Neutral charm mixing results from the UTfit Collaboration

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We update here the analysis of $D$ meson mixing including the latest experimental results. 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.

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1. Introduction

Since 2012, the UTfit Collaboration has performed its own combination of the $D$ mixing experimental data, yielding a quite precise determination of the mixing parameters showing no sign of CP violation \cite{1,2}. The spectacular experimental progress that we have witnessed in the past few years is leading us in the precision charm physics era, calling for substantial theoretical advances to fully exploit the wealth of available data.

Fig. 1 shows the lower bounds on the new-physics (NP) scale $\Lambda$ coming from all the neutral meson systems: the case shown corresponds to a general NP scenario, with arbitrary NP flavour structures ($|F_i| \sim 1$ where $F_i$ is a function of the NP flavour couplings) with arbitrary phase and a loop factor $L_i = 1$ corresponding to strongly-interacting and/or tree-level NP. If we consider the most general effective Hamiltonian for $\Delta F = 2$ processes, we can translate the current constraints from a model-independent NP global UT fit into allowed ranges for the Wilson coefficients of $H_{\Delta F = 2}^{\text{eff}}$. The full procedure and analysis details are given in \cite{3}. These coefficients have the general form

$$C_i(\Lambda) = \frac{F_i L_i}{\Lambda^2}$$  \hspace{1cm} (1.1)

For a generic strongly-interacting theory with arbitrary flavour structure, one expects $F_i \sim L_i \sim 1$ so that the allowed range from the fit for each of the $C_i(\Lambda)$ can be immediately translated into a lower bound on $\Lambda$. Specific assumptions on the flavour structure of NP corresponds to particular choices of the $F_i$ functions. As Fig. 1 shows, the overall constraint on the NP scale comes from the kaon system ($\text{Im } C_k^4$), but charm physics also provides quite stringent constraints, allowing us to probe energies as high as $10^4$ TeV, with ample room for sizable improvements, both from the theoretical and experimental point of view.

We present here the updated fit to the experimental data that are reported in Table 1 of the 2014 Ref. \cite{2}: Table 1 here shows only the results updated after the 2014 analysis, following the statistical method described in Ref. \cite{4} improved with a Markov-chain Monte Carlo as implemented.
Table 1: Subset of the experimental data updated since the 2014 analysis [2]. The averages are taken from the HFAG [6]. \(\alpha = (1 + |q/p|^2)/2\). Asymmetric errors have been symmetrised.

<table>
<thead>
<tr>
<th>Observable (y_{CP})</th>
<th>Correlation Coeff.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(y_{CP}) (0.835 \pm 0.155)%</td>
<td>[7, 8, 9, 10]</td>
<td></td>
</tr>
<tr>
<td>(A_\Gamma) ((-0.059 \pm 0.040)%</td>
<td>[11, 12, 13, 14]</td>
<td></td>
</tr>
<tr>
<td>(x) ((0.53 \pm 0.19 \pm 0.06 \pm 0.07)%</td>
<td>1</td>
<td>0.054</td>
</tr>
<tr>
<td>(y) ((0.28 \pm 0.15 \pm 0.05 \pm 0.05)%</td>
<td>0.054</td>
<td>1</td>
</tr>
<tr>
<td>(</td>
<td>q/p</td>
<td>) ((0.91 \pm 0.16 \pm 0.50 \pm 0.60)</td>
</tr>
<tr>
<td>(\phi) ((-6 \pm 11 \pm 3 \pm 4)^0) -0.031</td>
<td>-0.019</td>
<td>0.044</td>
</tr>
</tbody>
</table>

in the BAT library [5]. The input averages are taken from the Heavy Flavour Averaging Group (HFAG) [6]. 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 \(|D_{LS}| = p|D^{0}| \pm q|D^{0}|\) with \(|p|^2 + |q|^2 = 1\), \(\delta_{K\pi}\) is the strong phase difference between the amplitudes \(A(D \to K^+\pi^-(\pi^0))\) and \(A(D \to K^+\pi^-(\pi^0))\) and

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

We make the following assumptions in order to combine the measurements in Table 1: i) we assume that Cabibbo allowed (CA) and doubly Cabibbo suppressed (DCS) decays are purely tree-level SM processes, neglecting direct CP violation; ii) we neglect the weak phase difference between these channels, which is of \(O(10^{-3})\). One can then write the following equations [19, 20, 21, 22, 23, 1]:

\[
\begin{align*}
\delta &= 1 - |q/p|^2, \quad \arctan\left(\frac{\Gamma_{12} q/p}{\Gamma_{12}}\right) = \arctan(y + i\delta x), \\
A_M &= \frac{|q/p|^4 - 1}{|q/p|^4 + 1}, \quad R_M = \frac{x^2 + y^2}{2}, \\
\left(\begin{array}{c}
x'_f \\ y'_f
\end{array}\right) &= \left(\begin{array}{cc}
\cos \delta_f & \sin \delta_f \\
-\sin \delta_f & \cos \delta_f
\end{array}\right) \left(\begin{array}{c}
x \\ y
\end{array}\right), \\
(x'_\pm)_f &= \left| \frac{q}{p} \right| \left(\begin{array}{c}
x'_f \cos \phi \mp y'_f \sin \phi
\end{array}\right), \quad (y'_\pm)_f = \left| \frac{q}{p} \right| \left(\begin{array}{c}
x'_f \cos \phi \mp y'_f \sin \phi
\end{array}\right), \\
y_{CP} &= \left(\frac{\tilde{q}}{q} + \frac{\tilde{p}}{q}\right) \frac{y}{2} \sin \phi - \left(\frac{\tilde{q}}{q} - \frac{\tilde{p}}{q}\right) \frac{x}{2} \cos \phi, \\
A_\Gamma &= \left(\frac{q}{p} - \frac{\tilde{p}}{q}\right) \frac{y}{2} \sin \phi - \left(\frac{q}{p} + \frac{\tilde{p}}{q}\right) \frac{x}{2} \cos \phi, \\
(y'_{CP})_f &= \frac{(y'_{+})_f + (y'_{-})_f}{2}, \quad (x'_{CP})^2 + (y'_{CP})^2 = \frac{(x'_{+})^2 + (x'_{-})^2 + (y'_{+})^2 + (y'_{-})^2}{2},
\end{align*}
\]
valid for CA and DCS final states $f$.

In the standard CKM phase convention (taking $CP(D) = |\bar{D}\rangle$), 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

$$\phi = \arg(y + i\delta x). \tag{1.4}$$

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 $\Gamma_{12}$:

$$|M_{12}| = \frac{1}{\tau_D} \sqrt{\frac{\delta^2 y^2}{4(1 - \delta^2)}} \sim \frac{x}{2 \tau_D} + \mathcal{O}(\delta^2), \quad |\Gamma_{12}| = \frac{1}{\tau_D} \sqrt{\frac{\delta^2 y^2}{1 - \delta^2}} \sim \frac{y}{\tau_D} + \mathcal{O}(\delta^2),$$

$$\sin \Phi_{12} = \frac{\Gamma_{12}^2 + 4|M_{12}|^2 - (x^2 + y^2)|q/p|^2/\tau_D^2}{4|M_{12}|\Gamma_{12}} \sim \frac{x^2 + y^2}{xy} \delta + \mathcal{O}(\delta^2), \tag{1.5}$$

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 non-vanishing $\Phi_{12} = -\Phi_{M12}$ can be interpreted as a signal of new sources of CP violation in $M_{12}$.

The results of the fit are reported in Table 2. The corresponding probability density functions (p.d.f.’s) are shown in Figs. 2 and 3. As can be seen from Table 2, 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. (1.5). However in our fit we used the exact formulae since the region of $x \lesssim 10^{-4}$,

### Table 2: Results of the fit to $D$ mixing data.

<table>
<thead>
<tr>
<th>parameter</th>
<th>result @ 68% prob.</th>
<th>95% prob. range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>M_{12}</td>
<td>$ [ps$^{-1}$]</td>
</tr>
<tr>
<td>$</td>
<td>\Gamma_{12}</td>
<td>$ [ps$^{-1}$]</td>
</tr>
<tr>
<td>$\Phi_{M12}$ [°]</td>
<td>$(0.8 \pm 2.6)$</td>
<td>$[-5.8, 8.8]$</td>
</tr>
<tr>
<td>$x$</td>
<td>$(3.5 \pm 1.5) \cdot 10^{-3}$</td>
<td>$[0.5, 6.3] \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$y$</td>
<td>$(5.8 \pm 0.6) \cdot 10^{-3}$</td>
<td>$[4.5, 7.1] \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td>- 1$</td>
</tr>
<tr>
<td>$\phi$ [°]</td>
<td>$-0.21 \pm 0.57$</td>
<td>$[-1.53, 1.02]$</td>
</tr>
</tbody>
</table>

Figure 2: One-dimensional p.d.f. for the parameters $|M_{12}|$, $|\Gamma_{12}|$ and $\Phi_{M12}$.
still allowed by experimental data (although with probability less than 5%), breaks the validity of the small $\delta$ expansion.

The results in Table 2 can be used to constrain NP contributions to $D - \bar{D}$ mixing and decays. Our results are in very good agreement with the fit labelled “No direct CPV in DCS decays” by HFAG [6], now that HFAG uses the theoretical relation in eq. (1.4) as we suggested in our first paper [1].

References


