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Rare *B* Decays with the *BaBar* Detector

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for the *BaBar* Collaboration

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Rare B Decays with the *BABAR* Detector

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Abstract

The *BABAR* detector at SLAC's PEP-II storage ring collected a luminosity equivalent data of about 22 fb^{-1} at the $\Upsilon(4\mathrm{S})$ resonance during 1999 and 2000. Results on branching fractions of rare and charmless B-meson decays and first fits for direct CP violation are presented.

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1 *B*-decay reconstruction

The data was collected with the *BABAR* detector [1] at the PEP-II asymmetric e^+e^- collider [2] located at the Stanford Linear Accelerator Center. The results presented in this paper are based on data taken in the 1999–2000 run. An integrated luminosity of 20.7 fb^{-1} was recorded corresponding to 22.7 million $B\overline{B}$ pairs at the $\Upsilon(4S)$ resonance ("on-resonance") and 2.6 fb^{-1} about 40 MeV below this energy ("off-resonance").

The asymmetric beam configuration in the laboratory frame provides a boost to the $\Upsilon(4S)$ increasing the momentum range of the B-meson decay products up to 4.3 GeV/c. Charged particles are detected and their momenta are measured by a combination of a silicon vertex tracker (SVT) consisting of five double-sided layers and a 40-layer central drift chamber (DCH), both operating in a 1.5 T solenoidal magnetic field. With the SVT, a position resolution of about 15 μm at 90^o incident angle is achieved for the highest momentum charged particles near the interaction point, allowing the determination of the z-coordinate of decay vertices with a precision of about 70 μm. The SVT is the primary detection device for low momentum charged particles. The tracking system covers 92% of the solid angle in the center-of-mass system. The track finding efficiency is, on average, $(98\pm1)\%$ for momenta above 0.2 GeV/c and polar angle greater than 0.5 rad. The relative p_t resolution above 1 GeV/c particle momentum is $\sigma(p_t)/p_t = 0.13 \cdot p_t(\mathrm{Gev/c})\% + 0.45\%$. Photons are detected by a CsI electromagnetic calorimeter (EMC), which provides excellent angular and energy resolution with high efficiency. We reconstruct π^0 mesons as pairs of photons with a minimum energy deposition of 30 MeV. The typical width of the reconstructed π^0 mass is 7 MeV/c^2.

Charged particle identification is provided by the average energy loss (dE/dx) in the tracking devices and by an unique, internally reflecting ring imaging Cherenkov detector (DIRC) covering the central region. A Cherenkov angle K–π separation of better than 4σ is achieved for tracks below 3 GeV/c momentum, decreasing to 2.5σ at the highest momenta in our final states. This allows kaon identification with an efficiency of better than 90% and pion misidentification of about 2% for momenta below 3 GeV/c. The primary sources of information used in lepton identification in addition to the calorimeter is the muon system, which is the Instrumented Flux Return (IFR) consisting of resistive plate chambers interleaved with iron plates. There are 19 layers in the central region of the detector and 18 in the endcap regions. The resolution of the reconstructed $J/\Psi \to e^+e^-/\mu^+\mu^-$ signals is better than 8 MeV.

The B-meson candidates are kinematically identified using two independent variables [1],

$$\Delta E = (E_i E_B - \mathbf{p}_i \cdot \mathbf{p}_B - s/2)/\sqrt{s} \tag{1}$$

and the energy-substituted mass

$$m_{\mathrm{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}, \tag{2}$$

where $\sqrt{s}$ is the total e^+e^- CM energy. The initial state four-momentum $(E_i, \mathbf{p}_i)$ derived from the beam kinematics and the four-momentum $(E_B, \mathbf{p}_B)$ of the reconstructed B candidate are all defined in the laboratory. The calculation of m_{ES} only involves the three-momenta of the decay products, and is therefore independent of the masses assigned to them. For signal events ΔE peaks at zero and $m_{\rm ES}$ at the B mass. The initial selection of rare signals typically requires $|\Delta E| < 0.2$ GeV and $m_{\rm ES} > 5.2$ GeV/c^2.

Rare hadronic modes suffer from large backgrounds due to random combinations of tracks produced in the quark-antiquark ($q\bar{q}$) continuum. The distinguishing feature of such backgrounds is their characteristic event shape resulting from the two-jet production mechanism. A quantity that characterizes the event shape is the angle between the thrust axis of the B candidate and the thrust axis of the rest of the event where the thrust axis is defined as the axis that maximizes the sum of the magnitudes of the longitudinal momenta. This angle is small for continuum events, where the B-candidate daughters tend to lie in the $q\bar{q}$ jets, and uniformly distributed for true $B\overline{B}$ events.

2 Determination of $\sin 2\beta$ from angular analyses

The decay $B^0 \to J/\Psi K^{*0}$ [3] with $K^{*0} \to K^0_S\pi^0$ allows a measurement of the CP-violation parameter $\sin 2\beta$ that is theoretically as clean as for $B^0 \to J/\Psi K^0_S$ [4]. However, due to the presence of even ($L = 0, 2$) and odd ($L = 1$) orbital angular momenta in the $J/\Psi K^*$ final state, there can be CP-even and CP-odd contributions to the decay rate. If the information contained in the decay angles is ignored, the measured time-dependent CP asymmetry is reduced by the dilution factor $D_\perp = 1 - 2R_\perp$, where $R_\perp$ is the fraction of P-wave. If the angular information is used, the CP components can be separated [6].

The decay $B^0 \to J/\Psi K^{*0}(892)$ is described by three amplitudes. In the transversity basis [6] the amplitudes $A_\parallel$, A_0 and $A_\perp$ have CP eigenvalues $+1, +1$ and -1, respectively. A_0 corresponds to longitudinal polarization, and $A_\parallel$ and $A_\perp$ respectively to parallel and perpendicular transverse polarizations, of the vector mesons; $R_\perp$ is defined as $|A_\perp|^2$. For a $\Delta I = 0$ transition, all $K^* \to K\pi$ channels involve the same amplitudes, and so the data for the different decay modes $K^0_S\pi^0$, $K^+\pi^-$, $K^0_S\pi^+$, and $K^+\pi^0$ can be combined for this study (941 events) (see Fig. 1).

Although the $K\pi$ mass distribution for $B^0 \to J\Psi(K\pi)$ is dominated by the $K^*(892)$, a significant number of candidates are at higher mass with a clear peak at ~ 1.4 GeV/c^2 ($K^*_0(1430)$ and $K^*_2(1430)$). The amount of S-wave in the $K^*(892)$ region has been estimated to be (1.2 ± 0.7) by including a scalar term in the total amplitude. The P-wave fraction is $R_\perp = (16.0 \pm 3.2 \pm 1.4)\%$ and the longitudinal polarization fraction $(59.7 \pm 2.8 \pm 2.4)\%$. If $\sin 2\beta$ were measured in the $B^0 \to J/\Psi(K^0_S\pi^0)$ channel from the decay-time information only, the value of the dilution from the present measurement, $D_\perp = 0.68 \pm 0.07$, would contribute a 10% uncertainty. The measurement of the relative phase $\phi_\parallel = arg(A_\parallel/A_0)$ of neither 0 nor π, $\phi_\parallel = 2.50 \pm 0.20 \pm 0.08$ radians, favors a departure from the factorization hypothesis.

The time-dependent CP-violating asymmetries in the decays of the type $B \to D^{(*)}\bar{D}^{(*)}$ are complementary measurements of $\sin 2\beta$ in $B^0 \to J/\Psi K^{(*)0}$ [5]. As above, in the vector-vector decay $B^0 \to D^{*+}D^{*-}$ a time-dependent angular analysis of the decay products [6] is necessary. The D^{*+} mesons are reconstructed in their decays $D^{*+} \to D^0\pi^+$ and $D^{*+} \to D^+\pi^0$. For this analysis the decay combinations $D^{*+}D^{*-}$ decaying to ($D^0\pi^+$, $\bar{D}^0\pi^-$)

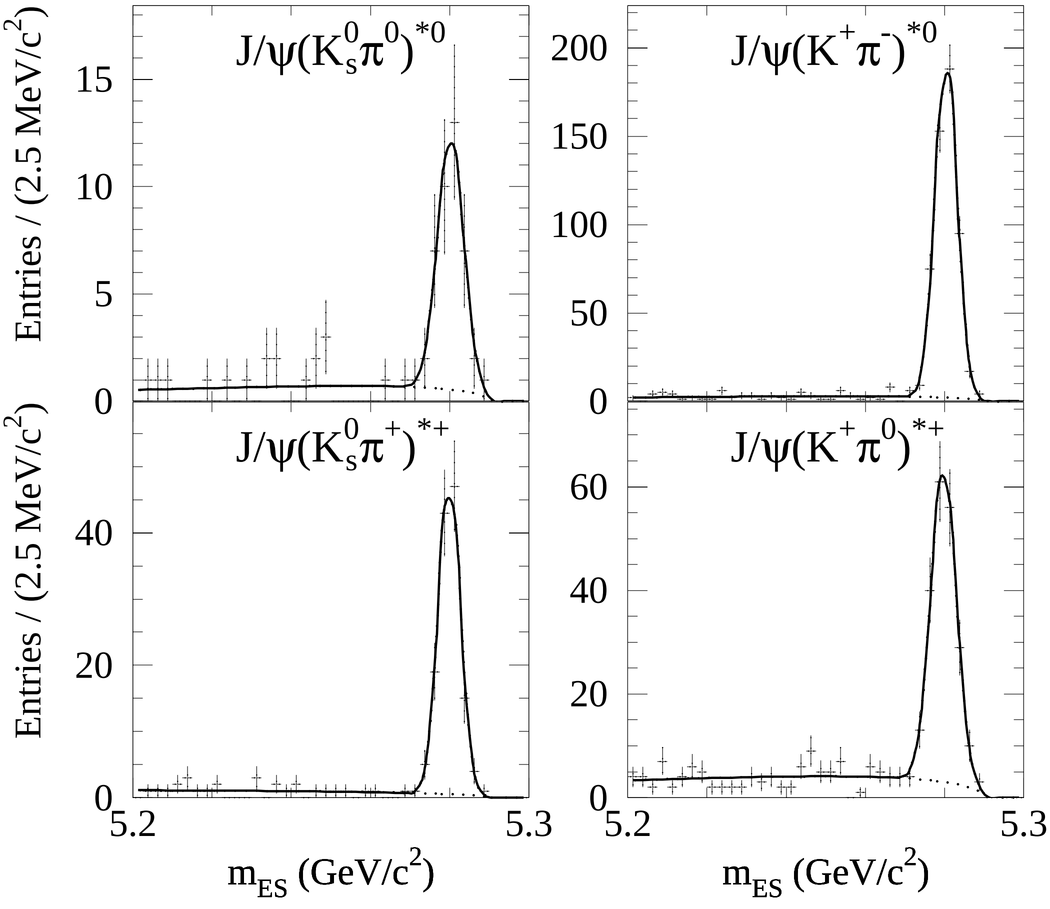

Figure 1: *Beam-energy substituted mass spectra for the four $K\pi$ modes in the decay $B \rightarrow J/\Psi K^*$. The curves show likelihood fits to the data.*

or ($D^0\pi^+$, $D^-\pi^0$) are included, but not ($D^+\pi^0$, $D^-\pi^0$) due to the smaller branching fraction and larger expected backgrounds. A total of 38 events is located in the signal region. The estimated number of background events in the same region is $6.24\pm0.33(stat)\pm0.36(syst)$ yielding the preliminary branching fraction $BF(B^0 \rightarrow D^{*+}D^{*-} = (8.0 \pm 1.6(stat) \pm 1.2(syst)) \times 10^{-4}$.

3 Charmless two-body decays

Measurements of the rates and charge asymmetries for B decays into the charmless final states $\pi\pi$ and $K\pi$ [7] can be used to constrain the angles α and γ of the Unitarity Triangle. B-meson candidates are reconstructed in several two-body decays. All charged tracks (except K^0_S decay products) are required to have a polar angle, θ, within the tracking fiducial region $0.41 < \theta < 2.54$ rad and a Cherenkov angle, θ_c, measurement from the DIRC with a minimum of six photons above background, where the average is approximately 30 for both pions and kaons. The efficiency of requiring a θ_c measurement is 91% per track, and 97% of such tracks satisfy the minimum photon requirement. Tracks with a θ_c within $3\,\sigma$ of the expected value for a proton are rejected. Electrons are rejected based on specific ionization (dE/dx) in the DCH system, shower shape in the EMC, and the ratio of shower energy to track momentum. Signal yields n are determined from an unbinned maximum likelihood fit that uses m_{ES}, ΔE, $\mathcal{F}$, and θ_c (where applicable). The θ_c PDFs are derived from a control sample of approximately 42 000 $D^{*+} \rightarrow D^0\pi^+$ ($D^0 \rightarrow K^-\pi^+$) decays. The achieved separation in the Cherenkov angle is demonstrated in Fig. 2.

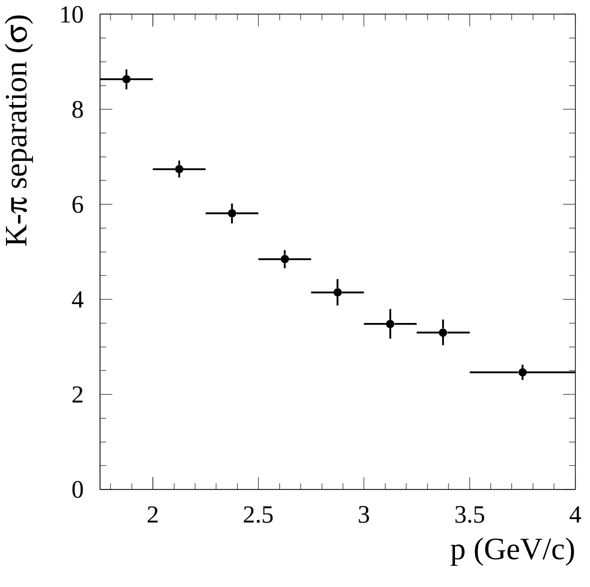

Figure 2: The K–π separation, in units of standard deviations, as a function of momentum, derived from the Cherenkov angle measurements of kaon and pion tracks in a $D^{*+} \rightarrow D^0\pi^+$ control sample.

For the $K^\pm\pi^\mp$, $\pi^\pm\pi^0$, $K^\pm\pi^0$, $K^0_S\pi^\pm$, and $K^0_SK^\pm$ terms, the yields n are rewritten in terms of the sum $n_f + n_{\bar{f}}$ and the asymmetry $\mathcal{A} = (n_{\bar{f}} - n_f)/(n_{\bar{f}} + n_f)$, where n_f ($n_{\bar{f}}$) is the fitted number of events in the mode $B \rightarrow f$ ($\bar{B} \rightarrow \bar{f}$). The largest source of systematic error is the uncertainty in the PDF shapes, except in $B^+ \to K^+\pi^0$ where it is due to the 5% uncertainty on π^0 reconstruction efficiency. Systematic errors due to PDF shapes are estimated either by varying the parameters within one standard deviation, or by substituting alternative parameter sets. Results are summarized in Table 1.

Table 1: *Summary of two-body decay results for statistical significances (S), measured branching fractions (BF), and charge asymmetries $\mathcal{A}$. The 90% confidence level (C.L.) intervals for the $\mathcal{A}$ include the systematic uncertainties, which have been added in quadrature with the statistical errors.*

Mode	S (σ)	$BF(10^{-6})$	$\mathcal{A}$	$\mathcal{A}$ 90% C.L.
$\pi^+\pi^-$	4.7	$4.1 \pm 1.0 \pm 0.7$		
$K^+\pi^-$	15.8	$16.7 \pm 1.6 \pm 1.3$	$-0.19 \pm 0.10 \pm 0.03$	$[-0.35, -0.03]$
K^+K^-	1.3	< 2.5 (90% C.L.)		
$\pi^+\pi^0$	3.4	< 9.6 (90% C.L.)		
$K^+\pi^0$	8.0	$10.8^{+2.1}_{-1.9} \pm 1.0$	$0.00 \pm 0.18 \pm 0.04$	$[-0.30, +0.30]$
$K^0\pi^+$	9.8	$18.2^{+3.3}_{-3.0} \pm 2.0$	$-0.21 \pm 0.18 \pm 0.03$	$[-0.51, +0.09]$
$\bar{K}^0K^+$	–	< 2.4 (90% C.L.)		
$K^0\pi^0$	4.5	$8.2^{+3.1}_{-2.7} \pm 1.2$		

4 Gluonic penguins ($B \to \phi K$)

Decays into final states containing a ϕ [8] meson are dominated by $b \to s(d)\bar{s}s$ penguins, with gluonic and electroweak contributions, while other Standard Model contributions are highly suppressed [9]. These modes thus provide a direct measurement of the penguin process, with potential benefits to estimates of direct CP violation. They also allow an independent measurement of $\sin 2\beta$. Comparison of the value of $\sin 2\beta$ obtained from these modes with that from charmonium modes, as well as various tests of isospin relationships, can probe for new physics participating in penguin loops.

The ϕ candidates are formed from pairs of tracks with opposite charge from a common vertex (see Fig. 3). Both decay daughters are required to be kaon candidates based on dE/dX and Cherenkov detector information. The invariant mass for the K^+K^- pair must lie within 30 MeV/c^2 of the ϕ mass. The ϕ-mass resolution is 1.1 MeV/c^2. The reconstructed recoil partner of the ϕ is either K^0_S, K^+ or π^+ ($K-\pi$ separation using the Cherenkov angle), or $K^*(892)$ decaying into $K^+\pi^0$, $K^0_S\pi^+$ or $K^+\pi^-$. In the ϕK final states the angle between one ϕ resonance-daughter direction and the parent B direction in the resonance rest frame follows a $\cos^2$ distribution because of angular momentum conservation. The continuum background distribution in that variable follows a low-degree polynomial, and hence can be distinguished. In the ϕK^* decays the distribution of this helicity angle is the result of an *a priori* unknown superposition of transverse and longitudinal polarizations and is averaged accordingly.

The agreement between the branching fractions of charged and neutral modes as summarized

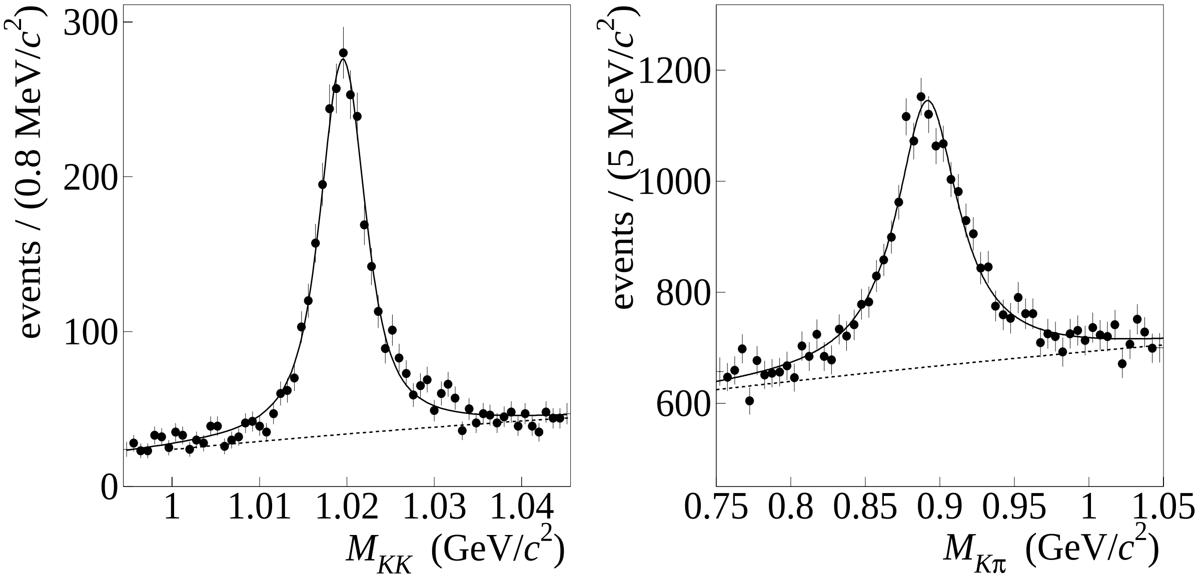

Figure 3: The two-kaon invariant mass in the ϕ signal region (left). Superimposed to the data is the fit to a relativistic P-wave Breit-Wigner for the ϕ convoluted with a Gaussian on top of a polynomial background. The mass resolution is 1.1 MeV/c^2. The plot to the right shows a Breit-Wigner fit to the $K^0\pi^+$ invariant mass in the K^{*+} signal region. Both fits use Breit-Wigner parameters from Ref. [10].

Table 2: *Measurements of $\phi K^{(*)}$ branching fractions (statistical significance given in brackets).*

$BF(B^+ \to \phi K^+)$	=	$7.7^{+1.6}_{-1.4} \pm 0.8$	(10.5)
$BF(B^0 \to \phi K^0)$	=	$8.1^{+3.1}_{-2.5} \pm 0.8$	(6.4)
$BF(B^+ \to \phi K^{*+})$	=	$9.7^{+4.2}_{-3.4} \pm 1.7$	(4.5)
$BF(B^+ \to \phi(K^{*+} \to K^+\pi^0))$	=	$12.8^{+7.7}_{-6.1} \pm 3.2$	(2.7)
$BF(B^+ \to \phi(K^{*+} \to K^0\pi^+)$	=	$8.0^{+5.0}_{-3.7} \pm 1.3$	(3.6)
$BF(B^0 \to \phi(K^{*0} \to K^+\pi^-)$	=	$8.7^{+2.5}_{-2.1} \pm 1.1$	(7.5)
$BF(B^+ \to \phi\pi^+)$	=	< 1.4 (90% CL)	(0.6)

in Table 2 is in accordance with isospin invariance under the assumption of penguin diagram dominance. The decay $B^+ \to \phi\pi^+$ has both CKM and color suppression relative to ϕK^+ and is therefore not expected to be observed in the present data sample.

5 Radiative penguins ($B \rightarrow K^*\gamma$)

In the Standard Model (SM) the exclusive decay $B \rightarrow K^*\gamma$ proceeds by the electromagnetic loop "penguin" transition $b \rightarrow s\gamma$. The calculation of the exclusive rate $BF(B \rightarrow K^*\gamma)$ in that model is an ongoing challenge [11]. Extended SM diagrams can interfere with the SM diagram to cause CP-violating charge asymmetries at a level as high as 20% [12] - from the SM alone the asymmetry is expected to be $< 1\%$.

For the reconstruction a high energy photon candidate in the electromagnetic calorimeter is required. It must have an energy between 1.5 GeV and 4.5 GeV in the laboratory frame (2.3 GeV to 2.85 GeV in the $\Upsilon(4S)$ rest frame). The electromagnetic shower must be localized in a polar angle θ region of good calorimetry ($-0.74 < \cos\theta < 0.93$) and be isolated by 5 crystals from other showers or charged track entries. The lateral shower profile has to be consistent with a photon shower. Combinations with other photons in a π^0 and η mass window are excluded. The K^* is reconstructed from K^+, K^0_S, π^- and π^0 candidates in four modes yielding the following combined branching fractions: $BF(B^\pm \rightarrow K^{*\pm}\gamma) = (3.92 \pm 0.62 \pm 0.21) \times 10^{-5}$ and $BF(B^0 \rightarrow K^{*0}\gamma) = (4.23 \pm 0.40 \pm 0.22) \times 10^{-5}$. The weighted average of the CP-violating charge asymmetries is $\mathcal{A}(B \rightarrow K^*\gamma) = -0.044 \pm 0.076 \pm 0.012$, and at 90% confidence level: $-0.170 < \mathcal{A} < 0.082$. Its systematic uncertainty due to possible detector effects is estimated from independent datasets to be less than 2%.

6 Outlook

The *BABAR* experiment surpassed the design luminosity of $3 \times 10^{33}/cm^2s$ and intends to accumulate about 100 fb^{-1} until end of 2002. This will turn many more rare B-decay channels into potential probes for CP violation.

7 Acknowledgement

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References

[1] *BABAR* Collaboration, B. Aubert *et al.*, SLAC-PUB-8569 (hep-ex/0105044), submitted to Nucl. Instrum. and Methods.

[2] PEP-II Conceptual Design Report, SLAC-R-418 (1993).

[3] B. Aubert et al. (*BABAR* Collaboration), SLAC-PUB-8898 (hep-ex/0107049), submitted to Phys.Rev.Lett.

[4] I. I. Bigi *et al.*, in CP Violation, C. Jarlskog, Editor, World Scientific, Singapore (1987); Y. Nir and H. R. Quinn, Phys. Rev. D **42**, 1473 (1990).

[5] B. Aubert et al. (*BABAR* Collaboration), SLAC-PUB-8925 (hep-ex/0107057)

[6] I. Dunietz *et al.*, Phys. Rev. D **43**, 2193 (1991); A.S. Dighe, I. Dunietz, H.J. Lipkin and J.L. Rosner, Phys. Lett. B**369**, 144 (1996).

[7] B. Aubert et al. (*BABAR* Collaboration), SLAC-PUB-8838 (hep-ex/0105061), submitted to Phys.Rev.Lett.

[8] B. Aubert et al. (*BABAR* Collaboration), SLAC-PUB-8823 (hep-ex/0105001), submitted to Phys.Rev.Lett.

[9] N.G. Deshpande and J. Trampetic, Phys. Rev. D **41**, 895 (1990); N.G. Deshpande and X.-G. He, Phys. Lett. B **336**, 471 (1994); R. Fleischer, Z. Phys. C **62**, 81 (1994).

[10] Particle Data Group, D.E. Groom *et al.*, Eur. Phys. J. C **15**, 1 (2000).

[11] Beneke, Feldman and Seidel, hep-ph/0106067; Bosch and Buchalla, hep-ph/0106081; Ligeti and Wise, hep-ph/9905277.

[12] A.Kagan and M.Neubert, Phys. Rev. D **58**, 094912 (1998).