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# Measurement of *CP* Asymmetry in $B^0 \to K^+K^-K^0_s$ Decays

The *BABAR* Collaboration

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## Abstract

We present preliminary measurements of the *CP* asymmetry parameters and *CP* content in $B^0 \to K^+K^-K^0_S$ decays, with $\phi K^0_S$ events excluded. In a sample of 227 M $B\overline{B}$ pairs collected by the *BABAR* detector at the PEP-II $B$ Factory at SLAC, we find the *CP* parameters to be $S = -0.42 \pm 0.17 \pm 0.04$ and $C = 0.10 \pm 0.14 \pm 0.06$, where the first error is statistical and the second is systematic. Extracting the fraction of *CP*-even final states from angular moments $f_{even} = 0.89 \pm 0.08 \pm 0.06$, and setting $C = 0$, we determine $\sin 2\beta = 0.55 \pm 0.22 \pm 0.04 \pm 0.11$, where the last error is due to uncertainty on the *CP* content.

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# 1 INTRODUCTION

In the Standard Model (SM) of particle physics, the decays $B^0 \rightarrow K^+K^-K^0_S$ [1] are dominated by $b \rightarrow s\bar{s}s$ gluonic penguin diagrams [2]. *CP* violation in such decays arises from the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing mechanism [3].

The time-dependent *CP* asymmetry is obtained by measuring the proper time difference $\Delta t$ between a fully reconstructed neutral $B$ meson ($B_{CP}$) decaying into $K^+K^-K^0_S$, and the partially reconstructed recoil $B$ meson ($B_{\rm tag}$). The asymmetry in the decay rate $\mathrm{f}_+(\mathrm{f}_-)$ when the tagging meson is a $B^0$ ($\overline{B}^0$) is given as

$$\mathrm{f}_\pm(\,\Delta t) \;=\; \frac{\mathrm{e}^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\,[\,1 \pm S\sin(\Delta m_d\Delta t) \mp C\cos(\Delta m_d\Delta t)], \qquad (1)$$

where $\tau_{B^0}$ is the $B^0$ lifetime and $\Delta m_d$ is the $B^0$–$\overline{B}^0$ mixing frequency. The parameters $C$ and $S$ describe the magnitude of *CP* violation in the decay and in the interference between decay and mixing, respectively. In the SM, we expect $C = 0$ because there is only one decay mechanism and direct *CP* violation requires amplitudes with different *CP*-violating phases. If $K^+K^-K^0_S$ decays proceed through a P(S)-wave leading to a *CP*-odd (even) final state, we expect $S = (-)\sin 2\beta$, where $\sin 2\beta = 0.731 \pm 0.056$ [4, 5].

However, contributions from physics beyond the SM could invalidate these predictions [6]. Since $b \rightarrow s\bar{s}s$ decays involve one-loop transitions, they are especially sensitive to such contributions. Recent results in decays of neutral $B$ mesons through the $\phi K^0_S$ intermediate state are inconclusive due to large statistical errors [7, 8].

A more accurate *CP* measurement can be made using all decays to $K^+K^-K^0_S$ that do not contain a $\phi$ meson. This sample is several times larger than the sample of $\phi K^0_S$ [9, 10, 11], but the *CP* content of the final state is not known. In this paper we present measurements of the *CP* content in $K^+K^-K^0_S$ decays using an angular-moment analysis and cross-check it with an isospin analysis [10]. We update our measurement of the *CP* asymmetry parameters and extract the SM parameter $\sin 2\beta$ with almost twice the statistics of the previous *BABAR* result [11].

# 2 EVENT SELECTION

This analysis is based on about 227 million $B\overline{B}$ pairs collected with the *BABAR* detector [12] at the PEP-II asymmetric-energy $e^+e^-$ storage rings at SLAC, operating on the $\Upsilon(4S)$ resonance.

We reconstruct $B$ mesons from $K^0_S \rightarrow \pi^+\pi^-$ and $K^\pm$ candidates. Charged kaons are distinguished from pions and protons using energy-loss ($\mathrm{d}E/\mathrm{d}x$) information in the tracking system and from the Cherenkov angle and number of photons measured by the detector of internally reflected Cherenkov light (DIRC). We accept $K^0_S \rightarrow \pi^+\pi^-$ candidates that have a two-pion invariant mass within 12 MeV/$c^2$ of the nominal $K^0_S$ mass [13], a decay length greater than three standard deviations, and an angle between the line connecting the $B$ and $K^0_S$ decay vertices and the direction of $K^0_S$ momentum vector less than 45 mrad. The three daughters in the $B$ decay are fitted constraining their paths to a common vertex, and the $\pi^+\pi^-$ mass to the nominal $K^0_S$ mass.

In the characterization of the $B$ candidates we use two kinematic variables. The energy difference $\Delta E = E_B{}^* - \sqrt{s}/2$ is reconstructed from the energy of the $B$ candidate $E_B{}^*$ and the total energy $\sqrt{s}$, both evaluated in the $e^+e^-$ center-of-mass (CM) frame. The $\Delta E$ resolution for signal $B$ decays is 18 MeV. We also use the beam-energy-substituted mass $m_{\rm ES} = \sqrt{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2/E_i^2 - \vec{p}_B^{\,2}}$, where $(\vec{p}_i, E_i)$ is the four-momentum of the initial $e^+e^-$ system and $\vec{p}_B$ is the momentum of the $B$ candidate, both measured in the laboratory frame. The $m_{\rm ES}$ resolution for signal $B$ decays is $2.6\ {\rm MeV}/c^2$. We retain candidates with $|\Delta E| < 200$ MeV and $5.2 < m_{\rm ES} < 5.3\ {\rm GeV}/c^2$.

The background is dominated by random combinations of tracks created in $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum events. We suppress this background by utilizing the difference in the topology in the CM frame between jet-like $q\bar{q}$ events and spherical signal events. The topology is described using the angle $\theta_T$ between the thrust axis of the $B$ candidate and the thrust axis of the charged and neutral particles in the rest of the event (ROE) [12]. Other quantities that characterize the event topology are two sums over the ROE: $L_0 = \sum |\vec{p}_i^{\,*}|$ and $L_2 = \sum |\vec{p}_i^{\,*}| \cos^2\theta_i$, where $\theta_i$ is the angle between the momentum $\vec{p}_i^{\,*}$ of particle $i$ and the thrust axis of the $B$ candidate. Additional separation is achieved using the angle $\theta_B$ between the $B$-momentum direction and the beam axis. After requiring $|\cos\theta_T| < 0.9$, these four event-shape variables are combined into a Fisher discriminant $\mathcal{F}$ [14].

The remaining background originates from $B$ decays where a neutral or charged pion is missed during reconstruction (peaking $B$ background). We use samples of exclusive Monte Carlo (MC) events to model the signal and the peaking background, and data sidebands to model the continuum background.

We suppress background from $B$ decays that proceed through a $b \to c$ transition leading to the $K^+K^-K^0_S$ final state by applying invariant mass cuts to remove $D^0$, $J/\psi$, $\chi_{c0}$, and $\psi(2S)$ decaying into $K^+K^-$, and $D^+$ and $D_s^+$ decays into $K^+K^0_S$. Finally, to suppress $B$ decays into final states with pions, we apply particle identification criteria to limit the pion misidentification rate to less than 2%.

## 3 MEASUREMENT OF *CP* CONTENT

The extraction of the *CP* content of the $K^+K^-K^0_S$ final state is based on an unbinned extended maximum likelihood fit. The likelihood function $\mathcal{L}$ is defined as:

$$\mathcal{L} = \exp\left(-\sum_i N_i\right) \prod_{j=1} \left[\sum_i N_i \mathcal{P}_{i,j}\right] \tag{2}$$

where $j$ runs over all 27368 $K^+K^-K^0_S$ events in the sample. The probability density function (PDF) $\mathcal{P}$ is formed as $\mathcal{P}(m_{\rm ES}) \cdot \mathcal{P}(\Delta E) \cdot \mathcal{P}(\mathcal{F})$. Event yields $N_i$ for signal, continuum, and peaking $B$ background are floated in the fit. We find a total of $525 \pm 30$ signal events in the entire $K^+K^-K^0_S$ sample (including $\phi K^0_S$), and show projection plots of the fit variables in Figure 1.

The *CP* content is extracted using an angular moment analysis [15] which examines the distribution of the cosine of the helicity angle $\theta_H$ between the $K^+$ and $B^0$ directions in the $K^+K^-$ center of mass frame. In this approach, we assume the decay rate for a given $m(K^+K^-)$ invariant mass can be represented in terms of moments $\langle P_l \rangle$ of Legendre polynomials $P_l(\cos\theta_H)$ (see Appendix A)

$$|\mathcal{A}|^2 = \sum_l \langle P_l \rangle \cdot P_l(\cos\theta_H), \tag{3}$$

where $\mathcal{A}$ is the decay amplitude. Since the dynamics of the decay is not known, we extract the moments by summing over all events

$$\langle P_l \rangle \approx \sum_j P_l(\cos\theta_{H,j})\ \mathcal{W}_j / \varepsilon_j, \tag{4}$$

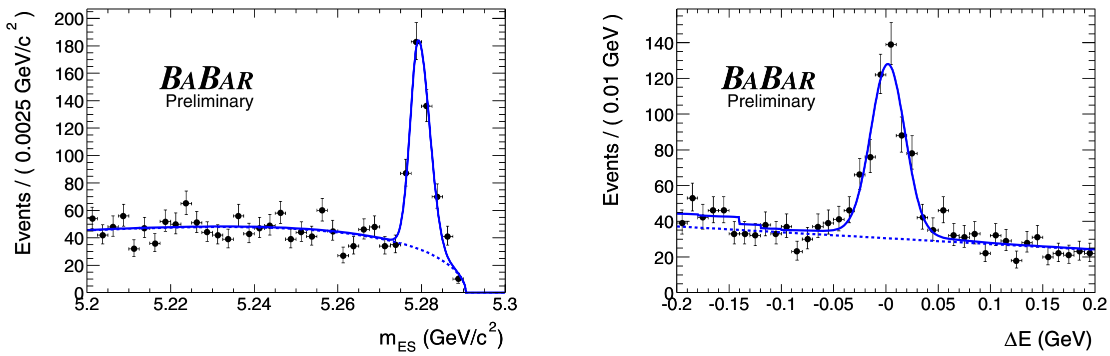


Figure 1: Projection plots of the $m_{\rm ES}$ and $\Delta E$ variables. The points are data and the curves are projections from the likelihood fit for all events (full line) and continuum background (dashed line). The signal-to-background ratio is enhanced with a cut on the signal probability.

where $\mathcal{W}$ is the weight for event $j$ to belong to the signal decay. We use the ${}_s$Plot background-substraction technique [16] to compute the weights as $\mathcal{W}_j = \frac{\sum_i V_{s,i}\mathcal{P}_{i,j}}{\sum_i N_i \mathcal{P}_{i,j}}$, where $V_{s,i}$ is the signal row of the covariance matrix obtained from the fit. The efficiency $\varepsilon$ is evaluated from a high-statistics MC sample in $m(KK) - \cos\theta_H$ bins. The covariance matrix for the moments is computed as

$$\sigma^2_{ll'} \;\approx\; \sum_j P_l(\cos\theta_{H,j}) P_{l'}(\cos\theta_{H,j})\; \mathcal{W}_j^2/\varepsilon_j^2, \tag{5}$$

where the sum runs over events. Limiting ourselves to the two lowest partial waves, we can write the total decay amplitude in terms of the S-wave (*CP*-even) and the P-wave (*CP*-odd) amplitudes,

$$\mathcal{A} \;=\; A_s P_0(\cos\theta_H) \;+\; e^{i\phi_p} A_p P_1(\cos\theta_H), \tag{6}$$

where $\phi_p$ is the relative phase between the partial-wave amplitudes $A_s$ and $A_p$. It can be easily shown that the angular moments $\langle P_{0,2}\rangle$ give infomation on S- and P-wave strengths, and $\langle P_1\rangle$ arises from their interference. Comparing Equations (3) and (6), we can relate the moments with the wave intensities and the total fraction of *CP*-even events, $f_{even}$ as

$$A_s^2 \;=\; \sqrt{2}\,\langle P_0\rangle - \sqrt{\frac{5}{2}}\langle P_2\rangle, \tag{7}$$

$$A_p^2 \;=\; \sqrt{\frac{5}{2}}\langle P_2\rangle, \tag{8}$$

$$f_{even} \;=\; \frac{A_s^2}{A_s^2 + A_p^2} \;=\; 1 - \sqrt{\frac{5}{4}}\frac{\langle P_2\rangle}{\langle P_0\rangle}, \tag{9}$$

where $A_s^2$ and $A_p^2$ are the S- and P-wave intensities, respectively. As a cross-check, we extract the fraction of *CP*-even events by comparing the event rates of two isospin-equivalent channels [10]:

$$f_{even}^{SU(2)} \;=\; \frac{\Gamma(B^+ \to K^+ K^0_S K^0_S)}{\Gamma(B^0 \to K^+ K^- K^0_S)} = \frac{N_{K^+K^0_SK^0_S}}{N_{K^+K^-K^0_S}} \frac{\left\langle \varepsilon_{K^+K^-K^0_S}\right\rangle}{\left\langle \varepsilon_{K^+K^0_SK^0_S}\right\rangle} \frac{\tau_{B^0}}{\tau_{B^+}} \tag{10}$$

where efficiencies $\langle\varepsilon\rangle$ are averaged over the Dalitz plot and include branching fractions for $K^0_S \to \pi^+\pi^-$.

# 4 MEASUREMENT OF *CP* ASYMMETRY

The *CP* asymmetry parameters are extracted from a $K^+K^-K^0_S$ sample that excludes $\phi K^0_S$ decays by requiring $|m(K^+K^-) - m(\phi)| > 15\,\mathrm{MeV}/c^2$. We use the maximum-likelihood fit from Eq. (2), where the total PDF is formed as $\mathcal{P}(m_{\mathrm{ES}}) \cdot \mathcal{P}(\Delta E) \cdot \mathcal{P}(\mathcal{F}) \cdot \mathcal{P}_c(\Delta t; \sigma_{\Delta t})$. The time difference $\Delta t$ is extracted from the measurement of the separation $\Delta z$ between the $B_{CP}$ and $B_{\mathrm{tag}}$ vertices, along the boost axis ($z$) of the $B\overline{B}$ system. The vertex position of the $B_{CP}$ meson is reconstructed primarily from the kaon tracks, and its MC-estimated resolution ranges between 40–80$\,\mu$m, depending on the opening angle and direction of the kaon pair. The final resolution is dominated by the uncertainty on the $B_{\mathrm{tag}}$ vertex which allows for a $\Delta t$ ($\Delta z$) precision with an r.m.s. of 1.1 ps (180 $\mu$m). We retain events that have $|\Delta t| < 20$ ps and whose estimated uncertainty $\sigma_{\Delta t}$ is less than 2.5 ps. The $\Delta t$ resolution function is parameterized as a sum of two Gaussian distributions whose widths are given by a scale factor times the event-by-event uncertainty $\sigma_{\Delta t}$. A third Gaussian distribution, with a fixed large width, accounts for a small fraction of outlying events [17].

Recoil side decay products are used to determine the flavor of the $B_{\mathrm{tag}}$ meson (flavor tag) and to classify the event into seven mutually exclusive tagging categories [17]. If the fraction of events in category $c$ is $\epsilon_c$ and the mistag probability is $w_c$, the overall quality of the tagging, $\sum_c \epsilon_c(1-2w_c)^2$, is $(30.5 \pm 0.5)\%$. Parameters describing the tagging performance and the $\Delta t$ resolution function for signal events are extracted from approximately 30,000 $B^0$ decays into $D^{(*)-}X^+$ ($X^+ = \pi^+, \rho^+, a_1^+$) flavor eigenstates.

In the fit we float *CP* asymmetry parameters, parameters describing the $\Delta t$ resolution function and tagging, event yields, and the signal PDF parameters for $m_{\mathrm{ES}}$, $\Delta E$, and the Fisher discriminant.

# 5 SYSTEMATIC STUDIES

In the measurement of the *CP*-even fraction based on the angular moments we estimate a bias due to the efficiency modeling from high-statistics MC events (2.5%). We do not find indication for the existence of higher moments $\langle P_l \rangle$, $l = 3 \ldots 6$ (see Figure 4 in Appendix A), that could arise from intermediate D-wave decays into $K^+$ $K^-$ or decays proceeding through an $I = 1$ resonance into $K^\pm K^0_S$. Nevertheless, we estimate a systematic error from the D-wave by examining the $\langle P_2 \rangle$ moment in the $f_2(1270)$, $a_2^0(1320)$ and $f_2'(1525)$ mass region (1.1-1.7$\,\mathrm{GeV}/c^2$) and assuming that $\langle P_2 \rangle$ arises only from D-wave and S-D interference. Since the moment itself is consistent with zero, we assign a systematic error of 4% based on the $\langle P_2 \rangle$ error. We also assign a systematic error due to potential contributions from decays proceeding through isovector resonances into $K^+K^0_S$. In addition to not being included in the angular moment analysis, decays of charged $a_0^+(980)$, $a_2^+(1320)$ and $a_0^+(1540)$ are not *CP* eigenstates. We set the error on the *CP* content by counting events in $K^\pm K^0_S$ invariant mass regions under these resonances [13]. We do not observe events in the $a_0(980)$ region, or a peak consistent with the $a_0(1540)$ resonance. We estimate events that could come from $a_2(1320)$ decays and conservatively include them into the systematic error (4.6%).

The systematic errors on the time-dependent *CP*-asymmetry parameters ($\sigma_S, \sigma_C$) are estimated similarly to our previous analysis [11]. We account for the fit bias (0.02, 0.01), the presence of double CKM-suppressed decays in $B_{\mathrm{tag}}$ [18] (0.018, 0.053), the uncertainty in the beam spot and detector alignment (0.022, 0.012), and the asymmetry in the tagging efficiency for signal and background events (0.011, 0.014). Other smaller effects come from the $\Delta t$ resolution and uncertainty on the $B^0$ lifetime and mixing frequency (0.006, 0.006). We use $\tau_{B^0} = 1.536 \pm 0.014$ ps and $\Delta m_d = 0.502 \pm 0.007$ ps$^{-1}$ [13].

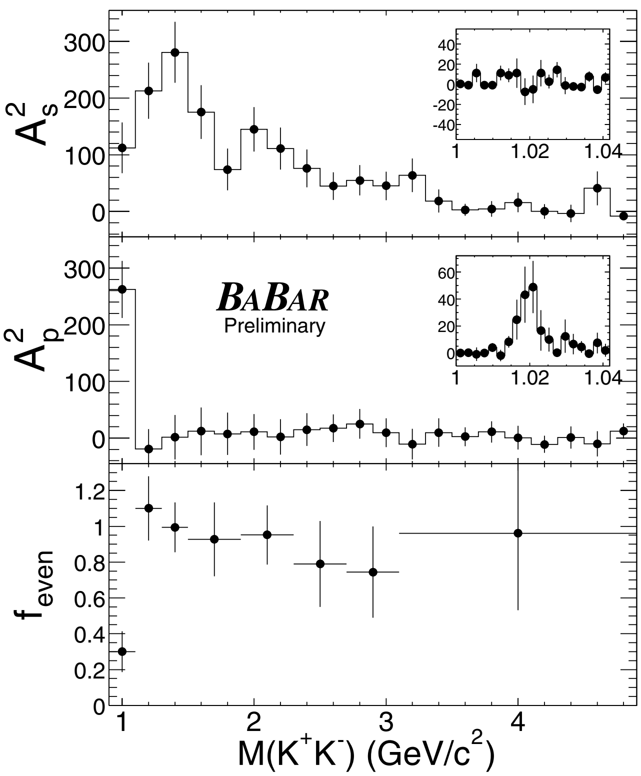


Figure 2: Distributions of S- and P-wave intensities and *CP* even fraction as a function of $K^+K^-$ invariant mass. Insets show S- and P-wave intensities in the $\phi$ mass region. Events within 15 MeV/$c^2$ of the nominal $\phi$ mass [13] are removed from the *CP* fit.

# 6 RESULTS

Distributions of the S- and P- wave intensities, and the *CP*-even fraction as a function of $K^+K^-$ invariant mass are shown in Figure 2. $\phi K_S^0$ events give a significant enhancement of P-wave decays in the first bin. In the sample that excludes $\phi K_S^0$ events, we compute $\langle P_{0,2}\rangle$ moments from the remaining events and find the total fraction of *CP*-even final states to be

$$f_{even} = 0.89 \pm 0.08 \pm 0.06,$$

where the first error is statistical and the second is systematic. We cross-check this result using the isospin approach of Eq (10). We find $452 \pm 28$ signal events in the $K^+K^-K_S^0$ *CP* sample with a total efficiency of $\langle\varepsilon\rangle = (17.3 \pm 0.3)\%$ and $208 \pm 18$ signal events in the $K^+K_S^0K_S^0$ sample with $\langle\varepsilon\rangle = (9.8 \pm 0.8)\%$. This gives $f_{even}^{SU(2)} = 0.75 \pm 0.11$ which is consistent with our nominal estimate.

The coefficients of the time-dependent *CP* asymmetry in $B^0 \rightarrow K^+K^-K_S^0$ decays (excluding $\phi K_S^0$ final states) are determined to be

$$S = -0.42 \pm 0.17 \pm 0.04,$$
$$C = 0.10 \pm 0.14 \pm 0.06.$$

The $\Delta t$ distributions of events with $B^0$ and $\overline{B}^0$ tags, with projections from the likelihood fit superimposed, are shown in Figure 3. The fit procedure is verified with the $K^+K_S^0K_S^0$ sample, where we measure zero asymmetry, and the $J/\psi K_S^0$ sample where the results are consistent with previous measurements [4, 5].

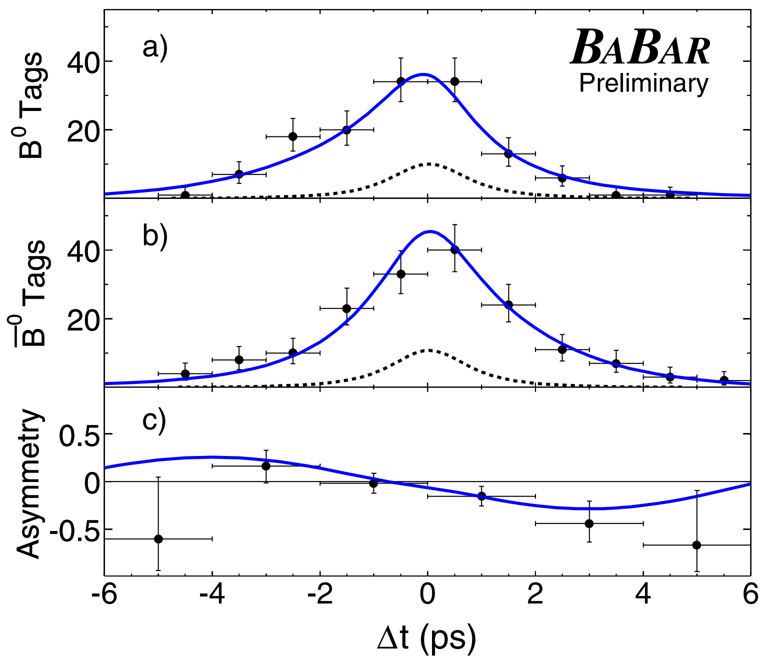


Figure 3: Distributions of $\Delta t$ for $B^0 \to K^+K^-K_S^0$ candidates with (a) $B^0$ tags and (b) $\overline{B}^0$ tags. The solid lines refer to the fit for all events and the dashed lines correspond to the background contribution. The distribution of the raw asymmetry is shown in (c), where the solid line is obtained from the fit. The signal-to-background ratio is enhanced with a cut on the signal probability.

The presence of both P- and S-wave decays in our *CP* sample dilutes the measurement of the sine coefficient. If we account for the measured *CP*-odd fraction, we can extract the SM parameter $\sin 2\beta$. Using the estimate of the *CP* content based on the angular moments, and setting $C = 0$ in the fit, we get

$$\sin 2\beta = -S/(2f_{even} - 1) = 0.55 \pm 0.22 \pm 0.04 \pm 0.11,$$

where the last error is due to uncertainty on the *CP* content.

# 7 SUMMARY

In a sample of 227 million $B\overline{B}$ mesons, we have obtained preliminary measurements of the *CP* content and *CP* parameters in the $K^+K^-K_S^0$ final state that excludes $\phi K_S^0$ decays. From the distribution of the helicity angle in the $K^+K^-$ frame, described in terms of moments of Legendre polynomials, we extract the fraction of P-wave decays. The result is consistent with our cross-check and previous measurements based on isospin symmetry [7, 11], and confirms the dominance of *CP*-even final states.

We measure a time-dependent *CP* asymmetry in $B^0 \to K^+K^-K_S^0$ decays at the $2.3\sigma$ level. The obtained value for $\sin 2\beta$ is consistent with the SM expectation and previous measurements in decays into the $K^+K^-K^0_S$ final state [7, 11].

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## A APPENDIX: ANGULAR MOMENTS

In the analysis we use the following definitions for the Legendre polynomials

$$
\begin{aligned}
P_0 &= \frac{1}{\sqrt{2}}, \\
P_1 &= \sqrt{\frac{3}{2}}\cos\theta_H, \\
P_2 &= \sqrt{\frac{5}{8}}\left(3\cos^2\theta_H - 1\right), \\
P_3 &= \sqrt{\frac{7}{8}}\left(5\cos^3\theta_H - 3\cos\theta_H\right), \\
P_4 &= \sqrt{\frac{9}{128}}\left(35\cos^4\theta_H - 30\cos^2\theta_H + 3\right),
\end{aligned}
$$

which are orthogonal and normalized to unity $\int d(\cos\theta_H)P_l P_{l'} = \delta_{ll'}$. Moments of Legendre polynomials $\langle P_l\rangle = \int d(\cos\theta_H)P_l(\cos\theta_H)|\mathcal{A}|^2$ can be extracted by replacing the integration over the unknown amplitude $\mathcal{A}$ with a sum over signal weights as shown in Eq. (4). The moments can be related with wave amplitudes $A_{s,p,d}$ and interference phases $\phi_{p,d}$ as follows

$$
\begin{aligned}
\langle P_0\rangle &= \frac{A_s^2 + A_p^2 + A_d^2}{\sqrt{2}}, \\
\langle P_1\rangle &= \sqrt{2}A_sA_p\cos\phi_p \;+\; \sqrt{\frac{8}{5}}A_pA_d\cos(\phi_p - \phi_d), \\
\langle P_2\rangle &= \sqrt{\frac{2}{5}}A_p^2 \;+\; \frac{\sqrt{10}}{7}A_d^2 \;+\; \sqrt{2}A_sA_d\cos\phi_d, \\
\langle P_3\rangle &= \sqrt{\frac{54}{35}}A_pA_d\cos(\phi_p - \phi_d),
\end{aligned}
$$

$$\langle P_4 \rangle \;=\; \frac{\sqrt{18}}{7} A_d^2,$$

where we kept only terms relevant for the S, P and D waves (in the nominal result we set $A_d = 0$). Lowest moments plotted in Figure 4 are used in the extraction of the P-wave fraction. Some of the higher moments shown in Figure 4 are used for systematic studies. In the normalization we assume that $\sqrt{2}\,\langle P_0 \rangle$ equals the total number of signal events.

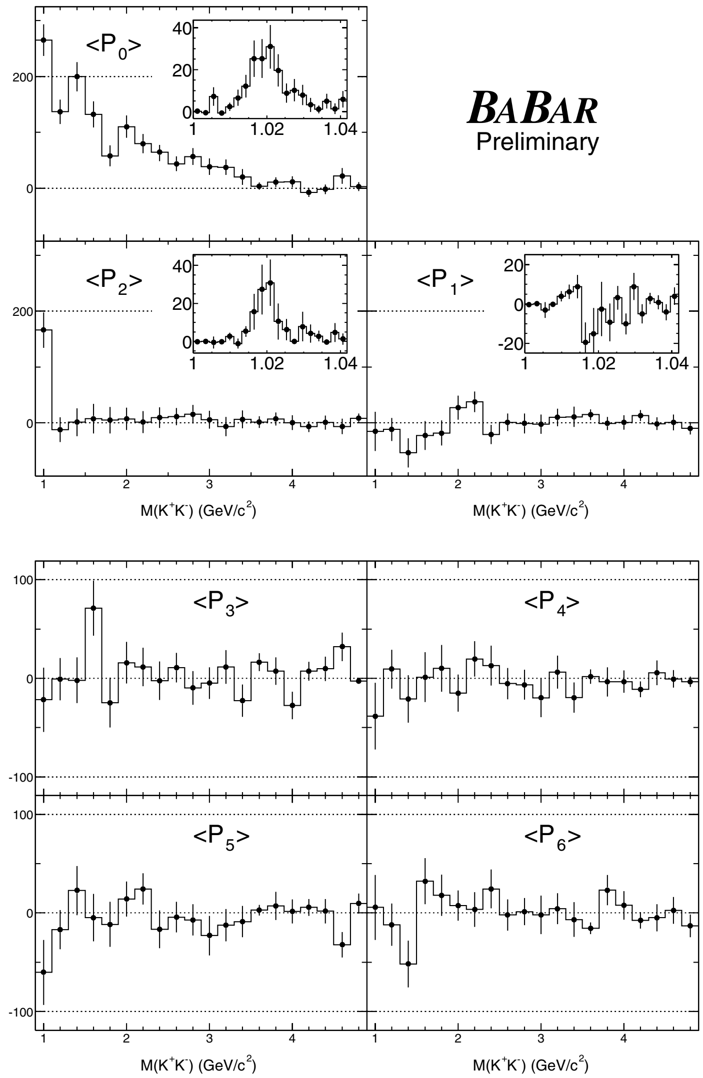


Figure 4: Distributions of angular moments $\langle P_l \rangle$ with $l = 0, \ldots, 6$. Insets show moments in the $\phi$ mass region.

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[1] Charge-conjugate states are included unless explicitly stated otherwise.

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