

Measurement of Time-Dependent CP -Violating Asymmetries in B^0 Meson Decays to $\eta'K^0$

The *BABAR* Collaboration

August 17, 2004

Abstract

We present a preliminary measurement of CP -violating parameters S and C from fits of the time-dependence of B^0 meson decays to $\eta'K^0$. The data were recorded with the *BABAR* detector at PEP-II and correspond to 227×10^6 $B\bar{B}$ pairs produced in e^+e^- annihilation through the $\Upsilon(4S)$ resonance. From a maximum likelihood fit we measure the CP -violation parameters $S = 0.27 \pm 0.14$ (stat) ± 0.03 (syst) and $C = -0.21 \pm 0.10$ (stat) ± 0.03 (syst).

Submitted to the 32nd International Conference on High-Energy Physics, ICHEP 04,
16 August—22 August 2004, Beijing, China

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Work supported in part by Department of Energy contract DE-AC02-76SF00515.

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1 Introduction

Measurements of time-dependent CP asymmetries in B^0 meson decays through a Cabibbo-Kobayashi-Maskawa (CKM) favored $b \rightarrow c\bar{c}s$ amplitude [1] have provided a crucial test of the CKM mechanism of CP violation in the Standard Model (SM) [2]. Such decays to a charmonium state plus a K^0 meson are dominated by a single weak phase. Decays of B^0 mesons to charmless hadronic final states, such as ϕK^0 , $\eta' K^0$, $K^+ K^- K^0$, $K^0 \pi^0$ and $f_0(980) K^0$, are expected to be dominated by penguin diagrams. If we neglect CKM-suppressed amplitudes, these decay modes have the same weak phase as the charmonium K^0 decays in the SM. Thus the time-dependent asymmetry measurement for these decays should yield an alternative measurement of $\sin 2\beta$ [3].

The processes shown in Fig. 1(b)-(d) are relevant for the decay $B^0 \rightarrow \eta' K^0$, and there are similar diagrams for $B^+ \rightarrow \eta' K^+$. All of the amplitudes for these processes have CKM suppression, but the tree diagram for B^0 shown in Fig. 1(b) is expected to be smaller [4, 5] since there is additional CKM suppression and color suppression. For the charged mode the corresponding tree diagram is external and not color suppressed.

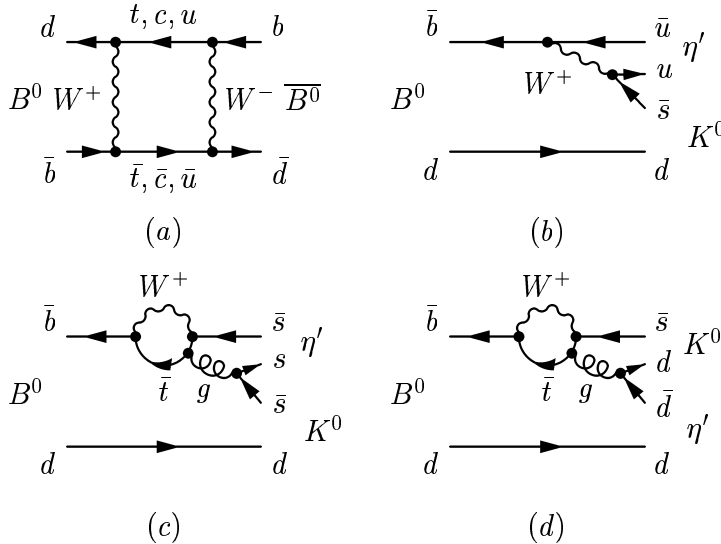


Figure 1: Feynman diagrams describing (a) $B - \bar{B}$ mixing; the decay $B^0 \rightarrow \eta' K^0$ via (b) color-suppressed tree, (c, d) internal gluonic penguin.

Additional higher-order amplitudes carrying different weak phases would lead to deviations, ΔS , between the measurements of the time-dependent CP violating parameter in these rare decay modes and in the charmonium K^0 decays. Theoretical bounds for these deviations have been calculated with an $SU(3)$ analysis [6, 7]. Such bounds have been improved by recent measurements of B^0 decays to a pair of neutral charmless light pseudoscalar mesons [8]. From this and other recent experimental measurements, improved model-independent correlated bounds in the (S, C) plane for the decay $B^0 \rightarrow \eta' K^0$ have been derived [9], with the conclusion that ΔS is expected to be less than 0.10 (with a theoretical uncertainty up to $\sim 30\%$ due to the assumptions in the calculation).

Specific model calculations conclude that ΔS is even smaller; for instance a recent calculation [10] finds $\Delta S = 0.011 \pm 0.009 \pm 0.010$, where the first error is due to theoretical uncertainties for $B^0 \rightarrow \eta' K^0$ and the second is for uncertainties in the charmonium- K_S^0 system. A significantly larger value of ΔS could arise from phases from non-SM amplitudes [3].

The CP -violating asymmetry in the decay $B^0 \rightarrow \eta' K^0$ has been measured previously by the *BABAR* [11] and Belle [12] experiments. The measurement presented in this paper is an update of the previous *BABAR* measurement. In the present analysis the measurements of time-dependent CP violating parameters in $B^+ \rightarrow \eta' K^+$ are used as a null control sample for the corresponding measurements in $B^0 \rightarrow \eta' K^0$.

2 The *BABAR* Detector and Dataset

The results presented in this paper are based on data collected in 1999–2004 with the *BABAR* detector [13] at the PEP-II asymmetric e^+e^- collider [14] located at the Stanford Linear Accelerator Center. An integrated luminosity of 205 fb^{-1} , corresponding to about 227 million $B\bar{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance (“on-resonance”, center-of-mass energy $\sqrt{s} = 10.58 \text{ GeV}$).

The asymmetric beam configuration in the laboratory frame provides a boost of $\beta\gamma = 0.56$ to the $\Upsilon(4S)$. Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker (SVT), consisting of five layers of double-sided detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a solenoid. The tracking system covers 92% of the solid angle in the center-of-mass (CM) frame.

Charged-particle identification (PID) is provided by the average energy loss (dE/dx) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. A K/π separation of better than four standard deviations (σ) is achieved for momenta below 3 GeV/ c , decreasing to 2.5 σ at the highest momenta in the B decay final states. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter (EMC). The EMC provides good energy and angular resolutions for detection of photons in the range from 30 MeV to 4 GeV. The energy and angular resolutions are 3% and 4 mrad, respectively, for a 1 GeV photon.

The flux return for the solenoid is composed of multiple layers of iron and resistive plate chambers for the identification of muons and long-lived neutral hadrons.

3 Event Selection and Analysis Method

Monte Carlo (MC) simulations of the signal decay modes, $B\bar{B}$ backgrounds, and detector response are used to establish the event selection criteria.

We reconstruct B meson candidates by combining a K_S^0 or a K^+ with an η' meson. We select $K_S^0 \rightarrow \pi^+\pi^-$ decays by requiring the invariant $\pi^+\pi^-$ to be within a mass window of 12 MeV around the nominal K_S^0 mass and requesting a flight length $> 3 \sigma$. We select $K_S^0 \rightarrow \pi^0\pi^0$ decays requiring the invariant $\pi^0\pi^0$ to be within a mass window of 30 MeV around the nominal K_S^0 mass and a fit of the two π^0 mesons to a common decay vertex. We reconstruct η' mesons through the decays $\eta' \rightarrow \rho^0\gamma$ and $\eta' \rightarrow \eta\pi^+\pi^-$ with $\eta \rightarrow \gamma\gamma$ or $\eta \rightarrow \pi^+\pi^-\pi^0$. The photon energy E_γ must be greater than 50 (30) MeV for η (π^0) candidates, and greater than 100 MeV in $\eta' \rightarrow \rho^0\gamma$. We make the following requirements on the invariant mass (in MeV): $490 < m_{\gamma\gamma} < 600$ for $\eta_{\gamma\gamma}$, $120 < m_{\gamma\gamma} < 150$ for π^0 ($100 < m_{\gamma\gamma} < 155$ in $K_S^0 \rightarrow \pi^0\pi^0$), $510 < m_{\pi\pi} < 1000$ for ρ^0 , $520 < m_{\pi\pi\pi} < 570$ for $\eta_{3\pi}$, $945 < m_{\eta'} < 970$ for $\eta' \rightarrow \eta\pi^+\pi^-$, and $930 < m_{\eta'} < 980$ for $\eta' \rightarrow \rho^0\gamma$.

We make several particle identification requirements to ensure the identity of the signal pions. In charged B decays for the K^+ track we require an associated DIRC Cherenkov angle between -5σ and $+2\sigma$ from the expected value for a kaon.

A B meson candidate is characterized kinematically by the energy-substituted mass $m_{\text{ES}} \equiv \sqrt{(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and the energy difference $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ frame. We require $|\Delta E| \leq 0.2$ GeV and $5.25 \leq m_{\text{ES}} \leq 5.29$ GeV.

To reject background in continuum $e^+e^- \rightarrow q\bar{q}$ events ($q = u, d, s, c$), we make use of the angle θ_T between the thrust axis of the B candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the center-of-mass frame. The distribution of $\cos\theta_T$ is sharply peaked near ± 1 for combinations drawn from jet-like $q\bar{q}$ pairs and is nearly uniform for the isotropic B meson decays; we require $|\cos\theta_T| < 0.9$. The remaining continuum background dominates the samples and is modeled from sideband data for the maximum likelihood fits.

We use Monte Carlo simulations of $B^0\bar{B}^0$ and B^+B^- pair production and decay to look for $B\bar{B}$ backgrounds. From these studies we find evidence for a small $B\bar{B}$ background component for the channels with $\eta' \rightarrow \rho^0\gamma$, and we have added a single $B\bar{B}$ component to the fit.

From a $B\bar{B}$ pair we reconstruct a B^0 decaying into the final state $f = \eta'K_S^0$ (B_{CP}). We also reconstruct the vertex of the other B meson (B_{tag}) and identify its flavor. The time difference $\Delta t \equiv t_{CP} - t_{\text{tag}}$, where t_{CP} and t_{tag} are the proper decay times of the CP and tagged B mesons, respectively, is obtained from the measured distance between the B_{CP} and B_{tag} decay vertices and from the boost ($\beta\gamma = 0.56$) of the e^+e^- beam system. The distribution of Δt is:

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \{1 \mp \Delta\omega \pm (1 - 2\omega) [S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\}, \quad (1)$$

where the upper (lower) sign denotes a decay accompanied by a B^0 (\bar{B}^0) tag, τ is the mean B^0 lifetime, Δm_d is the mixing frequency, and the mistag parameters ω and $\Delta\omega$ are the average and difference, respectively, of the probabilities that a true B^0 (\bar{B}^0) meson is tagged as \bar{B}^0 (B^0). The tagging algorithm, based on six tagging categories, is an improved version of what was used in the previous *BABAR* publication [11]. Separate neural networks are trained to identify primary leptons, kaons, soft pions from D^* decays, and high-momentum charged particles from B decays. Each event is assigned to one of the six mutually exclusive tagging categories based on the estimated mistag probability and on the source of tagging information.

4 Maximum Likelihood Fit

We use an unbinned, multivariate maximum-likelihood fit to extract signal yields and CP violating parameters. We indicate with j the species of event: signal, continuum background, or $B\bar{B}$ background ($\eta' \rightarrow \rho^0\gamma$). We use four discriminating variables: m_{ES} , ΔE , Δt , and a Fisher discriminant \mathcal{F} . The Fisher discriminant combines five variables: the angles with respect to the beam axis of the B momentum and B thrust axis in the $\Upsilon(4S)$ frame, the zeroth and second angular moments of the energy flow excluding the B candidate around the B thrust axis, and the tagging category. For each species j and each tagging category c , we define a total probability density function (PDF) for event i as

$$\mathcal{P}_{j,c}^i \equiv \mathcal{P}_j(m_{\text{ES}}^i) \cdot \mathcal{P}_j(\Delta E^i) \cdot \mathcal{P}_j(\mathcal{F}^i) \cdot \mathcal{P}_j(\Delta t^i, \sigma_{\Delta t}^i, c), \quad (2)$$

where $\sigma_{\Delta t}^i$ is the error on Δt for the event i . With n_j defined to be the number of events of the species j and $f_{j,c}$ the fraction of events of species j for each category c , we write the extended

likelihood function for all events belonging to category c as

$$\mathcal{L}_c = \frac{e^{-N_c}}{N_c!} \prod_i^{N_c} (n_{\text{sig}} f_{\text{sig},c} \mathcal{P}_{\text{sig},c}^i + n_{q\bar{q}} f_{q\bar{q},c} \mathcal{P}_{q\bar{q}}^i + n_{B\bar{B}} f_{\text{sig},c} \mathcal{P}_{B\bar{B}}^i), \quad (3)$$

where N_c is the total number of input events in category c . In the last term of this formula we have assumed $f_{\text{sig},c} = f_{B\bar{B},c}$. The total likelihood function for all categories is given as the product over the seven tagging categories (including a category for untagged events for yield determinations). The product is extended to additional sub-decays by multiplying the above product likelihoods for each decay.

We maximize the likelihood function while varying a set of free parameters: S , C , three background \mathcal{F} PDF parameters, and, for each sub-decay, signal and background yields, ΔE and m_{ES} background parameters, and six parameters representing the background Δt shape.

5 Results

The results of the fits to the neutral modes are shown in Table 1. We combine the five sub-decay modes shown in Table 1. The decay mode $B^0 \rightarrow \eta'_{\eta_3\pi\pi} K^0(\pi^0\pi^0)$ has not been reconstructed because of its expected low signal yield. The results for the three charged modes, used as a crosscheck, are presented in Table 2; the values of S and C are consistent with zero, as expected. The first two columns in each table represent the primary modes that we reported on in our previous analysis. The last three columns of Table 1 and the last column of Table 2 are for decay modes that we have not reported on previously. The efficiency of the selection after all cuts is about 25% for the four primary decay modes and 15% for the four new decay channels.

Table 1: Results from fits to sub-decay modes of $B^0 \rightarrow \eta' K_S^0$.

	$\eta'_{\eta\pi\pi} K^0(\pi^+\pi^-)$	$\eta'_{\rho\gamma} K^0(\pi^+\pi^-)$	$\eta'_{\eta_3\pi\pi} K^0(\pi^+\pi^-)$	$\eta'_{\eta\pi\pi} K^0(\pi^0\pi^0)$	$\eta'_{\rho\gamma} K^0(\pi^0\pi^0)$
Signal yield	192 ± 15	438 ± 27	55 ± 9	50 ± 9	86 ± 20
$B\bar{B}$ yield	–	93 ± 33	–	–	78 ± 23
S	0.05 ± 0.28	0.41 ± 0.19	0.53 ± 0.49	-0.18 ± 0.50	-0.26 ± 0.61
C	-0.12 ± 0.18	-0.29 ± 0.13	0.18 ± 0.38	-0.69 ± 0.40	0.19 ± 0.44
Combined fit					
Signal Yield	819 ± 38				
S	0.27 ± 0.14				
C	-0.21 ± 0.10				

In Fig. 2 we show projections onto m_{ES} and ΔE of a subset of the data of the primary decay modes for which the signal likelihood (computed without the plotted variable) exceeds a mode-dependent threshold that optimizes the sensitivity. In Fig. 3 we show the same projections onto m_{ES} and ΔE for the new decay modes considered in the present analysis.

We show in Fig. 4 the Δt projections and asymmetry of all combined neutral modes for events selected as for Fig. 2 and Fig. 3. In Fig. 5 we show the $-2\ln\mathcal{L}$ scans for S and C . The best fit value for S is 3.0 standard deviations from the *BABAR* value of $\sin 2\beta$ in charmonium decays [15].

Table 2: Results of fits to sub-decay modes $B^+ \rightarrow \eta' K^+$.

	$\eta'_{\eta\pi\pi} K^+$	$\eta'_{\rho\gamma} K^+$	$\eta'_{\eta(3\pi)\pi\pi} K^+$
Signal yield	585 ± 26	1322 ± 48	221 ± 17
$B\bar{B}$ yield	–	774 ± 75	–
S	-0.13 ± 0.13	-0.05 ± 0.10	-0.31 ± 0.23
C	0.00 ± 0.10	-0.10 ± 0.08	-0.06 ± 0.16
Combined fit			
Signal Yield	2124 ± 57		
S	-0.10 ± 0.07		
C	-0.05 ± 0.06		

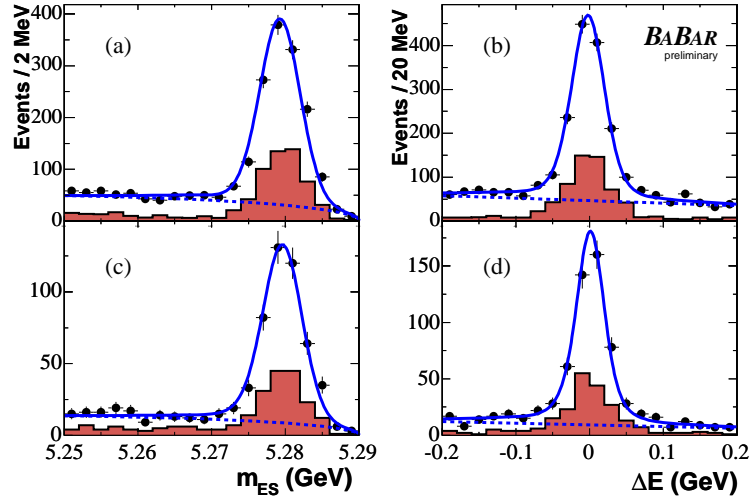


Figure 2: The B candidate m_{ES} and ΔE projections for $B^+ \rightarrow \eta' K^+$ (a, b) and $B^0 \rightarrow \eta' K^0$ (c, d) in main decay modes. Points with errors represent the data, solid curves the full fit functions, and dashed curves the background functions; the shaded histogram represents the $\eta'_{\eta\pi\pi} K$ subset.

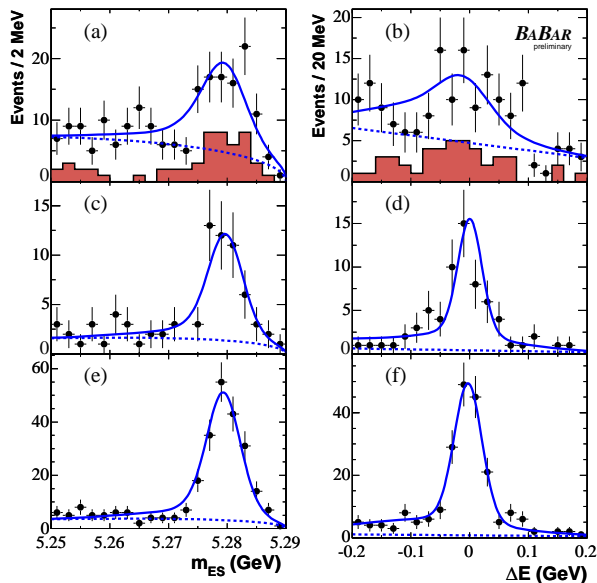


Figure 3: B candidate m_{ES} and ΔE projections for $\eta'K^0(\rightarrow \pi^0\pi^0)$ (a, b), $B^0 \rightarrow \eta'_{(3\pi)\pi\pi} K_S^0(\rightarrow \pi^+\pi^-)$ (c, d), and $B^+ \rightarrow \eta'_{(3\pi)\pi\pi} K^+$ (e, f). Points with errors represent the data, solid curves the full fit functions, and dashed curves the background functions. The shaded histogram in (a, b) represents the $\eta'_{(\gamma\gamma)\pi\pi} K_S^0$ subset.

6 Systematic Uncertainties and Crosschecks

The contributions to the systematic uncertainties in S and C are summarized in Table 3. We evaluate the uncertainties associated with the PDF shapes by variation of the parameters describing each discriminating variable. Systematic errors associated with signal parameters (Δt resolution function, tagging fractions, and dilutions) are determined by varying their values within their errors. Uncertainties due to Δm_d and τ_B are obtained by varying these parameters by the uncertainty in their world average values [16]. All changes are combined in quadrature obtaining an error of 0.01 for both S and C .

We vary the SVT alignment parameters in the signal Monte Carlo events by the size of misalignments found in the real data, and assign the resulting shift in the fit results as the systematic error.

The systematic errors due to interference between the CKM-suppressed $\bar{b} \rightarrow \bar{u}c\bar{d}$ amplitude and the favored $b \rightarrow c\bar{u}d$ for some tag-side B decays is found to be negligible for S and gives a contribution to the C uncertainty of about 0.012. The effect of $B\bar{B}$ background is estimated to be negligible, but we assign an uncertainty of 0.01 in S due to statistical limitations of this statement. An uncertainty of 0.02 is assigned to account for limitations of Monte Carlo statistics and modeling of the signal. We assign an uncertainty of 0.01 to account for the uncertainty in the position and size of the beam spot, determined from variation of these quantities in signal MC. The total systematic error is obtained by summing individual errors in quadrature.

We have also performed a number of checks of our results. We divide the sample into two sub-samples — the previously published sample and the data collected in 2003/2004. We find consistency with our previous results and between the two sub-samples. When we fit with the value for C fixed to zero, we find $S = 0.29 \pm 0.14$. We produce samples of pseudo-experiments

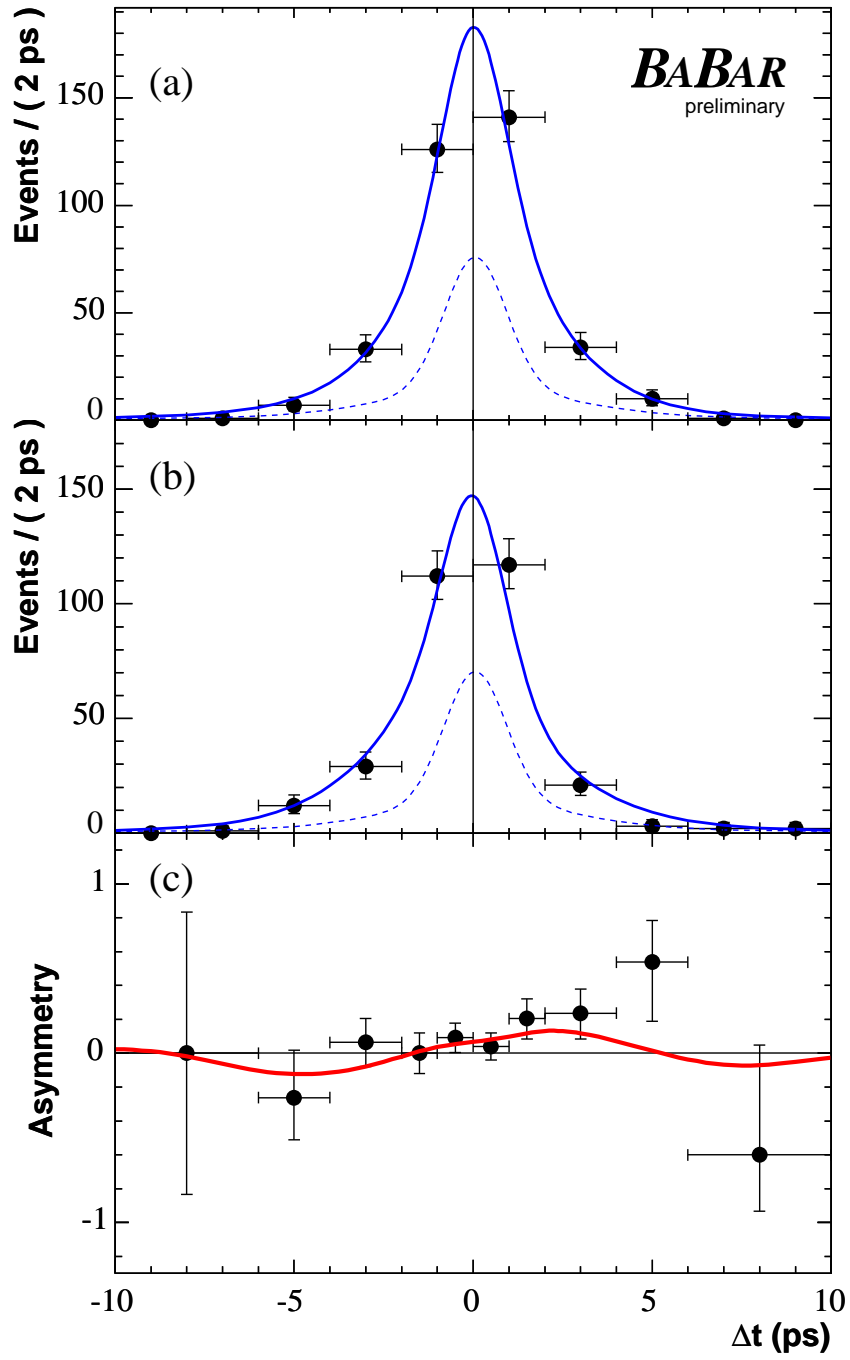


Figure 4: Projections onto Δt for $B^0 \rightarrow \eta' K_S^0$, showing the data (points with errors), fit function (solid line), and background function (dashed line), for (a) B^0 and (b) \bar{B}^0 tagged events and (c) the asymmetry between B^0 and \bar{B}^0 tags.

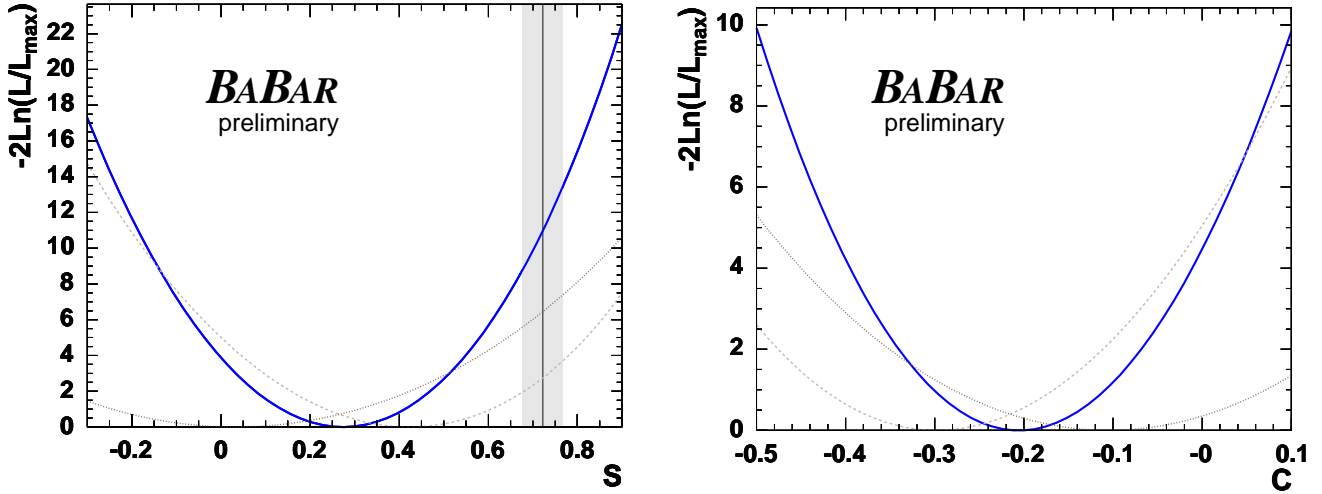


Figure 5: $-2\ln\mathcal{L}$ scan for S (left) and C (right) parameters. The solid blue line refers to all combined neutral sub-decays, the dotted line to the $B^0 \rightarrow \eta'_{\eta\pi\pi} K_S^0$ sub-decay and the dashed line to the $B^0 \rightarrow \eta'_{\rho\gamma} K_S^0$ sub-decay. The shaded band shows the *BABAR* value of $\sin 2\beta$ in charmonium decays [15].

Table 3: Estimates of systematic errors.

Source of error	$\sigma(S)$	$\sigma(C)$
PDF Shapes	0.01	0.01
SVT alignment	0.01	0.01
Tag-side interference	0.00	0.01
$B\bar{B}$ Background	0.01	0.00
MC statistics/modeling	0.02	0.02
Beam spot	0.01	0.01
Total	0.03	0.03

generated with events produced to match the PDF distributions. From these samples, we verify that the fit bias on S and C is negligible and that there is a good agreement between expected and observed errors.

7 Conclusion

We have reconstructed 2124 ± 57 $B^+ \rightarrow \eta' K^+$ events and 819 ± 38 $B^0 \rightarrow \eta' K_S^0$ events, about two-thirds of which have a flavor tag. We have used the latter sample to measure the time-dependent CP-violating parameters for $B^0 \rightarrow \eta' K_S^0$. We find $S = 0.27 \pm 0.14(\text{stat}) \pm 0.03(\text{syst})$ and $C = -0.21 \pm 0.10(\text{stat}) \pm 0.03(\text{syst})$.

The measured value of S is 3.0 standard deviations from the the *BABAR* measurement of $\sin 2\beta$, $0.722 \pm 0.040 \pm 0.023$, from $B \rightarrow$ charmonium K_S^0 decays [15]. The observed deviation ΔS is large compared with the expected theoretical uncertainty.

8 Acknowledgments

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l'Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from CONACyT (Mexico), the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

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