

Measurement of CP Asymmetry in $B^0 \rightarrow K^+K^-K_s^0$ Decays

The *BABAR* Collaboration

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Abstract

We present preliminary measurements of the CP asymmetry parameters and CP content in $B^0 \rightarrow K^+K^-K_s^0$ decays, with ϕK_s^0 events excluded. In a sample of 227 M $B\bar{B}$ 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 $B^0 \rightarrow K^+K^-K_s^0$ [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 Δt between a fully reconstructed neutral B meson (B_{CP}) decaying into $K^+K^-K_s^0$, and the partially reconstructed recoil B meson (B_{tag}). The asymmetry in the decay rate $f_+(f_-)$ when the tagging meson is a B^0 (\bar{B}^0) is given as

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

where τ_{B^0} is the B^0 lifetime and Δm_d is the B^0 – \bar{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 $K^+K^-K_s^0$ 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 ϕK_s^0 intermediate state are inconclusive due to large statistical errors [7, 8].

A more accurate CP measurement can be made using all decays to $K^+K^-K_s^0$ that do not contain a ϕ meson. This sample is several times larger than the sample of ϕK_s^0 [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 $K^+K^-K_s^0$ 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 $B\bar{B}$ 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 $K_s^0 \rightarrow \pi^+\pi^-$ and K^\pm candidates. Charged kaons are distinguished from pions and protons using energy-loss (dE/dx) 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 $K_s^0 \rightarrow \pi^+\pi^-$ candidates that have a two-pion invariant mass within $12 \text{ MeV}/c^2$ of the nominal K_s^0 mass [13], a decay length greater than three standard deviations, and an angle between the line connecting the B and K_s^0 decay vertices and the direction of K_s^0 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_s^0 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 ΔE resolution for signal B decays is 18 MeV. We also use the beam-energy-substituted mass $m_{\text{ES}} = \sqrt{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2/E_i^2 - \vec{p}_B^2}$,

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_{ES} resolution for signal B decays is 2.6 MeV/ c^2 . We retain candidates with $|\Delta E| < 200$ MeV and $5.2 < m_{\text{ES}} < 5.3$ GeV/ c^2 .

The background is dominated by random combinations of tracks created in $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) 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 θ_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 θ_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 θ_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 $b \rightarrow c$ transition leading to the $K^+K^-K_s^0$ final state by applying invariant mass cuts to remove D^0 , J/ψ , χ_{c0} , and $\psi(2S)$ decaying into K^+K^- , and D^+ and D_s^+ decays into $K^+K_s^0$. 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 $K^+K^-K_s^0$ final state is based on an unbinned extended maximum likelihood fit. The likelihood function \mathcal{L} is defined as:

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

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

The CP content is extracted using an angular momentum analysis [15] which examines the distribution of the cosine of the helicity angle θ_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)

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

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

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

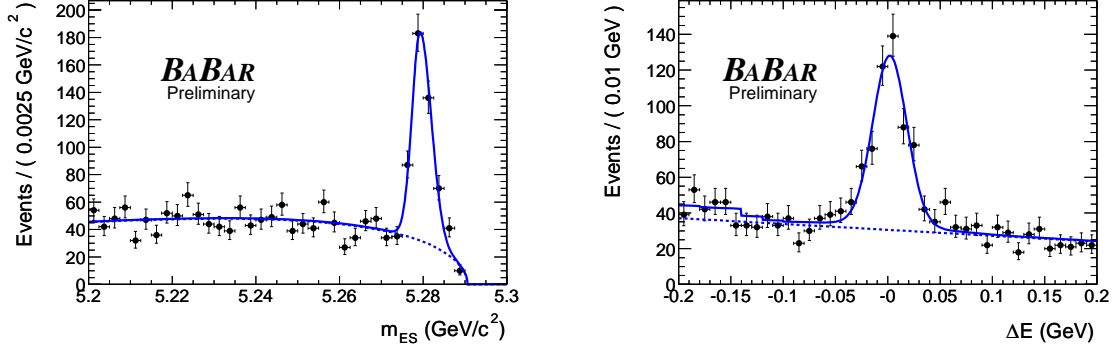


Figure 1: Projection plots of the m_{ES} and ΔE variables. The points are data and the curves are projections from the likelihood fit for all events (full line) and continuum background (dashed line). The signal-to-background ratio is enhanced with a cut on the signal probability.

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

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

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,

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

where ϕ_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 information 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

$$A_s^2 = \sqrt{2} \langle P_0 \rangle - \sqrt{\frac{5}{2}} \langle P_2 \rangle, \quad (7)$$

$$A_p^2 = \sqrt{\frac{5}{2}} \langle P_2 \rangle, \quad (8)$$

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

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]:

$$f_{even}^{SU(2)} = \frac{\Gamma(B^+ \rightarrow K^+ K_S^0 K_S^0)}{\Gamma(B^0 \rightarrow K^+ K^- K_S^0)} = \frac{N_{K^+ K_S^0 K_S^0} \langle \varepsilon_{K^+ K^- K_S^0} \rangle \tau_{B^0}}{N_{K^+ K^- K_S^0} \langle \varepsilon_{K^+ K_S^0 K_S^0} \rangle \tau_{B^+}} \quad (10)$$

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

4 MEASUREMENT OF CP ASYMMETRY

The CP asymmetry parameters are extracted from a $K^+K^-K_S^0$ sample that excludes ϕK_S^0 decays by requiring $|m(K^+K^-) - m(\phi)| > 15 \text{ MeV}/c^2$. We use the maximum-likelihood fit from Eq. (2), where the total PDF is formed as $\mathcal{P}(m_{\text{ES}}) \cdot \mathcal{P}(\Delta E) \cdot \mathcal{P}(\mathcal{F}) \cdot \mathcal{P}_c(\Delta t; \sigma_{\Delta t})$. The time difference Δt is extracted from the measurement of the separation Δz between the B_{CP} and B_{tag} vertices, along the boost axis (z) of the $B\bar{B}$ 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 μm , depending on the opening angle and direction of the kaon pair. The final resolution is dominated by the uncertainty on the B_{tag} vertex which allows for a Δt (Δz) precision with an r.m.s. of 1.1 ps (180 μm). We retain events that have $|\Delta t| < 20$ ps and whose estimated uncertainty $\sigma_{\Delta t}$ is less than 2.5 ps. The Δt 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_{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 ϵ_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 Δt 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 Δt resolution function and tagging, event yields, and the signal PDF parameters for m_{ES} , ΔE , 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 $\langle P_l \rangle$, $l = 3 \dots 6$ (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 $K^\pm K_S^0$. 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 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 $K^+K_S^0$. 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 $K^\pm K_S^0$ 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 (σ_S, σ_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_{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 Δt 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 $\Delta m_d = 0.502 \pm 0.007 \text{ ps}^{-1}$ [13].

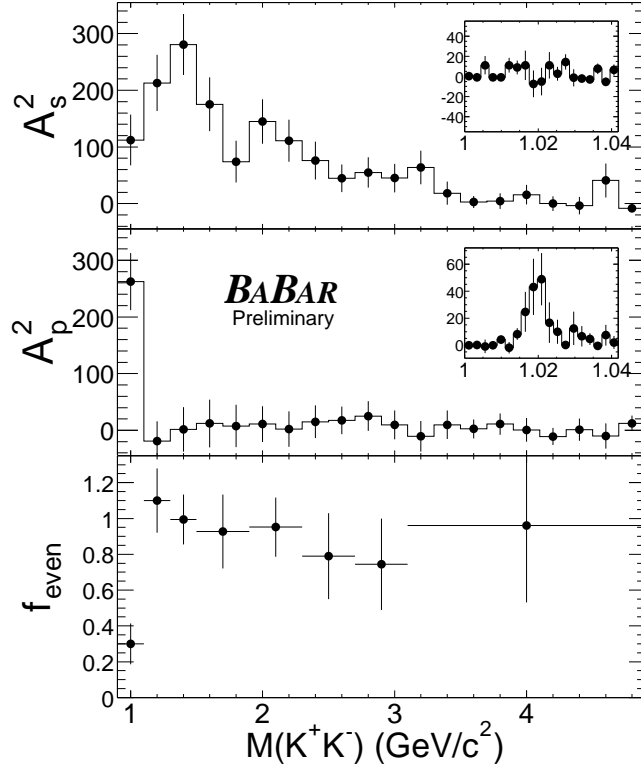


Figure 2: Distributions of S- and P-wave intensities and CP even fraction as a function of K^+K^- invariant mass. Insets show S- and P-wave intensities in the ϕ mass region. Events within 15 MeV/ c^2 of the nominal ϕ mass [13] are removed from the CP fit.

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. ϕK_S^0 events give a significant enhancement of P-wave decays in the first bin. In the sample that excludes ϕK_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 ± 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 ± 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 ϕK_S^0 final states) are determined to be

$$\begin{aligned} S &= -0.42 \pm 0.17 \pm 0.04, \\ C &= 0.10 \pm 0.14 \pm 0.06. \end{aligned}$$

The Δt distributions of events with B^0 and \bar{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].

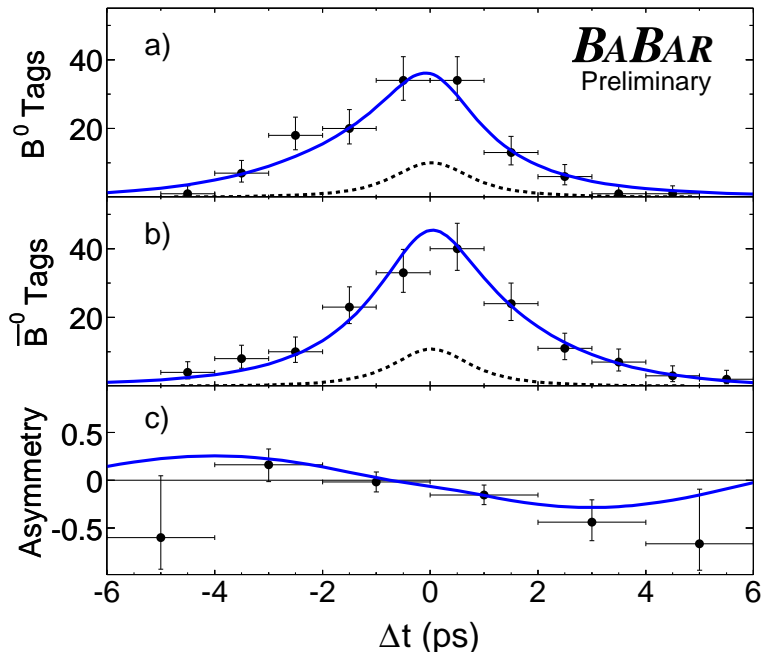


Figure 3: Distributions of Δt for $B^0 \rightarrow K^+K^-K_S^0$ candidates with (a) B^0 tags and (b) \bar{B}^0 tags. The solid lines refer to the fit for all events and the dashed lines correspond to the background contribution. The distribution of the raw asymmetry is shown in (c), where the solid line 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

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

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

7 SUMMARY

In a sample of 227 million $B\bar{B}$ mesons, we have obtained preliminary measurements of the CP content and CP parameters in the $K^+K^-K_S^0$ final state that excludes ϕK_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 $B^0 \rightarrow K^+K^-K_S^0$ decays at the 2.3σ level. The obtained value for $\sin 2\beta$ is consistent with the SM expectation and previous measurements in

decays into the $K^+K^-K_s^0$ final state [7, 11].

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A APPENDIX: ANGULAR MOMENTS

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

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

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

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

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

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.

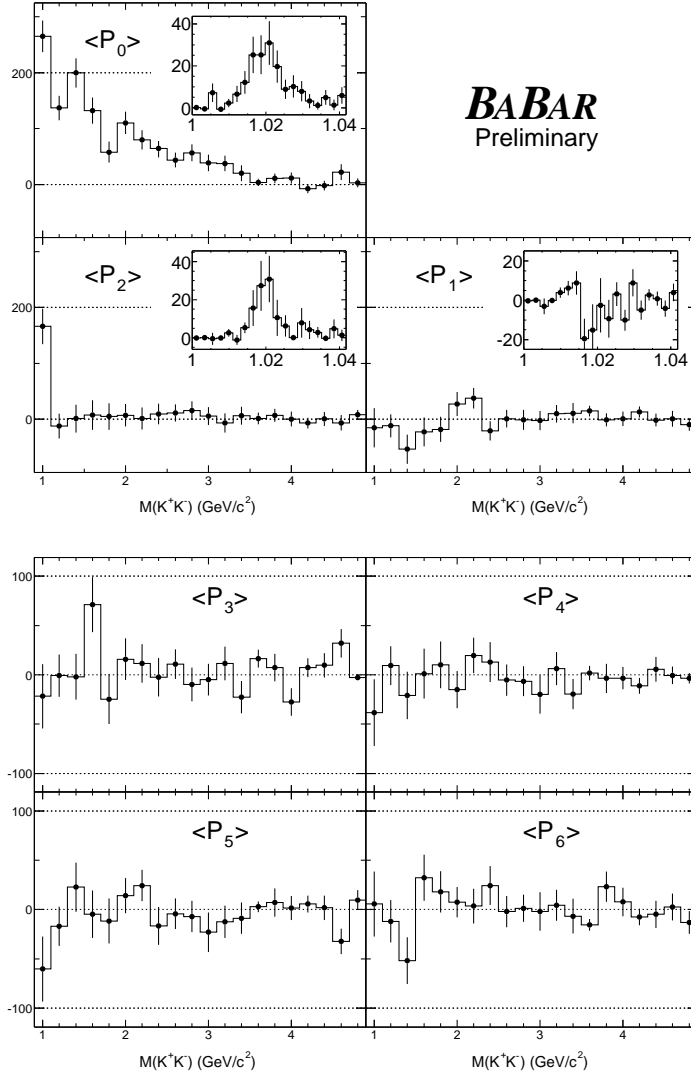


Figure 4: Distributions of angular moments $\langle P_l \rangle$ with $l = 0, \dots, 6$. Insets show moments in the ϕ mass region.

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