Title

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Journal

Physical Review D - Particles, Fields, Gravitation and Cosmology, 72(5)

ISSN

1550-7998

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Publication Date

2005-09-01

DOI

10.1103/PhysRevD.72.051103

PHYSICAL REVIEW D 72, 051103(R) (2005)

Measurement of the time-dependent CP-violating asymmetry in $B^0 \to K_S^0 \pi^0 \gamma$ decays

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(Received 8 July 2005; published 16 September 2005)

We present a measurement of the time-dependent CP-violating asymmetry in $B^0 \to K^{*0}\gamma$ decays with $K^{*0} \to K_S^0\pi^0$ based on 232×10^6 $\Upsilon(4S) \to B\bar{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC. In a sample containing 157 ± 16 signal decays, we measure $S_{K^{*0}\gamma} = -0.21 \pm 0.40 \pm 0.05$ and $C_{K^{*0}\gamma} = -0.40 \pm 0.23 \pm 0.03$, where the first error is statistical and the second systematic. We also explore $B^0 \to K_S^0\pi^0\gamma$ decays with $1.1 < m_{K_S^0\pi^0} < 1.8$ GeV/c^2 and find 59 ± 13 signal events with $S_{K_S^0\pi^0\gamma} = 0.9 \pm 1.0 \pm 0.2$ and $C_{K_S^0\pi^0\gamma} = -1.0 \pm 0.5 \pm 0.2$.

DOI: 10.1103/PhysRevD.72.051103 PACS numbers: 13.20.He, 11.30.Er, 14.40.Nd

The decay transition $b \to s\gamma$ is sensitive to contributions from physics beyond the Standard Model (SM) [1]. There has been extensive experimental and theoretical investigation of the inclusive decay rate $\mathcal{B}(B \to X_s\gamma)$, which to date shows no significant deviation from the SM [2]. Various new physics scenarios can accommodate large deviations from the SM in other $b \to s\gamma$ decay properties as well, in particular in CP-violating (CPV) asymmetries and the polarization of the final state photon [3]. The photon polarization in $b \to s\gamma$ ($\bar{b} \to \bar{s}\gamma$) is predominantly left handed (right handed) in the SM. As a consequence, in the exclusive decay $B^0 \to (K_S^0\pi^0)\gamma$ interference of the amplitude for the direct decay and the amplitude for the decay via $B^0 - \bar{B}^0$ mixing is suppressed. Therefore, time-dependent CP-violating asymmetry is expected to be small [3], $S_{K^{*0}\gamma} \approx -2\frac{m_s}{m_b}\sin 2\beta \approx -0.04$, where m_s (m_b) is the mass of the s (b) quark, $\beta \equiv \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ and V is the quark mixing matrix [4]. Any significant deviation that goes beyond possible hadronization corrections of order 0.1 [5] would indicate phenomena beyond the SM.

In this paper we report new measurements of the time-dependent CPV asymmetry in $B^0 \to K_S^0\pi^0\gamma$ [6] based on 232 million $\Upsilon(4S) \to B\bar{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at SLAC. Measurements of the CPV asymmetry in $B^0 \to K^{*0}\gamma$, the subset of events with $0.8 < m_{K_S^0\pi^0} < 1.0$ GeV/c^2, have previously been reported by *BABAR* on 110 fb^{-1} [7] and BELLE on 253 fb^{-1} [8]. The BELLE collaboration has also reported a measurement of inclusive $B^0 \to K_S^0\pi^0\gamma$ with $0.6 < m_{K_S^0\pi^0} < 1.8$ GeV/c^2 [8]. The latter measurement is motivated by a recent theoretical result that indicates that all contributions to the $K_S^0\pi^0\gamma$ final state have the same CP eigenvalue [9], so that beyond-the-SM effects can be discovered even if the $m_{K_S^0\pi^0}$ resonance structure is not resolved. Since the correctness of such an averaging procedure is still under discussion [5], we present our results for events with an invariant mass of the $K_S^0\pi^0$ pair near and above the $K^*(892)^0$ resonance separately. For simplicity we refer these two contributions as "K^*" and "non-K^*", respectively.

The *BABAR* detector is fully described in Ref. [10]. The components that are most important for this analysis are a five-layer double-sided silicon micro-strip detector (SVT), a 40-layer drift chamber (DCH) and a CsI(Tl) electromagnetic calorimeter (EMC). For event simulation we use the Monte-Carlo event generator EVTGEN [11] and GEANT4 [12].

At the $\Upsilon(4S)$ resonance time-dependent CPV asymmetries are extracted from the distribution of the difference of the proper decay times $\Delta t \equiv t_{CP} - t_{\rm tag}$, where t_{CP} refers to the decay time of the signal B (B_{CP}) and $t_{\rm tag}$ to that of the other B ($B_{\rm tag}$). The Δt distribution for $B_{CP} \to f$ follows

$$\mathcal{P}_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}[1 \pm S_f \sin(\Delta m_d \Delta t) \mp C_f \cos(\Delta m_d \Delta t)], \quad (1)$$

where the upper (lower) sign corresponds to $B_{\rm tag}$ decaying as B^0 ($\bar{B}^0$), τ_B is the B^0 lifetime and Δm_d is the mixing frequency. The coefficients C_f and S_f can be expressed in terms of the B^0-$\bar{B}^0$ mixing amplitude and the decay amplitudes for $B^0 \to f$ and $\bar{B}^0 \to f$ [13]. Direct CP violation in the decay $B^0 \to f$ results in a nonzero value of C_f. For $B^0 \to K^{*0}\gamma$ direct CP violation is constrained by measurements of the partial rate asymmetry in decays with $K^{*0} \to K^+\pi^-$, $\mathcal{A}^{CP}_{K^{*0}\gamma} = -C_{K^{*0}\gamma} = -0.010 \pm 0.028$ [14], which is in good agreement with the SM prediction [15].

We search for $B^0 \to K_S^0\pi^0\gamma$ decays in $B\bar{B}$ candidate events, which are selected based on charged particle multiplicity and event topology [16]. Candidates for $K_S^0 \to \pi^+\pi^-$ are formed from pairs of oppositely charged tracks with a vertex χ^2 probability larger than 0.001, a $\pi^+\pi^-$ invariant mass $487 < m_{\pi^+\pi^-} < 507$ MeV/c^2 ($\sim 3\sigma$) and a reconstructed decay length greater than 5 times its uncertainty. Photon candidates are reconstructed from clusters in the EMC that are isolated from any charged tracks and have the expected lateral shower shape. We form $\pi^0 \to \gamma\gamma$ candidates with an invariant mass $115 < m_{\gamma\gamma} < 155$ MeV/c^2 ($\sim 3\sigma$) and energy $E_{\pi^0} > 590$ MeV from pairs of candidate photons each of which carries a minimum energy of 30 MeV. For the photon from the B decay, the so-called primary photon, we require an energy in the e^+e^- frame of $1.5 < E^*_\gamma < 3.5$ GeV. We veto primary photons that form a $\pi^0 \to \gamma\gamma$ ($\eta \to \gamma\gamma$) candidate with invariant mass $115 < m_{\gamma\gamma} < 155$ MeV/c^2 ($470 < m_{\gamma\gamma} < 620$ MeV/c^2) when combined with another photon with energy $E_\gamma > 50$ MeV ($E_\gamma > 250$ MeV).

To identify B^0 decays in $K^0_S\pi^0\gamma$ combinations we use the energy-substituted mass $\mathrm{m_{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - p_B^2}$ and the energy difference $\Delta\mathrm{E} = E^*_B - \sqrt{s}/2$. Here $(E_i, \mathbf{p}_i)$ and $(E_B, \mathbf{p}_B)$ are the four-vectors of the initial e^+e^- system and the B candidate, respectively, $\sqrt{s}$ is the center-of-mass energy, and the asterisk denotes the e^+e^- rest frame. For signal decays, the $m_{\rm ES}$ distribution peaks near the B mass with a resolution of about 3.5 MeV/c^2 and ΔE peaks near 0 MeV with a resolution of about 50 MeV. Both $m_{\rm ES}$ and ΔE exhibit a lowside tail from energy leakage in the EMC. We require $5.2 < \mathrm{m_{ES}} < 5.3$ GeV/c^2 and $|\Delta\mathrm{E}| < 250$ MeV, which includes the signal region as well as a large "sideband" region for background estimation. We also require $|\cos\theta^*_B| < 0.9$, where θ^*_B is the angle of the B candidate with respect to the e^- momentum in the e^+e^- rest frame. Finally, for the subset of events with $m_{K^0_S\pi^0} < 1.1$ GeV/c^2, we require $|\cos\theta_{K^*}| < 0.9$, where θ_{K^*} is the angle between the K^0_S and the primary photon in the $K^0_S\pi^0$ rest frame (the "helicity" angle).

Event topology is exploited to further suppress the background from continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events. We calculate the ratio L_2/L_0 of two moments defined as $L_j \equiv \sum_i |\mathbf{p}^*_i||\cos\theta^*_i|^j$, where $\mathbf{p}^*_i$ is the momentum of particle i in the e^+e^- rest frame, θ^*_i is the angle between $\mathbf{p}^*_i$ and the thrust axis of the B candidate and the sum runs over all reconstructed particles except for the B candidate daughters. We require $L_2/L_0 < 0.55$, which suppresses the background by more than a factor 3 at the cost of approximately 10% signal efficiency. After all selections are applied the average candidate multiplicity in events with at least one candidate is approximately 1.1. We select the candidate with a reconstructed π^0 mass closest to the expected value and if ambiguity persists we select the candidate with K^0_S mass closest to the expected value.

Selected events are divided in events with $0.8 < m_{K^0_S\pi^0} < 1.0$ GeV/c^2, where signal decays are predominantly $B^0 \to K^{*0}\gamma$, and events with $1.1 < m_{K^0_S\pi^0} < 1.8$ GeV/c^2, where the contribution from $K^*(892)$ is small. In the data we find respectively 1469 and 2629 candidate events in these categories. The selection efficiency for $B^0 \to K^{*0}\gamma$, evaluated with simulated events, is approximately 16%. Using the current world average for the branching fraction [17] we expect 176 ± 18 signal events. Compared to our previous measurement [7] the current event selection is more effective in suppressing background from B decays, leading to a reduced systematic uncertainty from an eventual CPV asymmetry in the background without a significant loss in statistical sensitivity. The selection efficiency for $B^0 \to K^0_S\pi^0\gamma$ events with $1.1 < m_{K^0_S\pi^0} < 1.8$ GeV/c^2 is approximately 15%, but depends on the helicity structure. Besides the $K^*(892)$ the only observed $K\pi$ resonance in $B \to K\pi\gamma$ decays is the $K^*_2(1430)$. Using the world average for the $B^0 \to K^*_2(1430)^0\gamma$ branching fraction [18] we expect 24 ± 7 events. However, since upper bounds on other resonances are weak, the actual observed signal yield may be appreciably higher.

For each B candidate we examine the remaining tracks in the event to determine the decay vertex position and the flavor of $B_{\rm tag}$. Using a neural network based on kinematic and particle identification information [19] each event is assigned to one of seven mutually exclusive tagging categories, designed to combine flavor tags with similar performance and Δt resolution. We parametrize the performance of this algorithm in a data sample ($B_{\rm flav}$) of fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$ decays. The average effective tagging efficiency obtained from this sample is $Q = \sum_c \epsilon^c_S(1 - 2w^c)^2 = 0.305 \pm 0.004$, where ϵ^c_S and w^c are the efficiencies and mistag probabilities, respectively, for events tagged in category $c = 1, \ldots 7$.

The proper-time difference is extracted from the separation of the B_{CP} and $B_{\rm tag}$ decay vertices in a manner analogous to Ref. [20]. The $B_{\rm tag}$ vertex is reconstructed from the remaining charged particles in the event [16]. To reconstruct the B_{CP} vertex from the single K^0_S trajectory we exploit the knowledge of the average interaction point (IP), which is determined from the spatial distribution of vertices in two-track events and is calculated separately for each 10-minute period of data-taking. We compute Δt and its uncertainty from a geometric fit [21] to the $\Upsilon(4S) \to B^0\bar{B}^0$ system that takes this IP constraint into account. We further improve the Δt resolution by constraining the sum of the two B decay times ($t_{CP} + t_{\rm tag}$) to be equal to $2\tau_{B^0}$ with an uncertainty $\sqrt{2}\tau_{B^0}$. We have verified in a Monte-Carlo simulation that this procedure provides an unbiased estimate of Δt.

The per-event estimate of the uncertainty on Δt reflects the strong dependence of the Δt resolution on the K^0_S flight direction and on the number of SVT layers traversed by the K^0_S decay daughters. In about 70% of the events both pion tracks are reconstructed from at least 4 SVT hits, leading to sufficient resolution for the time-dependent measurement. The average Δt resolution in these events is about 1.1 ps. For events that fail this criterion or for which $\sigma(\Delta t) > 2.5$ ps or $|\Delta t| > 20$ ps, the Δt information is not used. However, these events still contribute to the measurement of $C_{K^{*0}\gamma}$, which can also be extracted from flavor-tagging information alone.

Signal yields and CPV asymmetries are extracted using an unbinned maximum-likelihood fit to $m_{\rm ES}$, ΔE, L_2/L_0, flavor-tag, Δt and $\sigma(\Delta t)$, as in Ref. [7]. For the analysis of the $B^0 \to K^{*0}\gamma$ sample $m_{K_S^0\pi^0}$ is also used in the fit. Because we expect a contribution from other B decays ("$B\bar{B}$ background"), we allow the fit to extract the fraction of such decays as well. We have verified using fits to simulated samples that the correlation between the observables is sufficiently small that the event likelihoods for signal $\mathcal{P}_S$, $B\bar{B}$ background $\mathcal{P}_{B\bar{B}}$ and continuum background $\mathcal{P}_{q\bar{q}}$ can be described by the product of one-dimensional probability density functions (PDF). The PDFs for signal events and $B\bar{B}$ background events are parametrized using either the $B_{\rm flav}$ sample (for the flavor-tag efficiency, mistag probabilities and Δt-resolution function) or simulated events. For the continuum background, we select the functional form of the PDFs in background-enhanced samples. We exploit the large fraction of background events in the final sample to extract the background parameters along with the physics measurements in the fit. The asymmetry in the rate of B^0 versus $\bar{B}^0$ tags in background events is also extracted from the fit.

The PDF for the Δt of signal events and $B\bar{B}$ background events is obtained from the convolution of Eq. (1) with a resolution function $\mathcal{R}(\delta t \equiv \Delta t - \Delta t_{\rm true}, \sigma_{\Delta t})$. The asymmetries $S_{B\bar{B}}$ and $C_{B\bar{B}}$ for the $B\bar{B}$ background are fixed to zero in the fit, but we account for a possible deviation from zero in the systematic uncertainty. The resolution function is parametrized as the sum of three Gaussian distributions [16]. The first two Gaussian distributions have a width proportional to the reconstructed $\sigma_{\Delta t}$ and a nonzero mean proportional to $\sigma_{\Delta t}$ to account for the small bias in Δt from charm decays on the $B_{\rm tag}$ side. The third distribution is centered at zero with a fixed width of 8 ps. We have verified in simulation that the parameters of $\mathcal{R}(\delta t, \sigma_{\Delta t})$ for $B^0 \to K_S^0\pi^0\gamma$ events are similar to those obtained from the $B_{\rm flav}$ sample, even though the distributions of $\sigma_{\Delta t}$ differ considerably. We therefore extract these parameters from a fit to the $B_{\rm flav}$ sample. We assume that the continuum background consists of prompt decays only and find that the Δt distribution is well described by a resolution function with the same functional form as used for signal events. The parameters of the background function are determined in the fit.

Figure 1 shows the background-subtracted distributions for $m_{\rm ES}$ and ΔE for the selected $B^0 \to K^{*0}\gamma$ candidates. The background subtraction is performed with the event weighting technique described in [22]. Events contribute according to a weight constructed from the covariance matrix for the signal, $B\bar{B}$ background and continuum background yields and the probability $\mathcal{P}_S$, $\mathcal{P}_{B\bar{B}}$ and $\mathcal{P}_{q\bar{q}}$ for the event, computed without the use of the variable that is being displayed. The curves in the figure represent the signal PDFs used in the fit. Figure 2 shows the background-subtracted distributions of Δt for B^0- and $\bar{B}^0$-tagged events, and the asymmetry as a function of Δt.

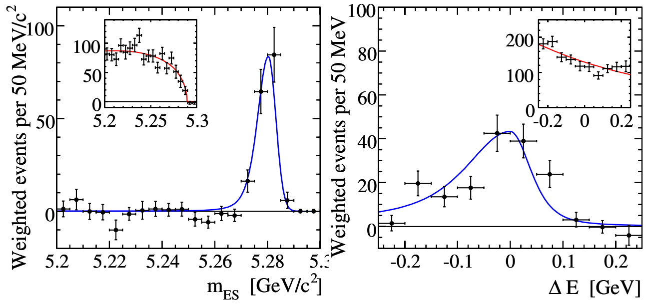

FIG. 1 (color online). Signal and background (inset) distributions for $m_{\rm ES}$ (left) and ΔE (right) for $0.8 < m_{K_S^0\pi^0} < 1.0\ {\rm GeV}/c^2$ obtained with the weighting technique described in the text. The curves represent the PDFs used in the fit, normalized to the fitted yield.

In the fit to the $B^0 \to K^{*0}\gamma$ sample we find 157 ± 16 signal events, with

$$S_{K^{*0}\gamma} = -0.21 \pm 0.40 \pm 0.05$$

and

$$C_{K^{*0}\gamma} = -0.40 \pm 0.23 \pm 0.03,$$

where the first error is statistical and the second systematic. The systematic uncertainties are described below. The linear correlation coefficient between $S_{K^{*0}\gamma}$ and $C_{K^{*0}\gamma}$ is 0.07. The value of $C_{K^{*0}\gamma}$ is consistent with the expectation of no direct CP violation. Since its uncertainty is much larger than that obtained from the partial rate asymmetry in self-tagging decays [14], we also perform the fit with $C_{K^{*0}\gamma}$

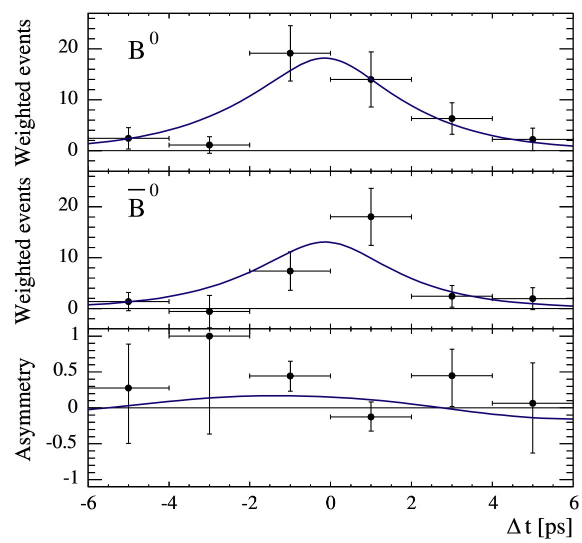

FIG. 2 (color online). Signal distribution for Δt, obtained with the weighting technique described in the text, with $B_{\rm tag}$ tagged as B^0 (top) or $\bar{B}^0$ (center), and the asymmetry (bottom). The curves represent the PDFs for signal decays in the likelihood fit, normalized to the final fit result.

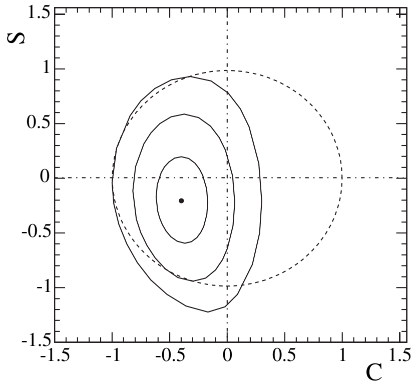

FIG. 3. Constant-likelihood contours in the *S*-*C* plane for $B^0 \to K^{*0}\gamma$ corresponding to $-2\Delta \log L = 1$, 2 and 3. The dashed circle is the physical boundary.

fixed to zero and find

$$S_{K^{*0}\gamma}(C \equiv 0) = -0.22 \pm 0.42 \pm 0.05.$$

The counterintuitive increase in the error on $S_{K^{*0}\gamma}$ is a consequence of the likelihood contours in the *S*-*C* plane, shown in Fig. 3, not being perfectly ellipsoidal.

Figure 4 shows the background-subtracted $K_S^0\pi^0$ invariant mass distribution for $B^0 \to K_S^0\pi^0\gamma$ candidates. The $K^*(892)$ resonance is clearly visible and there is some evidence for the $K_2^*(1430)$. Figure 5 shows the background-subtracted distributions for $m_{\rm ES}$ and ΔE events in the range $1.1 < m_{K_S^0\pi^0} < 1.8\ {\rm GeV}/c^2$. In the fit to this sample we find 59 ± 13 signal events with

$$S_{K_S^0\pi^0\gamma} = 0.9 \pm 1.0 \pm 0.2$$

and

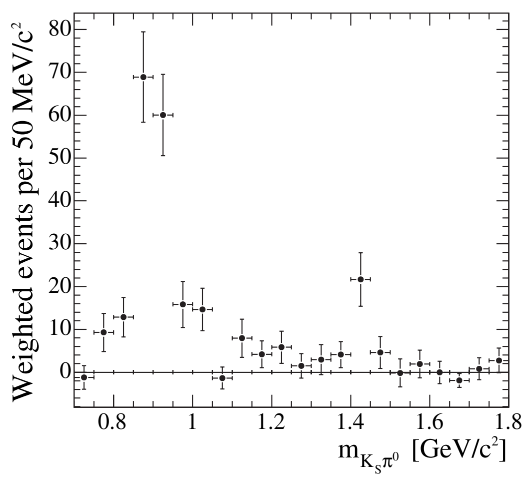

FIG. 4. Distribution for $m_{K_S^0\pi^0}$ obtained with the weighting technique described in the text. For events with $m_{K_S^0\pi^0} > 1.1\ {\rm GeV}/c^2$ the cut on the cosine of the helicity angle $\cos\theta_{K^*}$ is not applied.

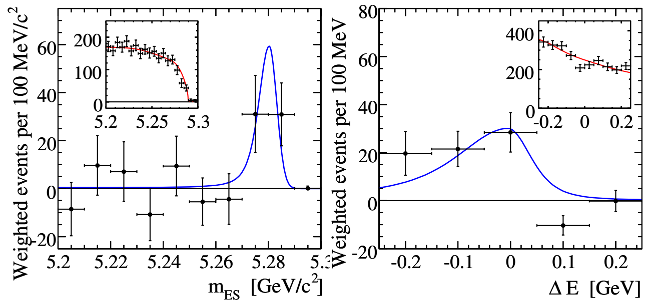

FIG. 5 (color online). Signal and background (inset) distributions for $m_{\rm ES}$ (left) and ΔE (right) for $1.1 < m_{K_S^0\pi^0} < 1.8\ {\rm GeV}/c^2$ obtained with the weighting technique described in the text. The curves represent the PDFs used in the fit, normalized to the fitted yield.

$$C_{K_S^0\pi^0\gamma} = -1.0 \pm 0.5 \pm 0.2.$$

The linear correlation coefficient between $S_{K_S^0\pi^0\gamma}$ and $C_{K_S^0\pi^0\gamma}$ is -0.09.

We consider several sources of systematic uncertainties related to the level and possible asymmetry of the background contribution from other *B* decays. We evaluate this contribution using simulated samples of generic *B* decays and of generic $B \to X_s\gamma$ decays. For the latter we use the Kagan-Neubert model [23] for the photon energy spectrum and JETSET for the fragmentation of the *s* quark. Since the final state multiplicity predicted by the fragmentation model is significantly different from a recent *BABAR* measurement [24], we reweight events according to their multiplicity. From these studies we estimate about 30 (140) events in the K^* (non-K^*) sample, with approximately equal contributions from $B \to X_s\gamma$ decays and other (generic) *B* decays. The $B\bar{B}$ background yields extracted for the fit to the data are 9 ± 13 and 130 ± 40 events, respectively. Although these agree with the expected yields, the latter are numerically larger. Therefore, we use the expected yields when evaluating the impact of a potential CPV asymmetry in the $B\bar{B}$ background. We vary $S_{B\bar{B}}$ and $C_{B\bar{B}}$ within an appropriate range that is derived from the composition of the $B\bar{B}$ background sample and assign a systematic uncertainty of 0.04 (0.03) on *S* (*C*) in the K^* sample and an uncertainty of 0.2 for both *S* and *C* in the non-K^* sample.

We quantify possible systematic effects due to the vertex reconstruction method in the same manner as in Ref. [20], estimating systematic uncertainties on *S* (*C*) of 0.023 (0.014) due to the vertex reconstruction technique and uncertainties in the resolution function, and 0.020 (0.007) due to possible misalignments of the SVT. Finally, we include a systematic uncertainty due to imperfect knowledge of the PDFs used in the fit, which amounts to 0.02 (0.01) for the K^* (non-K^*) sample.

In summary, we have performed a new measurement of the time-dependent CPV asymmetry in $B^0 \rightarrow K^{*0}\gamma$ decays. Within the large statistical uncertainties our measurement is consistent with the SM expectation of a small CPV asymmetry and with other measurements [8]. We have also explored the possibility of measuring the CPV asymmetry in the region with a $K_S^0\pi^0$ invariant mass above the K^{*0} region, $1.1 < m_{K_S^0\pi^0} < 1.8\ \mathrm{GeV}/c^2$. We find that the signal yield, though consistent with the expectation, is too small for a meaningful asymmetry measurement. These results supersede our previous measurement [7] which was based on a subset of the data presented here.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l'Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from CONACyT (Mexico), the A. P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.

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