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Recent Results on T and CP Violation at BABAR

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CP-violation (CPV) and Time-reversal violation (TRV) are intimately related through the CPT theorem: if one of these discrete symmetries is violated the other one has to be violated in such a way to conserve CPT. Although CPV in the $B^0\bar{B}^0$ system has been established by the B-factories, implying indirectly TRV, there is still no direct evidence of TRV. We report on the observation of TRV in the B-meson system performed with a dataset of 468×10^6 $B\bar{B}$ pairs produced in $\Upsilon(4S)$ decays collected by the BABAR detector at the PEP-II asymmetric-energy e^+e^- collider at the SLAC National Accelerator Laboratory. We also report on other CPV measurements recently performed on the B-meson system.

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1. First direct observation of T-reversal violation in B-mesons

The Cabibbo-Kobayashi-Maskawa (*CKM*) matrix mechanism [1] for the quark mixing describes all transitions between quarks in terms of only four parameters: three rotation angles and one irreducible phase. This irreducible phase being the only source of *CPV* in the standard model (SM). *CPV* has been well established both in the K-meson [2] and B-meson [3] systems, being consistent with the *CKM* mechanism. Local Lorentz invariant quantum field theories imply *CPT* invariance [4], in agreement with all experimental evidence up to date [5]. It is therefore expected that the *CP*-violating weak interaction also violates T-reversal.

In stable systems, a signature of TRV would be a non-zero expectation value for a T-odd observable, e.g. neutron or electron electric dipole moments, but no such observation has been made up to date. The only evidence of TRV has been found in the neutral K-meson system, with the measurement of the difference between the probabilities of $K^0 \to \bar{K}^0$ and $\bar{K}^0 \to K^0$ transitions for a given elapsed time [6]. However, since this flavour mixing asymmetry violates both *CP* and T, it is impossible to disentangle TRV from CPV. In unstable systems, TRV can be explored by studying a process under the $t \to -t$ transition combined with the exchange of $|in\rangle$ and $|out\rangle$ states, which can be experimentally challenging to achieve. As an example, comparing the rates of $B^0 \to K^+\pi^-$ and $K^+\pi \to B^0$ is not feasible due to the need to prepare the initial state and to disentangle weak from strong effects. However, the coherent production of B-mesons pairs at the B-factories, offers a unique opportunity to compare couple of processes where the initial and final states are exchanged by Time-reversal.

The experimental method described in Ref. [7] proposes to use the entangled quantum state $|i\rangle$ of the two neutral B-mesons produced through the $\Upsilon(4S)$ decay. This two-body state usually written in terms of the flavour eigenstates, B^0 and $\bar{B}^0$, can be as well expressed in terms of mutually orthogonal B_+ and B_- *CP*-eigenstates, which decay to $CP = +1$ and $CP = -1$, respectively: $|i\rangle = \frac{1}{\sqrt{2}}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)] = \frac{1}{\sqrt{2}}[B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)]$. Experimentally, the B_+ and B_- states are defined as the neutral B states filtered by the decay to *CP* eigenstates $J/\psi K^0_L$ ($CP = +1$) and $J/\psi K^0_S(\to \pi\pi)$ ($CP = -1$). We define reference transitions and their T-transformed counterparts (see table 1) and compare their transition rates as a test for T-reversal. The notation (X,Y) denotes the final states of the time ordered B-meson decays from the entangled state, with $B \to X$ ($B \to Y$) the earlier (later) decay. The time difference between the decays, $\Delta t = t_Y - t_X$, is then positive by definition. As an illustration, the pair of final states $(\ell^+,\ J/\psi K^0_S)$ denotes a $B^0 \to \ell^+ X$ decay, meaning that at that time the other B in the event is a $\bar{B}^0$, followed in time by a $B \to J/\psi K^0_S$ decay, projecting to a B_-. The full process is the transition $\bar{B}^0 \to B_-$. A difference between this rate $\bar{B}^0 \to B_-$ and its T-transformed one is an indication of TRV. As shown in table 1, a total of four T-reversed transitions can be studied. The experimental analysis exploits identical reconstruction algorithms and selection criteria of the *BABAR* time-dependent *CP* asymmetry measurement in $B \to c\bar{c}K^{(*)0}$ decays [3]. The *flavor tagging* is combined for the first time with the *CP tagging*, as required for the construction of T-transformed processes.

The decay rate is proportional to $g^{\pm}_{i,j}(\Delta t) \propto e^{-\Gamma_d \Delta t}\{1 + S^{\pm}_{i,j}\sin(\Delta m_d \Delta t) + C^{\pm}_{i,j}\cos(\Delta m_d \Delta t)\}$, where i denotes B^0 or $\bar{B}^0$, j denotes $J/\psi K^0_S$ or $J/\psi K^0_L$, and $\pm$ indicates whether the flavour final state occurs before (+) or after (−) the *CP* decay. Γ_d is the average decay width, Δm_d is the $B^0\bar{B}^0$ mass difference. There are eight distinct sets of $C^{\pm}_{i,j}$ and $S^{\pm}_{i,j}$ parameters. An unbinned maximum

Reference transition (X,Y)	T-transformed transition (X,Y)
$B^0 \to B_+(\ell^-, J/\psi K^0_L)$	$B_+ \to B^0(J/\psi K^0_S, \ell^+)$
$B^0 \to B_-(\ell^-, J/\psi K^0_S)$	$B_- \to B^0(J/\psi K^0_L, \ell^+)$
$\overline{B}^0 \to B_+(\ell^+, J/\psi K^0_L)$	$B_+ \to \overline{B}^0(J/\psi K^0_S, \ell^-)$
$\overline{B}^0 \to B_-(\ell^+, J/\psi K^0_S)$	$B_- \to \overline{B}^0(J/\psi K^0_L, \ell^-)$

Table 1: *Reference transitions and their T-transformed.*

likelihood fit is performed to the B^0, $\overline{B}^0$, $c\bar{c}K^0_S$ and $J/\psi K^0_L$ samples, to extract the $C^{\pm}_{i,j}$ and $S^{\pm}_{i,j}$ parameters. Out of this set of fitted parameters, a different set of T, CP and CPT violation parameters can be built, $\Delta C^{\pm}_i$, $\Delta S^{\pm}_i$ (with $i = T, CP, CPT$) which are constructed as differences of the $C^{\pm}_{i,j}$ and $S^{\pm}_{i,j}$ for symmetry-transformed transitions (see table 2). Any deviation of the $(\Delta C^{\pm}_i, \Delta S^{\pm}_i)$ from $(0,0)$ signals the violation of the corresponding symmetry.

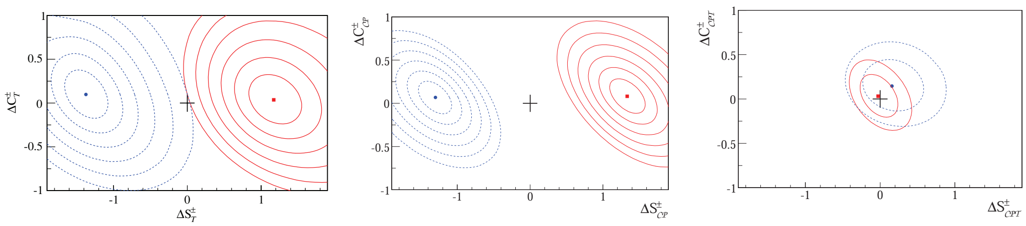

Figure 1: *Confidence level contours at intervals of 1σ for T- (left), CP- (middle) and CPT- (right) differences results. ΔS^+_i and C^+_i (ΔS^-_i and C^-_i) are shown as a blue dashed (solid red) curves. The no-violation point of the corresponding symmetry is indicated with a cross (+).*

Parameter	Measurement	Parameter	Measurement
$\Delta S^+_T = S^-_{\ell^-,K^0_L} - S^+_{\ell^+,K^0_S}$	$-1.37 \pm 0.14 \pm 0.06$	$\Delta C^+_T = C^-_{\ell^-,K^0_L} - C^+_{\ell^+,K^0_S}$	$0.10 \pm 0.14 \pm 0.08$
$\Delta S^-_T = S^+_{\ell^-,K^0_L} - S^-_{\ell^+,K^0_S}$	$1.17 \pm 0.18 \pm 0.11$	$\Delta C^-_T = C^+_{\ell^-,K^0_L} - C^-_{\ell^+,K^0_S}$	$0.04 \pm 0.14 \pm 0.08$
$\Delta S^+_{CP} = S^+_{\ell^-,K^0_S} - S^+_{\ell^-,K^0_S}$	$-1.30 \pm 0.11 \pm 0.07$	$\Delta C^+_{CP} = C^+_{\ell^-,K^0_S} - C^+_{\ell^-,K^0_S}$	$0.07 \pm 0.09 \pm 0.03$
$\Delta S^-_{CP} = S^-_{\ell^-,K^0_S} - S^-_{\ell^+,K^0_S}$	$1.33 \pm 0.12 \pm 0.06$	$\Delta C^-_{CP} = C^-_{\ell^-,K^0_S} - C^-_{\ell^+,K^0_S}$	$0.08 \pm 0.10 \pm 0.04$
$\Delta S^+_{CPT} = S^-_{\ell^+,K^0_L} - S^+_{\ell^+,K^0_S}$	$-1.30 \pm 0.11 \pm 0.07$	$\Delta C^+_{CPT} = C^-_{\ell^+,K^0_L} - C^+_{\ell^+,K^0_S}$	$0.07 \pm 0.09 \pm 0.03$
$\Delta S^-_{CPT} = S^+_{\ell^+,K^0_L} - S^-_{\ell^+,K^0_S}$	$1.33 \pm 0.12 \pm 0.06$	$\Delta C^-_{CPT} = C^+_{\ell^+,K^0_L} - C^-_{\ell^+,K^0_S}$	$0.08 \pm 0.10 \pm 0.04$

Table 2: *Measured values of the T, CP and CPT difference parameters. The first uncertainty is statistical and the second systematic. The indexes $\ell^{\pm}$ and K^0_S/K^0_L are described in the text.*

The results on the T, CP and CPT asymmetries are shown in table 2. The significance of the corresponding differences is shown graphically in figure 2, with the two-dimensional contours in the $(\Delta S^{\pm}_i, \Delta C^{\pm}_i)$ planes ($i = T, CP, CPT$). time-reversal violation is clearly established, with the exclusion of the $(0,0)$ point with a significance of 14σ. CP-violation is also observed at the level of 16σ. No evidence of CPT-violation is observed, the measurement being consistent with the conservation hypothesis within the 1σ level [8].

2. CP-violation in $B^0\bar{B}^0$ mixing

Two of the three types of CP-violation that can be observed in neutral B-mesons systems have been well established, i.e. CP-violation in direct B^0 decays and in the interference between mixing and decay [3]. The third one, CP-violation in mixing has so far eluded observation. The weak-Hamiltonian eigenstates are related to the flavour eigenstates as $|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$. The asymmetry between the oscillation probabilities $P = P(B^0 \to \bar{B}^0)$ and $\bar{P} = P(\bar{B}^0 \to B^0)$ is defined as: $A_{CP} = \frac{\bar{P}-P}{\bar{P}+P} = \frac{1-|q/p|^4}{1+|q/p|^4} \simeq 2(1-|q/p|^2)$. Hence, there is CP-violation in mixing if the parameter $|q/p| \neq 1$. The SM prediction is $A_{CP} = -(4.0\pm 0.6)\times 10^{-4}$ [10].

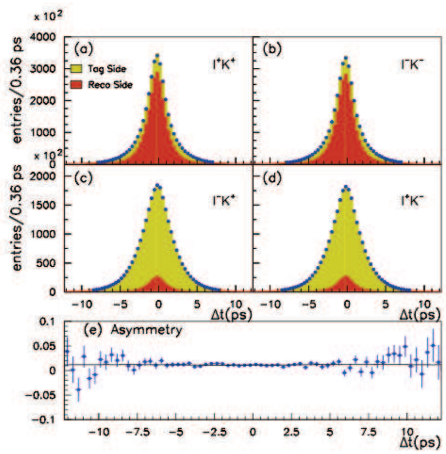

Figure 2: *Δt distribution for the continuum subtracted data (points with error bars) and fitted contribution from K_R (dark) and K_T (light) for ℓ^+K^+ (top-left), ℓ^-K^- (top-right), ℓ^-K^+ (middle-left) and ℓ^+K^- (middle-right) events. The bottom plot is the Δt-dependent raw asymmetry between ℓ^+K^+ and ℓ^-K^- events.*

The usual observable to measure the mixing A_{CP} is the di-lepton asymmetry, $A_{CP} = \frac{N(\ell^+\ell^+)-N(\ell^-\ell^-)}{N(\ell^+\ell^+)+N(\ell^-\ell^-)}$, where $\ell = e$ or μ, and ℓ^+ (ℓ^-) tags a B^0 ($\bar{B}^0$). This measurement benefits from the high statistics but has the drawback on relying on control samples to subtract charge-asymmetric backgrounds. The systematic uncertainty related to this correction constitutes a severe limitation on the precision of the measurement. The present analysis measures A_{CP} with a new technique in which one of the B^0-mesons in the event is reconstructed in $B^0 \to D^{*-}X\ell^+\nu$ (referred to as the B_R), with a partial reconstruction of the $D^{*-} \to \pi^-\bar{D}^0$ decay. The flavour of the other B^0 (referred to as the B_T) is tagged by looking at the charge of the charged kaons in the event (K_T). Because a B^0 ($\bar{B}^0$) decays most often to a K^+ (K^-), then when mixing takes place ℓ and K_T have the same charge. A kaon with the same sign as ℓ may also come from the partially reconstructed D^0 in the event (K_R). To extract A_{CP}, three raw asymmetries are measured,

$$A_\ell = A_{r\ell} + A_{CP}\chi_d, \tag{2.1}$$

$$A_T = \frac{N(\ell^+K_T^+) - N(\ell^-K_T^-)}{N(\ell^+K_T^+) + N(\ell^-K_T^-)} = A_{r\ell} + A_K + A_{CP}, \tag{2.2}$$

$$A_R = \frac{N(\ell^+K_R^+) - N(\ell^-K_R^-)}{N(\ell^+K_R^+) + N(\ell^-K_R^-)} = A_{r\ell} + A_K + A_{CP}, \tag{2.3}$$

where A_ℓ is the inclusive single lepton asymmetry, i.e. the asymmetry between events with ℓ^+ compared to those with ℓ^-, $\chi_d = 0.1862 \pm 0.0023$ [11] and $A_{r\ell}$ (A_K) the detector induced charge asymmetry in the B_R ($K^\pm$) reconstruction.

The B_R is selected by combining a high momentum lepton and an opposite charge soft pion from the decay $D^{*-} \to \bar{D}^0 \pi_s^-$, both consistent with originating from a common vertex. The B_R events are discriminated against backgrounds by using the unobserved neutrino mass squared $\mathscr{M}_\nu^2 = (E_{\rm beam} - E_{D^*} - E_\ell)^2 - (\mathbf{p}_{D^*} + \mathbf{p}_\ell)^2$, where the B^0 momentum is neglected. E_ℓ and $\mathbf{p}_\ell$ are the energy and momentum of the lepton, and $\mathbf{p}_{D^*}$ is an estimation of the of the D^* momentum by approximating its direction the same as the π_s^- and parameterizing its momentum as a linear function of $\mathbf{p}_{\pi_s^-}$ using MC. $\mathscr{M}_\nu^2$ peaks near zero for signal. The production point of the reconstructed K (K-vertex) is estimated by the intersection of its track and the beam-region. Δz is defined as the distance from the $\ell\pi_s$ vertex and K-vertex along the beam-axis. Finally, the proper time difference Δt between B_R and B_T is defined as $\Delta t = \Delta z/\beta\gamma$ (with $\beta\gamma = 0.56$ the average Lorentz boost of the e^+e^- collision). The estimated error on the estimated Δt, $\sigma(\Delta t)$, is as well used as a discriminant variable. Events in which ℓ and K have the same sign are defined as mixed and unmixed otherwise. K_R candidates tend to have a smaller Δt than K_T candidates, therefore Δt is used as one of the main discriminant variables. Furthermore, K_R are usually emitted mainly back-to-back with respect to ℓ, while K_T are produced at random, so we use in addition the angle $\theta_{\ell K}$ between K and ℓ.

The number of B_R events is extracted by fitting the $\mathscr{M}_\nu^2$ distributions. The events are split in four lepton categories ($(e^\pm, \mu^\pm)$) and in eight tagged samples ($e^\pm K^\pm, \mu^\pm K^\pm$) for the extraction of A_ℓ and (A_T, A_R), respectively. A total of $(5.945 \pm 0.007) \times 10^6$ peaking events are found. We measure A_{CP} with a binned four dimensional fit to Δt, $\sigma(\Delta t)$, $\cos(\theta_{\ell K})$ and p_K. Figure 2 show the fit projections for Δt. We find $A_{CP} = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$, and $1 - |q/p|^2 = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$ [12]. This is the single most precise measurement of this mixing asymmetry well in agreement with the SM expectations.

3. Time-dependent amplitude analysis of $B^0 \to (\rho\pi)^0$

The $B^0 \to \pi^+\pi^-\pi^0$ decay is well suited for *CP*-violation studies. The phase space of this final state is dominated by intermediate vector resonances (ρ). A complete time-dependent Dalitz plot (DP) analysis is sensitive to the interference between the resonant ρ^+, ρ^- and ρ^0 intermediate states, allowing to extract the strong and weak relative phases, and of the *CP*-violation parameter $\alpha = \arg[-(V_{td}V_{tb}^*)/(V_{ud}V_{ub}^*)$, with $V_{qq'}$ the elements of the *CKM* matrix [14].

The time-dependent amplitude for B^0 decays to the $\pi^+\pi^-\pi^0$ is given by $A_{3\pi} = f_+A^+ + f_-A^- + f_0A^0$, and similarly for $\bar{B}^0$ decays, with the A^i replaced by $\overline{A^i}$ ($i = +,-,0$). The DP-dependent f_i, and are defined in terms of modified Breit-Wigner resonances. The time-dependent probability for a meson which is a B^0 ($g_{3\pi}^-$) or $\bar{B}^0$ ($g_{3\pi}^+$) at the time the other one decays, to decay to $\pi^+\pi^-\pi^0$ is given by,

$$g_{3\pi}^{\pm}(\Delta t, DP) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} (|A_{3\pi}|^2 + |\bar{A}_{3\pi}|^2)\big(1 \mp C_{3\pi}\cos(\Delta m_d \Delta t) \pm S_{3\pi}\sin(\Delta m_d \Delta t)\big) \tag{3.1}$$

where $C_{3\pi} = \frac{|A_{3\pi}|^2 - |\bar{A}_{3\pi}|^2}{|A_{3\pi}|^2 + |\bar{A}_{3\pi}|^2}$, $S_{3\pi} = 2\mathrm{Im}\Big\{\frac{(q/p)\bar{A}_{3\pi}A_{3\pi}^*}{|A_{3\pi}|^2 + |\bar{A}_{3\pi}|^2}\Big\}$ and is τ_{B^0} the B^0 lifetime. The decay amplitudes $A_{3\pi}$ and $\bar{A}_{3\pi}$ [15] are written in terms of 27-real valued parameters U and I coefficients which have a number of advantages: there is a unique solution of the U-I from the fit to data; their uncertainties are more Gaussian than those from fits where the decay amplitudes are directly parameterized in terms of the A^i moduli and phases; and it is simpler to combine measurements from different experiments. The physical quantities (branching fraction, CP-asymmetry) for each $\rho\pi$ charge states are functions of the U and I parameters.

The present analysis [15] is an update of the previous *BABAR* measurement [13] with the full dataset. Background events are discriminated by using two kinematic variables: $m_{ES}^2 = [(s/2 + \vec{p}_i \cdot \vec{p}_B)/E_i]^2 - |\vec{p}_B|^2$ and $\Delta E = E_B^* - \sqrt{s}/2$, where $\sqrt{s}$ is the e^+e^- beam energy in the CM frame, $(E_i, \vec{p}_i)$ and $\vec{p}_B$ the four-momentum of the e^+e^- system and the momentum of the B-candidate in the laboratory frame, and E_B^* the B-candidate energy in the CM frame. m_{ES} and ΔE peak at the B-mass and at zero for signal events, respectively. Further background discrimination is achieved by using a neural-network (NN) which exploits the topological differences between signal and background. A maximum likelihood fit using the Δt and DP variables, as well as m_{ES}, ΔE and NN, is performed to extract the values of the U-I coefficients. Two direct CP-violation parameters,

$$A_{\rho\pi}^{+-} = \frac{\Gamma(\overline{B}^0 \to \rho^-\pi+) - \Gamma(B^0 \to \rho^+\pi-)}{\Gamma(B^0 \to \rho^-\pi+) + \Gamma(B^0 \to \rho^+\pi-)}, \quad A_{\rho\pi}^{-+} = \frac{\Gamma(\overline{B}^0 \to \rho^+\pi-) - \Gamma(B^0 \to \rho^-\pi+)}{\Gamma(B^0 \to \rho^+\pi-) + \Gamma(B^0 \to \rho^-\pi+)} \tag{3.2}$$

are extracted with the values $A_{\rho\pi}^{+-} = 0.09^{+0.05}_{-0.06} \pm 0.04$ and $A_{\rho\pi}^{-+} = -0.12 \pm 0.08^{+0.04}_{-0.05}$. A two-dimensional likelihood scan is provided in the left hand plot of figure 3. The origin, corresponding to no direct CP-violation, is excluded at the level of $\sim 2\sigma$.

Scans of the likelihood function in fits where a given value of the CKM α angle is assumed are performed enforcing the $SU(2)$ symmetry in a loose (*unconstrained* analysis using only the $B^0 \to \rho\pi$ amplitudes) or tight (*constrained* analysis adding the charged $B^+ \to \rho\pi$ amplitudes) fashion. The Σ scan vs α is shown in the right hand plot of figure 3. The Σ value is commonly referred as "1 - C.L.", however robustness studies have shown that with the current data sample the Σ cannot interpreted in terms of the usual Gaussian statistics [15]. Hence with the current statistics, the analysis cannot reliably determine the angle α. This analysis would benefit greatly from increased sample sizes available at higher-luminosity experiments.

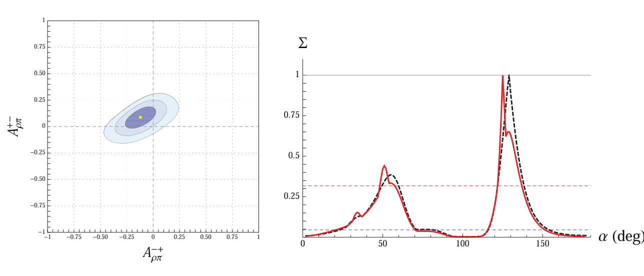

Figure 3: *Left: two-dimensional likelihood scan of $A_{\rho\pi}^{+-}$ vs $A_{\rho\pi}^{-+}$ with 1,2 and 3 σ C.L. contours. The yellow dot inside the contours indicate the central value. Right: Isospin-constrained (solid red) and unconstrained (dashed black) scans of Σ (see text) as a function of α.*

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4. Conclusion

We presented the fist direct observation of T-reversal violation in the B-meson system, which is established at the level of 14σ. Deviations of CPT conservation are also tested giving null results, in agreement with the expectations of the CPT-theorem. We also reported on a new experimental technique for the measurement of the mixing induced CP-violation parameter $1-|q/p|^2$. The measurement is the most precise single measurement up to date and is well in agreement with the SM expectations. Finally, we reported on the update using the full BABAR dataset of the time-dependent amplitude analysis of the $B^0 \to \pi^+\pi^-\pi^0$ decays. Measurements of direct CP-violation asymmetries are measured, excluding the CP-violation conservation hypothesis at the level of 2σ. Constrains on the α CKM angle are calculated. Robustness studies show that with the current dataset the method for extracting α is not robust, meaning that the current constrains cannot be interpreted in terms of the usual Gaussian statistics, but the analysis should benefit from increased data-samples from future experiments.

References

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

[2] J. H. Christenson *et al. Phys. Rev. Lett.* **13**, 138 (1964).

[3] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **87**, 091801 (2001); K. Abe *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **87**, 091802 (2001); B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **93**, 131801 (2004); Y. Chao *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **93**, 191802 (2004).

[4] G. Lüders *et al.* 1954, Vol. 28, p. 5; J. S. Bell, Ph.D. thesis, Birmingham University, 1954; Niels Bohr and the Development of Physics, edited by W. Pauli, L. Rosenfold, and V. Weisskopf (McGraw-Hill, New York, 1955).

[5] R. Carosi *et al.*, *Phys. Lett.* B **237**, 303 (1990); A. AlaviHarati *et al.*, *Phys. Rev.* D **67**, 012005 (2003); B. Schwingenheuer *et al.*, *Phys. Rev. Lett.* **74**, 4376 (1995).

[6] A. Angelopoulus *et al.* (CPLEAR Collaboration), *Phys. Lett.* B **444**, 43 (1998).

[7] J. Bernabeu *et al.*, *J. High Energy Phys.* **08** (2012) 064.

[8] J. P. Lees *et al.*, *Phys. Rev. Lett.* **109**, 211801 (2012).

[9] G. C. Branco, L. Lavoura and J. P. Silva, *CP Violation*, International Series of Monographs on Physics (1999).

[10] A. Lenz, U. Nierste, arXiv:1102.4274 [hep-ph] (2010); U. Nierste, arXiv:1212.5805 [hep-ph] (2012); J. Charles *et al.*, *Phys. Rev.* D **84**, 033005 (2011).

[11] J. Beringer et al., (Particle Data Group), *Phys. Rev.* D **86**, 010001 (2012).

[12] J. P. Lees *et al.*, arXiv:1305.1575 [hep-ex] (2013).

[13] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev.* D**76**, 012004 (2007).

[14] H.R. Quinn and A.E. Snyder, *Phys. Rev.* D **48**, 2139 (1993).

[15] J. P. Lees *et al.*, arXiv:1304.3503 [hep-ex] (2013).