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New Measurements of CP Violation in $B^0 \to (c\overline{c})K^{0(*)}$ Decays from *BABAR*

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Abstract

We present new measurements of CP asymmetries in $\boldsymbol{B^0 \to (c\overline{c})K^{0(*)}}$ decays recorded by the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC between 1999 and 2004. We determine sin2β from decay-time distributions of 7730 signal events in a data sample of approximately 227×10^6 $\Upsilon(4S) \to B\overline{B}$ decays. The measured value of sin$2\beta = 0.722 \pm 0.040(\mathrm{stat}) \pm 0.023(\mathrm{syst})$ is in agreement with the value expected from the Standard Model. In a separate time-dependent angular analysis of $B \to J/\psi\, K^{*0}(K^{*0} \to K^0_S\pi^0)$ decays we measure $\cos 2\beta$ to be positive at 86% CL.

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1 Introduction

CP violation is described in the Standard Model by a single irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix[1]. The B meson system provides an excellent probe for testing the completeness of the CKM ansatz in a variety of CP asymmetries.

In particular, the Standard Model predicts differences in the time dependent decay rates of B^0 and $\overline{B}^0$ to a CP eigenstate. Assuming $\Delta\Gamma$, the difference in decay widths between the B^0 mass eigenstates B_H and B_L, to be negligible, the decay rate $\mathrm{f}_+(\mathrm{f}_-)$ of mesons that have been determined to be $\overline{B}^0$ (B^0) at $\Delta t = 0$ is given by:

$$\mathrm{f}_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 \pm \frac{2\,\mathcal{I}m\,\lambda}{1+|\lambda|^2}\sin(\Delta m_d \Delta t) \mp \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_d \Delta t)\right]. \tag{1}$$

Here τ_{B^0} is the B^0 lifetime and Δm_d is the difference in mass between B_H and B_L. The complex parameter λ is given by

$$\lambda = \frac{q}{p}\frac{\bar{A}_f}{A_f}, \tag{2}$$

where A_f ($\bar{A}_f$) is the decay amplitude for $B^0 \to f$ ($\overline{B}^0 \to f$) and q and p define the basis transformation between the mass eigenstates and the weak eigenstates: $|B_{H/L}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$.

In $B^0 \to (c\bar{c})K^{0(*)}$ decays, we expect CP violation mainly due to the interference between mixing and decay[2], with[3] $|\lambda| = 1$ and

$$\mathcal{I}m\,\lambda = -\eta_{CP}\sin 2\beta \tag{3}$$

$$\beta = \arg\left[-V_{\rm cd}V_{\rm cb}^*/V_{\rm td}V_{\rm tb}^*\right], \tag{4}$$

where the CP eigenvalue $\eta_{CP} = -1$ for $J/\psi\, K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$, and $+1$ for $J/\psi\, K^0_L$. The $J/\psi\, K^{*0}$ final state can be both CP even ($L = 0, 2$) and CP odd ($L = 1$), depending on the orbital angular momentum. A full angular analysis of $J/\psi\, K^*$ decays[4] gives an effective $\eta_{CP} = 0.51 \pm 0.04$ after acceptance corrections.

CP violation in B mesons has now been firmly established with the measurements of $\sin 2\beta$ by the *BABAR*[5] and Belle[6] experiments. The current world average[9] of $\sin 2\beta = 0.736 \pm 0.049$ is in good agreement with the range implied by other measurements in the context of the Standard Model.

Since its last measurement of $\sin 2\beta$ of $0.741 \pm 0.067 \pm 0.034$, *BABAR* has recorded an additional 140 million $B\bar{B}$ decays, more than doubling the data sample. Our new measurement[7] uses the full data set recorded between 1999 and 2004.

2 Measurement method

The measurement technique is analogous to previous *BABAR* measurements described in detail elsewhere [8]. We fully reconstruct a decay B_{CP} to any of the final states $J/\psi\, K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$, $J/\psi\, K^0_L$ or $J/\psi\, K^{*0}$. The beam-energy substituted mass $m_{\rm ES} = \sqrt{(E^{\rm cm}_{\rm beam})^2 - (p^{\rm cm}_B)^2}$ (for all modes except $J/\psi\, K^0_L$) or the difference ΔE between the candidate center-of-mass energy and $E^{\rm cm}_{\rm beam}$ ($J/\psi\, K^0_L$ only) (Fig. 1) is used to determine a per-event signal probability. Remaining tracks in the event are assigned to the other B meson $B_{\rm tag}$, and are used in a neural network to determine the $B_{\rm tag}$ flavor and thus the flavor of the B_{CP} meson at $\Delta t = 0$. The value of Δt and its estimated uncertainty $\sigma_{\Delta t}$ are determined from the reconstructed decay vertices of B_{CP} and $B_{\rm tag}$.

Due to uncertainty in the vertex positions and tag flavor determinations, the observed Δt distribution of CP signal events $\mathrm{F}_{\pm}^{CP}(\Delta t')$ is described by a convolution of $\mathrm{f}_{\pm}(\Delta t)$ with an empirical resolution function $R(\Delta t - \Delta t'; \sigma_{\Delta t})$:

$$\mathrm{F}_{\pm}^{CP}(\Delta t') = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 \mp \eta_{CP} \sin 2\beta \; \times (1-2w) \sin(\Delta m_d \Delta t) \right] \otimes R(\Delta t - \Delta t'; \sigma_{\Delta t}), \qquad (5)$$

where w is the probability of assigning the wrong flavor to $B_{\rm tag}$. The output of the neural-network determining the $B_{\rm tag}$ flavor is used to classify the event in one of six mutually exclusive tag categories, which are (in order of increasing mis-tag probability w) `Lepton`, `Kaon I`, `Kaon II`, `Kaon-Pion`, `Pion`, or `Other`.

We determine $\sin 2\beta$ by performing a maximum-likelihood fit of $\mathrm{F}_{\pm}^{CP}(\Delta t')$ (and additional terms describing background events) to the $\Delta t'$ distributions. In order to determine the values of w for each of the tag categories and to increase the statistical precision on parameters such as those describing the resolution function, we include in the fit a large sample $B_{\rm flav}$ of reconstructed B^0 decays to the flavor eigenstates $D^{(*)-}h^+ (h^+ = \pi^+, \rho^+$, and $a_1^+)$ and $J/\psi K^{*0}(K^{*0} \to K^+\pi^-)$. The Δt distribution F_+ (F_-) for $B_{\rm flav}$ decays with opposite (same) flavor as $B_{\rm tag}$ is given by

$$\mathrm{F}_{\pm}^{B_{\rm flav}}(\Delta t') = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 \pm (1-2w) \times \cos(\Delta m_d \Delta t) \right] \otimes R(\Delta t - \Delta t'; \sigma_{\Delta t}), \qquad (6)$$

There are in total 65 floating parameters in the simultaneous fit: $\sin 2\beta$ (1), the average mis-tag fractions w and the differences Δw between B^0 and $\overline{B}^0$ mis-tag fractions for each tagging category (12), parameters for the signal (7) and background (3) resolution functions, differences between B^0 and $\overline{B}^0$ reconstruction (1) and tagging (6) efficiencies, parameters for background time dependence of the CP (8) and $B_{\rm flav}$(3) sample, and w and Δw for $B_{\rm flav}$ background (24). The other physics parameters are fixed to current world averages[9]: $\tau_{B^0} = 1.536\,\mathrm{ps}$, $\Delta m_d = 0.502\,\mathrm{ps}^{-1}$, and varied to determine the systematic uncertainty.

The increase in statistics since our last measurement has allowed some refinements in the analysis. These include a more sophisticated treatment of signal probabilities, as determined from the m_{ES} spectrum, and more floating parameters describing the background of the CP sample, leading to a reduced systematic uncertainty. Other improvements are a better event reconstruction and a more powerful tag flavor determination, with an effective tagging efficiency $Q \equiv \sum_i \varepsilon_i (1-2w_i)^2$ of 30.5%, about 5% (relative) higher than the algorithm previously used.

3 Results

The simultaneous fit yields

$$\sin 2\beta = 0.722 \pm 0.040(\mathrm{stat}) \pm 0.023(\mathrm{syst}).$$

Projections of the fitted PDF on the $\eta_{CP} = -1$ and $\eta_{CP} = +1$ subsamples are shown in figure 2, together with the raw time-dependent CP asymmetry

$$\begin{aligned} A_{CP}^{\rm raw}(\Delta t) &\equiv \frac{\mathrm{F}_+ - \mathrm{F}_-}{\mathrm{F}_+ + \mathrm{F}_-} \\ &\propto -\eta_{CP}(1-2w)\sin 2\beta \sin(\Delta m_d \Delta t). \end{aligned}$$

The systematic uncertainty of 0.023 is dominated by three sources: uncertainty related to background events that peak in the $m_{\rm ES}$ signal region (0.012), uncertainty in the signal resolution function (0.011), and the uncertainty in the composition of the $J/\psi\, K^0_L$ background (0.11). It is considerably smaller than in our previous measurement (0.034), mainly due to improvements in Monte Carlo statistics and fewer assumptions about the background of the CP sample.

Separate fits have been performed on individual decay modes, data-sets and tagging categories

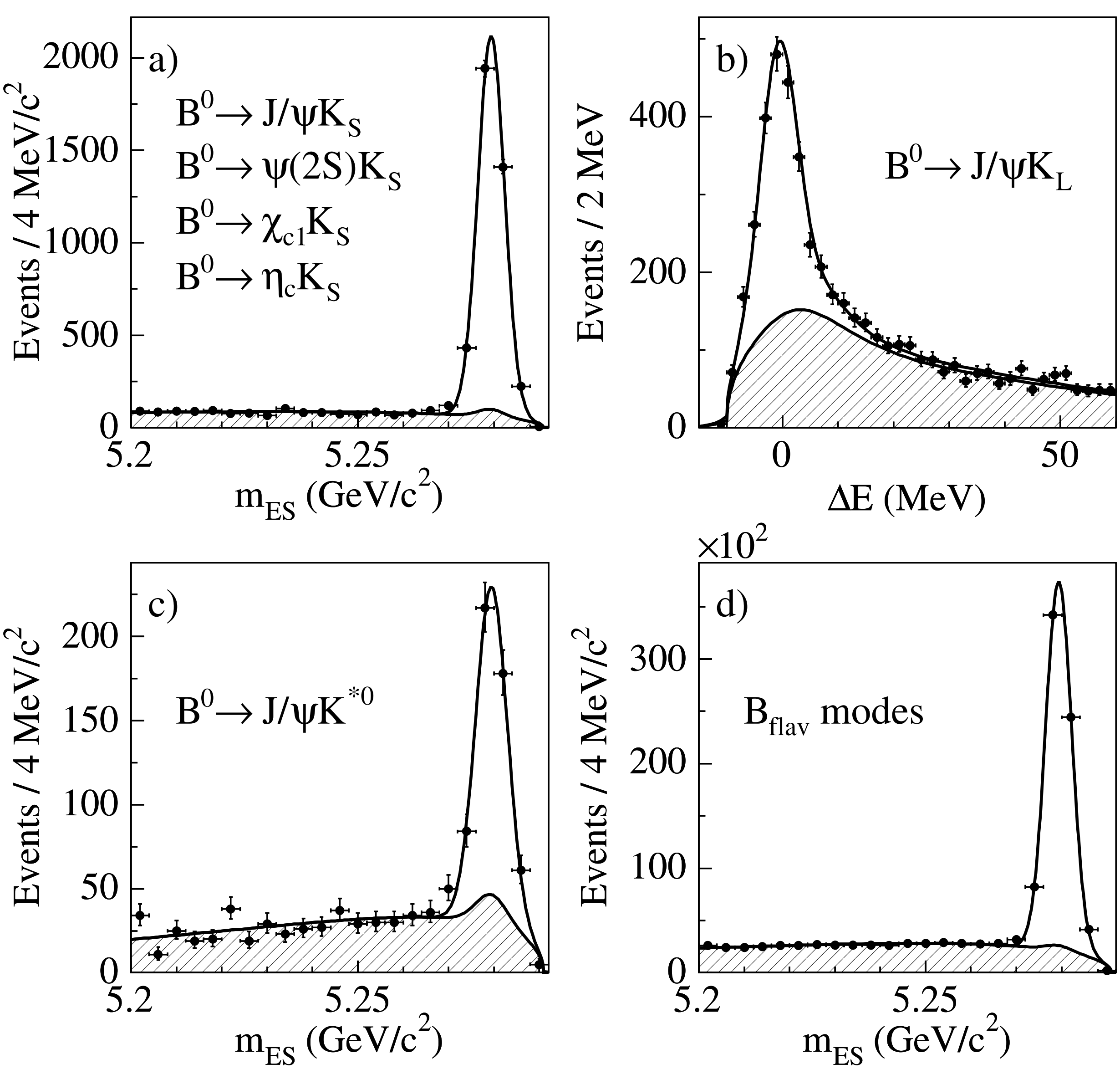

Figure 1: Distributions for B_{CP} and $B_{\rm flav}$ candidates satisfying the tagging and vertexing requirements: a) $m_{\rm ES}$ for the final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$, b) ΔE for the final state $J/\psi\, K^0_L$, c) $m_{\rm ES}$ for $J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$, and d) $m_{\rm ES}$ for the $B_{\rm flav}$ sample. In each plot, the shaded region is the estimated background contribution.

as consistency checks. The results, shown in table 1, show consistent values of sin2β within errors. Fits on B^+ and $B_{\rm flav}$ control samples give sin2β values consistent with zero, as expected.

Table 1: Number of flavor tagged events $N_{\rm tag}$ and purity P in the signal region ($5.27 < m_{\rm ES} < 5.29\,{\rm GeV}/c^2$ (or $|\Delta E| < 10\,{\rm MeV}$ for $J/\psi\,K^0_L$)) and values of sin2β obtained from the fit on the *CP* sample, various sub-samples and B^+ and $B_{\rm flav}$ control samples.

Sample	$N_{\rm tag}$(P)	sin2β
Full *CP* sample	7730(76%)	0.722±0.040
$\eta_{CP} = -1$ sample	4370(90%)	0.75± 0.04
$J/\psi\,K^0_S(\pi^+\pi^-)$	2751(96%)	0.79± 0.05
$J/\psi\,K^0_S(\pi^0\pi^0)$	653(88%)	0.65± 0.12
$\psi(2S)K^0_S(\pi^+\pi^-)$	485(82%)	0.88± 0.14
$\chi_{c1}K^0_S$	194(81%)	0.69± 0.23
$\eta_c K^0_S$	287(64%)	0.17± 0.25
$J/\psi\,K^0_L$	2788(56%)	0.57± 0.09
$J/\psi\,K^{*0}(K^0_S\pi^0)$	572(68%)	0.96± 0.32
1999-2002 data	3032(77%)	0.74 ±0.06
2003-2004 data	4698(77%)	0.71 ±0.05
`Lepton`	490(96%)	0.75± 0.08
`Kaon I`	648(93%)	0.75± 0.08
`Kaon II`	1021(89%)	0.77± 0.09
`Kaon-Pion`	769(90%)	0.77± 0.15
`Pion`	835(87%)	0.96± 0.22
`Other`	607(88%)	0.23± 0.51
$B_{\rm flav}$ sample	72878(85%)	0.021± 0.013
B^+ sample	18294(88%)	0.003± 0.020

To assess whether the assumption of no direct CP violation ($|\lambda| = 1$) in $B^0 \to (c\bar{c})K^{0(*)}$ decays is valid, we have performed a separate fit on the $\eta_{CP} = -1$ sample with $|\lambda|$ floating and obtained:

$$|\lambda| = 0.950 \pm 0.031({\rm stat}) \pm 0.013({\rm syst}). \tag{7}$$

4 Measurement of cos2β

A measurement of sin2β leads to a four-fold ambiguity in β, which can be reduced to a two-fold ambiguity with a separate measurement of the sign of cos2β. *BABAR* has measured this in a time-dependent angular analysis of 104 $B^0 \to J/\psi\,K^{*0}(K^* \to K^0_S\pi^0)$ decays in 81.9fb^{-1} of data recorded between 1999 and 2002[4]. Interference between decays to CP-even (L=0,2) and CP-odd (L=1) final states give terms proportional to cos2β in the decay rate. Strong phase differences and transversity amplitudes A, that appear also in these terms, have been separately measured in a time-integrated angular analysis of $B^\pm \to J/\psi\,K^{*\pm}$ and $J/\psi\,K^{*0}(K^* \to K^+\pi^-)$ decays:

$$\begin{aligned} \delta_\parallel - \delta_0 &= (-2.73 \pm 0.10 \pm 0.05)\,{\rm rad}, \\ \delta_\perp - \delta_0 &= (+2.96 \pm 0.07 \pm 0.05)\,{\rm rad}, \end{aligned}$$

$$
\begin{aligned}
|A_0|^2 &= 0.566 \pm 0.012 \pm 0.005, \\
|A_\parallel|^2 &= 0.204 \pm 0.015 \pm 0.005, \\
|A_\perp|^2 &= 0.230 \pm 0.015 \pm 0.004,
\end{aligned} \tag{8}
$$

The analysis in principle allows a second solution for the strong phase differences, leading to a sign ambiguity in cos2β. This ambiguity has been resolved with the inclusion of S-wave $K\pi$ final states in the analysis. The interference between the S-wave and P-wave contributions gives additional terms in the decay rates with a clear dependence on the $K\pi$ mass due to the resonance shapes. The other solution for the strong phase differences can be excluded as leading to an unphysical dependence of the strong phase differences on the $K\pi$ mass.

Using the values from Eq. 8, and fixing sin2β to 0.731, the fit to the $B^0 \to J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$ sample gives:

$$\text{cos}2\beta = +2.72^{+0.50}_{-0.79} \pm 0.27.$$

By comparing this result with the outcomes of fits to 2000 data-sized Monte Carlo samples, the sign of $\cos 2\beta$ is determined to be positive at the 86% C.L., in agreement with Standard Model expectations.

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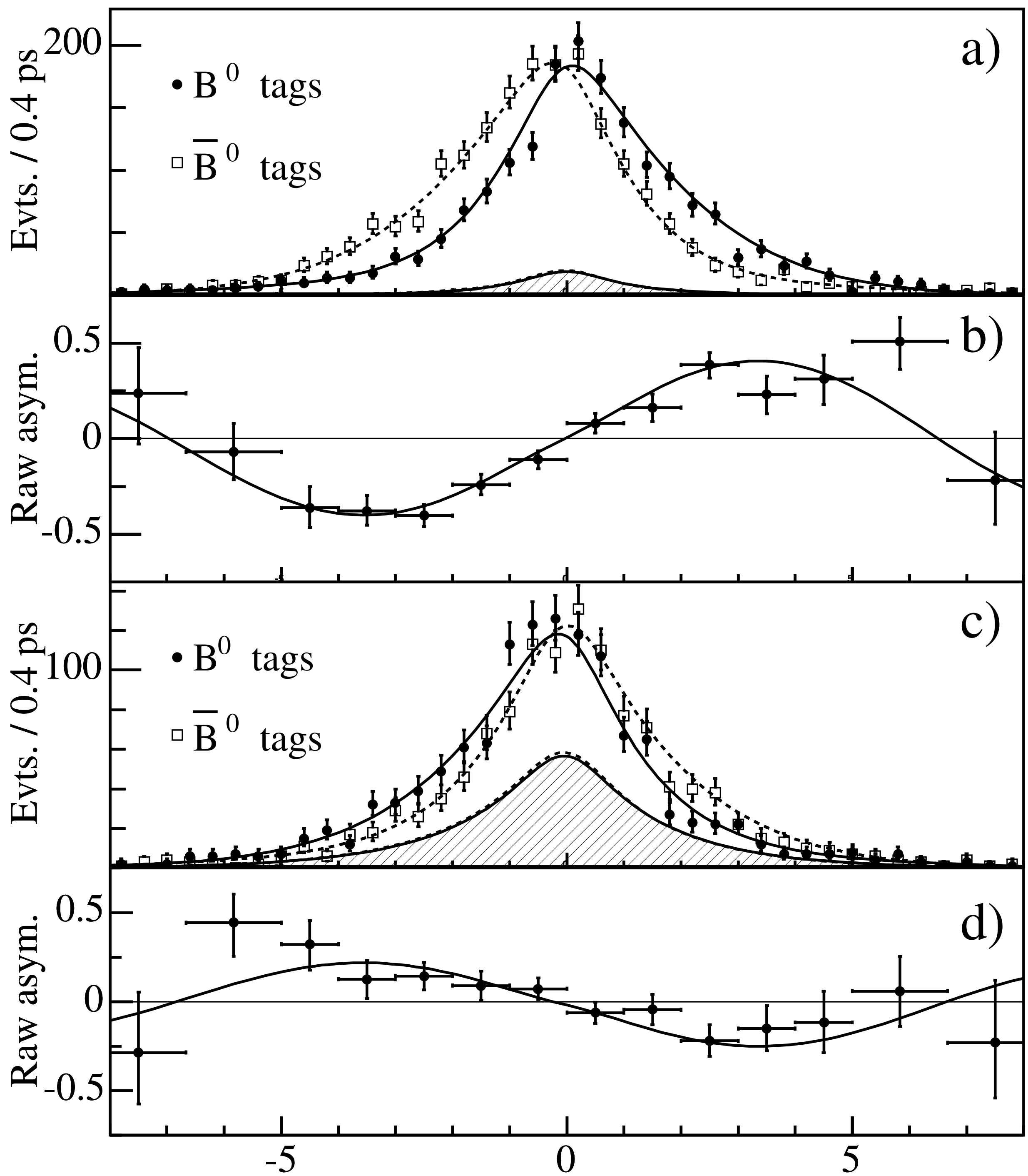

Figure 2: a) Number of $\eta_f = -1$ candidates ($J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, and $\eta_c K_S^0$) in the signal region with a B^0 tag N_{B^0} and with a $\overline{B}^0$ tag $N_{\overline{B}^0}$, and b) the raw asymmetry $A_{CP}^{\rm raw}$, as function of Δt. Figs. c) and d) are the corresponding plots for the $\eta_f = +1$ mode $J/\psi K_L^0$. All plots exclude `Other`- tagged events. The solid (dashed) curves represent the fit projections in Δt for B^0 ($\overline{B}^0$) tags. The shaded regions represent the estimated background contributions.