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Observation of *CP* violation in $B^0 \to \eta' K^0$ Decays *

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Abstract

We present measurements of the time-dependent *CP*-violation parameters S and C in $B^0 \to \eta' K^0$

decays. The data sample corresponds to 384 million $B\overline{B}$ pairs produced by e^+e^- annihilation at the $\Upsilon(4S)$. The results are $S = 0.58 \pm 0.10 \pm 0.03$, and $C = -0.16 \pm 0.07 \pm 0.03$. We observe mixing-induced *CP* violation with a significance of 5.5 standard deviations in this $b \to s$ penguin dominated mode.

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Measurements of time-dependent *CP* asymmetries in B^0 meson decays through Cabibbo-Kobayashi-Maskawa (CKM) favored $b \to c\bar{c}s$ amplitudes [1] have provided crucial tests of the mechanism of *CP* violation in the Standard Model (SM) [2]. Decays of B^0 mesons to charmless hadronic final states such as $\eta' K^0$ proceed mostly via a single loop (penguin) amplitude. In the SM the penguin amplitude has approximately the same weak phase as the $b \to c\bar{c}s$ transition, but it is sensitive to the possible presence of new heavy particles in the loop [3]. The measurement of *CP* asymmetries in $B^0 \to \eta' K^0$ thus provides an important test for such effects.

Within the SM, CKM-suppressed amplitudes and multiple particles in the loop introduce additional weak phases whose contribution may not be negligible [4–7]. The time-dependent *CP*-violation parameter S (defined in Eq. 1 below) measured in the decay $B^0 \to \eta' K^0$ is compared with the value of $\sin 2\beta$ from measurements of time-dependent *CP* violation in B decays to states containing charmonium and a neutral kaon. The deviation $\Delta S = S - \sin 2\beta$ has been estimated in several theoretical approaches: QCD factorization (QCDF) [6, 8], QCDF with modeled rescattering [9], Soft Collinear Effective Theory [10], and SU(3) symmetry [4, 5, 11]. These models estimate $|\Delta S|$ to be of the order 0.01, and with uncertainties give bounds $|\Delta S| \lesssim 0.05$.

The time-dependent *CP* asymmetry in the decay $B^0 \to \eta' K^0_S$ has been measured previously by the BABAR [12] and Belle [13] Collaborations. In this Letter we update our previous measurements using an integrated luminosity of 349 fb^{-1}, corresponding to 384 ± 4 million $B\overline{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV). The data were collected with the BABAR detector [14] at the PEP-II asymmetric-energy e^+e^- collider. In addition to the $B^0 \to \eta' K^0_S$ decays used previously, we now also include the decay $B^0 \to \eta' K^0_L$.

Charged particles from e^+e^- interactions are detected, and their momenta measured, by a combination of five layers of double-sided silicon microstrip detectors and a 40-layer drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. Photons and electrons are identified with a CsI(Tl) electromagnetic calorimeter (EMC). Charged particle identification is provided by the average energy loss in the tracking devices and by an internally reflecting ring imaging Cherenkov detector covering the central region. The instrumented flux return (IFR) of the magnet allows the identification of muons and K^0_L mesons.

We reconstruct a B^0 decaying into the *CP* eigenstate $\eta' K^0_S$ or $\eta' K^0_L$ (B_{CP}). From the remaining particles in the event we also reconstruct the decay vertex of the other B meson ($B_{\rm tag}$) and identify its flavor. The difference $\Delta t \equiv t_{CP} - t_{\rm tag}$ of the proper decay times t_{CP} and $t_{\rm tag}$ of the *CP* and tag B mesons, respectively, is obtained from the measured distance between the B_{CP} and $B_{\rm tag}$ decay vertices and from the boost ($\beta\gamma = 0.56$) of the e^+e^- system. The Δt distribution is given by:

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \mp \Delta w \pm (1-2w)\left(-\eta S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t)\right)] \qquad (1)$$

where η is the *CP* eigenvalue of the final state (-1 for $\eta' K^0_S$, $+1$ for $\eta' K^0_L$). The upper (lower) sign denotes a decay accompanied by a B^0 ($\overline{B}^0$) tag, τ is the mean B^0 lifetime, Δm_d is the mixing frequency, and the mistag parameters w and Δw are the average and difference, respectively, of the probabilities that a true B^0 is incorrectly tagged as a $\overline{B}^0$ or vice versa. The tagging algorithm has six mutually exclusive tagging categories and a measured analyzing power of $(30.4 \pm 0.3)\%$ [15]. A non-zero value of the parameter C would indicate direct *CP* violation.

We establish the event selection criteria with the aid of a detailed Monte Carlo (MC) simulation of the B production and decay sequences, and of the detector response [16]. These criteria are designed to retain signal events with high efficiency while removing most of the background.

The B-daughter candidates are reconstructed through their decays $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ ($\eta_{\gamma\gamma}$), $\eta \to \pi^+\pi^-\pi^0$ ($\eta_{3\pi}$), $\eta' \to \eta_{\gamma\gamma}\pi^+\pi^-$ ($\eta'_{\eta(\gamma\gamma)\pi\pi}$), $\eta' \to \eta_{3\pi}\pi^+\pi^-$ ($\eta'_{\eta(3\pi)\pi\pi}$), $\eta' \to \rho^0\gamma$ ($\eta'_{\rho\gamma}$), where $\rho^0 \to \pi^+\pi^-$, $K^0_S \to \pi^+\pi^-$ ($K^0_{\pi^+\pi^-}$) or $\pi^0\pi^0$ ($K^0_{\pi^0\pi^0}$). Only the $\eta'_{\eta(\gamma\gamma)\pi\pi}$ mode is used for the $\eta' K^0_L$ sample. The requirements on the invariant masses of these particle combinations are the same as in our previous analysis [12]. The list of all decay modes used in the

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[§] Also with IPPP, Physics Department, Durham University, Durham DH1 3LE, United Kingdom current analysis can be seen in Table I. Signal K_L^0 candidates are reconstructed from clusters of energy deposited in the EMC or from hits in the IFR not associated with any charged track in the event [17]. From the cluster centroid and the B^0 decay vertex we determine the direction (but not the magnitude) of the K_L^0 momentum $\mathbf{p}_{K_L^0}$.

For $\eta' K_S^0$ decays we reconstruct the B-meson candidate by combining the four-momenta of the K_S^0 and η' with a vertex constraint. We also constrain the η, η', and π^0 masses to world-average values [18]. From the kinematics of $\Upsilon(4S)$ decays we determine the energy-substituted mass $m_{\rm ES} \equiv \sqrt{(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and the energy difference $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$, where $(E_0, \mathbf{p}_0)$ and $(E_B, \mathbf{p}_B)$ are the laboratory four-momenta of the $\Upsilon(4S)$ and the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. The resolution is 3 MeV in $m_{\rm ES}$ and $20-50$ MeV in ΔE, depending on the decay mode.

For $\eta' K_L^0$ candidates we obtain ΔE and $\mathbf{p}_{K_L^0}$ from a fit with the B^0 and K_L^0 masses constrained to world-average values [18]. To make a match with the measured K_L^0 direction we construct the missing momentum $\mathbf{p}_{\rm miss}$ from $\mathbf{p}_0$ and all charged tracks and neutral clusters other than the K_L^0 candidate. We then project $\mathbf{p}_{\rm miss}$ onto $\mathbf{p}_{K_L^0}$, and require the component perpendicular to the beam line, $p_{\rm miss\perp}^{\rm proj}$, to satisfy $p_{\rm miss\perp}^{\rm proj} - p_{K_L^0\perp} > -0.5$ GeV. This value was chosen to minimize the yield uncertainty in the presence of background.

For $\eta' K_S^0$ we require $5.25 < m_{\rm ES} < 5.29$ GeV and $|\Delta E| < 0.2$ GeV, for $\eta' K_L^0$ we require $-0.01 < \Delta E < 0.04$ GeV, and for all decays $|\Delta t| < 20$ ps, and, for the error on Δt, $\sigma_{\Delta t} < 2.5$ ps.

Background events arise primarily from random combinations of particles in continuum $e^+e^- \to q\bar{q}$ events ($q = u, d, s, c$). We reduce these with requirements on the angle $\theta_{\rm T}$ between the thrust axis of the B candidate in the $\Upsilon(4S)$ frame and that of the rest of the charged tracks and neutral calorimeter clusters in the event. In the fit we discriminate further against $q\bar{q}$ background with a Fisher discriminant $\mathcal{F}$ that combines several variables that characterize the production dynamics and energy flow in the event [19]. For the $\eta'_{\rho\gamma}$ decays we require $|\cos\theta_{\rm dec}^{\rho}| < 0.9$ to reduce the combinatorial background. Here $\theta_{\rm dec}^{\rho}$ is the angle between the momenta of the ρ^0 daughter π^- and of the η', measured in the ρ^0 rest frame.

For $B^0 \to \eta' K_L^0$ candidates we require that the cosine of the polar angle of the total missing momentum in the laboratory system be less than 0.95, to reject very forward $q\bar{q}$ jets. The purity of the K_L^0 candidates reconstructed in the EMC is further improved by a requirement on the output of a neural network (NN) that takes cluster-shape variables as inputs. The NN was trained on MC signal events and data events in the region $0.02 < \Delta E < 0.04$ GeV. We check the performance of the NN on data with K_L^0 candidates in the larger $B^0 \to J/\psi K_L^0$ data sample.

The average number of candidates found per selected event is between 1.08 and 1.32, depending on the final state. In the case of events with multiple candidates we choose the candidate with the smallest value of a χ^2 constructed from the deviations from expected values of one or more of the daughter resonance masses, or with the best decay vertex probability for the B, depending on the decay channel. Furthermore, in the $\eta' K_L^0$ sample, if several B candidates have the same vertex probability, we choose the candidate with the K_L^0 reconstructed from, in order, EMC and IFR, EMC only, or IFR only. From the simulation we find that this algorithm selects the correct-combination candidate in about two thirds of the events containing multiple candidates.

We obtain the common *CP*-violation parameters and signal yields for each channel from a maximum likelihood fit with the input observables ΔE, $m_{\rm ES}$, $\mathcal{F}$, and Δt. The selected sample sizes are given in the first column of Table I. We estimate from the simulation a contribution to the input sample of less than 1.1 % of background from other charmless B decay modes. These events have final states different from the signal, but similar kinematics, and exhibit broad peaks in the signal regions of some observables. We find that the $B\overline{B}$ background component is needed only for the channels with $\eta'_{\rho\gamma}$. We account for these with a separate component in the probability density function (PDF). For each component j (signal, $q\bar{q}$ combinatorial background, or $B\overline{B}$ background) and tagging category c, we define a total probability density function for event i as:

$$\mathcal{P}_{j,c}^{i} \equiv \mathcal{P}_j({m_{\rm ES}}^i) \cdot \mathcal{P}_j(\Delta E^i) \cdot \mathcal{P}_j(\mathcal{F}^i) \cdot \mathcal{P}_j(\Delta t^i, \sigma_{\Delta t}^i; c)\,, \tag{2}$$

except for $\eta' K_L^0$ for which $\mathcal{P}_j({m_{\rm ES}}^i)$ is omitted. The factored form of the PDF is a good approximation since linear correlations are small.

We write the extended likelihood function for all events of the decay mode d as

$$\mathcal{L}_d = \prod_c \exp\left(-n_c\right) \prod_i^{N_c} \left[\sum_j n_j f_{j,c} \mathcal{P}_{j,c}^i\right]\,, \tag{3}$$

where n_j is the yield of events of component j, $f_{j,c}$ is the fraction of events of component j for each category c, $n_c = n_{sig} f_{sig,c} + n_{q\bar{q}} f_{q\bar{q},c} + n_{B\bar{B}} f_{B\bar{B},c}$ is the number of events found by the fitter for category c, and N_c is the number of events of category c in the sample. When combining decay modes we form the grand likelihood $\mathcal{L} = \prod \mathcal{L}_d$. We fix both $f_{\mathrm{sig},c}$ and $f_{B\bar{B},c}$ to $f_{B_{\mathrm{flav}},c}$, the values measured with the large sample of fully reconstructed B^0 decays into flavor eigenstates (B_{flav} sample) [20].

The PDF $\mathcal{P}_{\mathrm{sig}}(\Delta t,\, \sigma_{\Delta t}; c)$, for each category c, is the convolution of $F(\Delta t;\, c)$ (Eq. 1) with the signal resolution function (sum of three Gaussians) determined from the B_{flav} sample. The other PDF forms are: the sum of two Gaussians for $\mathcal{P}_{\mathrm{sig}}(m_{\mathrm{ES}})$ and $\mathcal{P}_{\mathrm{sig}}(\Delta E)$; the sum of three Gaussians for $\mathcal{P}_{q\bar{q}}\ (\Delta t; c)$ and $\mathcal{P}_{B\overline{B}}(\Delta t; c)$; an asymmetric Gaussian with different widths below and above the peak for $\mathcal{P}_j(\mathcal{F})$ (a small "tail" Gaussian is added for $\mathcal{P}_{q\bar{q}}\ (\mathcal{F})$); a linear dependence for $\mathcal{P}_{q\bar{q}}\ (\Delta E)$ and a fourth-order polynomial for $\mathcal{P}_{B\overline{B}}(\Delta E)$; for $\mathcal{P}_{q\bar{q}}\ (m_{\mathrm{ES}})$ and $\mathcal{P}_{B\overline{B}}(m_{\mathrm{ES}})$ the function $x\sqrt{1-x^2}\exp\left[-\xi(1-x^2)\right]$, with $x \equiv 2m_{\mathrm{ES}}/\sqrt{s}$ and ξ a free parameter [21] and the same function plus a Gaussian, respectively.

For the signal and $B\overline{B}$ background components we determine the PDF parameters from simulation. We study large control samples of B decays to charm final states of similar topology to verify the simulated resolutions in ΔE and m_{ES}, adjusting the PDFs to account for any differences found. The $q\bar{q}$ background parameters are free to vary in the final fit. Thus, for the six channels listed in Table I, we perform a single fit with 93 free parameters: S, C, signal yields (6), $\eta'_{\rho\gamma}K^0$ $B\overline{B}$ background yields (2), continuum background yields (6) and fractions (30), background Δt, m_{ES}, ΔE, $\mathcal{F}$ PDF parameters (47). The parameters τ and Δm_d are fixed to world-average values [18].

We test and calibrate the fitting procedure by applying it to ensembles of simulated experiments with $q\bar{q}$ events drawn from the PDF into which we have embedded the expected number of signal and $B\overline{B}$ background events randomly extracted from the fully simulated MC samples. We find negligible bias for C. For S we find and apply multiplicative correction factors for bias from dilution due to cross-feed from $B\overline{B}$ background to signal events equal to 1.03 in the final states $\eta'_{\rho\gamma}K^0_{\pi^+\pi^-}$, $\eta'_{\eta(\gamma\gamma)\pi\pi}K^0_L$, and $\eta'_{\rho\gamma}K^0_{\pi^0\pi^0}$.

TABLE I: Results of the fits. Subscripts for η' decay modes denote $\eta'_{\eta(\gamma\gamma)\pi\pi}$ (1), $\eta'_{\rho\gamma}$ (2), and $\eta'_{\eta(3\pi)\pi\pi}$ (3).

Mode	# events	Signal yield	S	C
$\eta'_1K^0_{\pi^+\pi^-}$	664	224 ± 16	0.61 ± 0.23	-0.26 ± 0.14
$\eta'_2K^0_{\pi^+\pi^-}$	11943	566 ± 30	0.56 ± 0.14	-0.24 ± 0.10
$\eta'_3K^0_{\pi^+\pi^-}$	177	73 ± 9	0.89 ± 0.35	0.14 ± 0.25
$\eta'_1K^0_{\pi^0\pi^0}$	490	52 ± 9	0.84 ± 0.42	-0.26 ± 0.36
$\eta'_2K^0_{\pi^0\pi^0}$	13915	133 ± 24	0.56 ± 0.41	0.15 ± 0.27
$\eta'K^0_S$			0.62 ± 0.11	-0.18 ± 0.07
$\eta'_1K^0_L$	4199	204 ± 24	0.32 ± 0.28	0.08 ± 0.23
$\eta'K^0$			0.58 ± 0.10	-0.16 ± 0.07

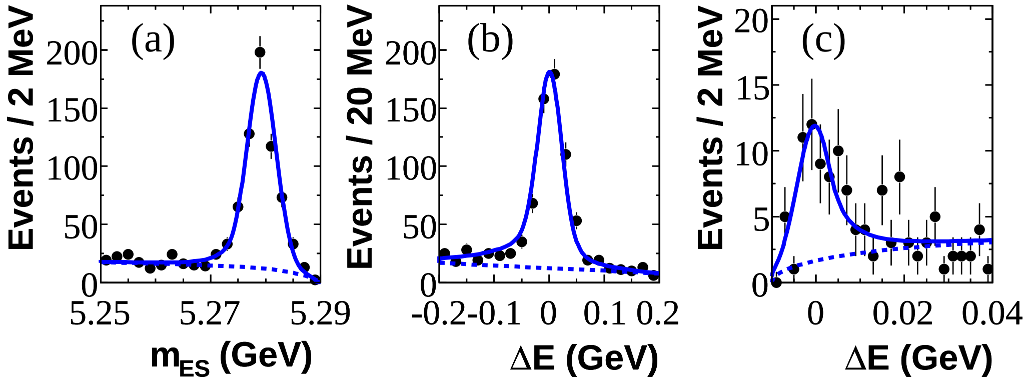

FIG. 1: Distributions projected (see text) onto (a) m_{ES} and (b) ΔE for $\eta'K^0_S$ candidates, and (c) ΔE for $\eta'K^0_L$ candidates. The solid lines shows the full fit result and the dashed lines show the background contributions.

Results from the fit for the signal yields and the CP parameters S and C are presented in Table I. In Fig. 1 we show the projections onto m_{ES} and ΔE for a subset of the data for which the ratio between the likelihood of signal events and the sum of likelihoods of signal and background events (computed without the variable plotted) exceeds a mode-dependent threshold that optimizes the sensitivity. In Fig. 2 we give the Δt and asymmetry projections of the events selected as for Fig. 1. We measure a correlation of 3.2% between S and C in the fit.

We perform several crosschecks of our analysis technique including time-dependent fits for B^+ decays to the charged final states $\eta'_{\eta(\gamma\gamma)\pi\pi}K^+$, $\eta'_{\rho\gamma}K^+$, and $\eta'_{\eta(3\pi)\pi\pi}K^+$; fits removing one fit variable at a time; fits without $B\overline{B}$ PDFs; fits with multiple $B\overline{B}$ components; fits allowing for non-zero CP information in $B\overline{B}$ events; fits with $C = 0$. In all cases, we find results consistent with expectation. The value $S = 0.62 \pm 0.11$ for $\eta' K^0_S$ differs from our previous measurement $S = 0.30 \pm 0.14$ [12] due to the improved event reconstruction and selection and to the additional data collected. The former contributes a change of 0.20, mostly due to events added or removed from the original dataset, which, based on simulation, is consistent with expectations for statistical fluctuations. The new data contributes the rest of the difference.

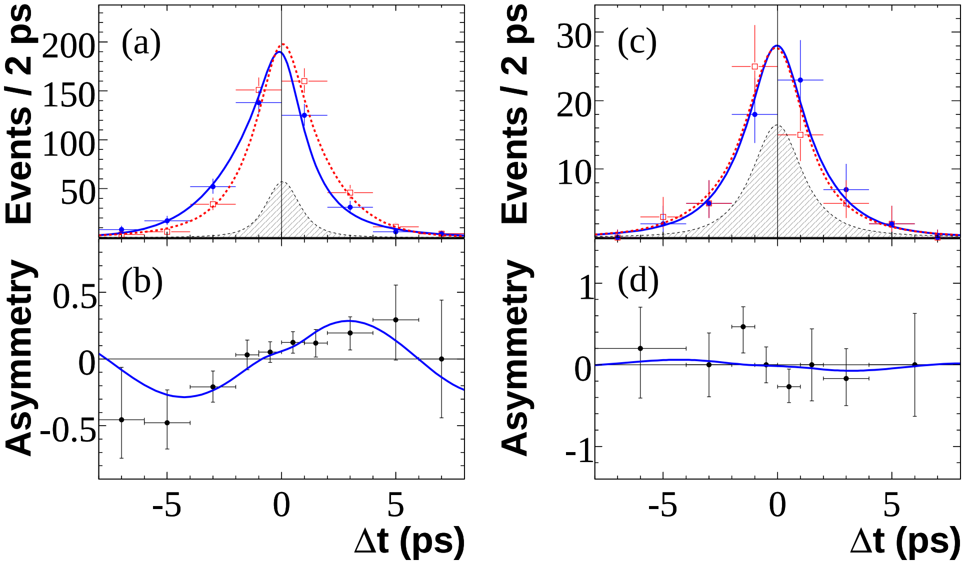

FIG. 2: Projections (see text) onto Δt for (a) $\eta' K^0_S$ and (c) $\eta' K^0_L$ of the data (points with error bars for B^0 tags in blue solid circles and $\overline{B}^0$ tags in red empty rectangles), fit function (blue solid and red dashed lines for B^0 and $\overline{B}^0$ tagged events, respectively), and background function (black shaded regions). We show the asymmetry between B^0 and $\overline{B}^0$ tags for (b) $\eta' K^0_S$ and (d) $\eta' K^0_L$; the lines represent the fit functions.

We have studied the systematic uncertainties arising from several sources (in decreasing order of magnitude): variation of the signal PDF shape parameters within their errors, modeling of the signal Δt distribution, use of Δt signal parameters from the $B_{\rm flav}$ sample, interference between the CKM-suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude and the favored $b \to c\bar{u}d$ amplitude for some tag-side B decays [22], $B\overline{B}$ background, SVT alignment, and position and size of the beam spot. The $B_{\rm flav}$ sample is used to determine the errors associated with the signal Δt resolutions, tagging efficiencies, and mistag rates. We take the uncertainties in τ_B and Δm_d from published measurements [18]. Summing all systematic errors in quadrature, we obtain 0.03 for S and 0.03 for C.

In conclusion, we have used a sample containing 1252 ± 50 flavor-tagged $\eta' K^0$ events to measure the time-dependent CP violation parameters, $S = 0.58 \pm 0.10 \pm 0.03$ and $C = -0.16 \pm 0.07 \pm 0.03$. This sample is 2.1 times as large as that of our previous measurement [12]. Our result for S is consistent with the world average of sin2β measured in $B^0 \to J/\psi K^0_S$ [18]. We observe mixing-induced CP violation in B^0 decays to $\eta' K^0$ with a significance (systematic uncertainties included) of 5.5 standard deviations. Our result for direct-CP violation is 2.1 standard deviations from zero.

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[1] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002); Belle Collaboration, K. Abe *et al.*, Phys. Rev. D **66**, 071102(R) (2002).
[2] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
[3] Y. Grossman and M. P. Worah, Phys. Lett. B **395**, 241 (1997); D. Atwood and A. Soni, Phys. Lett. B **405**, 150 (1997); M. Ciuchini *et al.*, Phys. Rev. Lett. **79**, 978 (1997).

[4] Y. Grossman *et al.*, Phys. Rev. D **68**, 015004 (2003).
[5] C.-W. Chiang *et al.*, Phys. Rev. D **68**, 074012 (2003); M. Gronau *et al.*, Phys. Lett. B **596**, 107 (2004).
[6] M. Beneke and M. Neubert, Nucl. Phys. B **675**, 333 (2003).
[7] D. London and A. Soni, Phys. Lett. B **407**, 61 (1997).
[8] M. Beneke, Phys. Lett. B **620**, 143 (2005); G. Buchalla *et al.*, JHEP **0509**, 074 (2005).
[9] H. Y. Cheng *et al.*, Phys. Rev. D **72**, 014006 (2005), Phys. Rev. D **71**, 014030 (2005); S. Fajfer *et al.*, Phys. Rev. D **72**, 114001 (2005).
[10] A. R. Williamson and J. Zupan, Phys. Rev. D **74**, 014003 (2006).
[11] M. Gronau *et al.*, arXiv:hep-ph/0608085, 2006.
[12] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **94**, 191802 (2005).
[13] Belle Collaboration, K. Abe *et al.*, Phys. Rev. D **72**, 012004 (2005).
[14] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instr. Meth. A **479**, 1 (2002).
[15] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **94**, 161803 (2005).
[16] S. Agostinelli *et al.*, Nucl. Instr. Meth. A **506**, 250 (2003).
[17] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **66**, 032003 (2002).
[18] Particle Data Group, Y.-M. Yao *et al.*, J. Phys. **G33**, 1 (2006).
[19] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **92**, 061801 (2004).
[20] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **66**, 032003 (2002).
[21] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **241**, 278 (1990).
[22] O. Long *et al.*, Phys. Rev. D **68**, 034010 (2003).