The UTfit Collaboration Average of $D$ meson mixing data: Winter 2014

(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

1 Queen Mary, University of London, Mile End Road, London E1 4NS, United Kingdom
2 INFN, Sezione di Roma Tre, Via della Vasca Navale 84, I-00146 Roma, Italy
3 Department of Physics, University of Oxford, OX1 3PN Oxford, United Kingdom
4 INFN, Sezione di Roma, Piazzale A. Moro 2, I-00185 Roma, Italy
5 Dipartimento di Matematica e Fisica, Università di Roma Tre, Via della Vasca Navale 84, I-00146 Roma, Italy
6 SISSA-ISAS, Via Bonomea 265, I-34136 Trieste, Italy
7 Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, I-16146 Genova, Italy
8 CERN, CH-1211 Geneva 23, Switzerland
9 IPNL-IN2P3, 4 Rue Enrico Fermi, F-69622 Villeurbanne Cedex, France
10 Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex, France
11 INFN, Sezione di Bologna, Via Irnerio 46, I-40126 Bologna, Italy

We update the analysis of $D$ meson mixing including the latest experimental results as of January 2014. 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 for observable parameters appearing in $D$ physics.

Almost two years ago, we presented our combination of the $D$ mixing experimental data, yielding a quite precise determination of the mixing parameters showing no sign of CP violation [1]. Recently, the LHCb Collaboration has improved several important measurements [2, 3], and updates have also come from the other experiments [4–7]. These improvements result in a remarkable accuracy in the determination of the CP violating phase in charm mixing, implying strong contraints on possible extensions of the Standard Model (SM). An update of our fit is timely and can be of use for phenomenological analyses of physics beyond the SM.

In this letter, we perform a fit to the experimental data in Table I following the statistical method described in ref. [24] improved with a Markov-chain Monte Carlo as implemented in the BAT library [25]. The following parameters are varied with flat priors in a sufficiently large range:

$$x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2 \Gamma}, \quad \left| \frac{q}{p} \right|, \quad \delta_{K\pi}, \quad \delta_{K\pi\pi}, \quad R_D,$$

where $q$ and $p$ are defined as $|D_{L,S}| = p|D^0| + q|\bar{D}^0|$ with $|p|^2 + |q|^2 = 1$, $\delta_{K\pi(\pi)}$ is the strong phase difference between the amplitudes $A(\bar{D} \to K^+\pi^-(\pi^0))$ and $A(D \to K^+\pi^-(\pi^0))$ and

$$R_D = \frac{\Gamma(D^0 \to K^+\pi^-) + \Gamma(\bar{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+) + \Gamma(\bar{D}^0 \to K^+\pi^-)}.$$

We make the following assumptions in order to combine the measurements in Table I: i) we assume that Cabibbo allowed (CA) and doubly Cabibbo suppressed (DCS) decays are purely tree-level SM processes, neglecting direct CP

* http://www.utfit.org
| Observable          | Value                  | Correlation Coeff. | Reference |
|---------------------|------------------------|--------------------|-----------|
| $y_{CP}$            | (0.866 ± 0.155)%       |                    | [11]      |
| $A_\Gamma$          | (0.014 ± 0.052)%       |                    | [2]       |
| $x$                 | (0.79 ± 0.29 ± 0.08 ± 0.12)% | 1  -0.007 -0.255$\alpha$  0.216 | [13] |
| $y$                 | (0.30 ± 0.24 ± 0.1 ± 0.07)% | -0.007 1 -0.019$\alpha$ -0.280 | [13] |
| $|q/p|$              | (0.96 ± 0.21)         | -0.255$\alpha$ -0.019$\alpha$ 1 -0.128$\alpha$ | [13] |
| $\phi$              | ($-2.5 + 10.5)^\circ$ | 0.216 -0.280 -0.128$\alpha$ 1 | [13] |
| $x$                 | (0.16 ± 0.23 ± 0.12 ± 0.08)% | 1  0.0615 | [14] |
| $y$                 | (0.57 ± 0.20 ± 0.13 ± 0.07)% | 0.0615 1 | [14] |
| $R_M$               | (0.013 ± 0.0269)%      |                    | [15]      |
| $(x'_+)^{K\pi}$     | (2.48 ± 0.59 ± 0.39)% | 1  -0.69 | [20] |
| $(y'_+)^{K\pi}$     | (-0.07 ± 0.65 ± 0.50)% | -0.69 1 | [20] |
| $(x'_-)^{K\pi}$     | (3.50 ± 0.78 ± 0.65)% | 1  -0.66 | [20] |
| $(y'_-)^{K\pi}$     | (-0.82 ± 0.68 ± 0.41)% | -0.66 1 | [20] |
| $R_D$               | (0.533 ± 0.107 ± 0.045)% | 1  0 0 -0.42 0.01 | [6] |
| $x^2$               | (0.06 ± 0.23 ± 0.11)% | 0 1 -0.73 0.39 0.02 | [6] |
| $y$                 | (4.2 ± 2 ± 1)%         | 0  -0.73 1 -0.53 -0.03 | [6] |
| $\cos \delta_{K\pi}$ | (0.84 ± 0.2 ± 0.06)  | -0.42 0.39 -0.53 1 0.04 | [6] |
| $\sin \delta_{K\pi}$ | (-0.01 ± 0.41 ± 0.04) | 0.01 0.02 -0.03 0.04 1 | [6] |
| $R_D$               | (0.303 ± 0.0189)%      | 1  0.77 -0.87 | [21] |
| $(x'_+)^2_{K\pi}$   | (-0.024 ± 0.052)%      | 0.77 1 -0.94 | [21] |
| $(y'_+)^2_{K\pi}$   | (0.98 ± 0.78)%         | -0.87 -0.94 1 | [21] |
| $A_D$               | (-2.1 ± 5.4)%          | 1  0.77 -0.87 | [21] |
| $(x'_-)^2_{K\pi}$   | (-0.020 ± 0.050)%      | 0.77 1 -0.94 | [21] |
| $(y'_-)^2_{K\pi}$   | (0.96 ± 0.75)%         | -0.87 -0.94 1 | [21] |
| $R_D$               | (0.364 ± 0.018)%       | 1  0.655 -0.834 | [22] |
| $(x'_+)^2_{K\pi}$   | (0.032 ± 0.037)%       | 0.655 1 -0.909 | [22] |
| $(y'_+)^2_{K\pi}$   | (-0.12 ± 0.58)%        | -0.834 -0.909 1 | [22] |
| $A_D$               | (2.3 ± 4.7)%           | 1  0.655 -0.834 | [22] |
| $(x'_-)^2_{K\pi}$   | (0.006 ± 0.034)%       | 0.655 1 -0.909 | [22] |
| $(y'_-)^2_{K\pi}$   | (0.20 ± 0.54)%         | -0.834 -0.909 1 | [22] |
| $R_D$               | (0.356 ± 0.035)%       | 1  0.967 0.900 | [7] |
| $(y'_{CPA})_{K\pi}$ | (0.43 ± 0.43)%         | -0.967 1 -0.975 | [7] |
| $(x'_{CPA})_{K\pi}$ | (0.008 ± 0.018)%       | 0.900 -0.975 1 | [7] |
| $R_D$               | (0.356 ± 0.0058 ± 0.0033)% | 1  -0.894 0.77 -0.895 0.772 | [3] |
| $(y'_+)^2_{K\pi}$   | (0.48 ± 0.09 ± 0.06)%  | -0.894 1 -0.949 0.765 -0.662 | [3] |
| $(x'_+)^2_{K\pi}$   | (6.4 ± 4.7 ± 3) x 10^{-5} | 0.77 -0.949 1 -0.662 0.574 | [3] |
| $(y'_-)^2_{K\pi}$   | (0.48 ± 0.09 ± 0.06)%  | -0.895 0.765 -0.662 1 -0.95 | [3] |
| $(x'_-)^2_{K\pi}$   | (4.6 ± 4.6 ± 3) x 10^{-5} | 0.772 -0.662 0.574 -0.95 1 | [3] |

TABLE I. Experimental data used in the analysis, from ref. [23]. $\alpha = (1+|q/p|)^2/2$. Asymmetric errors have been symmetrized.
can assume $\Gamma$ DCS decay amplitudes have vanishing weak phase and the following equations [1, 26–30]: violation; ii) we neglect the weak phase difference between these channels, which is of $O(10^{-3})$. One can then write the following equations [11 26[30]:

$$\delta = 1 - \frac{|q/p|^2}{1 + |q/p|^2}, \quad \arg(\Gamma_12 \ q/p) = \arg(y + i\delta x), \quad A_M = \frac{|q/p|^4 - 1}{|q/p|^4 + 1}, \quad R_M = \frac{x^2 + y^2}{2}, \quad (3)$$

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

$$y_{CP} = \left( \frac{|q/p|}{y} + \frac{|p/q|}{y} \right) \frac{y}{2} \cos \phi - \left( \frac{|q/p|}{y} - \frac{|p/q|}{y} \right) \frac{x}{2} \sin \phi, \quad A_G = \left( \frac{|q/p|}{y} - \frac{|p/q|}{y} \right) \frac{y}{2} \cos \phi - \left( \frac{|q/p|}{y} + \frac{|p/q|}{y} \right) \frac{x}{2} \sin \phi,$$

$$(y'_{CPA})^2_f = \left( \frac{y'_f \cos \phi - x'_f \sin \phi}{2} \right)^2 + \left( \frac{x'_f \sin \phi + y'_f \cos \phi}{2} \right)^2,$$

valid for Cabibbo allowed and doubly Cabibbo suppressed final states.

In the standard CKM phase convention (taking CP|D$^+$| = |D$^-$|), within the approximation we are using, CA and DCS decay amplitudes have vanishing weak phase and $\phi = \arg(q/p)$. Given the present experimental accuracy, one can assume $\Gamma_12$ to be real leading to the relation

$$\phi = \arg(y + i\delta x). \quad (4)$$

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 $\Gamma_{12}$:

$$|M_{12}| = \frac{1}{\tau_D} \sqrt{x^2 + \delta^2 y^2} \sim \frac{x}{2\tau_D} + O(\delta^2), \quad |\Gamma_{12}| = \frac{1}{\tau_D} \sqrt{y^2 + \delta^2 x^2} \sim \frac{y}{\tau_D} + O(\delta^2),$$

$$\sin \Phi_{12} = \frac{|\Gamma_{12}|^2 + 4|M_{12}|^2 - (x^2 + y^2)|q/p|^2/\tau_D^2}{4|M_{12}|^2 \Gamma_{12}} \sim \frac{x^2 + y^2}{2xy} \delta + O(\delta^2), \quad (5)$$

with $\Phi_{12} = \arg(\Gamma_{12}/M_{12})$ and $\tau_D = 0.41$ ps. Consistently with the assumptions above, $\Gamma_{12}$ can be taken real with negligible NP contributions, and a nonvanishing $\Phi_{12} = -\Phi_{M_{12}}$ can be interpreted as a signal of new sources of CP violation in $M_{12}$.

The results of the fit are reported in Table [II. The corresponding probability density functions (p.d.f.’s) are shown in Figs. [I and [2. Some two-dimensional p.d.f.’s are displayed in Fig. [3.

| parameter | result @ 68% prob. | 95% prob. range |
|-----------|--------------------|-----------------|
| $|M_{12}| \ [\text{ps}^{-1}]$ | $(4.4 \pm 2.0) \cdot 10^{-3}$ | $[0.3, 7.7] \cdot 10^{-3}$ |
| $|\Gamma_{12}| \ [\text{ps}^{-1}]$ | $(14.9 \pm 1.6) \cdot 10^{-3}$ | $[11.7, 18.5] \cdot 10^{-3}$ |
| $\Phi_{M_{12}} \ [^\circ]$ | $(2.0 \pm 2.7)$ | $[-4, 12]$ |
| $\delta_{K^{*}} \ [^\circ]$ | $(8 \pm 13)$ | $[-22, 30]$ |
| $\delta_{K^{*}} \ [^\circ]$ | $(-6 \pm 23)$ | $[-50, 43]$ |

Table II. Results of the fit to $D$ mixing data.

---

1 See ref. [11] for a discussion of the size of $\arg(\Gamma_{12})$. 
As can be seen from Table II, the fitted value of $\delta$ is at the percent level and indeed the central values of $|M_{12}|$, $|\Gamma_{12}|$ and $\Phi_{12}$ are compatible with the expanded formulae in eq. (5). However in our fit we used the exact formulae since the region of $x \lesssim 10^{-4}$, still allowed by experimental data (although with probability less than 5%), breaks the validity of the small $\delta$ expansion.

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

Our results are in very good agreement with the fit labeled “No direct CPV in DCS decays” by HFAG [23], now that HFAG uses the theoretical relation in eq. (4) as we suggested in our previous paper.
ACKNOWLEDGMENTS

M.C. is associated to the Dipartimento di Matematica e Fisica, Università di Roma Tre. E.F. and L.S. are associated to the Dipartimento di Fisica, Università di Roma “La Sapienza”. The research leading to these results has received funding from the European Research Council under the European Union’s Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreements n. 279972 “NPFlavour”, n. 267985 “DaMeSyFla” and from the People Programme (Marie Curie Actions) under European Union’s Seventh Framework Programme (FP7/2007-2013) / REA Grant Agreement n. 329017 “Charm@LHCb”.

[1] A. Bevan et al. (UTfit Collaboration), JHEP 1210, 068 (2012), arXiv:1206.6245 [hep-ph].
[2] R. Aaij et al. (LHCb collaboration), Phys.Rev.Lett. 111, 251801 (2013), arXiv:1309.6534 [hep-ex].
[3] J. Lees et al. (BaBar Collaboration), Phys.Rev. D87, 012004 (2013), arXiv:1209.3896 [hep-ex].
[4] M. Staric (Belle Collaboration), Phys.Lett. B655, 62 (2007), arXiv:hep-ex/0604034 [hep-ex].
[5] D. Asner et al. (CLEO Collaboration), Phys.Rev. D86, 112001 (2012), arXiv:1210.0939 [hep-ex].
[6] T. A. Aaltonen et al. (CDF Collaboration), Phys.Rev.Lett. 109, 231801 (2012), arXiv:1209.6534 [hep-ex].
[7] J. Link et al. (FOCUS Collaboration), Phys.Lett. B485, 62 (2000), arXiv:hep-ex/0004034 [hep-ex].
[8] S. Csorna et al. (CLEO Collaboration), Phys.Rev. D65, 092001 (2002), arXiv:hep-ex/0110124 [hep-ex].
[9] E. Aitala et al. (E791 Collaboration), Phys.Rev.Lett. 90, 2384 (1998), arXiv:hep-ex/9903012 [hep-ex].
[10] M. Ciuchini, G. D’Agostini, E. Franco, V. Lubicz, G. Martinelli, et al., JHEP 0107, 013 (2001), arXiv:hep-ph/0012308 [hep-ph].
[11] A. Caldwell, D. Kollar, and K. Kroninger, Comput.Phys.Commun. 180, 2197 (2009), arXiv:0808.2552 [physics.data-an].
[12] G. C. Branco, L. Lavoura, and J. P. Silva, Int.Ser.Monogr.Phys. 103, 1 (1999).
[13] G. Raz, Phys.Rev. D66, 057502 (2002), arXiv:hep-ph/0205113 [hep-ph].
[14] M. Ciuchini, E. Franco, D. Guadagnoli, V. Lubicz, M. Pierini, et al., Phys.Lett. B655, 162 (2007), arXiv:hep-ph/0703204 [hep-ph].
[15] A. L. Kagan and M. D. Sokoloff, Phys.Rev. D80, 076006 (2009), arXiv:0907.3917 [hep-ph].
[16] Y. Grossman, Y. Nir, and G. Perez, Phys.Rev.Lett. 103, 071602 (2009), arXiv:0904.0305 [hep-ph].
[17] A. Kagan, talk presented at the Workshop on Tau-Charm at High Luminosity, (2013).