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The UTfit collaboration average of D meson mixing data: spring 2012

A.J. Bevan,[a] **M. Bona,**[a] **M. Ciuchini,**[b] **D. Derkach,**[c] **E. Franco,**[d] **V. Lubicz,**[b,e] **G. Martinelli,**[d,f] **F. Parodi,**[g] **M. Pierini,**[c] **C. Schiavi,**[g] **L. Silvestrini,**[d] **V. Sordini,**[h] **A. Stocchi,**[i] **C. Tarantino**[b,e] **and V. Vagnoni**[j]

[a] *Queen Mary, University of London, Mile End Road, London E1 4NS, U.K.*
[b] *INFN, Sezione di Roma Tre, Via della Vasca Navale 84, I-00146 Roma, Italy*
[c] *CERN, CH-1211 Geneva 23, Switzerland*
[d] *INFN, Sezione di Roma, Piazzale A. Moro 2, I-00185 Roma, Italy*
[e] *Dipartimento di Fisica, Università di Roma Tre, Via della Vasca Navale 84, I-00146 Roma, Italy*
[f] *SISSA-ISAS, Via Bonomea 265, I-34136 Trieste, Italy*
[g] *Dipartimento di Fisica, Università di Genova and INFN,*
Via Dodecaneso 33, I-16146 Genova, Italy
[h] *IPNL-IN2P3, 4 Rue Enrico Fermi, F-69622 Villeurbanne Cedex, France*
[i] *Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université de Paris-Sud,*
BP 34, F-91898 Orsay Cedex, France
[j] *INFN, Sezione di Bologna, Via Irnerio 46, I-40126 Bologna, Italy*

E-mail: A.J.Bevan@qmul.ac.uk, Marcella.Bona@cern.ch, ciuchini@roma3.infn.it, Derkach@lal.in2p3.fr, Enrico.Franco@roma1.infn.it, Lubicz@fis.uniroma3.it, Guido.Martinelli@sissa.it, Fabrizio.Parodi@cern.ch, Maurizio.Pierini@cern.ch, Carlo.Schiavi@ge.infn.it, Luca.Silvestrini@roma1.infn.it, Viola.Sordini@cern.ch, Achille.Stocchi@lal.in2p3.fr, tarantino@fis.uniroma3.it, Vincenzo.Vagnoni@bo.infn.it

Abstract: We derive constraints on the parameters M_{12}, Γ_{12} and Φ_{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.

Keywords: Quark Masses and SM Parameters, Heavy Quark Physics, CP violation

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[1] Collaboration homepage: http://www.utfit.org/.

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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 $D \to \pi\pi$ and $D \to KK$ decays [9, 10], which may signal the presence of NP [11–16]. 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 $D \to \pi\pi$ and $D \to KK$, 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 1 following the statistical method described in ref. [39]. A number of assumptions can be made in order to combine the measurements in table 1. First of all, let us assume that Cabibbo allowed (CA) and doubly Cabibbo suppressed (DCS) decays are purely tree-level SM processes, so that there is no direct CP violation (for the moment, we do not specify any phase convention). Furthermore, we neglect the weak phase difference between these channels, which is of $\mathcal{O}(10^{-3})$. Then, for these decay channels, one has

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \left|\frac{q}{p}\right| R_f e^{i(\phi+\delta_f)}\,, \qquad \lambda_{\bar{f}} = \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}} = \left|\frac{q}{p}\right| R_f^{-1} e^{i(\phi-\delta_f)}\,, \tag{1}$$

where $A_f = A(D \to f)$ corresponds to a Cabibbo allowed (or doubly Cabibbo suppressed) decay, $\bar{A}_f = A(\bar{D} \to f)$, $R_f = |\bar{A}_f/A_f|$, δ_f is the strong phase and ϕ is the relative weak phase between mixing and decay. One can then write the following equations [4, 40–43], with $|D_{L,S}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ and $|p|^2 + |q|^2 = 1$:

$$\begin{aligned}
&\delta = \frac{1-|q/p|^2}{1+|q/p|^2}\,, \quad \arg(\Gamma_{12}\, q/p) = \arg(y+i\delta x)\,, \qquad A_M = \frac{|q/p|^4-1}{|q/p|^4+1}\,, \quad R_M = \frac{x^2+y^2}{2}\,,\\
&\begin{pmatrix} x'_f \\ y'_f \end{pmatrix} = \begin{pmatrix} \cos\delta_f & \sin\delta_f \\ -\sin\delta_f & \cos\delta_f \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}, \qquad (x'_\pm)_f = \left|\frac{q}{p}\right|^{\pm 1} (x'_f \cos\phi \pm y'_f \sin\phi)\,,\\
&(y'_\pm)_f = \left|\frac{q}{p}\right|^{\pm 1} (y'_f \cos\phi \mp x'_f \sin\phi)\,,\\
&y_{\rm CP} = \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) \frac{y}{2}\cos\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) \frac{x}{2}\sin\phi\,,\\
&A_\Gamma = \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) \frac{y}{2}\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) \frac{x}{2}\sin\phi\,,
\end{aligned} \tag{2}$$

valid for Cabibbo allowed and doubly Cabibbo suppressed final states.

Let us now choose for convenience a specific phase convention: $\mathrm{CP}|D\rangle = |\bar{D}\rangle$ and the standard CKM phase convention, so that CA and DCS decay amplitudes have vanishing weak phase and $\phi = \arg(q/p)$.

For singly Cabibbo suppressed decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ we allow for direct CP violation to be present. Direct CP violation requires a subdominant amplitude: $A_f = A_{\rm tree}(1 + r_f e^{i(\phi_f+\delta_f)})$, $\bar{A}_f = A_{\rm tree}(1 + r_f e^{i(-\phi_f+\delta_f)})$. Present experimental results

Observable	Value	Correlation Coeff.					Reference
y_{CP}	$(0.866\pm0.155)\%$						[2, 17–25]
A_Γ	$(0.022\pm0.161)\%$						[2, 20, 23–26]
x	$(0.811\pm0.334)\%$	1	-0.007	-0.255α	0.216		[3]
y	$(0.309\pm0.281)\%$	-0.007	1	-0.019α	-0.280		[3]
$\lvert q/p\rvert$	$(0.95\pm0.22\pm0.10)\%$	-0.255α	-0.019α	1	-0.128 α		[3]
ϕ	$(-0.035\pm0.19\pm0.09)$	0.216	-0.280	-0.128 α	1		[3]
x	$(0.16\pm0.23\pm0.12\pm0.08)\%$	1	0.0615				[27]
y	$(0.57\pm0.20\pm0.13\pm0.07)\%$	0.0615	1				[27]
R_M	$(0.0130\pm0.0269)\%$						[28–32]
$(x'_+)_{K\pi\pi^0}$	$(2.48\pm0.59\pm0.39)\%$	1	-0.69				[33]
$(y'_+)_{K\pi\pi^0}$	$(-0.07\pm0.65\pm0.50)\%$	-0.69	1				[33]
$(x'_-)_{K\pi\pi^0}$	$(3.50\pm0.78\pm0.65)\%$	1	-0.66				[33]
$(y'_-)_{K\pi\pi^0}$	$(-0.82\pm0.68\pm0.41)\%$	-0.66	1				[33]
x^2	$(0.1549\pm0.2223)\%$	1	-0.6217	-0.00224	0.3698	0.01567	[34]
y	$(2.997\pm2.293)\%$	-0.6217	1	0.00414	-0.5756	-0.0243	[34]
R_D	$(0.4118\pm0.0948)\%$	-0.00224	0.00414	1	0.0035	0.00978	[34]
$2\sqrt{R_D}\cos\delta_{K\pi}$	$(12.64\pm2.86)\%$	0.3698	-0.5756	0.0035	1	0.0471	[34]
$2\sqrt{R_D}\sin\delta_{K\pi}$	$(-0.5242\pm6.426)\%$	0.01567	-0.0243	0.00978	0.0471	1	[34]
R_D	$(0.3030\pm0.0189)\%$	1	0.77	-0.87			[1]
$(x'_+)^2_{K\pi}$	$(-0.024\pm0.052)\%$	0.77	1	-0.94			[1]
$(y'_+)_{K\pi}$	$(0.98\pm0.78)\%$	-0.87	-0.94	1			[1]
A_D	$(-2.1\pm5.4)\%$	1	0.77	-0.87			[1]
$(x'_-)^2_{K\pi}$	$(-0.020\pm0.050)\%$	0.77	1	-0.94			[1]
$(y'_-)_{K\pi}$	$(0.96\pm0.75)\%$	-0.87	-0.94	1			[1]
R_D	$(0.364\pm0.018)\%$	1	0.655	-0.834			[35]
$(x'_+)^2_{K\pi}$	$(0.032\pm0.037)\%$	0.655	1	-0.909			[35]
$(y'_+)_{K\pi}$	$(-0.12\pm0.58)\%$	-0.834	-0.909	1			[35]
A_D	$(2.3\pm4.7)\%$	1	0.655	-0.834			[35]
$(x'_-)^2_{K\pi}$	$(0.006\pm0.034)\%$	0.655	1	-0.909			[35]
$(y'_-)_{K\pi}$	$(0.20\pm0.54)\%$	-0.834	-0.909	1			[35]
CP asymmetry	Value	$\Delta\langle t\rangle/\tau_{D^0}$					Reference
$A_{\rm CP}(D^0\to K^+K^-)$	$(-0.24\pm0.24)\%$						[36, 37]
$A_{\rm CP}(D^0\to\pi^+\pi^-)$	$(0.11\pm0.39)\%$						[36, 37]
$\Delta A_{\rm CP}$	$(-0.82\pm0.21\pm0.11)\%$	$(9.83\pm0.22\pm0.19)\%$					[9]
$\Delta A_{\rm CP}$	$(-0.62\pm0.21\pm0.10)\%$	$(26\pm1)\%$					[10]

Table 1. Experimental data used in the analysis of D mixing, from ref. [38]. [1] $\alpha=(1+|q/p|)^2/2$ and $\Delta A_{\rm CP}=A_{\rm CP}(D^0\to K^+K^-)-A_{\rm CP}(D^0\to\pi^+\pi^-)$. Asymmetric errors have been symmetrized. We do not use measurements that do not allow for CP violation in mixing, except for ref. [27] (as shown in ref. [3], the results for x and y from the Dalitz analysis of $D\to K_s\pi\pi$ are not sensitive to the assumptions about CP violation in mixing).

imply $r_f \sin\delta_f \sin\phi_f \sim 6\times 10^{-3}$. These amplitudes also contribute to Γ_{12}, possibly leading to $\arg(\Gamma_{12}) \leq \mathcal{O}(10^{-3})$. Given the present experimental accuracy, one can then assume Γ_{12} to be real, leading to the relation

$$\phi = \arg(y + i\delta x)\,. \tag{3}$$

We assume flat priors for $x = \Delta m_D/\Gamma_D$, $y = \Delta\Gamma_D/(2\Gamma_D)$ and $|q/p|$. We can then express all mixing-related observables in terms of x, y and $|q/p|$ using the formulæ above. Furthermore,

$$R_D = \frac{\Gamma(D^0\to K^+\pi^-)+\Gamma(\bar{D}^0\to K^-\pi^+)}{\Gamma(D^0\to K^-\pi^+)+\Gamma(\bar{D}^0\to K^+\pi^-)}\,,\quad A_D = \frac{\Gamma(D^0\to K^+\pi^-)-\Gamma(\bar{D}^0\to K^-\pi^+)}{\Gamma(D^0\to K^+\pi^-)+\Gamma(\bar{D}^0\to K^-\pi^+)}\,, \tag{4}$$

with A_{D} forced to vanish in the fit. In addition, for the CP asymmetries we have

$$A_{\mathrm{CP}}(f) = \frac{\Gamma(D^0\to f)-\Gamma(\bar{D}^0\to \bar{f})}{\Gamma(D^0\to f)+\Gamma(\bar{D}^0\to \bar{f})} \approx a_{\mathrm{CP}}^{\mathrm{dir}}(f) - A_\Gamma \int_0^\infty dt\, \frac{t}{\tau_{D^0}}\, D_f(t) = a_{\mathrm{CP}}^{\mathrm{dir}}(f) - \frac{\langle t\rangle_f}{\tau_{D^0}}\, A_\Gamma\,, \tag{5}$$

where $D_f(t)$ is the observed distribution of proper decay time and τ_{D^0} is the lifetime of the neutral D mesons.

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 Γ_{12}:

$$\begin{aligned}
|M_{12}| &= \frac{1}{\tau_D}\sqrt{\frac{x^2+\delta^2 y^2}{4(1-\delta^2)}}\,,\quad |\Gamma_{12}| = \frac{1}{\tau_D}\sqrt{\frac{y^2+\delta^2 x^2}{1-\delta^2}}\,,\\
\sin\Phi_{12} &= \frac{|\Gamma_{12}|^2 + 4|M_{12}|^2 - (x^2+y^2)|q/p|^2/\tau_D^2}{4|M_{12}\Gamma_{12}|}\,,
\end{aligned} \tag{6}$$

with $\Phi_{12} = \arg\Gamma_{12}/M_{12}$. Consistently with the assumptions above, Γ_{12} can be taken real with negligible NP contributions, and a nonvanishing Φ_{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 δ from M_{12} and Γ_{12}:

$$\begin{aligned}
\sqrt{2}\,\Delta m &= \mathrm{sign}(\cos\Phi_{12})\sqrt{4|M_{12}|^2 - |\Gamma_{12}|^2 + \sqrt{(4|M_{12}|^2+|\Gamma_{12}|^2)^2 - 16|M_{12}|^2|\Gamma_{12}|^2\sin^2\Phi_{12}}}\,,\\
\sqrt{2}\,\Delta\Gamma &= 2\sqrt{|\Gamma_{12}|^2 - 4|M_{12}|^2 + \sqrt{(4|M_{12}|^2+|\Gamma_{12}|^2)^2 - 16|M_{12}|^2|\Gamma_{12}|^2\sin^2\Phi_{12}}}\,,\\
\delta &= \frac{2|M_{12}||\Gamma_{12}|\sin\Phi_{12}}{(\Delta m)^2 + |\Gamma_{12}|^2}\,,
\end{aligned} \tag{7}$$

in agreement with [42] up to a factor of $\sqrt{2}$.

The results of the fit are reported in table 2. The corresponding p.d.f are shown in figures 1 and 2. Some two-dimensional correlations are displayed in figure 3.

A direct comparison with the HFAG results [38][1] 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

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[1] And online updates at http://www.slac.stanford.edu/xorg/hfag/.

parameter	result @ 68% prob.	95% prob. range
$\lvert M_{12}\rvert$ [1/ps]	$(6.9 \pm 2.4) \cdot 10^{-3}$	$[2.1, 11.5] \cdot 10^{-3}$
$\lvert\Gamma_{12}\rvert$ [1/ps]	$(17.2 \pm 2.5) \cdot 10^{-3}$	$[12.3, 22.4] \cdot 10^{-3}$
Φ_{12} [°]	(-6 ± 9)	$[-37, 13]$
x	$(5.6 \pm 2.0) \cdot 10^{-3}$	$[1.4, 9.6] \cdot 10^{-3}$
y	$(7.0 \pm 1.0) \cdot 10^{-3}$	$[5.0, 9.1] \cdot 10^{-3}$
$\lvert q/p\rvert - 1$	$(5.3 \pm 7.7) \cdot 10^{-2}$	$[-8.5, 25.6] \cdot 10^{-2}$
ϕ [°]	(-2.4 ± 2.9)	$[-8.8, 3.7]$
A_Γ	$(0.7 \pm 0.8) \cdot 10^{-3}$	$[-0.9, 2.3] \cdot 10^{-3}$
A_M	$(11 \pm 14) \cdot 10^{-2}$	$[-15, 44] \cdot 10^{-2}$
R_M	$(4.0 \pm 1.4) \cdot 10^{-5}$	$[1.7, 7.2] \cdot 10^{-5}$
R_D	$(3.27 \pm 0.08) \cdot 10^{-3}$	$[3.10, 3.44] \cdot 10^{-3}$
$\delta_{K\pi}$ [°]	(18 ± 12)	$[-14, 40]$
$\delta_{K\pi\pi^0}$ [°]	(31 ± 20)	$[-11, 73]$
$a_{\rm CP}^{\rm dir}(D^0 \to K^+K^-)$	$(-2.6 \pm 2.2) \cdot 10^{-3}$	$[-7.1, 1.9] \cdot 10^{-3}$
$a_{\rm CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$	$(4.1 \pm 2.4) \cdot 10^{-3}$	$[-0.8, 9.0] \cdot 10^{-3}$
$\Delta a_{\rm CP}^{\rm dir}$	$(6.6 \pm 1.6) \cdot 10^{-3}$	$[-9.8, 3.5] \cdot 10^{-3}$

Table 2. Results of the fit to D mixing data. $\Delta a_{\rm CP}^{\rm dir} = a_{\rm CP}^{\rm dir}(D^0 \to K^+K^-) - a_{\rm CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$.

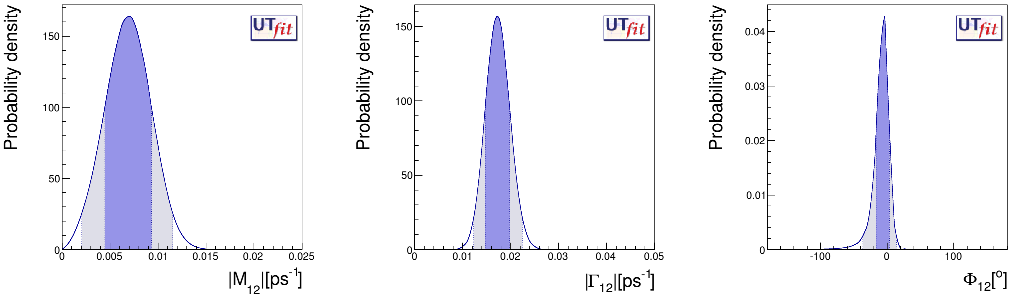

Figure 1. One-dimensional p.d.f. for the parameters $|M_{12}|$, $|\Gamma_{12}|$ and Φ_{12}.

compatible results within errors. We notice, however, that HFAG performs a fit with four independent parameters (x, y, ϕ and $|q/p|$), while in our analysis only three of these parameters are independent, as can be seen from eq. (3). With these assumptions, ϕ should vanish for $|q/p| = 1$. This feature can be seen in figure 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 $\phi = \arg(y + i\delta x) - \arg \Gamma_{12}$ always into account.

The results in table 2 can be used to constrain NP contributions to $D - \bar{D}$ mixing and decays.

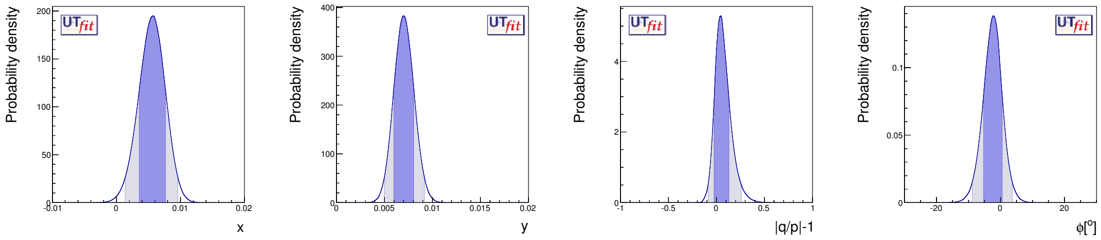

Figure 2. One-dimensional p.d.f. for the parameters x, y, $|q/p| - 1$ and ϕ.

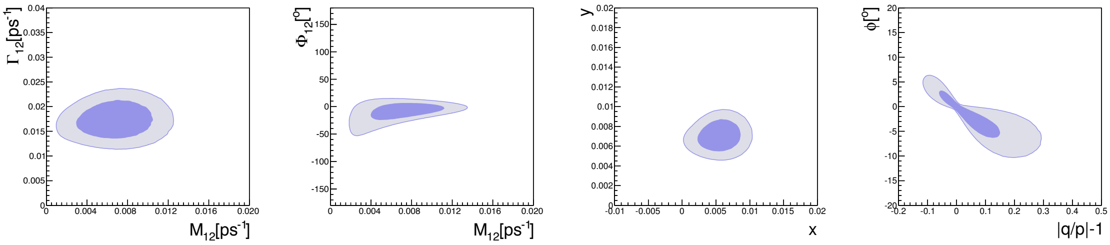

Figure 3. Two-dimensional p.d.f. for $|\Gamma_{12}|$ vs $|M_{12}|$ (top left), Φ_{12} vs $|M_{12}|$ (top right), y vs x (bottom left) and ϕ vs $|q/p| - 1$ (bottom right).

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