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Branching Fractions and CP Asymmetries in $B^0 \to \pi^0\pi^0$, $B^+ \to \pi^+\pi^0$ and $B^+ \to K^+\pi^0$ Decays and Isospin Analysis of the $B \to \pi\pi$ System

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Based on a sample of 227 million $B\overline{B}$ pairs collected by the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC, we measure the branching fraction $\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$, and the asymmetry $C_{\pi^0\pi^0} = -0.12 \pm 0.56 \pm 0.06$. The $B^0 \to \pi^0\pi^0$ signal has a significance of 5.0σ. We also measure $\mathcal{B}(B^+ \to \pi^+\pi^0) = (5.8 \pm 0.6 \pm 0.4) \times 10^{-6}$, $\mathcal{B}(B^+ \to K^+\pi^0) = (12.0 \pm 0.7 \pm 0.6) \times 10^{-6}$, and the charge asymmetries $\mathcal{A}_{\pi^+\pi^0} = -0.01 \pm 0.10 \pm 0.02$ and $\mathcal{A}_{K^+\pi^0} = 0.06 \pm 0.06 \pm 0.01$. Using isospin relations we find an upper bound on the angle difference $|\alpha - \alpha_{\rm eff}|$ of $35^{\rm o}$ at the 90% C.L.

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In the Standard Model (SM), the Cabibbo-Kobayashi-Maskawa (CKM) matrix $V_{qq'}$ [1] describes the charged-current couplings in the quark sector. The Unitarity Triangle is a useful representation of relations between CKM matrix elements, and measurements of its sides and angles provide a stringent test of the SM. Following the success in measuring the CKM angle β [2], an important challenge for the B Factories is the determination of the remaining angles. The extraction of the CKM angle $\alpha \equiv \arg\left[-V_{\rm td}V_{\rm tb}^*/V_{\rm ud}V_{\rm ub}^*\right]$ from the time-dependent *CP*-violating asymmetry in the $B^0 \to \pi^+\pi^-$ decay mode [3] is complicated by the interference of competing amplitudes ("tree" and "penguin") with different weak phases. The difference between α and $\alpha_{\rm eff}$, where $\alpha_{\rm eff}$ is derived from the time-dependent $B^0 \to \pi^+\pi^-$ *CP* asymmetry, may be evaluated using the isospin-related decays $B^0 \to \pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ [4]. Here and throughout this Letter, charge conjugate reactions are included implicitly. For $B^0 \to \pi^0\pi^0$ the asymmetry may deviate from zero if the tree and penguin amplitudes have different weak and strong phases. In the SM the decay $B^+ \to \pi^+\pi^0$ is governed by a pure tree amplitude since penguin diagrams cannot contribute to the $I = 2$ final state; as a result no charge asymmetry is expected. The $B \to K\pi$ system is a rich source of information on the understanding of *CP* violation, as has been illustrated by the recent observation of direct *CP* asymmetry in $B^0 \to K^+\pi^-$ decays [5]. Both the rate and asymmetry of the $B^+ \to K^+\pi^0$ decay may be used to extract constraints on penguin contributions to the $B \to K\pi$ amplitudes [6].

In this Letter, we report a constraint on $\delta_{\pi\pi} \equiv \alpha_{\rm eff} - \alpha$, using the measurement of the asymmetry $C_{\pi^0\pi^0}$ and updated measurements of the branching fractions for $B^0 \to \pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ and the charge asymmetry $\mathcal{A}_{\pi^+\pi^0}$. We also measure the branching fraction for the $B^+ \to K^+\pi^0$ decay and its charge asymmetry $\mathcal{A}_{K^+\pi^0}$. The asymmetry $C_{\pi^0\pi^0}$ is defined as $(|A_{00}|^2 - |\overline{A}_{00}|^2)/(|A_{00}|^2 + |\overline{A}_{00}|^2)$, where A_{00} ($\overline{A}_{00}$) is the $B^0(\overline{B}^0) \to \pi^0\pi^0$ decay amplitude. For $B^\pm$ modes, the *CP*-violating charge asymmetry is defined as $\mathcal{A} = (|\overline{A}|^2 - |A|^2)/(|\overline{A}|^2 + |A|^2)$, where A ($\overline{A}$) is the B^+ (B^-) decay amplitude. This study is based on 227×10^6 $\Upsilon(4S) \to B\overline{B}$ decays (on-resonance), collected with the *BABAR* detector. We also use $16\,{\rm fb}^{-1}$ of data recorded 40 MeV below the $B\overline{B}$ production threshold (off-resonance).

The *BABAR* detector is described in Ref. [7]. The primary components used in this analysis are a tracking system consisting of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) surrounded by a 1.5 T solenoidal magnet, an electromagnetic calorimeter (EMC) comprising 6580 CsI(Tl) crystals, and a ring imaging Cherenkov counter (DIRC).

Candidate π^0 mesons are reconstructed as pairs of photons, spatially separated in the EMC, with an invariant mass $m_{\gamma\gamma}$ satisfying $110 < m_{\gamma\gamma} < 160\,{\rm MeV}/c^2$. The mass resolution is 8 ${\rm MeV}/c^2$ for high energy (above 2 GeV) π^0's [7]. Photon candidates are required to be consistent with the expected lateral shower shape, not to be matched to a track, and to have a minimum energy of 30 MeV. To reduce the background from false π^0 candidates, the angle θ_γ between the photon momentum vector in the π^0 rest frame and the π^0 flight direction is required to satisfy $|\cos\theta_\gamma| < 0.95$. Candidate tracks are required to be within the tracking fiducial volume, to originate from the interaction point, to consist of at least 12 DCH hits, and to be associated with at least 6 Cherenkov photons in the DIRC.

B meson candidates are reconstructed by combining a π^0 with a charged pion or kaon (h^+) or by combining two π^0 mesons. Two variables, used to isolate the $B^0 \to \pi^0\pi^0$ and $B^+ \to h^+\pi^0$ signal events, take advantage of the kinematic constraints of B mesons produced at the $\Upsilon(4S)$. The first is the beam-energy-substituted mass $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, where $(E_i, \mathbf{p}_i)$ is the four-momentum of the initial e^+e^- system, $\mathbf{p}_B$ is the B candidate momentum, both measured in the laboratory frame, and $\sqrt{s}$ is the e^+e^- center-of-mass (CM) energy. The second variable is $\Delta E = E_B - \sqrt{s}/2$, where E_B is the B candidate energy in the CM frame. The ΔE resolution for signal is approximately 80 MeV for $B^0 \to \pi^0\pi^0$, and 40 MeV for $B^+ \to h^+\pi^0$.

The primary source of background is $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) events where a π^0 or h^+ from each jet randomly combine to mimic a B decay. This jet-like $q\overline{q}$ background is suppressed by requiring that the angle θ_S between the sphericity axis of the B candidate and that of the remaining tracks and photons in the event, in the CM frame, satisfy $|\cos\theta_S| < 0.7\,(0.8)$ for $B^0 \to \pi^0\pi^0$ ($B^+ \to h^+\pi^0$).

The other sources of background are B decays to final states containing one vector meson and one pseudoscalar meson, where one pion is produced almost at rest in the B rest frame and the remaining decay products match the kinematics of a $B^0 \to \pi^0\pi^0$ or $B^+ \to h^+\pi^0$ decay.

For the $B^0 \to \pi^0\pi^0$ analysis we restrict the $m_{\rm ES}$-ΔE plane to the region with $m_{\rm ES} > 5.2\,{\rm GeV}/c^2$ and $|\Delta E| < 0.4$ GeV. For the on-resonance sample we define the signal region as the band in the plane with $|\Delta E| < 0.2\,{\rm GeV}$ and the sideband region as the rest of the plane excluding the region which is also populated with $B^+ \to \rho^+\pi^0$ events. The entire plane for the off-resonance data and the sideband region for the on-resonance data are kept in the fit in order to constrain the $q\overline{q}$ background parameters. $B^+ \to h^+\pi^0$ candidates are selected in the region with $m_{\rm ES} > 5.22\,{\rm GeV}/c^2$ and $-0.11 < \Delta E < 0.15\,{\rm GeV}$.

For $B^0 \to \pi^0\pi^0$ candidates, the other tracks and clusters in the event are used to determine whether the other B meson ($B_{\rm tag}$) decays as a B^0 or $\overline{B}^0$ (flavor tag). We use a multivariate technique [8] to determine the flavor of the $B_{\rm tag}$ meson. Events are assigned to one of several mutually exclusive categories based on the estimated mistag probability and on the source of tagging information.

The number of signal B candidates is determined with an extended, unbinned maximum-likelihood fit. The probability density function (PDF) $\mathcal{P}_i\left(\vec{x}_j;\vec{\alpha}_i\right)$ for a signal or background hypothesis is the product of PDFs for the variables $\vec{x}_j$ given the set of parameters $\vec{\alpha}_i$. The likelihood function is a product over the N events of the M signal and background hypotheses:

$$\mathcal{L} = \exp\left(-\sum_{k=1}^{M} n_k\right)\prod_{j=1}^{N}\left[\sum_{i=1}^{M} c_{ij}\mathcal{P}_i\left(\vec{x}_j;\vec{\alpha}_i\right)\right]. \qquad (1)$$

For $B^0 \to \pi^0\pi^0$ the coefficients c_{ij} are defined as $c_{ij} = \frac{1}{2}(1 - s_j A_i)n_i$, where s_j refers to the sign of the flavor tag of the other B in the event j and is zero for untagged events. The fit parameters n_i and A_i are the number of events and raw asymmetry for $B^0 \to \pi^0\pi^0$ signal, $B^+ \to \rho^+\pi^0$ background, and continuum background components. The average of branching fraction measurements [9] is used to fix $n(B^+ \to \rho^+\pi^0)$ to 32 ± 6. The raw asymmetry for signal is $(1-2\chi)(1-2\omega)C_{\pi^0\pi^0}$, where $\chi = 0.186 \pm 0.004$ [10] is the neutral B mixing probability, and ω is the mistag probability.

For $B^+ \to h^+\pi^0$ the probability coefficients are $c_{ij} = \frac{1}{2}(1-q_j\mathcal{A}_i)n_i$, where q_j is the charge of the track h in the event j. The fit parameters n_i and $\mathcal{A}_i$ are the number of events and asymmetry for $B^+ \to \pi^+\pi^0$ and $B^+ \to K^+\pi^0$ signal, continuum, and B background components. The B background yields are fixed to the expected number of events using the current world averages of branching ratios [11], which are 18 ± 4 for $B^0 \to \rho^+\pi^-$ and $B^+ \to \rho^+\pi^0$ combined, and 3 ± 1 events for $B^0 \to \rho^- K^+$. Uncertainties on these numbers are dominated by the uncertainty on selection efficiencies, due to the sensitivity to the tight requirement in ΔE.

The variables $\vec{x}_j$ used for $B^0 \to \pi^0\pi^0$ are $m_{\rm ES}$, ΔE, and a Fisher discriminant F. The Fisher discriminant is an optimized linear combination of $\sum_i p_i$ and $\sum_i p_i \cos^2\theta_i$, where p_i is the momentum and θ_i is the angle with respect to the thrust axis of the B candidate, both in the CM frame, for all tracks and neutral clusters not used to reconstruct the B meson. For both the $B^0 \to \pi^0\pi^0$ signal and the $B^+ \to \rho^+\pi^0$ background the $m_{\rm ES}$ and ΔE variables are correlated and therefore a two-dimensional PDF from a smoothed, simulated distribution is used. For the continuum background, the $m_{\rm ES}$ distribution is modeled as a threshold function [12], and the ΔE distribution as a second-order polynomial. The PDF for the F variable is modeled as a parametric step function (PSF) [13] for all event components. A PSF is a variable width binned distribution whose parameters are the heights of each bin. The limits of the ten bins F PSF are chosen so that each bin contains 10% of the signal sample. For $B^0 \to \pi^0\pi^0$ and $B^+ \to \rho^+\pi^0$ the F PSF parameters are correlated with the flavor tagging, and the PSF parameters are different for each tagging category. Simulated events are used to determine the PSF distributions for both $B^0 \to \pi^0\pi^0$ and $B^+ \to \rho^+\pi^0$. For $q\overline{q}$ background, the F PSF parameters are free in the fit.

An additional discriminating variable for $B^+ \to h^+\pi^0$ is the Cherenkov angle θ_c of the h^+ track. The PDF parameters for $m_{\rm ES}$, ΔE, θ_c, and F for the background are determined using the data, while the PDFs for signal are found from a combination of simulated events and data. The $m_{\rm ES}$ and ΔE distributions for $q\overline{q}$ events are treated as in the $B^0 \to \pi^0\pi^0$ case, with parameters allowed to vary freely in the fit. For the signal, the $m_{\rm ES}$ and ΔE distributions are both modeled as a Gaussian distribution with a low-side power law tail whose parameters are determined from simulation. The means of the Gaussian components are determined from the fit to the $B^+ \to h^+\pi^0$ sample and their values used to tune the π^0 energy scale in the $B^0 \to \pi^0\pi^0$ analysis. The mean of ΔE for the $B^+ \to K^+\pi^0$ mode is a function of the kaon laboratory momentum, since a pion mass hypothesis is used. The distribution of F is modeled as a Gaussian function with an asymmetric variance for the signal, whose parameters are obtained from simulation, and as a double Gaussian for the continuum background, whose parameters are determined in the likelihood fit. The difference of the measured and expected values of θ_c for the pion or kaon hypothesis, divided by the uncertainty on θ_c, is modeled as a double Gaussian function, whose parameters are obtained from a control sample of kaon and pion tracks, from $D^{*+} \to D^0\pi^+\,, D^0 \to K^-\pi^+$ decays.

The result of the maximum-likelihood fit for $B^0 \to \pi^0\pi^0$ is $n(B^0 \to \pi^0\pi^0) = 61 \pm 17$ (see Table I), with a corresponding statistical significance of 5.2σ. The asymmetry is $C_{\pi^0\pi^0} = -0.12 \pm 0.56$. Shown in Fig. 1 are distributions of $m_{\rm ES}$ and F, for signal-enriched samples of

TABLE I: The results for the modes $B^0 \to \pi^0\pi^0$ and $B^+ \to h^+\pi^0$ are summarized. For each mode, the sample size N, number of signal events N_S, total detection efficiency ε, branching fraction $\mathcal{B}$, asymmetry $\mathcal{A}$ or $C_{\pi^0\pi^0}$, and the 90% confidence interval for the asymmetry are shown. For $C_{\pi^0\pi^0}$ the confidence interval is obtained inferring minimum coverage inside the physical region $[-1, 1]$. The first errors are statistical, the second systematic, with the exception of ε whose error is purely systematic.

Mode	N	N_S	ε (%)	$\mathcal{B}(10^{-6})$	Asymmetry	(90% C.L.)
$B^0 \to \pi^0\pi^0$	8153	61 ± 17	23.5 ± 1.4	$1.17 \pm 0.32 \pm 0.10$	$-0.12 \pm 0.56 \pm 0.06$	$[-0.88, 0.64]$
$B^+ \to \pi^+\pi^0$	29950	379 ± 41	28.7 ± 1.1	$5.8 \pm 0.6 \pm 0.4$	$-0.01 \pm 0.10 \pm 0.02$	$[-0.19, 0.21]$
$B^+ \to K^+\pi^0$	13165	682 ± 39	25.0 ± 1.0	$12.0 \pm 0.7 \pm 0.6$	$0.06 \pm 0.06 \pm 0.01$	$[-0.06, 0.18]$

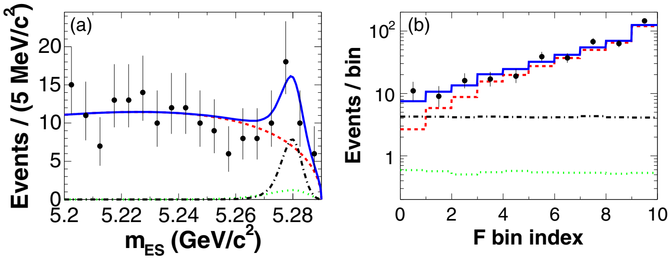

FIG. 1: Distributions and PDF projections for $B^0 \to \pi^0\pi^0$. Shown are $m_{\rm ES}$ (a) and F (b) for candidates that satisfy an optimized requirement on the signal probability, based on all variables except the one being plotted. PDF projections are shown as a dashed line for $q\overline{q}$ background, a dotted line for B background, and a dashed-dotted line for signal.

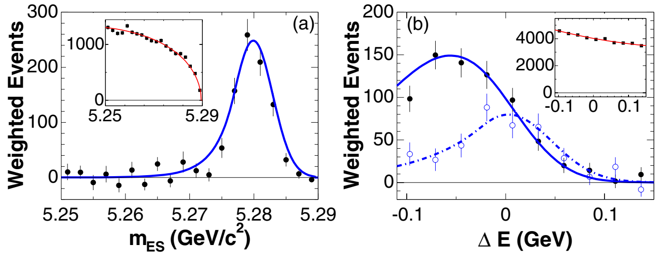

FIG. 2: Distributions and PDF projections for $B^+ \to h^+\pi^0$, using the method described in the text. For $m_{\rm ES}$ (a) the signal distributions are combined, while for ΔE (b) the signal $B^+ \to \pi^+\pi^0$ (open circles and dashed-dotted curve) and $B^+ \to K^+\pi^0$ (solid circles and curve) are shown separately. The insets show the combined background components.

$B^0 \to \pi^0\pi^0$ candidates. The projections contain 25% and 68% of the signal, 14% and 17% of the $\rho^+\pi^0$ background, and 2.2% and 4.4% of the continuum background, for $m_{\rm ES}$ and F respectively.

With changes in the analysis technique to measure the *CP* asymmetry, we now find 44 ± 13 signal events in the first 123 million $B\overline{B}$ events, compared to 46 ± 13 found in Ref. [13]. The additional 104 million $B\overline{B}$ events dataset has a signal of 17 ± 11. The signal rates in these two subsets agree at the 1.3σ level. This result also reflects an improved understanding of high energy π^0 detection efficiency. Using a sample of π^0 mesons from $\tau^+ \to \pi^+\pi^0\nu_\tau$ decays we apply a π^0 efficiency correction of 0.99 ± 0.03 to our GEANT simulation, compared to a correction of 0.88 ± 0.08 applied in Ref. [13].

For $B^+ \to h^+\pi^0$ the likelihood fit results are summarized in Table I. Using the event-weighting technique described in Ref. [14] we show signal and background projections in Fig. 2. For each event, a weight to be signal or background is assigned based on a fit performed without the specific variable that is plotted. The resulting distributions are normalized to the event yields, and are compared to the PDFs used in the full fit.

Systematic uncertainties on the event yields and *CP* asymmetries are evaluated on data control samples, or by varying the fixed parameters and refitting the data. In order of decreasing importance, the dominant systematics on the $B^0 \to \pi^0\pi^0$ branching fraction arise from the uncertainty on the ΔE resolution, the efficiency of the π^0 reconstruction, and the uncertainty on B background event yields. The significance of the $B^0 \to \pi^0\pi^0$ signal yield, taking systematic effects into account, is 5.0σ. The systematic uncertainty on $C_{\pi^0\pi^0}$ is dominated by the uncertainties on the B background asymmetry and tagging efficiency.

For $B^+ \to h^+\pi^0$ the dominant systematic uncertainties arise from the F signal PDF parameters, selection efficiencies, and the ΔE resolution. Additional systematics arise from uncertainties on the B background event yields and particle identification. The systematic uncertainty on the charge asymmetries is dominated by the 1% upper limit on the charge bias in the detector [15].

To extract information on $\delta_{\pi\pi}$ we use the isospin relations [4] in conjunction with *BABAR* measurements of $C_{\pi^+\pi^-} = -0.09 \pm 0.15 \pm 0.04$ [3], the branching fraction $\mathcal{B}(B^0 \to \pi^+\pi^-) = (4.7 \pm 0.6 \pm 0.2) \times 10^{-6}$ [16], the $B^0 \to \pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ decay rates and the $C_{\pi^0\pi^0}$ values reported here. We scan over all values of $|\delta_{\pi\pi}|$ and calculate a χ^2 for the decay amplitudes using the method described in Ref. [17]. The χ^2 is converted into a confidence level shown in Fig. 3, from which we derive an upper bound on $|\delta_{\pi\pi}|$ of 35° at the 90% C.L.

In summary, we observe $61 \pm 17 \pm 5$ $B^0 \to \pi^0\pi^0$ events with a significance of 5.0σ including systematic uncertainties. This corresponds to a branching fraction of $\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$, where the first error is statistical and the second is systematic. We measure the asymmetry $C_{\pi^0\pi^0} = -0.12 \pm 0.56 \pm 0.06$. We report branching fractions $\mathcal{B}(B^+ \to \pi^+\pi^0) = (5.8 \pm 0.6 \pm 0.4) \times 10^{-6}$ and $\mathcal{B}(B^+ \to K^+\pi^0) = (12.0 \pm 0.7 \pm$

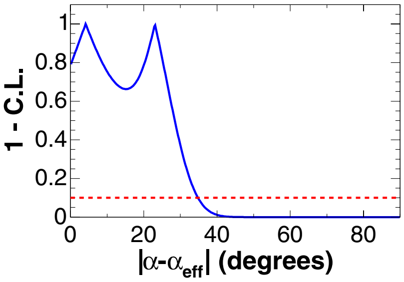

FIG. 3: Constraints on the $|\delta_{\pi\pi}|$ in terms of confidence level. We find an upper bound on $|\delta_{\pi\pi}|$ of 35° at the 90% C.L.

0.6) $\times\ 10^{-6}$. The charge asymmetries are $\mathcal{A}_{\pi^+\pi^0} = -0.01 \pm 0.10 \pm 0.02$ and $\mathcal{A}_{K^+\pi^0} = 0.06 \pm 0.06 \pm 0.01$; we find no evidence for *CP* violation. In contrast to the recent measurements of charge asymmetry in $B^0 \to K^+\pi^-$ decays [5], the $\mathcal{A}_{K^+\pi^0}$ value reported here is compatible with zero. We use isospin relations on $B \to \pi\pi$ decay rates and asymmetries to find an upper bound of $|\delta_{\pi\pi}| < 35^{\circ}$ at the 90% C.L.

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[1] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002); Belle Collaboration, K. Abe *et al.*, Phys. Rev. D **66**, 071102 (2002).

[3] *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0408089; Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **93**, 021601 (2004).

[4] M. Gronau and D. London, Phys. Rev. Lett. **65**, 3381 (1990).

[5] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **93**, 131801 (2004); Belle Collaboration, Y. Chao *et al.*, Phys. Rev. Lett. **93**, 191802 (2004).

[6] M. Gronau and J.L. Rosner, Phys. Rev. D **59**, 113002 (1999); H.J. Lipkin, Phys. Lett. B **445**, 403 (1999); J. Matías, Phys. Lett. B **520**, 131 (2001).

[7] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instrum. Methods **A479**, 1 (2002).

[8] *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0408127, submitted to Phys. Rev. Lett.

[9] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **93**, 051802 (2004); Belle Collaboration, J. Zhang *et al.*, hep-ex/0406006 to be published in Phys. Rev. Lett.

[10] Particle Data Group, S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).

[11] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **91**, 201802 (2003); Belle Collaboration, A. Gordon *et al.*, Phys. Lett. B **542**, 183 (2002); CLEO Collaboration, C.P. Jessop *et al.*, Phys. Rev. Lett. **85**, 2881 (2000).

[12] ARGUS Collaboration, H. Albrecht *et al.*, Z. Phys. C **48**, 543 (1990).

[13] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **91**, 241801 (2003); *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **91**, 021801 (2003).

[14] M. Pivk and F. Le Diberder, physics/0402083.

[15] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **65**, 051101 (2002).

[16] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 281802 (2002).

[17] J. Charles *et al.*, hep-ph/0406184, submitted to Eur. Phys. Jour. C .