The UTfit Collaboration Average of $D$ meson mixing data: Spring 2012

\texttt{(UTfit Collaboration)}

A.J. Bevan, M. Bona, M. Ciuchini, D. Derkach, E. Franco, V. Lubicz, G. Martinelli, F. Parodi, M. Pierini, C. Schiavi, L. Silvestrini, V. Sordini, A. Stocchi, C. Tarantino, and V. Vagnoni

1Queen Mary, University of London, Mile End Road, London E1 4NS, United Kingdom
2INFN, Sezione di Roma Tre, Via della Vasca Navale 84, I-00146 Roma, Italy
3CERN, CH-1211 Geneva 23, Switzerland
4INFN, Sezione di Roma, Piazzale A. Moro 2, I-00185 Roma, Italy
5Dipartimento di Fisica, Università di Roma Tre, Via della Vasca Navale 84, I-00146 Roma, Italy
6SISSA-ISAS, Via Bonomea 265, I-34136 Trieste, Italy
7Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, I-16146 Genova, Italy
8IPNL-IN2P3, 4 Rue Enrico Fermi, F-69622 Villeurbanne Cedex, France
9Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex, France
10INFN, Sezione di Bologna, Via Irnerio 46, I-40126 Bologna, Italy

We derive constraints on the parameters $M_{12}$, $\Gamma_{12}$ and $\Phi_{12}$ that describe $D$ meson mixing using all available data, allowing for CP violation. We also provide posterior distributions and predictions for observable parameters appearing in $D$ physics.

Meson-antimeson mixing in the neutral $D$ system has been established only in 2007 [1-3]. Early combinations of available data allowed to put stringent constraints on New Physics (NP) contributions, although the possibility of non-standard CP violation remained open [4-8]. More recently, CP violation in the $D$ system received considerable attention after the measurement at hadron colliders of large direct CP violation in $D \rightarrow \pi \pi$ and $D \rightarrow K \bar{K}$ decays [9,10], which may signal the presence of NP [11,12]. It then becomes crucial to extract updated information on the mixing amplitude in order both to disentangle more precisely indirect and direct CP violation in $D \rightarrow \pi \pi$ and $D \rightarrow K \bar{K}$, and to obtain up-to-date constraints on NP in $\Delta C = 2$ transitions that can be used to constrain NP contributions to $\Delta C = 1$ processes in any given model.

In this letter, we perform a fit to the experimental data in Table I following the statistical method described in ref. [23]. We assume that all Cabibbo allowed (and doubly Cabibbo suppressed) decay amplitudes in the phase convention CP $|D|$ and CP $|f\rangle = \eta_{CP}^{f}|f\rangle$ satisfy the relation $A(D \rightarrow f) = \eta_{CP}^{f}A(D \rightarrow \bar{f})$, which is expected to hold in the SM (in the standard CKM phase convention) with an accuracy much better than present experimental errors. In the same approximation this implies $\Gamma_{12}$ real. For singly Cabibbo suppressed decays $D^{0} \rightarrow K^{+}K^{-}$ and $D^{0} \rightarrow \pi^{+}\pi^{-}$ we allow for direct CP violation to be present. We assume flat priors for $x = \Delta m_{D}/\Gamma_{D}$, $y = \Delta \Gamma_{D}/(2\Gamma_{D})$ and $|q/p|$, with $|D_{L,S}| = p|D^{0}| \pm q|D^{0}|$ and $|p|^{2} + |q|^{2} = 1$. We can then express all mixing-related observables in terms of $x$, $y$ and $|q/p|$ using the following formula: [4,40,43]

$$\delta = \frac{1 - |q/p|^{2}}{1 + |q/p|^{2}}, \quad \phi = \arg(q/p) = \arg(y + i\delta x), \quad A_{M} = \frac{|q/p|^{4} - 1}{|q/p|^{4} + 1}, \quad R_{M} = \frac{x^{2} + y^{2}}{2},$$

$$\left(\begin{array}{c}
 x' \\
 y'
\end{array}\right) = \left(\begin{array}{cc}
 \cos \delta f & \sin \delta f \\
 -\sin \delta f & \cos \delta f
\end{array}\right) \left(\begin{array}{c}
 x \\
 y
\end{array}\right), \quad (x' \pm y')_{f} = \left|\frac{q}{p}\right|^{\pm 1} (x' \cos \phi \pm y' \sin \phi), \quad (y' \pm y')_{f} = \left|\frac{q}{p}\right|^{\pm 1} (y' \cos \phi \mp x' \sin \phi),$$

$$y_{CP} = \left|\frac{q}{p}\right| \left(\left|\frac{p}{q}\right| y \cos \phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x \sin \phi\right), \quad A_{\Gamma} = \left|\frac{q}{p}\right| \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos \phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin \phi,$$

$$R_{D} = \frac{\Gamma(D^{0} \rightarrow K^{+}\pi^{-}) + \Gamma(D^{0} \rightarrow K^{-}\pi^{+})}{\Gamma(D^{0} \rightarrow K^{-}\pi^{+}) + \Gamma(D^{0} \rightarrow K^{+}\pi^{-})}, \quad A_{D} = \frac{\Gamma(D^{0} \rightarrow K^{+}\pi^{-}) - \Gamma(D^{0} \rightarrow K^{-}\pi^{+})}{\Gamma(D^{0} \rightarrow K^{-}\pi^{+}) + \Gamma(D^{0} \rightarrow K^{+}\pi^{-})}.$$
are not sensitive to the assumptions about CP violation in mixing). CP violation in mixing, except for ref. [27] (as shown in ref. [3], the results for x and y from the Dalitz analysis of $D \rightarrow K_s\pi\pi$ are not sensitive to the assumptions about CP violation in mixing).

For the purpose of constraining NP, it is useful to express the fit results in terms of the $\Delta C = 2$ effective Hamiltonian matrix elements $M_{12}$ and $\Gamma_{12}$:

$$|M_{12}| = \frac{1}{\tau_D} \sqrt{x^2 + \delta^2 y^2 / 4(1 - \delta^2)}, \quad |\Gamma_{12}| = \frac{1}{\tau_D} \sqrt{y^2 + \delta^2 x^2 / 1 - \delta^2}, \quad \sin \Phi_{12} = \frac{|\Gamma_{12}|^2 + 4|M_{12}|^2 - (x^2 + y^2)|q/p|^2/\tau_D^2}{4|M_{12}\Gamma_{12}|},$$

(3)
HFAG categories (no CPV, no direct CPV, direct CPV), since we allow for direct CP violation only in singly Cabibbo dimensional correlations are displayed in Fig. 3.

A direct comparison with the HFAG results [38] is not straightforward, as our fit does not fall into any of the HFAG categories (no CPV, no direct CPV, direct CPV), since we allow for direct CP violation only in singly Cabibbo suppressed decays. However, our fit results should be close to the “no direct CPV” HFAG fit. Indeed, we find

| parameter       | result @ 68% prob. | 95% prob. range |
|----------------|--------------------|-----------------|
| $|M_{12}|$ [1/ps] | $6.9 \pm 2.4 \cdot 10^{-3}$ | $2.1, 11.5 \cdot 10^{-3}$ |
| $|\Gamma_{12}|$ [1/ps] | $17.2 \pm 2.5 \cdot 10^{-3}$ | $12.3, 22.4 \cdot 10^{-3}$ |
| $\Phi_{12}$ [°] | $(-6 \pm 9)$ | $[-37, 13]$ |
| $x$ | $(5.6 \pm 2.0) \cdot 10^{-3}$ | $1.4, 9.6 \cdot 10^{-3}$ |
| $y$ | $(7.0 \pm 1.1) \cdot 10^{-3}$ | $5.0, 9.1 \cdot 10^{-3}$ |
| $|q/p| - 1$ | $(5.3 \pm 7.7) \cdot 10^{-2}$ | $-8.5, 25.6 \cdot 10^{-2}$ |
| $\phi$ [°] | $(-2.4 \pm 2.9)$ | $[-8.8, 3.7]$ |
| $A_\Gamma$ | $(0.7 \pm 0.8) \cdot 10^{-3}$ | $-0.9, 2.3 \cdot 10^{-3}$ |
| $A_M$ | $(11 \pm 14) \cdot 10^{-2}$ | $[-15, 44] \cdot 10^{-2}$ |
| $R_M$ | $(4.0 \pm 1.4) \cdot 10^{-5}$ | $1.7, 7.2 \cdot 10^{-3}$ |
| $R_D$ | $(3.27 \pm 0.08) \cdot 10^{-3}$ | $3.10, 3.44 \cdot 10^{-3}$ |
| $\delta_{K^o\pi^0}$ [°] | $(18 \pm 12)$ | $-14, 40$ |
| $\delta_{K^o\pi^0}$ [°] | $(31 \pm 20)$ | $-11, 73$ |

$\Delta \alpha_{\text{CP}}^{\text{dir}}(D^0 \to K^+K^-) = (-2.6 \pm 2.2) \cdot 10^{-3}$ $-7.1, 1.9 \cdot 10^{-3}$

$\alpha_{\text{CP}}^{\text{dir}}(D^0 \to \pi^+\pi^-) = (4.1 \pm 2.4) \cdot 10^{-3}$ $-0.8, 9.0 \cdot 10^{-3}$

$\Delta \alpha_{\text{CP}}^{\text{dir}} = (6.6 \pm 1.6) \cdot 10^{-3}$ $-9.8, 3.5 \cdot 10^{-3}$

TABLE II. Results of the fit to $D$ mixing data. $\Delta \alpha_{\text{CP}}^{\text{dir}} = \alpha_{\text{CP}}^{\text{dir}}(D^0 \to K^+K^-) - \alpha_{\text{CP}}^{\text{dir}}(D^0 \to \pi^+\pi^-)$.

with $\Phi_{12} = \arg \Gamma_{12}/M_{12}$. Consistently with the assumption $A(D \to f) = A(\bar{D} \to \bar{f})$, $\Gamma_{12}$ can be taken real with negligible NP contributions, and a nonvanishing $\Phi_{12}$ can be interpreted as a signal of new sources of CP violation in $M_{12}$. For the sake of completeness, we report here also the formulæ to compute the observables $x$, $y$ and $\delta$ from $M_{12}$ and $\Gamma_{12}$:

$$\sqrt{2} \Delta m = \text{sign}(\cos \Phi_{12}) \sqrt{4|M_{12}|^2 - |\Gamma_{12}|^2 + \sqrt{(4|M_{12}|^2 + |\Gamma_{12}|^2)^2 - 16|M_{12}|^2|\Gamma_{12}|^2 \sin^2 \Phi_{12}}},$$

$$\sqrt{2} \Delta \Gamma = \sqrt{|\Gamma_{12}|^2 - 4|M_{12}|^2 + \sqrt{(4|M_{12}|^2 + |\Gamma_{12}|^2)^2 - 16|M_{12}|^2|\Gamma_{12}|^2 \sin^2 \Phi_{12}}},$$

$$\delta = \frac{2|M_{12}||\Gamma_{12}| \sin \Phi_{12}}{(\Delta m)^2 + |\Gamma_{12}|^2},$$

in agreement with [12] up to a factor of $\sqrt{2}$.

FIG. 1. One-dimensional p.d.f. for the parameters $|M_{12}|$, $|\Gamma_{12}|$ and $\Phi_{12}$.

The results of the fit are reported in Table II. The corresponding p.d.f are shown in Figs. 1 and 2. Some two-dimensional correlations are displayed in Fig. 3.

A direct comparison with the HFAG results [38] is not straightforward, as our fit does not fall into any of the HFAG categories (no CPV, no direct CPV, direct CPV), since we allow for direct CP violation only in singly Cabibbo suppressed decays. However, our fit results should be close to the “no direct CPV” HFAG fit. Indeed, we find
 FIG. 2. One-dimensional p.d.f. for the parameters $x$, $y$, $|q/p| - 1$ and $\phi$. 

 FIG. 3. Two-dimensional p.d.f. for $|\Gamma_{12}|$ vs $|M_{12}|$ (top left), $\Phi_{12}$ vs $|M_{12}|$ (top right), $y$ vs $x$ (bottom left) and $\phi$ vs $|q/p| - 1$ (bottom right).

 compatible results within errors. We notice, however, that HFAG performs a fit with four independent parameters ($x$, $y$, $\phi$ and $|q/p|$), while only three of these parameters are independent, as can be seen from eq. (1). In particular, $\phi$ should vanish for $|q/p| = 1$. This feature can be seen in Fig. 3 (up to the smoothing of the p.d.f) but not in the equivalent plot from HFAG, which displays completely different 2-dimensional contours. We can but recommend that in the future HFAG takes the relation $\phi = \text{arg}(y + i\delta x)$ always into account.

 The results in Table I can be used to constrain NP contributions to $D - \bar{D}$ mixing and decays.

 M.C. is associated to the Dipartimento di Fisica, Università di Roma Tre. E.F. and L.S. are associated to the Dipartimento di Fisica, Università di Roma “La Sapienza”. We acknowledge partial support from ERC Ideas Starting Grant n. 279972 “NPFlavour” and ERC Ideas Advanced Grant n. 267985 “DaMeSyFla”. We thank B. Golob and A. Schwartz for clarifications about the HFAG averages.

[1] B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 98, 211802 (2007), arXiv:hep-ex/0703020
[2] M. Staric et al. (Belle Collaboration), Phys.Rev.Lett. 98, 211803 (2007), arXiv:hep-ex/0703036 [hep-ex]
[3] K. Abe et al. (BELLE), Phys. Rev. Lett. 99, 131803 (2007) arXiv:0704.1000 [hep-ex].
[4] M. Ciuchini et al., Phys. Lett. B655, 162 (2007) arXiv:hep-ph/0703204.
[5] Y. Nir, JHEP 0705, 102 (2007) arXiv:hep-ph/0703235 [hep-ph].
[6] E. Golowich, J. Hewett, S. Pakvasa, and A. A. Petrov, Phys.Rev. D76, 095009 (2007) arXiv:0705.3650 [hep-ph].
[7] S. Fajfer, N. Kosnik, and S. Prelovsek, Phys.Rev. D76, 074014 (2007) arXiv:0706.1133 [hep-ph].
[8] M. Bona et al. (UTfit Collaboration), JHEP 0803, 049 (2008) arXiv:0707.0636 [hep-ph].
[9] R. Aaij et al. (LHCb Collaboration), (2011), arXiv:1112.0938 [hep-ex].
[10] CDF public note 10784 (2012).
[11] J. Brod, A. L. Kagan, and J. Zupan, (2011), arXiv:1111.5000 [hep-ph].
[12] D. Pirskkalava and P. Uppayarat, Phys.Lett. B712, 81 (2012), arXiv:1112.5451 [hep-ph].
[13] B. Bhattacharya, M. Gronau, and J. L. Rosner, Phys.Rev. D85, 054014 (2012), arXiv:1201.2351 [hep-ph].
[14] H.-Y. Cheng and C.-W. Chiang, Phys.Rev. D85, 034036 (2012), arXiv:1201.0785 [hep-ph].
[15] E. Franco, S. Mishima, and L. Silvestrini, JHEP 1205, 140 (2012), arXiv:1203.3131 [hep-ph].
[16] J. Brod, Y. Grossman, A. L. Kagan, and J. Zupan, (2012), arXiv:1203.6659 [hep-ph].
[17] J. Link et al. (FOCUS Collaboration), Phys.Lett. B485, 62 (2000) arXiv:hep-ex/0004034 [hep-ex].
