Improved Measurement of the $CP$-violating Asymmetry Amplitude $\sin 2\beta$

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We present updated results on time-dependent CP-violating asymmetries in neutral B decays to several CP eigenstates. The measurements use a data sample of about 62 million $\Upsilon(4S) \rightarrow B \bar{B}$ decays collected between 1999 and 2001 by the BABAR detector at the PEP-II asymmetric-energy B Factory at SLAC. In this sample we study events in which one neutral B meson is fully reconstructed in a final state containing a charmonium meson and the flavor of the other neutral B meson is determined from its decay products. The amplitude of the CP-violating asymmetry, which in the Standard Model is proportional to $\sin^2\beta$, is derived from the decay time distributions in such events.

We measure $\sin^2\beta = 0.75^{+0.09}_{-0.04}$ (stat) and $|\lambda| = 0.92^{+0.06}_{-0.02}$ (syst). The latter is consistent with the Standard Model expectation of no direct CP violation. These results are preliminary.

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The Standard Model of electroweak interactions describes CP violation in weak decays as a consequence of a
complex phase in the three-generation Cabibbo-Kobayashi-Maskawa \( \mathbb{K} \) (CKM) quark-mixing matrix. In this picture, measurements of CP-violating asymmetries in the time distributions of \( B^0 \) decays to charmonium final states provide a direct measurement of \( \sin 2\beta \) \( \mathbb{K} \), where \( \beta \equiv \arg \left( -V_{ud}V_{us}^* / V_{cd}V_{cs}^* \right) \).

Measurements of the CP-violating asymmetry parameter \( \sin 2\beta \) have recently been published by the BABAR \( \mathbb{K} \) and Belle \( \mathbb{K} \) collaborations from data taken between 1999 and summer 2001 at the PEP-II and KEKB asymmetric-energy \( e^+e^- \) colliders. These results, which followed less precise measurements \( \mathbb{K} \), established CP violation in the \( B^0 \) system. In this paper, we report an updated measurement of \( \sin 2\beta \), using a sample of 62 million \( B^0 \) decays collected with the BABAR detector. Since our previous measurement, we have added a sample of 30 million \( B^0 \) decays collected in the latter half of 2001, and have improved data reconstruction and analysis techniques. The measurement technique is described in detail in Ref. \( \mathbb{K} \). The discussion here is limited to the changes in the analysis with respect to the published results \( \mathbb{K} \).

Since the BABAR detector is described in detail elsewhere \( \mathbb{K} \), only a brief description is given here. Surrounding the beam-pipe is a silicon vertex tracker (SVT), which provides precise measurements of the trajectories of charged particles as they leave the beam-pipe. We use the GEANT4 \( \mathbb{K} \) software to simulate interactions of particles traversing the BABAR detector.

From approximately 56 fb\(^{-1} \) of data recorded at the \( \Upsilon(4S) \) resonance, corresponding to 62 million produced \( B\bar{B} \) pairs, we reconstruct a sample of neutral \( B \) mesons, \( B_{\text{cp}} \), decaying to the final states \( J/\psi K^0_S (K^0_S \to \pi^+\pi^-), \psi(2S)K^0_S (K^0_S \to \pi^+\pi^-), \chi_c1K^0_S (K^0_S \to \pi^+\pi^-), J/\psi K^{*0} (K^{*0} \to K^0\pi^0), K^0 \to \pi^+\pi^-), \) and \( J/\psi K^* \). The \( \psi(2S) \) and \( \chi_c \) mesons are reconstructed through their decays to \( \pi^+\pi^- \) and \( \mu^+\mu^- \); the \( \psi(2S) \) is also reconstructed through its decay to \( J/\psi \pi^+\pi^- \). The \( \chi_c1 \) meson is reconstructed in the decay mode \( J/\psi \gamma \). We examine each of the events in the \( B_{\text{cp}} \) sample for evidence that the recoiling neutral \( B \) meson decayed as a \( B^0 \) or \( \bar{B}^0 \) (flavor tag).

A time-dependent CP asymmetry of \( B \) decays to a CP eigenstate with a \( B^0 \) or \( \bar{B}^0 \) tag can be expressed in terms of a complex parameter \( \lambda \) that depends on both the \( B^0-\bar{B}^0 \) oscillation amplitude and the amplitudes describing \( \bar{B}^0 \) and \( B^0 \) decays to this final state \( \mathbb{K} \). The decay rate \( f_\pm(f_-) \) when the tagging meson is a \( B^0(\bar{B}^0) \) is given by

\[
f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times \left[ 1 \pm \frac{2 \Im \lambda}{1 + |\lambda|^2} \sin (\Delta m_d \Delta t) + \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos (\Delta m_d \Delta t) \right],
\]

where \( \Delta t = t_{\text{rec}} - t_{\text{tag}} \) is the difference between the proper decay time of the reconstructed \( B \) meson \( (t_{\text{rec}}) \) and the proper decay time of the tagging \( B \) meson \( (t_{\text{tag}}) \), \( \tau_{B^0} \) is the \( B^0 \) lifetime, \( \Delta m_d \) is the mass difference determined from \( B^0-\bar{B}^0 \) oscillations, and the lifetime difference between the neutral \( B \) mass eigenstates is assumed to be negligible. The sine term in Eq. \( \mathbb{K} \) is due to the interference between direct decay and decay after flavor change, and the cosine term is due to the interference between two or more decay amplitudes with different weak phases. Evidence for CP violation can be observed as a difference between the \( \Delta t \) distributions of \( B^0 \)- and \( \bar{B}^0 \)-tagged events or as an asymmetry with respect to \( \Delta t = 0 \) for either flavor tag.

In the Standard Model, \( \lambda = \eta_f e^{-2i\beta} \) for charmonium-containing \( b \to c\bar{s} \) decays where \( \eta_f \) is the CP eigenvalue of the final state \( f \). Thus, the time-dependent CP-violating asymmetry is

\[
A_{\text{CP}}(\Delta t) = \frac{f_\pm(\Delta t) - f_-(\Delta t)}{f_\pm(\Delta t) + f_-(\Delta t)} = -\eta_f \sin 2\beta \sin (\Delta m_d \Delta t),
\]

with \( \eta_f = -1 \) for \( J/\psi K^0_S, \psi(2S)K^0_S \), and \( \chi_c1K^0_S \), and \( +1 \) for \( J/\psi K^* \).

The measurement of \( \sin 2\beta \) with the decay mode \( B \to J/\psi K^{*0}(K^{*0} \to K^0\pi^0) \) is experimentally complicated by the presence of both even \( (L=0, 2) \) and odd \( (L=1) \) orbital angular momenta in the final state. With the measured \( CP \)-even and \( CP \)-odd contributions to the decay rate \( \mathbb{K} \), the experimental sensitivity to \( \sin 2\beta \) is reduced by 24% compared to pure CP eigenstates. The interference between \( CP \)-even and \( CP \)-odd amplitudes in this mode allows a measurement of \( \cos 2\beta \) up to a sign ambiguity. The time- and angle-dependent decay rate \( f_\pm(f_-) \) when the tagging meson is a \( B^0(\bar{B}^0) \) is given by
\[ f_\pm (\Delta t, \vec{\omega}) = \frac{e^{-|\Delta t|/\tau_{B0}}}{4\tau_{B0}} \left[ I(\vec{\omega}; \vec{A}) + \left\{ C(\vec{\omega}; \vec{A}) \cos(\Delta m_d \Delta t) \ight. \right. \\
\left. \left. + \left[ S_{\sin2\beta}(\vec{\omega}; \vec{A}) \sin2\beta + S_{\cos2\beta}(\vec{\omega}; \vec{A}) \cos2\beta \right] \sin(\Delta m_d \Delta t) \right\} \right](3) \]

where the coefficients \( I, C, S_{\sin2\beta}, \text{and} \ S_{\cos2\beta} \) are functions of three transversity angles \( \vec{\omega} \) and the previously measured transversity amplitudes \( \vec{A} \) (see appendix \( \text{[A]} \)).

The event selection, lepton and charged kaon identification, and \( J/\psi \) and \( \psi(2S) \) reconstruction used in this analysis are similar to those described in Ref. \( \text{[3], [6]} \). Since these earlier publications, significant improvements have been made in the analysis. Charged kaon identification has improved due to a better alignment of the Cherenkov detector and better Cherenkov angle reconstruction. For the \( B^0 \rightarrow J/\psi K_S^0 \) selection, we have loosened the muon selection requirements for \( J/\psi \rightarrow \mu^+ \mu^- \) and the \( \pi^0 \) veto for \( K_S^0 \) candidates. In the \( K_S^0 \rightarrow \pi^+ \pi^- \) selection for \( B^0 \rightarrow J/\psi K_S^0 \) candidates, the requirement on the \( \pi^+ \pi^- \) mass has been relaxed to \( 472 \leq m(\pi^+ \pi^-) < 522 \text{ MeV}/c^2 \). We have increased the sensitivity to \( \sin2\beta \) for the mode \( J/\psi K^{*0}(K^{*0} \rightarrow K^0_S \pi^0) \) by taking into account the transversity angles for each event instead of integrating out the angle dependence. Events reconstructed in this mode that have a candidate in the mode \( J/\psi K^{*+}(K^{*+} \rightarrow K^0_S \pi^+) \) are rejected. In addition, the whole dataset has been processed with a uniform reconstruction algorithm and detector calibration. This provides, in particular, better alignment of the tracking system and improved track reconstruction efficiency for the 20 fb\(^{-1}\) of data collected in 1999–2000. For example, the event yield increased by 11% (37%) for the \( \eta_f = -1 \) (\( J/\psi K_S^0 \)) sample while the purity only decreased by 4% (3%). The effect of all improvements decreases the error on \( \sin2\beta \) scaled to the same integrated luminosity by 13%.

Candidates in the \( B_{CP} \) sample are selected by requiring that the difference \( \Delta E \) between their energy and the beam energy in the center-of-mass frame be less than three standard deviations from zero. For modes involving \( K_S^0 \), the beam-energy substituted mass \( m_{ES} = \sqrt{(p_{\text{beam}}/m_B)^2 - (p_B^c)^2} \) must be greater than 5.2 GeV/c\(^2\). The resolution for \( \Delta E \) is about 10 MeV, except for the \( K_S^0 \rightarrow \pi^0 \pi^0 (33 \text{ MeV}) \), the \( J/\psi K^{*0} \) (20 MeV) and the \( J/\psi K_L^0 \) (3.5 MeV after \( B \) mass constraint) modes. For the purpose of determining numbers of events and purities, a signal region \( 5.270 \text{ (5.273)} < m_{ES} < 5.290 \text{ (5.288)} \text{ GeV}/c^2 \) is used for modes containing \( K_S^0 \) (\( K^{*0} \)). The signal region for the mode \( J/\psi K_L^0 \) is defined by \( |\Delta E| < 10 \text{ MeV} \).

A measurement of \( A_{CP} \) requires a determination of the experimental \( \Delta t \) resolution and the fraction of events in which the tag assignment is incorrect. A mistag fraction \( w \) reduces the observed \( CP \) asymmetry by a factor \( (1 - 2w) \). Mistag fractions and \( \Delta t \) resolution functions are determined from a sample \( B_{\text{raw}} \) of neutral \( B \) decays to flavor eigenstates consisting of the channels \( D^{(*)-} h^+ (h^+ = \pi^+, \rho^+, \text{and} \ a_1^+) \text{ and} J/\psi K^{*0}(K^{*0} \rightarrow K^0 \pi^+) \). Validation studies are performed with a control sample of charged \( B \) mesons decaying to the final states \( J/\psi K^{+} \), \( \psi(2S)K^+, \chi_{c1}K^+, \text{ and} D^{(*)0} \pi^+ \).

The methods for flavor tagging and vertex reconstruction, and the determination of \( \Delta t \), are described in Ref. \( \text{[6]} \). For flavor tagging, we exploit information from the recoil \( B \) decay in the event. The charges of energetic electrons and muons from semileptonic \( B \) decays, kaons, soft pions from \( D^* \) decays, and high momentum particles are correlated with the flavor of the decaying \( b \) quark. For example, a positive lepton indicates a \( B^0 \) tag. About 68% of the events can be assigned to one of four hierarchical, mutually exclusive tagging categories. The remaining untagged events are excluded from further analysis.

For a lepton tag we require an electron or muon candidate with a center-of-mass momentum \( p_{\text{cm}} > 1.0 \) or 1.1 GeV/c, respectively. This efficiently selects primary leptons from semileptonic \( B \) decays and reduces contamination due to oppositely-charged leptons from charm decays. Events satisfying these criteria are assigned to the \( \text{Lepton} \) category unless the lepton charge and the net charge of all kaon candidates indicate opposite flavor tags. Events without a lepton tag but with a non-zero net kaon charge are assigned to the \( \text{Kaon} \) category. All remaining events are passed to a neural network algorithm whose main inputs are the momentum and charge of the track with the highest center-of-mass momentum, and the outputs of secondary networks, trained with Monte Carlo samples to identify primary leptons, kaons, and soft pions. Based on the output of the neural network algorithm, events are tagged as \( B^0 \) or \( \bar{B}^0 \) and assigned to the \( \text{NT1} \) (more certain tags) or \( \text{NT2} \) (less certain tags) category, or not tagged at all. The tagging power of the \( \text{NT1} \) and \( \text{NT2} \) categories arises primarily from soft pions and from recovering unidentified isolated primary electrons and muons.

The time interval \( \Delta t \) between the two \( B \) decays is calculated from the measured separation \( \Delta z \) between the decay vertex of the reconstructed \( B \) meson (\( B_{\text{rec}} \)) and the vertex of the flavor-tagging \( B \) meson (\( B_{\text{tag}} \)) along the \( z \) axis. The calculation of \( \Delta t \) includes an event-by-event correction for the direction of the \( B_{\text{rec}} \) with respect to the \( z \) direction in the \( T(4S) \) frame. We determine the \( z \) position of the \( B_{\text{rec}} \) vertex from the charged tracks that constitute the \( B_{\text{rec}} \) candidate. The decay vertex of the \( B_{\text{tag}} \) is determined by fitting the tracks not belonging to the \( B_{\text{rec}} \) candidate to a
common vertex. An additional constraint on the tagging vertex comes from a pseudotrack computed from the \( B_{\text{rec}} \) vertex and three-momentum, the beam-spot (with a vertical size of 10 \( \mu \text{m} \)), and the \( \Upsilon(4S) \) momentum. For 99.5\% of the reconstructed events the r.m.s. \( \Delta z \) resolution is 180 \( \mu \text{m} \). An accepted candidate must have converged fits for the \( B_{\text{rec}} \) and \( B_{\text{tag}} \) vertices, a \( \Delta t \) error less than 2.5 ps, and a measured \( |\Delta t| < 20 \text{ ps} \). The fraction of events in data satisfying these requirements is 93\%.

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**FIG. 1:** Distribution of \( m_{ES} \) for flavor tagged \( B_{CP} \) candidates selected in the final states a) \( J/\psi K_S^0 (K_S^0 \rightarrow \pi^+ \pi^-) \), b) \( J/\psi K_S^0 (K_S^0 \rightarrow \pi^0 \pi^0) \), c) \( \psi(2S) K_S^0 \), d) \( \chi_{c1} K_S^0 \), e) \( J/\psi K^{*0} (K^{*0} \rightarrow K_S^0 \pi^0) \), and f) distribution of \( \Delta E \) for flavor tagged \( J/\psi K_L^0 \) candidates.
In Table I we list the numbers of events and the signal purities for the tagged $B_{CP}$ candidates. The purities are determined from fits to the $m_{ES}$ (all $K^0$ modes except $J/\psi K^{*0}$) or $\Delta E$ ($K^0_S$) mode distributions in data, or from Monte Carlo simulation ($J/\psi K^{*0}$ mode). Figure 1 shows the $m_{ES}$ distributions for modes containing a $K^0_S$, and $\Delta E$ for the $J/\psi K^0$ candidates. For modes containing a $K^0_S$, we use a Monte Carlo simulation to estimate the fractions of events in the signal peaks that are due to cross-feed from other decay modes. The fractions of peaking background range between (0.8 ± 0.2)% for $J/\psi K^0_S$ ($K^0_S \to \pi^+ \pi^-$) and (6.0 ± 1.8)% for $\psi(2S)K^0_S$. For the $J/\psi K^0_S$ decay mode, the composition, effective $\eta_f$, and $\Delta E$ distributions of the individual background sources are determined either from Monte Carlo simulation (for $B$ decays to $J/\psi$) or from the $m_{ET}\ell\ell$ sidebands in data (for fake $J/\psi \to \ell^+ \ell^-$). The tagging efficiencies for the four tagging categories are measured from data and summarized in Table I.

### Table I: Number of tagged events, signal purity, and result of fitting for $CP$ asymmetries in the full $CP$ sample and in various subsamples, as well as in the $B_{raw}$ and charged $B$ control samples. Purity is the fitted number of signal events divided by the total number of events in the $\Delta E$ and $m_{ES}$ signal region defined in the text. Errors are statistical only.

| Sample                | $N_{tag}$ | Purity (%) | sin2$\beta$ |
|-----------------------|-----------|------------|-------------|
| Full CP sample        | 1850      | 79         | 0.75 ± 0.09 |
| $J/\psi K^0_S$ ($K^0_S \to \pi^+ \pi^-$) | 693       | 96         | 0.79 ± 0.11 |
| $J/\psi K^0_S$ ($K^0_S \to \pi^0 \pi^0$) | 123       | 89         | 0.42 ± 0.33 |
| $\psi(2S)K^0_S$       | 119       | 89         | 0.84 ± 0.32 |
| $\chi_{c1} K^0_S$     | 60        | 94         | 0.84 ± 0.49 |
| $J/\psi K^0_S$        | 742       | 57         | 0.73 ± 0.19 |
| $J/\psi K^{*0} \to K^0_S \pi^0$ | 113       | 83         | 0.62 ± 0.56 |
| $J/\psi K^{*0}$, $\psi(2S)K^0_S$, $\chi_{c1} K^0_S$ only ($\eta_f = -1$) | 995       | 94         | 0.76 ± 0.10 |

**Lepton tags**
- lepton tags: 176
- kaon tags: 504
- NT1 tags: 117
- NT2 tags: 198

**$B^0$ tags**
- $B^0$: 471
- $\bar{B}^0$: 524

**$B_{raw}$ sample**
- 17546
- Charged $B$ sample
- 14768

### Table II: Average mistag fractions $w_i$ and mistag differences $\Delta w_i = w_i(B^0) - w_i(\bar{B}^0)$, extracted for each tagging category $i$ from the maximum-likelihood fit to the time distribution for the fully-reconstructed $B^0$ sample ($B_{raw}$ and $B_{CP}$). The figure of merit for tagging is the effective tagging efficiency $Q_i = \varepsilon_i(1-2w_i)^2$, where $\varepsilon_i$ is the fraction of events with a reconstructed tag vertex that is assigned to the $i^{th}$ category. Uncertainties are statistical only. The statistical error on sin2$\beta$ is proportional to $1/\sqrt{Q}$, where $Q = \sum Q_i$.

| Category | $\varepsilon$ (%) | $w$ (%) | $\Delta w$ (%) | $Q$ (%) |
|----------|-------------------|---------|----------------|--------|
| Lepton   | 11.1 ± 0.2        | 8.6 ± 0.9| 0.6 ± 1.5     | 7.6 ± 0.4 |
| Kaon     | 34.7 ± 0.4        | 18.1 ± 0.7| −0.9 ± 1.1   | 14.1 ± 0.6 |
| NT1      | 7.7 ± 0.2         | 22.0 ± 1.5| 1.4 ± 2.3    | 2.4 ± 0.3 |
| NT2      | 14.0 ± 0.3        | 37.3 ± 1.3| −4.7 ± 1.9   | 0.9 ± 0.2 |
| All      | 67.5 ± 0.5        |         |       | 25.1 ± 0.8 |

We determine sin2$\beta$ with a simultaneous unbinned maximum likelihood fit to the $\Delta t$ distributions of the $B_{CP}$ and $B_{raw}$ tagged samples. Equations 1 (with $|\lambda| = 1$) and 3 describe the $\Delta t$ distribution of the $\eta_f = 1$ and $J/\psi K^0_S$ samples, and the $J/\psi K^{*0}$ sample, respectively. The $\Delta t$ distributions of the $B_{raw}$ sample evolve according to the known frequency for flavor oscillation in neutral $B$ mesons. The observed amplitudes for the $CP$ asymmetry in the $B_{CP}$ sample and for flavor oscillation in the $B_{raw}$ sample are reduced by the same factor $(1-2w)$ due to mistags. The $\Delta t$ distributions for the $B_{CP}$ and $B_{raw}$ samples are both convolved with a common $\Delta t$ resolution function. Events are assigned signal and background probabilities based on the $m_{ES}$ (all modes except $J/\psi K^0_S$ or $\Delta E$ ($J/\psi K^0_S$) distributions. Backgrounds are incorporated with an empirical description of their $\Delta t$ evolution, containing prompt and non-prompt components convolved with a separate resolution function.

The $\Delta t$ resolution function $R$ for the signal is represented in terms of $\delta t \equiv \Delta t - \Delta t_{true}$ by a sum of three Gaussian distributions with different means and widths:
\[ R(\delta t) = \sum_{k=\text{core, tail}} \frac{f_k}{S_k \sigma_{\Delta t} \sqrt{2\pi}} \exp \left( -\frac{(\delta t - b_k \sigma_{\Delta t})^2}{2(S_k \sigma_{\Delta t})^2} \right) + \frac{f_{\text{outlier}}}{\sigma_{\text{outlier}} \sqrt{2\pi}} \exp \left( -\frac{\delta t^2}{2\sigma_{\text{outlier}}^2} \right). \]

For the core and tail Gaussians, we use two separate scale factors $S_{\text{core}}$ and $S_{\text{tail}}$ to multiply the measurement uncertainty $\sigma_{\Delta t}$ that is derived from the vertex fit for each event. The scale factor for the tail component $S_{\text{tail}}$ is fixed to the value found in Monte Carlo simulation since it is strongly correlated with the other resolution function parameters. The core and tail Gaussian distributions are allowed to have nonzero means to account for any daughters of long-lived charm particles included in the $B_{\text{tag}}$ vertex. In the resolution function, mean offsets $b_k$ are multiplied by the event-by-event measurement uncertainty $\sigma_{\Delta t}$ to account for an observed correlation between the mean of the $\delta t$ distribution and the measurement uncertainty $\sigma_{\Delta t}$ in Monte Carlo simulation. The mean of the core Gaussian is allowed to be different for each tagging category. One common mean is used for the tail component. The outlier Gaussian has a fixed width and no offset; it accounts for the fewer than 0.5% of events with incorrectly reconstructed vertices. In simulated events, we find no significant difference between the $\Delta t$ resolution function of the $B_{\text{CP}}$ sample and of the $B_{\text{ flav}}$ sample. This is expected, since the $B_{\text{tag}}$ vertex precision dominates the $\Delta t$ resolution. Hence, the same resolution function is used for all modes.

| TABLE III: $\Delta t$ resolution function parameters for $B_{\text{ flav}}$ and $B_{\text{CP}}$ candidates extracted from the simultaneous maximum-likelihood fit to the $\Delta t$ distributions for the $B_{\text{ flav}}$ and $B_{\text{CP}}$ samples. |
|---------------------------------------------------------------|
| $S_{\text{core}}$ | $1.19 \pm 0.07$ | $S_{\text{tail}}$ | $3.0$ (fixed) |
| $b_{\text{core}}$ (lepton) | $0.01 \pm 0.07$ | $b_{\text{tail}}$ | $-2.5 \pm 1.7$ |
| $b_{\text{core}}$ (kaon) | $-0.24 \pm 0.04$ | $\sigma_{\text{outlier}}$ | $8$ ps (fixed) |
| $b_{\text{core}}$ (NT1) | $-0.20 \pm 0.08$ | $f_{\text{tail}}$ | $0.05 \pm 0.04$ |
| $b_{\text{core}}$ (NT2) | $-0.21 \pm 0.06$ | $f_{\text{outlier}}$ | $0.004 \pm 0.002$ |

A total of 35 parameters are varied in the final fit, including the values of $\sin 2\beta$ (1), the average mistag fraction $w$ and the difference $\Delta w$ between $B^0$ and $\bar{B}^0$ mistags for each tagging category (8), parameters for the signal $\Delta t$ resolution (8), and parameters for background time dependence (6), $\Delta t$ resolution (3), and mistag fractions (8). In addition, we allow $\cos 2\beta$ (1), which is determined from the $J/\psi K^{*0}$ events, to vary in the fit. The sign of $\cos 2\beta$ cannot be determined due to a twofold ambiguity in the relative strong phases of the angular amplitudes [11]. We use the convention for the strong phases given in Appendix A.

The determination of the mistag fractions and $\Delta t$ resolution function for the signal is dominated by the high-statistics $B_{\text{ flav}}$ sample. The measured mistag fractions and the parameters of the signal resolution function are listed in Tables II and III. Background parameters are determined from events with $m_{\text{ES}} < 5.27$ GeV/$c^2$ (except $J/\psi K^*_L$ and $J/\psi K^{*0}$). We fix $\tau_{B^0} = 1.548$ ps and $\Delta m_d = 0.472$ ps$^{-1}$ [2]. The largest correlation between $\sin 2\beta$ and any linear combination of the other free parameters is 0.14.

The simultaneous fit to all $CP$ decay modes and the flavor decay modes yields

\[ \sin 2\beta = 0.75 \pm 0.09 \text{ (stat)} \pm 0.04 \text{ (syst)}. \]

Figure 2 shows the $\Delta t$ distributions and asymmetries in yields between $B^0$ tags and $\bar{B}^0$ tags for the $\eta_f = -1$ and $\eta_f = +1$ samples as a function of $\Delta t$, overlaid with the projection of the global likelihood fit result.

Repeating the fit with all parameters except $\sin 2\beta$ fixed to their values at the global maximum likelihood, we attribute a total contribution in quadrature of 0.01 to the error on $\sin 2\beta$ due to the combined statistical uncertainties in mistag rates, $\Delta t$ resolution, and background parameters. The dominant sources of systematic error are due to uncertainties in the level, composition, and $CP$ asymmetry of the background in the selected $CP$ events (0.022), limited Monte Carlo simulation statistics (0.014), and the assumed parameterization of the $\Delta t$ resolution function (0.013), due in part to residual uncertainties in the SVT alignment. Uncertainties in $\Delta m_d$ and $\tau_{B^0}$ each contribute 0.010 to the systematic error. We have performed fits with $\Delta m_d$ and $\tau_{B^0}$ fixed to a series of values around the corresponding world averages in order to determine the dependence of $\sin 2\beta$ on these two parameters and find that

\[ \sin 2\beta = [0.75 - 0.31(\Delta m_d - 0.472 \text{ ps}^{-1}) - 0.62(\tau_{B^0} - 1.548 \text{ ps})]. \]

The large sample of reconstructed events allows a number of consistency checks, including separation of the data by decay mode, tagging category, and $B_{\text{tag}}$ flavor. The results of fits to these subsamples for the $\eta_f = -1$ sample are shown in Table II and found to be statistically consistent. The fit results to the samples of non-$CP$ decay modes indicate no statistically significant asymmetry. The distributions and asymmetry in yields for $B^0$ and $\bar{B}^0$ tags as a function of $\Delta t$ for the $B_{\text{ flav}}$ sample are shown in Fig. 3. In addition, we have made a number of detailed analyses of the
expected distribution of changes in $\sin^2\beta$ that might result from reprocessing, in order to account for the correlations between the two results from the same sample. From these studies, we conclude that the observed difference in the 1999–2000 result, before and after reprocessing, is equivalent to about two standard deviations of the distribution of predicted changes due to reprocessing for events that appear in common. The change in the overall result in the 1999–2000 dataset, from $\sin^2\beta = 0.45 \pm 0.20$ to $0.60 \pm 0.15$, is consistent with the effects of both reprocessing and event selection modifications.

With the theoretically preferred choice of the strong phases, consistent with the hypothesis of the $s$-quark helicity conservation in the decay $K$, the parameter $\cos^2\beta$ is measured to be $+3.3^{+0.6}_{-1.0}$ (stat)$^{+0.6}_{-0.7}$ (syst). This value is $2.2 \sigma$ away from the one obtained using the relation $\sqrt{1 - \sin^2\Delta t} = 0.66$. The dominant contributions to the systematic error on $\cos^2\beta$ are due to uncertainties in the transversity amplitudes for the signal ($^{+0.4}_{-0.2}$) and the background ($^{+0.5}_{-0}$). If we fix $\cos^2\beta$ to 0.66, the measured value of $\sin^2\beta$ does not change.

If the parameter $|\lambda|$ in Eq. 1 is allowed to float in the fit to the $\eta_f = -1$ sample, which has high purity and requires minimal assumptions on the effect of backgrounds, the value obtained is $|\lambda| = 0.92 \pm 0.06$ (stat) $\pm 0.02$ (syst). The sources of the systematic error are the same as for the $\sin^2\beta$ measurement with an additional contribution in quadrature of 0.012 from the uncertainty on the difference in the tagging efficiencies for $B^0$ and $B^0$ tagged events. In this fit, the coefficient of the $\sin(\Delta m_t \Delta t)$ term in Eq. 1 is measured to be $0.76 \pm 0.10$ (stat) in agreement with Table 1.

This analysis supersedes our previous result [3]. It provides the single most precise measurement of $\sin^2\beta$ currently available and is consistent with the range implied by measurements and theoretical estimates of the magnitudes of CKM matrix elements in the context of the Standard Model.
FIG. 3: Number of $B_{\text{flav}}$ candidates in the signal region a) with a $B^0$ tag, $N_{B^0}$, and b) with a $\bar{B}^0$ tag, $N_{\bar{B}^0}$, and c) the raw asymmetry $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$, as functions of $\Delta t$. The solid curves represent the result of the combined fit to all selected $B_{\text{flav}}$ events. The shaded regions represent the background contributions.

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APPENDIX A: TIME-DEPENDENT $CP$ ASYMMETRY IN $B \rightarrow J/\psi K^{*0}(K^{*0} \rightarrow K^0\pi^0)$

The decay $B \rightarrow J/\psi K^{*}$ is described by three amplitudes. In the transversity basis, the amplitudes $A_0$, $A_\parallel$ and $A_\perp$ have $CP$ eigenvalues $+1$, $+1$ and $-1$, respectively. $A_0$ corresponds to longitudinal polarization of the vector mesons, and $A_\parallel$ and $A_\perp$ correspond to parallel and perpendicular transverse polarizations, respectively. The relative phase between the parallel (perpendicular) transverse amplitude and the longitudinal amplitude is given by $\phi_\parallel \equiv \arg(A_\parallel/A_0) \ (\phi_\perp \equiv \arg(A_\perp/A_0))$. The transversity frame is defined as the $J/\psi$ rest frame (see Fig. 4). The $K^*$ direction defines the negative $x$ axis. The $K\pi$ decay plane defines the $(x, y)$ plane, with $y$ oriented such that $p_y(K) > 0$. The $z$ axis is the normal to this plane, and the coordinate system is right-handed. The transversity angles
\( \theta_{tr} \) and \( \varphi_{tr} \) are defined as the polar and azimuthal angles of the positive lepton from the \( J/\psi \) decay; \( \theta_{K^*} \) is the \( K^* \) helicity angle defined in the \( K^* \) rest frame as the angle between the \( K \) direction and the direction opposite to the \( J/\psi \).

\[ \theta_{tr} \text{ and } \varphi_{tr} \text{ are determined in the } J/\psi \text{ rest frame. The angle } \theta_{K^*} \text{ is determined in the } K^* \text{ rest frame.} \]

The time- and transversity-angle-dependent decay rate distributions \( f_\pm (f_-) \) when the tagging meson is a \( B^0(B^0) \) are given by

\[
f_\pm (\Delta t, \bar{\omega}) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left[ I(\bar{\omega}; \bar{A}) \mp \left\{ C(\bar{\omega}; \bar{A}) \cos(\Delta m_d \Delta t) \right. \right.

\[
\left. + \left[ S_{\sin 2\beta} (\bar{\omega}; \bar{A}) \sin 2\beta + S_{\cos 2\beta} (\bar{\omega}; \bar{A}) \cos 2\beta \right] \sin(\Delta m_d \Delta t) \right\} \right].
\]  
(A1)

The coefficients \( I, C, S_{\sin 2\beta}, \) and \( S_{\cos 2\beta} \), which depend on the transversity angles \( \bar{\omega} = (\theta_{K^*}, \theta_{tr}, \varphi_{tr}) \) and the transversity amplitudes \( \bar{A} = (A_0, A_\parallel, A_\perp) \), are given by

\[
I(\bar{\omega}; \bar{A}) = f_1(\bar{\omega})|A_0|^2 + f_2(\bar{\omega})|A_\parallel|^2 + f_3(\bar{\omega})|A_\perp|^2 + f_5(\bar{\omega})|A_\parallel||A_0| \cos(\phi_\parallel - \phi_0)
\]

\[
C(\bar{\omega}; \bar{A}) = f_4(\bar{\omega})|A_\parallel| |A_\perp| \sin(\phi_\perp - \phi_\parallel) + f_6(\bar{\omega})|A_\parallel||A_0| \sin(\phi_\perp - \phi_0)
\]

\[
S_{\sin 2\beta} (\bar{\omega}; \bar{A}) = f_1(\bar{\omega})|A_0|^2 + f_2(\bar{\omega})|A_\parallel|^2 - f_3(\bar{\omega})|A_\perp|^2 + f_5(\bar{\omega})|A_\parallel||A_0| \cos(\phi_\parallel - \phi_0)
\]

\[
S_{\cos 2\beta} (\bar{\omega}; \bar{A}) = -f_4(\bar{\omega})|A_\parallel| |A_\perp| \cos(\phi_\perp - \phi_\parallel) - f_6(\bar{\omega})|A_\parallel||A_0| \cos(\phi_\perp - \phi_0)
\]  
(A2)

with

\[
f_1(\bar{\omega}) = \frac{9}{32\pi} 2 \cos^2(\theta_{K^*}) \left[ 1 - \sin^2(\theta_{tr}) \cos^2(\varphi_{tr}) \right]
\]

\[
f_2(\bar{\omega}) = \frac{9}{32\pi} \sin^2(\theta_{K^*}) \left[ 1 - \sin^2(\theta_{tr}) \sin^2(\varphi_{tr}) \right]
\]

\[
f_3(\bar{\omega}) = \frac{9}{32\pi} \sin^2(\theta_{K^*}) \sin^2(\theta_{tr})
\]

\[
f_4(\bar{\omega}) = \frac{9}{32\pi} \sin^2(\theta_{K^*}) \sin(2\theta_{tr}) \sin(\varphi_{tr})
\]

\[
f_5(\bar{\omega}) = -\frac{9}{32\pi} \sqrt{2} \sin(2\theta_{K^*}) \sin^2(\theta_{tr}) \sin(2\varphi_{tr})
\]

\[
f_6(\bar{\omega}) = \frac{9}{32\pi} \sqrt{2} \sin(2\theta_{K^*}) \sin(2\theta_{tr}) \cos(\varphi_{tr})
\]  
(A3)
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