Measurement of CP-Violating Asymmetry $\sin 2\beta$ with the *BABAR* Detector

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1 Introduction

The Standard Model of electroweak interactions describes *CP* violation in weak interactions as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. In this framework, measurements of *CP*-violating asymmetries in the time distribution of neutral B decays to charmonium final states provide a direct measurement of sin2β [2], where $\beta \equiv \arg\left[-V_{\rm cd}V_{\rm cb}^{*}/V_{\rm td}V_{\rm tb}^{*}\right]$.

We report an updated measurement of time-dependent *CP*-asymmetries in samples of fully reconstructed B decays to charmonium-containing *CP* eigenstates ($b \to c\bar{c}s$). The data for these studies were recorded at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at the Stanford Linear Accelerator Center.

We fully reconstruct a sample of neutral B mesons, B_{CP}, decaying to several *CP* final states. Each event in the B_{CP} is examined for evidence that the recoiling neutral B meson decayed as a B^0 or $\overline{B}^0$ (flavor tag). The time distribution of B meson decays to a *CP* eigenstate with a B^0 or $\overline{B}^0$ tag can be expressed in terms of a complex parameter λ that depends on both the B^0-$\overline{B}^0$ oscillation amplitude and the amplitudes describing $\overline{B}^0$ and B^0 decays to this final state [3]. The decay rate $\mathrm{f}_+(\mathrm{f}_-)$ when the tagging meson is a $B^0(\overline{B}^0)$ is given by

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

where $\Delta t = t_{\mathrm{rec}} - t_{\mathrm{tag}}$ is the difference between the proper decay times of the reconstructed B meson (B_{rec}) and the tagging B meson (B_{tag}), τ_{B^0} is the B^0 lifetime, and Δm_d is the B^0-$\overline{B}^0$ oscillation frequency.

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

$$A_{CP}(\Delta t) \equiv \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = -\eta_f \sin 2\beta \sin(\Delta m_{B^0}\, \Delta t), \quad (2)$$

with $\eta_f = -1$ for $J/\psi K^0_S$, $\psi(2S)K^0_S$, and $\chi_{c1}K^0_S$, and $+1$ for $J/\psi K^0_L$.

The measurement of $\sin 2\beta$ with the decay mode $B \to J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$ is experimentally complicated by the presence of both even (L=0, 2) and odd (L=1) orbital angular momenta in the final state. The decay rate $f_+(f_-)$ when the tagging meson is a $B^0(\overline{B}^0)$, in addition to Δt, is also a function of the angular distribution of the particles in the final state [4].

2 The *BABAR* detector

A detailed description of the *BABAR* detector can be found in Ref. [5]. Charged particles are detected and their momenta measured by a combination of a silicon vertex tracker (SVT) consisting of five double-sided layers and a central drift chamber (DCH), in a 1.5-T solenoidal field. The average vertex resolution in the z direction is $70\,\mu$m for a fully reconstructed B meson. We identify leptons and hadrons with measurements from all detector systems, including the energy loss ($\mathrm{d}E/\mathrm{d}x$) in the DCH and SVT. Electrons and photons are identified by a CsI electromagnetic calorimeter (EMC). Muons are identified in the instrumented flux return (IFR). A Cherenkov ring imaging detector (DIRC) covering the central region, together with the $\mathrm{d}E/\mathrm{d}x$ information, provides K-π separation of at least three standard deviations for B decay products with momentum greater than $250\,\mathrm{MeV}/c$ in the laboratory.

3 Data Sample

The data sample used in this analysis consists of approximately $56\,\mathrm{fb}^{-1}$, corresponding to about 62 million $B\overline{B}$ pairs, collected on the $\Upsilon(4S)$ resonance with the *BABAR* detector at the SLAC PEP-II storage ring between October 1999 and December 2001.

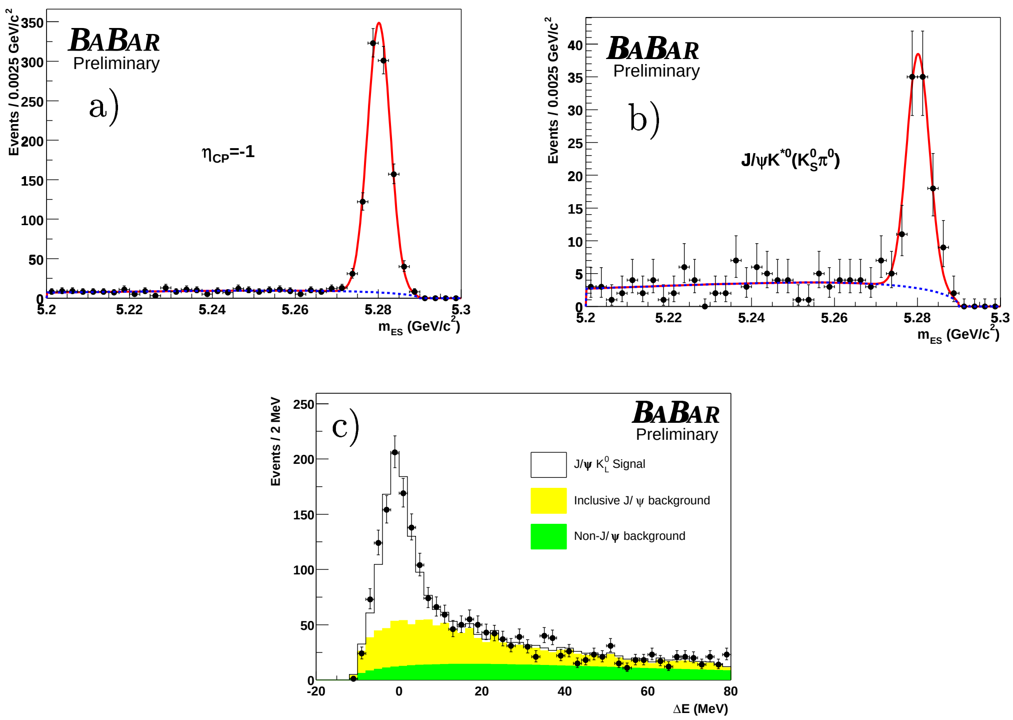

Figure 1: Distribution of $m_{\rm ES}$ for flavor tagged B_{CP} candidates selected in the final states a) $J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$), $J/\psi K^0_S$ ($K^0_S \to \pi^0\pi^0$), $\psi(2S)K^0_S$, and $\chi_{c1}K^0_S$, b) $J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$, and c) distribution of ΔE for flavor tagged $J/\psi\, K^0_L$ candidates.

We fully reconstruct B candidates in the final states $J/\psi\, K^0_S$ ($K^0_S \to \pi^+\pi^-$, $\pi^0\pi^0$), $\psi(2S)K^0_S$ ($K^0_S \to \pi^+\pi^-$), $\chi_{c1}K^0_S$ ($K^0_S \to \pi^+\pi^-$), $J/\psi\, K^{*0}$ ($K^{*0} \to K^0_S\pi^0$, $K^0_S \to \pi^+\pi^-$), and $J/\psi\, K^0_L$ as described in Ref. [4]. Figure 1 shows the distribution of the beam-energy substituted mass $m_{\rm ES} = \sqrt{(E^{\rm cm}_{\rm beam})^2 - (p^{\rm cm}_B)^2}$ for final states containing a K^0_S and ΔE for the $J/\psi\, K^0_L$ mode.

4 The Measurement Technique

A measurement of A_{CP} requires a determination of the experimental Δt resolution and the fraction w of events in which the tag assignment is incorrect. This mistag fraction reduces the observed CP asymmetry by a factor $(1-2w)$. Mistag fractions and Δt resolution functions are determined from a large sample $B_{\rm flav}$ of neutral B decays to flavor eigenstates consisting of the channels $D^{(*)-}h^+(h^+ = \pi^+, \rho^+$, and $a_1^+)$ and $J/\psi\, K^{*0}(K^{*0} \to K^+\pi^-)$. Figure 2 shows the distribution of the beam-energy substituted mass m_{ES} for this sample.

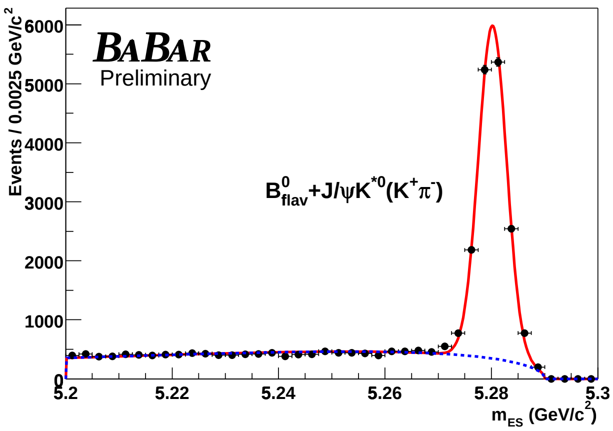

Figure 2: Beam-energy substituted mass distribution for the $B_{\rm flav}$ sample. In 56 fb^{-1}, we reconstruct about 17500 signal events. Average signal purity for $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$ is 85 %.

4.1 B Flavor-Tagging Algorithm

The algorithm used to determine the flavor of the tagging B meson $B_{\rm tag}$ is described in Ref. [6]. 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.

Each event is assigned to one of four hierarchical, mutually exclusive tagging categories or has no flavor tag. A lepton tag requires an electron (muon) candidate with a center-of-mass momentum $p_{\rm cm} > 1.0$ (1.1) GeV/c. This efficiently selects primary leptons and reduces contamination due to oppositely-charged leptons from charm decays. Events meeting these criteria are assigned to the `Lepton` category unless the lepton charge and the net charge of all kaon candidates indicate opposite tags. Events without a lepton tag but with a non-zero net kaon charge are assigned to the `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 $\overline{B}^0$ and assigned to the `NT1` (more certain tags) or `NT2` (less certain tags) category, or not tagged at all. The tagging power of the `NT1` and `NT2` categories arises primarily from soft pions and from recovering unidentified isolated primary electrons and muons.

The tagging efficiencies ε_i and mistag fractions w_i for the four tagging categories are measured from data and summarized in Table 1.

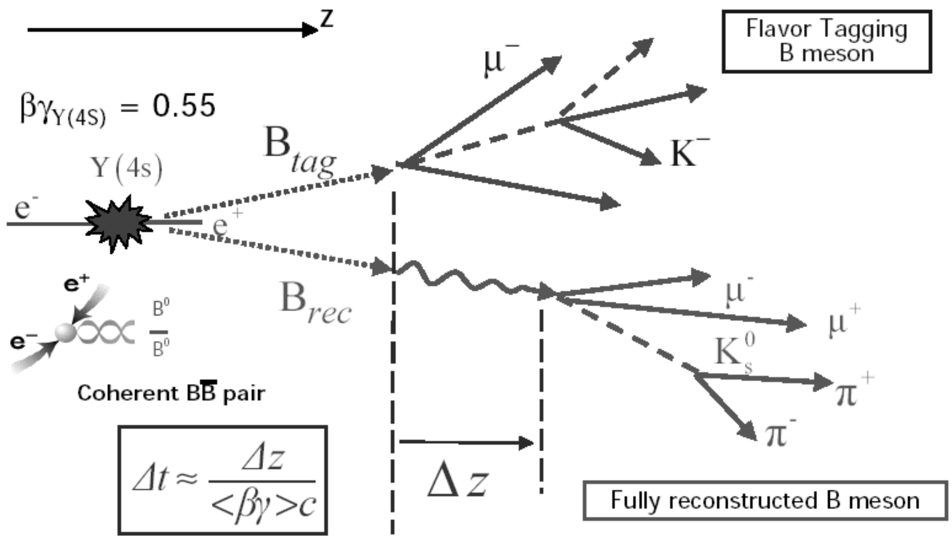

Figure 3: Topology of an event where one B meson is fully reconstructed in a *CP* eigenstate and the flavor of the other B meson is determined from its decay products.

4.2 Δt Measurement and Resolution Function

The topology of a typical *CP* event is shown in Figure 3. The time interval Δt between the two B decays is calculated from the measured separation Δz between the decay vertices of $B_{\rm rec}$ and $B_{\rm tag}$ along the collision (z) axis [6]. We determine the z position of the $B_{\rm rec}$ vertex from its charged tracks. The $B_{\rm tag}$ decay vertex is determined by fitting tracks not belonging to the $B_{\rm rec}$ candidate to a common vertex, employing constraints from the beam spot location and the $B_{\rm rec}$ momentum [6]. We accept events with a Δt uncertainty of less than 2.5 ps and $|\Delta t| < 20$ ps. The fraction of events satisfying these requirements is 93%. The r.m.s. Δt resolution for 99.5% of

Table 1: Efficiencies ϵ_i, average mistag fractions w_i, and mistag fraction differences $\Delta w_i = w_i(B^0) - w_i(\overline{B}^0)$, for the four tagging categories, determined from the likelihood fit to the time distribution of the $B_{\rm flav}$ sample.

Category	Efficiency (%)	w	Δw
`Lepton`	11.1 ± 0.2	8.6 ± 0.9	0.6 ± 0.5
`Kaon`	34.7 ± 0.4	18.1 ± 0.7	-0.9 ± 0.1
`NT1`	7.7 ± 0.2	22.0 ± 1.5	1.4 ± 0.3
`NT2`	14.0 ± 0.3	37.3 ± 1.3	-4.7 ± 0.9
All	67.5 ± 0.5		

these events is 1.1 ps.

The Δt resolution function for the signal is represented in terms of $\delta_t \equiv \Delta t - \Delta t_{\rm true}$ by a sum of three Gaussian distributions with different means and widths:

$$\mathcal{R}(\delta_{\rm t}) \;=\; \sum_{k={\rm core,tail}} \frac{f_k}{S_k\sigma_{\Delta t}\sqrt{2\pi}} \exp\left(-\frac{(\delta_{\rm t}-b_k\sigma_{\Delta t})^2}{2(S_k\sigma_{\Delta t})^2}\right) + \frac{f_{\rm outlier}}{\sigma_{\rm outlier}\sqrt{2\pi}} \exp\left(-\frac{\delta_{\rm t}^2}{2{\sigma_{\rm outlier}}^2}\right).$$

For the core and tail Gaussians, we use two separate scale factors S_k to multiply the measured uncertainty $\sigma_{\Delta t}$ that is derived from the vertex fit for each event. The scale factor for the tail component is fixed to the value found in simulated data since it is strongly correlated with the other resolution function parameters. The core and tail Gaussian distributions are allowed to have non-zero means to account for any daughters of long-lived charm particles included in the $B_{\rm tag}$ vertex. The mean of the core Gaussian is allowed to be different for each tagging category, but only one common mean is used for the tail component. These offsets are computed from the event-by-event $\sigma_{\Delta t}$ multiplied by a scale factor b_k which accounts for a correlation between the mean of the $\delta_{\rm t}$ distribution and $\sigma_{\Delta t}$ observed in simulated events. The outlier Gaussian has a fixed width of 8 ps and no offset; it accounts for less than 0.5% of events with incorrectly reconstructed vertices. In simulated events we find no significant difference between the Δt resolution function of the B_{CP} and the $B_{\rm flav}$ samples, hence the same resolution function is used for both.

5 Results

We determine sin2β with a simultaneous unbinned maximum likelihood fit to the Δt distributions of the tagged B_{CP} and $B_{\rm flav}$ samples. In this fit the Δt distributions of the B_{CP} sample are described by Eq. 1 with $|\lambda| = 1$. The Δt distributions of the $B_{\rm flav}$ sample evolve according to the known frequency for flavor oscillation in B^0 mesons. The observed amplitudes for the CP asymmetry in the B_{CP} sample and for flavor oscillation in the $B_{\rm flav}$ sample are reduced by the same factor $1-2w$ due to flavor mistags. Events are assigned signal and background probabilities based on the $m_{\rm ES}$ (all modes except $J/\psi K^{*0}$ and $J/\psi K^0_L$) or ΔE ($J/\psi K^0_L$) distributions. The Δt distributions for the signal are convolved with the resolution function described in Section 4.2. Backgrounds are incorporated with an empirical description of their Δt spectrum, containing prompt and non-prompt components convolved with a resolution function [6] distinct from that of the signal.

There are 35 free parameters in the fit: sin2β (1), the average mistag fractions w and the differences Δw between B^0 and $\overline{B}^0$ mistag fractions for each tagging category (8), parameters for the signal Δt resolution (8), and parameters for background time dependence (6), Δt resolution (3), and mistag fractions (8). In addition, we allow cos2β (1), which is determined from the $J/\psi K^{*0}$ events, to vary in the fit [4]. We fix τ_{B^0} and Δm_d [7]. The determination of the mistag fractions and Δt resolution function parameters for the signal is dominated by the high-statistics $B_{\rm flav}$ sample. The largest correlation between $\sin2\beta$ and any linear combination of the other free parameters is 0.14.

Figure 4 shows the Δt distributions and A_{CP} as a function of Δt overlaid with the likelihood fit result for the $\eta_f = -1$ and $\eta_f = +1$ samples. The fit to the B_{CP} and $B_{\rm flav}$ samples yields

$$\sin2\beta = 0.75 \pm 0.09 \text{ (stat)} \pm 0.04 \text{ (syst)}.$$

The dominant sources of systematic error are the 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 Δt resolution function (0.013), due in part to residual uncertainties in the internal alignment of the vertex detector. Uncertainties in Δm_d and τ_{B^0} each contribute 0.010 to the systematic error. The large sample of reconstructed events allows a number of consistency checks, including separation of the data by decay mode, tagging category and $B_{\rm tag}$ flavor. The results of fits to some subsamples and to the samples of non-*CP* decay modes are shown in Table 2. For the latter, no statistically significant asymmetry is found.

With the theoretically preferred choice of the strong phases, consistent with the hypothesis of the s-quark helicity conservation in the decay [8], the parameter $\cos2\beta$ is measured to be $+3.3^{+0.6}_{-1.0}$ (stat)$^{+0.6}_{-0.7}$ (syst) [4].

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) ± 0.02 (syst). The sources of the systematic error are the same as for the $\sin2\beta$ measurement with an additional contribution in quadrature of 0.012 from the uncertainty on the difference in the tagging efficien-

Table 2: Number of tagged events, signal purity and observed *CP* asymmetries in the *CP* samples and control samples. Errors are statistical only.

Sample	$N_{\rm tag}$	Purity (%)	$\sin2\beta$
$J/\psi\, K^0_S$,$\psi(2S) K^0_S$,$\chi_{c1} K^0_S$	995	94	0.76 ± 0.10
$J/\psi\, K^0_L$	742	57	0.73 ± 0.19
$J/\psi\, K^{*0}, K^{*0} \to K^0_S \pi^0$	113	83	0.62 ± 0.56
Full *CP* sample	1850	79	0.75 ± 0.09
$B_{\rm flav}$ non-*CP* sample	17546	85	0.00 ± 0.03
Charged B non-*CP* sample	14768	89	-0.02 ± 0.03

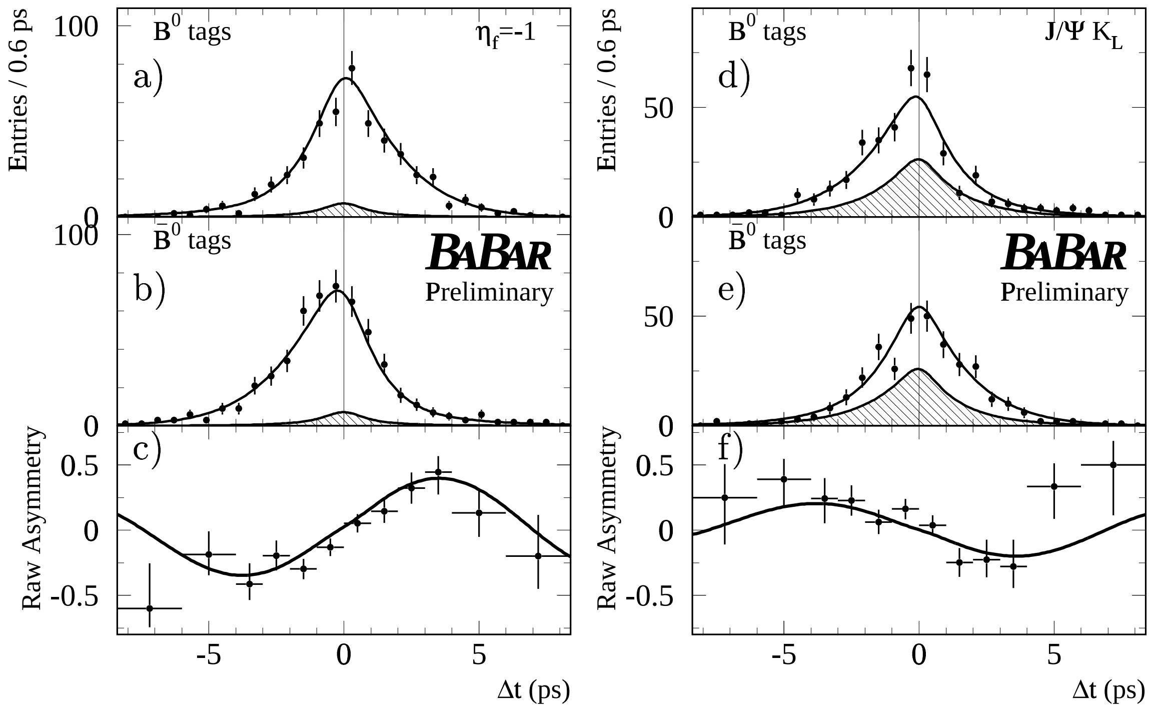

Figure 4: Number of $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$) in the signal region a) with a B^0 tag N_{B^0} and b) with a $\overline{B}^0$ tag $N_{\overline{B}^0}$, and c) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt. The solid curves represent the result of the combined fit to the full $B_{\rm CP}$ sample. The shaded regions represent the background contributions. Figures d) – f) contain the corresponding information for the $\eta_f = +1$ mode $J/\psi K^0_L$.

cies for B^0 and $\overline{B}^0$ tagged events. In this fit, the coefficient of the $\sin(\Delta m_d \Delta t)$ term in Eq. 1 is measured to be 0.76 ± 0.10 (stat) in agreement with Table 1.

6 Summary

We have presented a new preliminary measurement of CP-violating asymmetry sin2β using a sample of fully reconstructed B mesons decaying into CP final states.

Ever since this Conference we have further improved the analysis and updated our measurement [10]. Changes in the analysis with respect to the result presented here include a new flavor-tagging algorithm and the addition of the decay mode $B^0 \to \eta_c K^0_S$. The new result $\sin 2\beta = 0.741 \pm 0.067$ (stat) ± 0.033 (syst) improves upon and supersedes the result presented at this Conference and provides the most precise measurement of sin2β currently available. It 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 [11].

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