14] are included in the calculation of M_{rec} and the rest are ignored. The π^0 candidates are constructed from two clusters of energy deposits in the electromagnetic calorimeter that have no

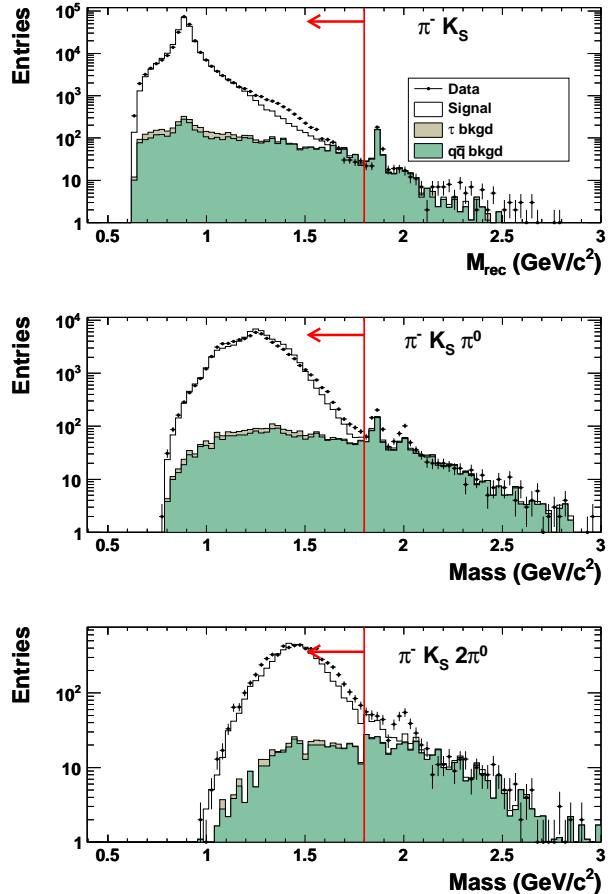


FIG. 1: Invariant-mass distributions for the combined e -tag and μ -tag samples. The label in each plot indicates the reconstructed decay mode (including the charge conjugate mode). Points with error bars represent data whereas the histograms represent the simulated sample. The histogram labeled as “Signal” includes the $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$, residual $\tau^- \rightarrow K^- K_S^0 (\geq 0\pi^0) \nu_\tau$, and $\tau^- \rightarrow \pi^- K^0 \bar{K}^0 \nu_\tau$ modes. All selection criteria (including the likelihood ratio requirement), except the invariant mass (M_{rec}) criterion, have been applied. The vertical lines and arrows indicate the $M_{\text{rec}} < 1.8\text{ GeV}/c^2$ selection criterion.

associated tracks. The energy of each cluster is required to be greater than 30 MeV in the laboratory frame and the invariant mass of the two clusters must be between $0.115\text{ GeV}/c^2$ and $0.150\text{ GeV}/c^2$. The number of events in the $\tau^- \rightarrow \pi^- K_S^0 3\pi^0 \nu_\tau$ mode is small and the corresponding invariant mass plot is not included in Fig. 1.

The imperfect agreement between the M_{rec} distributions in the data and MC simulation, seen in Fig. 1, is attributed to K^* resonances that are not included in the simulation. The impact of the modeling of the τ decay modes in the MC simulation on the decay-rate asymmetry is found to be small and is included in the systematic uncertainties.

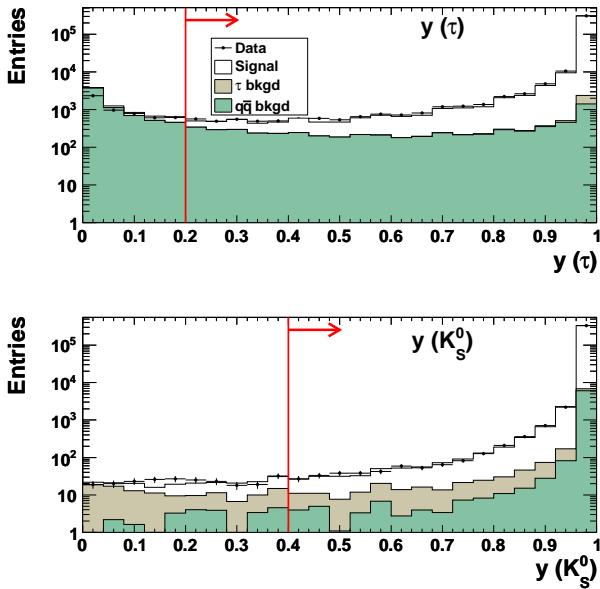


FIG. 2: The likelihood ratio $y(\tau)$ used to distinguish τ events¹⁴² from $q\bar{q}$ events (top plot) and the likelihood ratio $y(K_s^0)$ used¹⁴³ to select τ decays with a $K_s^0 \rightarrow \pi^+\pi^-$ (bottom plot). All¹⁴⁴ selection cuts, except the likelihood ratio requirement, have¹⁴⁵ been applied. Points with error bars represent data while¹⁴⁶ histograms correspond to simulated events. The histogram la-¹⁴⁷
beled as “Signal” includes the $\tau^- \rightarrow \pi^- K_s^0 (\geq 0\pi^0) \nu_\tau$, resi-¹⁴⁸
dual $\tau^- \rightarrow K^- K_s^0 (\geq 0\pi^0) \nu_\tau$, and $\tau^- \rightarrow \pi^- K^0 \bar{K}^0 \nu_\tau$ modes.¹⁴⁹
The vertical lines indicate the selection criteria.

e⁻ beam axis. The cosine of the polar angle is used to discriminate low-angle photon conversions from genuine K_s^0 candidates. All kinematic quantities used in the construction of the two likelihood ratios, except for thrust, are determined in the laboratory frame. Events are selected if $y(\tau) > 0.2$ and $y(K_s^0) > 0.4$ (see Fig. 2) in order to minimize the contamination from background events while maintaining a high selection efficiency.

After all selection criteria are applied, a total of 199064 (140602) candidates are obtained in the e-tag (μ -tag) sample, of which there are 99842 (70369) in the τ^- sample and 99222 (70233) in the τ^+ sample.

The sample contains backgrounds from two τ decay modes, $\tau^- \rightarrow K^- K_s^0 (\geq 0\pi^0) \nu_\tau$ and $\tau^- \rightarrow \pi^- K^0 \bar{K}^0 \nu_\tau$, that have known background asymmetries. The SM asymmetry from the $\tau^- \rightarrow K^- K_s^0 (\geq 0\pi^0) \nu_\tau$ mode is equal and opposite to that of the $\tau^- \rightarrow \pi^- K_s^0 (\geq 0\pi^0) \nu_\tau$ mode whereas the asymmetry for $\tau^- \rightarrow \pi^- K^0 \bar{K}^0 \nu_\tau$ is zero. The additional π^0 mesons in the decay modes are not expected to change the asymmetry. The MC simulation is used to predict the composition of the sample (see Table I) and to evaluate the correction to be applied to the measured asymmetry. The decay $\tau^- \rightarrow \pi^- K^0 \bar{K}^0 \nu_\tau$ satisfies the selection criteria if one of the neutral kaons decays into $\pi^+\pi^-$ and the other neutral kaon decays into $2\pi^0$ or appears as a K_L^0 meson.

The selected candidates contain a small background component from τ decays not containing a K_s^0 in the final state and continuum $q\bar{q}$ events. In a simulated sample, less than 10 $B\bar{B}$ background events are observed to pass the selection criteria. The numbers of background events are estimated from the Monte Carlo simulation. The accuracy of the background estimation is evaluated by measuring the ratios of data to simulated event yields in the region $y(\tau) < 0.1$ and $y(K_s^0) < 0.1$. A correction factor is then applied to the background such that the number of simulated events in the region matches with data. The numbers of background events are estimated to be 1393 ± 79 (1120 ± 65) for τ^- decays and 1401 ± 74 (1055 ± 74) for τ^+ decays in the e-tag (μ -tag) samples, where the uncertainties include the statistical uncertainties from the sizes of the Monte Carlo samples and the uncertainties of the correction factors.

After the subtraction of background composed of $q\bar{q}$ and non- K_s^0 τ decays, the decay-rate asymmetry is measured to be $(-0.32 \pm 0.23)\%$ for the e-tag sample and $(-0.05 \pm 0.27)\%$ for the μ -tag sample, where the errors are statistical. However, the asymmetry measured at this stage still includes other τ decays with K_s^0 in the final state.

A control sample of $\tau^- \rightarrow h^- h^- h^+ (\geq 0\pi^0) \nu_\tau$ (excluding $K_s^0 \rightarrow \pi^+\pi^-$ decays) in both data and MC simulation, where h^- (h^+) represents a negatively (positively) charged hadron, is used to confirm that no significant decay-rate asymmetry is induced by the BABAR detector or the selection criteria. The control sample is selected

A likelihood ratio $y(\tau)$ is used to distinguish τ -pair¹⁵² events from $q\bar{q}$ events, and a second likelihood ratio¹⁵³ $y(K_s^0)$ is used to reduce the background in the sam-¹⁵⁴ ple of $K_s^0 \rightarrow \pi^+\pi^-$ candidates. The likelihood ratio¹⁵⁵ $y_i(\vec{x}_i)$, where i refers to τ or K_s^0 , is defined as $y_i(\vec{x}_i) \equiv$
¹⁵⁶ $\mathcal{L}_i^s(\vec{x}_i)/(\mathcal{L}_i^s(\vec{x}_i) + w\mathcal{L}_i^b(\vec{x}_i))$ where w is the background-to-¹⁵⁷ signal ratio estimated from the MC simulation, \mathcal{L}_i^s (\mathcal{L}_i^b)¹⁵⁸ is the likelihood function for signal (background) events,¹⁵⁹ and \vec{x}_i is the set of variables used for likelihood i . Each¹⁶⁰ likelihood function is a product of one-dimensional prob-¹⁶¹ ability distribution functions of the variables \vec{x}_i obtained¹⁶² from the MC simulation. For $y(\tau)$, the variables \vec{x}_i are¹⁶³ the visible energy (sum of the energies associated with¹⁶⁴ all neutral calorimeter clusters and tracks in the event),¹⁶⁵ the number of neutral clusters in the tag hemisphere, the¹⁶⁶ number of neutral clusters in the signal hemisphere, the¹⁶⁷ magnitude of the thrust, and the component of the total¹⁶⁸ momentum of the event transverse to the e⁻ beam axis¹⁶⁹ (calculated from all tracks and neutral clusters in both¹⁷⁰ hemispheres). The variables used to construct $y(K_s^0)$ are¹⁷¹ the distance from the beam spot to the decay vertex of¹⁷² the K_s^0 candidate in the plane transverse to the e⁻ beam¹⁷³ axis, the invariant mass of the $\pi^+\pi^-$ daughters of the K_s^0 ,¹⁷⁴ the magnitude of the K_s^0 momentum, and the¹⁷⁵ cosine of the polar angle of the K_s^0 candidate. The po-¹⁷⁶ lar angle is the angle between the K_s^0 trajectory and the¹⁷⁷

TABLE I: Breakdown of the MC sample after all selection criteria have been applied. The errors of the decay modes with K_S^0 are dominated by the uncertainties in the branching fractions.

Source	Fractions (%)	
	e-tag	μ -tag
$\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$	78.4 ± 4.0	77.4 ± 4.0
$\tau^- \rightarrow K^- K_S^0 (\geq 0\pi^0) \nu_\tau$	4.2 ± 0.3	4.0 ± 0.3
$\tau^- \rightarrow \pi^- K^0 \bar{K}^0 \nu_\tau$	15.6 ± 3.7	15.7 ± 3.7
Other τ lepton decays	0.3 ± 0.0	0.3 ± 0.0
$e^+ e^- \rightarrow q\bar{q}$ background	1.4 ± 0.0	2.5 ± 0.0

isospin symmetry to the K^\pm nucleon cross-sections [14]. The correction, which is subtracted from the measured asymmetry, is found to be $(0.14 \pm 0.03)\%$ for e -tag and $(0.14 \pm 0.02)\%$ for μ -tag samples. The error includes the statistical uncertainty in the MC simulation, the uncertainties in the kaon-nucleon cross-sections [14], and an uncertainty due to the assumption of isospin invariance. The last effect is taken to be 5% by observing that isospin symmetry in pion-nucleon cross-sections holds to within a few percent.

The measured decay-rate asymmetries (after correcting for the difference in neutral kaon nuclear interactions) are $(-0.46 \pm 0.23 \pm 0.13)\%$ for the e -tag sample and $(-0.19 \pm 0.27 \pm 0.10)\%$ for the μ -tag sample, where the first error is statistical and the second is systematic. The systematic uncertainties of the e -tag and μ -tag results are almost completely uncorrelated. The weighted average of the two decay-rate asymmetries is $(-0.34 \pm 0.18 \pm 0.08)\%$.

The decay-rate asymmetry is diluted due to $\tau^- \rightarrow K^- K_S^0 \nu_\tau$ and $\tau^- \rightarrow \pi^- K^0 \bar{K}^0 \nu_\tau$ decays. The measured asymmetry \mathcal{A} is related to the signal asymmetry A_1 and the remaining background asymmetries A_2 and A_3 by:

$$\begin{aligned}\mathcal{A} &= \frac{f_1 A_1 + f_2 A_2 + f_3 A_3}{f_1 + f_2 + f_3} \\ &= \left(\frac{f_1 - f_2}{f_1 + f_2 + f_3} \right) A_{SM}\end{aligned}$$

where f_1 , f_2 , and f_3 are the fractions of $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$, $\tau^- \rightarrow K^- K_S^0 (\geq 0\pi^0) \nu_\tau$, and $\tau^- \rightarrow \pi^- K^0 \bar{K}^0 \nu_\tau$ in the total selected sample as shown in Table I. Within the Standard Model, $A_1 = -A_2 = A_{SM} = (0.33 \pm 0.01)\%$ and $A_3 = 0$. We compare our result with the prediction of Bigi and Sanda by dividing the measured decay-rate asymmetry of $(-0.34 \pm 0.18 \pm 0.08)\%$ by $(f_1 - f_2)/(f_1 + f_2 + f_3) = 0.75 \pm 0.04$ (the correction is identical for the e -tag and μ -tag samples). The uncertainty on the correction includes the statistical uncertainty and uncertainties in the branching fractions. Finally, the decay-rate asymmetry for the $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$ decay for the combined e -tag and μ -tag sample is calculated to be $A_Q = (-0.45 \pm 0.24 \pm 0.11)\%$.

In conclusion, we have performed a search for CP violation using the $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$ decay mode. The decay-rate asymmetry is measured, for the first time, to be $(-0.45 \pm 0.24 \pm 0.11)\%$. The measurement is approximately three standard deviations from the SM prediction of $(0.33 \pm 0.01)\%$.

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by requiring that all charged tracks originate from the interaction region, which suppresses K_S^0 contamination due to its displaced decay vertex. The asymmetries measured in the simulated and data control samples agree within 0.12% for the e -tag and 0.08% for the μ -tag, where the uncertainties include both statistical and systematic components. These errors are included as systematic uncertainties on the signal asymmetry (see Table II).

TABLE II: Summary of systematic uncertainties in the decay-rate asymmetries.

	e-tag	μ -tag
Detector and selection bias	0.12%	0.08%
Background subtraction	0.05%	0.06%
K^0/\bar{K}^0 interaction	0.03%	0.02%
Total	0.13%	0.10%

Additional studies show no evidence for any charge-dependent biases in the selection criteria. The decay-rate asymmetry is measured in the MC sample and found to be consistent with zero within a statistical precision of 0.14% for the e -tag and 0.17% for the μ -tag (no CP violation is modeled in the simulation). We vary the selection criteria around their nominal values and no significant changes in the asymmetry are observed. The decay-rate asymmetry of the background events was studied by examining the events rejected by the likelihood ratio criteria and was found to be consistent with zero for both data and MC simulation.

A recent paper [15] suggests that the decay-rate asymmetry will be modified due to the different nuclear interaction cross-sections of the K^0 and \bar{K}^0 mesons with the material in the detector. This effect is not included in the MC simulation. A correction to the asymmetry accounting for this effect is calculated on an event-by-event basis using the momentum and polar angle of the K_S^0 candidates together with the nuclear-interaction cross-sections for neutral kaons, which are related by

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294 [1] I. I. Bigi and A. I. Sanda, Phys. Lett. B **625**, 47 (2005).²⁹⁵
 295 [2] P. del Amo Sanchez *et al.* (BABAR Collaboration), Phys.²⁹⁶
 296 Rev. D 83, 071103 (2011).²⁹⁷

297 [3] M. Bischofberger *et al.* (Belle Collaboration),
 arXiv:1101.0349v1 [hep-ex]. Submitted to Phys. Rev.

- Lett. (2011)
- [4] G. Bonvicini *et al.* (CLEO Collaboration), Phys. Rev. Lett. 88, 111803 (2002).
- [5] B. Aubert *et al.* (BABAR Collaboration), Nucl. Instr. Methods Phys. Res., Sect. A **479**, 1 (2002).
- [6] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. Lett. 99, 021603 (2007).
- [7] J. P. Lees *et al.* (BABAR Collaboration), Phys. Rev. D 81, 111101(R) (2010).
- [8] B. F. L. Ward, S. Jadach, and Z. Was, Nucl. Phys. Proc. Suppl. **116**, 73 (2003).
- [9] S. Jadach *et al.* Comput. Phys. Commun. **76**, 361 (1993).
- [10] T. Sjostrand, Comput. Phys. Commun. **82**, 74 (1994).
- [11] E. Barberio and Z. Was, Comput. Phys. Commun. **79**, 291 (1994).
- [12] S. Agostinelli *et al.* Nucl. Instr. Methods Phys. Res., Sect. A506, 250 (2003).
- [13] S. Brandt *et al.*, Phys. Lett. **12**, 57 (1964); E. Farhi, Phys. Rev. Lett. **39**, 1587 (1977).
- [14] K. Nakamura *et al.* (Particle Data Group), J. Phys. **G37**, 075021 (2010).
- [15] B. R. Ko *et al.* arXiv:1006.1938v1 [hep-ex] (2010).