CHARM DECAYS, MIXING AND VILATION AT THE B FACTORIES *

Nicola Neri
(representing the BaBar collaboration)
Università di Pisa and INFN Sezione di Pisa
Largo B. Pontecorvo, 3 - 56127, Pisa - Italy

Abstract

Flavor oscillation in D^0-$\overline{D}^0$ system is predicted to be of order of percent or less in the Standard Model (SM), while *CP* violation is predicted to be of order $10^{-5} \div 10^{-3}$, and therefore not measurable with the current data sample. Evidence of *CP* violation with present statistics would constitute evidence of New Physics as long as a measurement of the mixing parameters x and y, not consistent with the SM predictions. We report on recent results from *BABAR* and *BELLE* experiments of D^0-$\overline{D}^0$ mixing and *CP* violation measurements in D^0 decays for the most sensitive analyses: time dependent analysis of $D^0 \rightarrow K^+\pi^-$ wrong sign decays, the measurement of the ratio of lifetimes of the decays $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ relative to $D^0 \rightarrow K^-\pi^+$, search for mixing in semileptonic decays $D^0 \rightarrow K^{(*)}l\nu$ where $l = e, \mu$. New limits on *CP*-violating time-integrated asymmetries in two body decays $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$ and in three body decays $D^0 \rightarrow K^+K^-\pi^0$, $D^0 \rightarrow \pi^+\pi^-\pi^0$ are also discussed. The analyses presented are based on 384 fb^{-1} data for the *BABAR* experiment and on $400 \div 500$ fb^{-1} data for the *BELLE* experiment. Data have been collected with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC and with the *BELLE* detector at the KEKB asymmetric-energy B Factory at KEK.

---

*Work supported by Università di Pisa and INFN. Also supported by U.S. Department of Energy and SLAC, Stanford University.

1 Introduction

B Factories are ideal laborarories [1, 2] to study charm physics which represents an important part of their scientific program. The main topics of charm physics are: D^0-$\overline{D}^0$ mixing and CP violation (CPV), search for rare charm decays, Dalitz plot analysis and charm spectroscopy. In the following we will focus on D^0-$\overline{D}^0$ mixing and CPV.

D^0-$\overline{D}^0$ oscillations can be explained by the fact that the effective Hamiltonian which determines the time-evolution of the neutral D meson system is not diagonal in the $|D^0\rangle$, $|\overline{D}^0\rangle$ flavor defined base. The eigenstates of the effective Hamiltonian, $|D_{1,2}\rangle$, are therefore a linear combination of $|D^0\rangle$ and $|\overline{D}^0\rangle$:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \qquad \text{with} \quad |p|^2 + |q|^2 = 1. \tag{1}$$

If CP is conserved, then $q/p = 1$ and the physical states are CP eigenstates.

The mixing parameters x and y are defined as

$$x \equiv \frac{m_1 - m_2}{\overline{\Gamma}}, \ y \equiv \frac{\Gamma_1 - \Gamma_2}{2\overline{\Gamma}}, \tag{2}$$

where $m_{1,2}$ and $\Gamma_{1,2}$ are the mass and the width values for the effective Hamiltonian eigenistates and $\overline{\Gamma} = (\Gamma_1 + \Gamma_2)/2$.

The effects of CPV in D^0-$\overline{D}^0$ mixing can be parameterized in terms of the quantities

$$r_m \equiv \left|\frac{q}{p}\right| \text{ and } \varphi_f \equiv \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right), \tag{3}$$

where $A_f \equiv \langle f|\mathcal{H}_D|D^0\rangle$ ($\bar{A}_f \equiv \langle f|\mathcal{H}_D|\overline{D}^0\rangle$) is the amplitude for D^0 ($\overline{D}^0$) to decay into a final state f, and $\mathcal{H}_D$ is the Hamiltonian for the decay. A value of $r_m \neq 1$ would indicate CPV in mixing. A non-zero value of φ_f would indicate CPV in the interference of mixing and decay.

In the SM D^0-$\overline{D}^0$ oscillations are predicted to proceed quite slowly. The short distance contributions to D^0-$\overline{D}^0$ mixing from the SM box diagrams are expected to be very small [3, 4]. Long-distance effects from intermediate states coupling to both D^0 and $\overline{D}^0$ are expected to contribute, but are difficult to estimate precisely [5].

Within the SM, CPV is also expected to be small in the D^0-$\overline{D}^0$ system. An observation of CPV in D^0-$\overline{D}^0$ mixing with the present experimental sensitivity would be evidence for physics beyond the SM [6].

Recent results from *BABAR* [7] and *BELLE* [8] show an evidence of D^0-$\overline{D}^0$ oscillation at 3.9σ and 3.2σ level respectively. At this level of precision the measurements are compatibles with the predicted values from SM and put significant constraints on New Physics models [4, 9].

2 Selection of signal events

Signal events are selected via the cascade decay $D^{*+} \to D^0\pi_s^+$ [1], and the flavor of the D meson is identified at production by the charge of the soft pion (π_s). The difference of the reconstructed D^{*+} and D^0 masses (Δm), which has an experimental resolution at the level of $\simeq 350\,\mathrm{keV}/c^2$, is used to remove background events by requiring typically to be less than $1\,\mathrm{MeV}/c^2$ from the expected value, $145.5\,\mathrm{MeV}/c^2$ [10]. In order to reject background events with D^0 candidates from B meson decays, the momentum of the D^0, evaluated in the center-of-mass (CM) of the e^+e^- system, is required to be greater than $2.4-2.5\,\mathrm{GeV}/c$ for most of the analyses. The D^0 proper-time, t, is determined in a vertex constrained combined fit to the D^0 production and decay vertices. In this fit the D^0 and the π_s tracks are imposed to originate from the e^+e^- luminous region. The average error on the proper time, $\sigma_t \sim 0.2\,\mathrm{ps}$, is comparable with half of the D^0 lifetime [10]. Particle identification algorithms are used to identify the charged tracks from D^0 decays.

3 Time Dependent measurements for mixing and CP violation

3.1 Wrong-sign decays $\boldsymbol{D^0 \to K^+\pi^-}$

The final wrong sign (WS) state can be produced via the doubly Cabibbo-suppressed (DCS) decay or via mixing followed by the Cabibbo-favored (CF) decay $D^0 \to \overline{D}^0 \to K^+\pi^-$. The time dependence of the WS decay of a meson produced as a D^0 at time $t=0$ in the limit of small mixing ($|x|$, $|y| \ll 1$) and *CP* conservation can be approximated as

$$\frac{T_{\mathrm{WS}}(t)}{e^{-\overline{\Gamma}t}} \propto R_{\mathrm{D}} + \sqrt{R_{\mathrm{D}}}y'\,\overline{\Gamma}t + \frac{x'^2+y'^2}{4}(\overline{\Gamma}t)^2\,, \tag{4}$$

where R_{D} is the ratio of doubly Cabibbo-suppressed to Cabibbo-favored (CF) decay rates, $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$, $y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$, and $\delta_{K\pi}$ is the strong phase between the DCS and CF amplitudes.

The time dependence of the WS decays is used to separate the contribution of DCS decays from that of D^0-$\overline{D}^0$ mixing. The mixing parameters are determined by an unbinned extended maximum-likelihood fit to the reconstructed D^0 invariant mass m_{D^0}, Δm, t, σ_t variables for WS decays.

The *BABAR* experiment has found evidence of D^0-$\overline{D}^0$ mixing at 3.9σ level [7]. The results of the different fits - no *CPV* or mixing, no *CPV*, *CPV* allowed - including statistical and systematic errors are reported in Table 1.

[1]Consideration of charge conjugation is implied throughout this paper, unless otherwise stated.

Table 1: *BABAR* results from the different fits. The first uncertainty listed is statistical and the second systematic.

Fit type	Parameter	Fit Results ($\times 10^{-3}$)
No *CPV* or mixing	$R_{\rm D}$	$3.53 \pm 0.08 \pm 0.04$
No *CPV*	$R_{\rm D}$	$3.03 \pm 0.16 \pm 0.10$
	x'^2	$-0.22 \pm 0.30 \pm 0.21$
	y'	$9.7 \pm 4.4 \pm 3.1$
CPV allowed	$R_{\rm D}$	$3.03 \pm 0.16 \pm 0.10$
	$A_{\rm D}$	$-21 \pm 52 \pm 15$
	x'^{2+}	$-0.24 \pm 0.43 \pm 0.30$
	y'^{+}	$9.8 \pm 6.4 \pm 4.5$
	x'^{2-}	$-0.20 \pm 0.41 \pm 0.29$
	y'^{-}	$9.6 \pm 6.1 \pm 4.3$

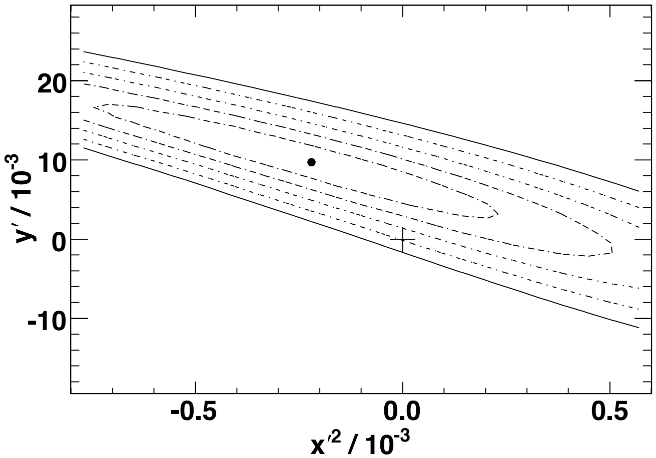

Figure 1: *BABAR* results. The central value (point) and confidence-level (CL) contours for $1 - \mathrm{CL} = 0.317$ (1σ), 4.55×10^{-2} (2σ), 2.70×10^{-3} (3σ), 6.33×10^{-5} (4σ) and 5.73×10^{-7} (5σ), calculated from the change in the value of $-2 \ln \mathcal{L}$ compared with its value at the minimum. Systematic uncertainties are included. The no-mixing point is shown as a plus sign (+).

The confidence level countours including systematic errors are shown in Fig. 1, where the no-mixing point $(x'^2, y') \equiv (0, 0)$ is shown as a plus sign (+).

The *BABAR* results have been confirmed by the CDF experiment with a significance for mixing at 3.8σ level [11]. *BELLE* experiment - on an equivalent data sample to *BABAR*- finds no evidence for mixing [12].

3.2 Lifetime Ratio of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ relative to $D^0 \to K^-\pi^+$

One consequence of D^0-$\overline{D}^0$ mixing is that D^0 decay time distribution can be different for decays to different CP eigenstates. D^0-$\overline{D}^0$ mixing will alter the decay time distribution of D^0 and $\overline{D}^0$ mesons that decay into final states of specific *CP* [13]. To a good approximation, these decay time distributions can be treated as exponential with effective lifetimes τ^+_{hh} and τ^-_{hh}, for D^0 and $\overline{D}^0$ events respectively, decaying to *CP*-even final states (such as K^-K^+ and $\pi^-\pi^+$). The effective lifetimes measurements can be combined into the quantities y_{CP} and ΔY:

$$\begin{aligned} y_{CP} &= \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} - 1 \\ \Delta Y &= \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} A_\tau \ , \end{aligned} \tag{5}$$

where $\langle \tau_{hh} \rangle = (\tau^+_{hh} + \tau^-_{hh})/2$ and $A_\tau = (\tau^+_{hh} - \tau^-_{hh})/(\tau^+_{hh} + \tau^-_{hh})$. Both y_{CP} and ΔY are zero if there is no D^0-$\overline{D}^0$ mixing. In the limit where *CP* is conserved in mixing and decay, but violated in the interference between them, these quantities are related to the mixing parameters $y_{CP} = y \cos\varphi_f$ and $\Delta Y = x \sin\varphi_f$, with the convention that $\cos\varphi_f > 0$.

BELLE experiment measures the relative difference of the apparent lifetime of D^0 mesons between decays to CP-even eigenstates and the $K^-\pi^+$ final state to be

$$y_{CP} = (1.31 \pm 0.32(\text{stat.}) \pm 0.25(\text{syst.}))\%, \tag{6}$$

which represents a significance for D^0-$\overline{D}^0$ mixing at 3.2σ level [8]. The effect is presented visually in Fig. 2(d), which shows the ratio of decay time distributions for $D^0 \to K^+K^-, \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays. The *CPV* parameter $A_\Gamma \equiv -A_\tau$ was found to be consistent with zero:

$$A_\Gamma = (0.01 \pm 0.30(\text{stat.}) \pm 0.15(\text{syst.}))\%. \tag{7}$$

BABAR experiment measures $y_{CP} = (1.03 \pm 0.33(\text{stat.}) \pm 0.19(\text{syst.}))\%$, which represents evidence of mixing at 3.0σ level, and $\Delta Y = (-0.26 \pm 0.36(\text{stat.}) \pm 0.08(\text{syst.}))\%$ consistent with no *CPV* [14].

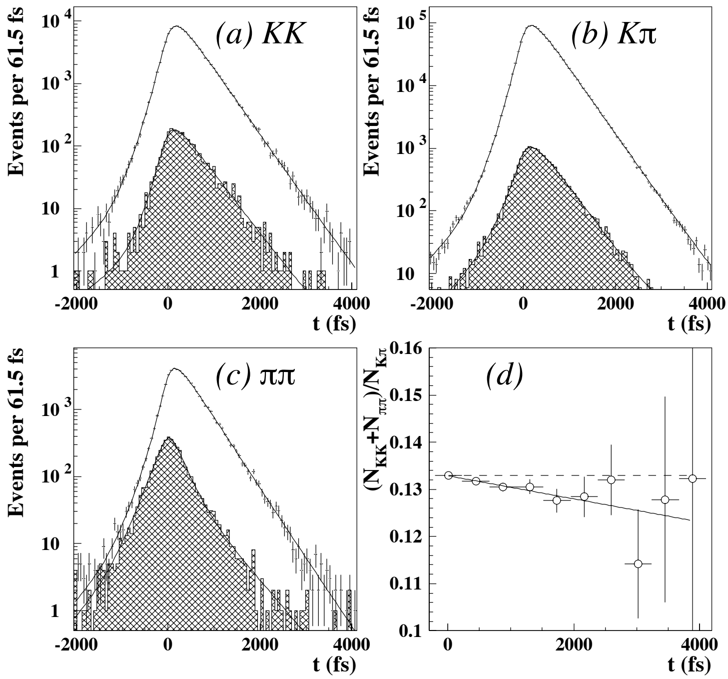

Figure 2: *BELLE* results of the simultaneous fit to decay time distributions of (a) $D^0 \to K^+K^-$, (b) $D^0 \to K^-\pi^+$ and (c) $D^0 \to \pi^+\pi^-$ decays. The cross-hatched area represents background contributions, the shape of which was fitted using D^0 invariant mass sideband events. (d) Ratio of decay time distributions between $D^0 \to K^+K^-, \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays. The solid line is a fit to the data points.

4 Time integrated measurements for mixing and CP violation

4.1 Search for mixing in semileptonic decays $D^0 \to K^{(*)} l \nu$

The search for mixing in semileptonic WS decays is performed by reconstructing events from the decay chain $D^{*+} \to D^0 \pi_s^+$ with $D^0 \to \overline{D}^0 \to K^{(*)+} l^- \overline{\nu}$, where $l = e, \mu$. Any WS event, characterized by the opposite charge of the π_s from D^* and the lepton from the neutral D, would be evidence of D^0-$\overline{D}^0$ mixing. In the approximation of small x and y and *CP* conservation, the decay time distribution of neutral D meson which changes flavor and decays semileptonically, and thus involves no doubly interfering Cabibbo-suppressed (DCS) amplitudes, is

$$R_{\rm mix}(t) \simeq R_{\rm unmix}(t) \frac{x^2 + y^2}{4} \left(\frac{t}{\tau_{D^0}} \right)^2 \tag{8}$$

where τ_{D^0} is the characteristic D^0 lifetime, and $R_{\rm unmix}(t) \propto e^{-t/\tau_{D^0}}$. The time integrated mixing rate relative to the unmixed rate is

$$R_{\rm M} = \frac{x^2 + y^2}{2}. \tag{9}$$

BELLE experiment did not find any evidence of WS events and sets the limit on the time integrated mixing rate, $R_{\rm M} < 6.1 \times 10^{-4}$ at 90% CL [15]. *BABAR* experiment using a more exclusive reconstruction technique which fully reconstructs charm decays in the hemisphere opposite the semileptonic signal, sets the constraint $R_{\rm M} \in [-13, 12] \times 10^{-4}$ [16].

4.2 Two body decays $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$

The *CP*-even decays $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ are Cabibbo suppressed, with the two neutral charmed mesons, D^0 and $\overline{D}^0$, sharing the final states. CP-violating asymmetries in these modes are predicted to be of order 0.001% $\div$ 0.01% in the SM [3, 17]. The observation of *CP* asymmetries at the level of current experimental sensitivity [18] would indicate a clear sign of physics beyond the SM [4, 19]. The *BABAR* experiment performed a search for *CPV* in neutral D mesons [20], produced from the reaction $e^+e^- \to c\bar{c}$, by measuring the time-integrated asymmetries

$$a_{CP}^{hh} = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}, \tag{10}$$

where $h = K$ or π.

Table 2: *CPV* asymmetries in D^0 two body decays. The first error is statistical, the second systematic.

Quantity	Value
a_{CP}^{KK}	$(\ \ 0.00 \pm 0.34 \pm 0.13)\%$
$a_{CP}^{\pi\pi}$	$(-0.24 \pm 0.52 \pm 0.22)\%$

The precise measurement of the time-integrated asymmetry is experimentally challenging due to the forward backward (FB) asymmetry in $e^+e^- \to c\bar{c}$ production - which creates a different number of D^0 and $\overline{D}^0$ reconstructed events due to the FB detection asymmetry due to the boost of the CM system relatively to the laboratory - and to different flavor tag efficiencies for D^0 and $\overline{D}^0$. Those effects are ruled out by using both tagged and untagged control samples to measure the relative efficiency for soft pions on data and by measuring the integrated asymmetry as a function of the cosine of the angle of the D^0 in the CM, $\cos\theta \equiv \cos\theta_{D^0}^{\rm CMS}$, and projecting out the even part due to *CPV*. The measured asymmetries, found to be consistend with zero, are listed in Table 2.

4.3 Three body decays $D^0 \to \pi^-\pi^+\pi^0$ and $D^0 \to K^-K^+\pi^0$

The three body decays $D^0 \to \pi^-\pi^+\pi^0$ and $D^0 \to K^-K^+\pi^0$ proceed via *CP* eigenstates (e.g., $\rho^0\pi^0$, $\phi\pi^0$) and also via flavor states (e.g., $\rho^{\pm}\pi^{\mp}$, $K^{*\pm}K^{\mp}$), thus making it possible to probe *CPV* in both types of amplitudes and in the interference between them. Measuring interference effects in a Dalitz plot (DP) probes asymmetries in both the magnitudes and phases of the amplitudes, not simply in the overall decay rates.

The *BABAR* experiment searched for *CPV* asymmetries in both $D^0 \to \pi^-\pi^+\pi^0$ and $D^0 \to K^-K^+\pi^0$ decays quantifying D^0-$\overline{D}^0$ differences in four different methods: difference between Dalitz plots, difference between the angular moments, difference in phase space integrated asymmetry, difference in Dalitz plot fit results for amplitudes and phases, where only the latter is a model dependent approach. There is no evidence of *CPV* in any of the four different methods [21]. Result for phase space integrated asymmetry are reported in Table 3.

The *BELLE* experiment has measured the time integrated asymmetry in $D^0 \to \pi^-\pi^+\pi^0$ and found no evidence of *CPV* [22], see Table 3. *BELLE* also measured the relative branching ratio of $D^0 \to \pi^-\pi^+\pi^0$ to $D^0 \to K^-K^+\pi^0$ to be BR $= (10.12 \pm 0.04(\text{stat}) \pm 0.18(\text{syst})) \times 10^{-2}$.

Table 3: *CPV* time integrated asymmetries for D^0 three body decays. The first error is statistical, the second systematic. For *BELLE* results the error is the sum of the statistical and the systematic contribution.

Quantity	*BABAR*	*BELLE*
$a_{CP}^{KK\pi^0}$	$(\ \ 0.00 \pm 0.34 \pm 0.13)\%$	-
$a_{CP}^{\pi\pi\pi^0}$	$(-0.24 \pm 0.52 \pm 0.22)\%$	$(0.43 \pm 1.30)\%$

5 Conclusions

In conclusion, the results from B Factories show evidence of charm mixing in WS $D^0 \to K^+\pi^-$ decays at 3.9σ level (*BABAR*) and in the lifetime ratio analysis at 3.2σ level (*BELLE*) and 3.0σ level (*BABAR*). Significance of charm mixing exceeds 6.7σ when combining all the available mixing results [23]. No evidence of *CPV* has been found in D^0 decays. The above results are compatible with the Standard Model predictions and provide useful constraints for New Physics models [4, 9].

6 Acknowledgements

I would like to thank the Istituto Nazionale di Fisica Nucleare (INFN) and the University of Pisa for the support for this work. I would like to thank also SLAC for its support and the kind hospitality.

References

1. B. Aubert *et al.* [BABAR Collaboration], Nucl. Instrum. Meth. A **479**, 1 (2002)

2. Nucl. Instrum. Meth. A **479**, 117 (2002).

3. S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. **26N7**, 1 (2003)

4. G. Burdman and I. Shipsey, Ann. Rev. Nucl. Part. Sci. **53**, 431 (2003)

5. L. Wolfenstein, Phys. Lett. B **164**, 170 (1985). J. F. Donoghue, E. Golowich, B. R. Holstein and J. Trampetic, Phys. Rev. D **33**, 179 (1986). I. I. Y. Bigi and N. G. Uraltsev, Nucl. Phys. B **592**, 92 (2001). A. F. Falk, Y. Grossman, Z. Ligeti and A. A. Petrov, Phys. Rev. D **65**, 054034 (2002).

A. F. Falk, Y. Grossman, Z. Ligeti, Y. Nir and A. A. Petrov, Phys. Rev. D **69**, 114021 (2004).

6. G. Blaylock, A. Seiden and Y. Nir, Phys. Lett. B **355**, 555 (1995)
7. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 211802 (2007)
8. M. Staric *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 211803 (2007)
9. A. A. Petrov, Int. J. Mod. Phys. A **21**, 5686 (2006)
10. W. M. Yao *et al.* [Particle Data Group], J. Phys. G **33**, 1 (2006).
11. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 121802 (2008)
12. L. M. Zhang *et al.* [BELLE Collaboration], Phys. Rev. Lett. **96**, 151801 (2006)
13. T. h. Liu, arXiv:hep-ph/9408330.
14. B. Aubert *et al.* [BABAR Collaboration], arXiv:0712.2249 [hep-ex].
15. U. Bitenc *et al.* [BELLE Collaboration], arXiv:0802.2952 [hep-ex].
16. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **76**, 014018 (2007)
17. F. Buccella, M. Lusignoli, G. Miele, A. Pugliese and P. Santorelli, Phys. Rev. D **51**, 3478 (1995)
18. D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 122001 (2005); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **71**, 091101 (2005).
19. Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D **75**, 036008 (2007)
20. B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **100**, 061803 (2008)
21. B. Aubert *et al.* [BABAR Collaboration], arXiv:0802.4035 [hep-ex].
22. K. Arinstein [Belle Collaboration], Phys. Lett. B **662**, 102 (2008)
23. A. J. Schwartz, arXiv:0803.0082 [hep-ex].