HFA\textsuperscript{g} Charm Mixing Averages

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Recently the rst evidence for charm mixing has been reported by several experiments. To provide averages of these mixing results and other charm results, a new group of the Heavy Flavor Averaging Group has been formed. We here report on the method and results of averaging the charm mixing results.

1. Introduction

Almost since the discovery of charm mesons, mixing of $D^0$ and $\bar{D}^0$ mesons have been sought in analogy to the well-known $K^0 - \bar{K}^0$ mixing. Due to very effective $GIM$ suppression, the expected mixing rate in the charm system is much smaller than for kaons. Only very recently, the BaBar\cite{1} and Belle\cite{2} collaborations have reported the rst evidence for charm mixing\textsuperscript{1}. These results have renewed the interest from the theory community as the observed mixing rate could be caused by physics beyond the standard model or at least provide additional constraints on new physics.

None of the mixing measurements have a signi cant ability above four standard deviations, but several have similar precision for the mixing parameters. By combining the measurements, we therefore obtain more precise values for the mixing parameters and exclude the non-mixing hypothesis with larger con dence. Combining the different mixing measurements is not complete straightforward, since not all measurements are sensitive to the same charm mixing parameters.

The Heavy Flavor Averaging Group (HFA\textsuperscript{g}) in 2006 created a subgroup with the responsibility of providing averages of charm physics measurements. One of the high priority tasks of this group is to combine the charm mixing measurements into world-average values for the fundamental charm mixing parameters. The rst average assuming CP conservation was shown at FCNP\cite{3}. Besides those results, we here report the rst results of combining mixing measurements where we allow for CP violation.

2. Averaging Method

Mixing is present in the $D^0 - \bar{D}^0$ system if the mass eigenstates, $|p\rangle_1$ and $|p\rangle_2$, differ from the aver eigenstates, $|p\rangle_0$ and $|\bar{p}\rangle_0$. Generally one can write $|p\rangle_1 = |p\rangle_0 e^{i\theta_1}$ and $|p\rangle_2 = |p\rangle_0 e^{i\theta_2}$. The variables of fundamental interest are the mass difference, $M = |M_1 - M_2|$, and decay width difference, $\Gamma_1 - \Gamma_2$. Between the two mass eigenstates, the phase $\Delta \varphi = \arg(p_1/p_2)$ is a measure of CP violation in mixing or in the interference between $D$ mixing and decay.

The phase $\Delta \varphi$ is for the moment assumed to be independent of decay mode.

\textsuperscript{1}Shortly after the CHARM 2007 workshop additional results with evidence for charm mixing have been reported by the BaBar and CDF collaborations. In these proceedings we will summarize the status at the time of the workshop.

\textsuperscript{2}The phase $\Delta \varphi$ is for the moment assumed to be independent of decay mode.
is therefore performed by forming a \( \frac{2}{3} \) of all measured
mixing rates expressed in terms of thefundamental mixing param-
eresults. The \( \frac{2}{3} \) assume Gaussian errors, but corre-
correlations between observables in each individual measure-
ent are taken account by using the full covariance matrix for each result.

3. CP Conserving Averages

The following averages were performed by adding log likelihoods from
tests where CP conservation was assumed.

3.1. Lifetime Ratio Average

One can observe charm mixing by noticing a difference in the lifetime measured in decays to CP eigen states such as \( D^0 \to K^- \pi^+ \) and \( D^0 \to K^- \pi^+ \) and the mixed-CP decay \( D^0 \to K^- \pi^+ \). We combine six results \([2, 5, 6, 7, 8, 9]\) from such analyses. All of
these measure \( y_{CP} = \frac{M}{K} = \frac{\beta}{\alpha} \). In the limit of CP
conservation one has \( y_{CP} = y \). The average of the six
measurements is \( y_{CP} = (1.12 \pm 0.32) \times 10^{-2} \). This is
3.5 times the non-mixing hypothesis. As can be seen from Figure 1, this average is mainly driven by the recent Belle measurement.

3.2. Mixing Rate Average

Wrong-signed semi-leptonic decays provide a clean
way of searching for charm mixing, but the mea-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Measured \( y_{CP} \) values and the HFAG average.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The mixing rate from measurements using semi-leptonic \( D^0 \) decays are averaged with results from multi-body hadronic charm decays.}
\end{figure}

3.3. \((x;y)\) Average

One can measure \( x \) and \( y \) directly using a time-
dependent Dalitz plot analysis of \( D^0 \to K^0 \to K^+ \pi^- \) decays. Two measurement \([14,15]\) have been published and these have been averaged by HFAG and gives
\( x = (8.1 \pm 3.3) \times 10^{-3} \) and \( y = (3.1 \pm 2.8) \times 10^{-3} \). Combining this average with the averages above for
\( R_M \) and \( y_{CP} \) using likelihood mapped as a function of \((x;y)\) we obtain \( x = (9.2 \pm 3.4) \times 10^{-3} \) and \( y = (7.0 \pm 2.2) \times 10^{-3} \). Contours of the combined likelihood function at the levels corresponding to 1 to 5 confidence levels are shown in Figure 3. Note that the confidence levels shown correspond to two-dimensional coverage probabilities of 68.27%, 95.45%, etc., and therefore $2 \ln L = 2.30, 6.18, \text{etc.}$
other mixing results in Section 3.3 which do not depend on $K$. An additional constraint comes from a CLEO-c measurement of $\cos K = 1.09 \pm 0.66$, where a small dependence on $x$ and $y$ is ignored in the combination. Figure 4 shows the likelihood contours in $(x;y)$ after minimizing over $K$. The region around the central value is almost unchanged with respect to the result without the $D^0 ! K^+$ decays (Figure 3). This is also reflected in the overall average for $x$ and $y$ which are

$$x = (8.7^{+3.0}_{-3.4}) \times 10^{-3};$$
$$y = (6.5^{+2.1}_{-2.0}) \times 10^{-3};$$

The $D^0 ! K^+$ measurements do not contribute much to the central value, because of the poorly known phase $K$. However, they do help exclude the no-mixing hypothesis and cause the dip seen in the contours close to $(x;y) = (0;0)$. At $(x;y) = (0;0)$ we obtain $2 \ln L = 37$ with respect to the minimum. This corresponds to a significance of the combined mixing signal of 5.7.

### 3.4. Averages for $D^0 ! K^+$ Decays

As mentioned above, one can measure $x^0$ and $y^0$ using the doubly-Cabibbo suppressed (DCS) decay $D^0 ! K^+$. The likelihood functions are available for two measurements [1, 18] of this type. These are combined and give the averages $x^0 = (0.1 \pm 2.1) \times 10^{-4}$ and $y^0 = (5.7^{+2.8}_{-3.7}) \times 10^{-3}$. The corresponding likelihood contours are shown in Figure 4.

### 3.5. World Average

The combined likelihood for $D^0 ! K^+$ decays can be expressed as a function of $(x;y; K)$ ignoring the part with $x^0 < 0$. This likelihood can be combined with the likelihood from the combination of the

### 4. CP Violating Averages

Measurements of charm mixing can be done without assuming CP conservation by fitting $D^0$ and $D^*$ mesons as separate samples. Most of the measurements above have done that and we therefore can combine those to also provide constraints on the CP violating parameters. When allowing for CP violation,
the measured parameters are related slightly differently to the mixing parameters. For the lifetime ratio measurement, one has

\[ 2\gamma_{CP} = (j\bar{p}p^+ \bar{p}q^+) y \cos (j\bar{p}p^+ \bar{p}q^+) x \sin ; \]
\[ 2A = (j\bar{p}p^+ \bar{p}q^+) y \cos (j\bar{p}p^+ \bar{p}q^+) x \sin ; \]

where \( A \) is the measured relative lifetime difference for \( D^0 \to h^+ h^- \) and \( D^0 \to h^+ h^- \). For \( D^0 \to K^+ \) decays, the \( x^0 \) and \( y^0 \) measured for \( D^0 \) and \( D^0 \) are related as follows

\[ x^0 = \frac{1}{A_M} \left( \frac{1}{1} \right)^{1-4} (x^0 \cos y^0 \sin ); \]
\[ y^0 = \frac{1}{A_M} \left( \frac{1}{1} \right)^{1-4} (y^0 \cos x^0 \sin ); \]

where \( A_M = \frac{M_{CP} - M_{CP}^0}{M_{CP} + M_{CP}^0} \). For \( D^0 \to K^0 \) decays the measurement directly gives \( x, y, j\bar{p}p^+ \) and \( j\bar{p}p^+ \), while for the \( R_M \) analysis the results are not separated and therefore just measure \( R_M = (x^2 + y^2) = 2 \). The measurement of \( K \) from CLEO-c is not done separately for \( D^0 \) and \( D^0 \) mesons and is not included in the combined result allowing for CP violation.

In total 22 measurements are combined in a 2-t extract seven parameters, the four mixing and CP violation parameters, \( x, y, j\bar{p}p^+ \) and \( j\bar{p}p^+ \), and three characterizing \( D^0 \to K^+ \), namely \( x \), the DCS rate \( R_D \), and the direct decay rate asymmetry \( A_D \). The t gives \( x = 14\% \) and the following mixing parameters

\[ x = (8.4 \pm 3.2^{+3.2}_{-3.2}) \times 10^{-3}; \]
\[ y = (6.9 \pm 2.1) \times 10^{-3}; \]
\[ j\bar{p}p^+ = 0.28 \pm 0.23; \]
\[ = (0.29 \pm 0.21) \text{ rad}; \]

The mixing parameters are almost unchanged with respect to the CP conserving average. This is also seen from the confidence levels shown in Figure 7. One can also draw the 1 to 5 confidence level contour for \( j\bar{p}p^+ \) using \( x \). This is shown in Figure 8. The no-CP violation hypothesis is seen to lie well within the 1 contour.

The combined results for the \( D^0 \to K^0 \) parameters are

\[ K = 0.33^{+0.26}_{-0.21} \text{ rad}; \]
\[ R_D = (3.35 \pm 0.14) \times 10^{-3}; \]
\[ A_D = (0.3 \pm 3.31); \]

There is little change in \( x \) with respect to the CP conserving average and no evidence for direct CP violation as \( A_D \) is consistent with zero.

5. Summary

Evidence of charm mixing has been reported from several experiments in the last year. A new subgroup of HFAG has performed an average of these and other existing charm mixing results. The combined result is a signal significance in excess of 5 standard deviations and gives the mixing parameters

\[ x = (8.4 \pm 3.2^{+3.2}_{-3.2}) \times 10^{-3}; \]
\[ y = (6.9 \pm 2.1) \times 10^{-3}; \]

Figure 6: Log-likelihood function for the strong phase, \( \kappa \), from combining all mixing measurements.
Figure 8: Confidence level contours for ($|q/p|$) from combining mixing measurements with CP violation allowed.

CP violation parameters have also been combined and gives

$$|q/p| = 0.88^{+0.23}_{-0.20};$$
$$= (0.89^{+0.27}_{-0.20}) \text{rad};$$

This is fully consistent with no CP violation being present in charm mixing. HFAG intends to periodically update these averages as new results become available in order to provide the most precise mixing parameters to the community.

References

[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/0703030].
[3] A. J. Schwartz, In the Proceedings of 5th Flavor Physics and CP Violation Conference (FFCP 2007), Klied, Slovenia, 12-16 May 2007, pp 024 [arXiv:0704.2225 [hep-ex]].
[4] D. M. Asner et al. [CLEO Collaboration], Int. J. Mod. Phys. A 21, 5456 (2006) [arXiv:hep-ex/0607078].
[5] E. M. Aitala et al. [CLEO Collaboration], Phys. Rev. Lett. 83, 36 (1999) [arXiv:hep-ex/9903012].
[6] J. M. Link et al. [FOCUS Collaboration], Phys. Lett. B 485, 62 (2000) [arXiv:hep-ex/0004034].
[7] S. E. Cao et al. [CLEO Collaboration], Phys. Rev. D 65, 092001 (2002) [arXiv:hep-ex/0111024].
[8] B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 91, 121801 (2005) [arXiv:hep-ex/0306003].
[9] K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 88, 162001 (2002) [arXiv:hep-ex/0111027].
[10] E. M. Aitala et al. [CLEO Collaboration], Phys. Rev. Lett. 77, 2384 (1996) [arXiv:hep-ex/9606018].
[11] C. Cawthorn et al. [CLEO Collaboration], Phys. Rev. D 71, 077101 (2005) [arXiv:hep-ex/0502012].
[12] U. Benciveni et al. [Belle Collaboration], Phys. Rev. D 72, 071101 (2005) [arXiv:hep-ex/0507020].
[13] B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 96, 014018 (2007) [arXiv:0705.0704 [hep-ex]].
[14] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 97, 221803 (2006) [arXiv:hep-ex/0608003].
[15] B. Aubert et al. [BABAR Collaboration], arXiv:hep-ex/0607090.
[16] D. M. Asner et al. [CLEO Collaboration], Phys. Rev. D 72, 012001 (2005) [arXiv:hep-ex/0503045].
[17] L. Zhang et al. [BELLE Collaboration], Phys. Rev. Lett. 99, 131803 (2007) [arXiv:0704.1000].
[18] L. M. Zhang et al. [BELLE Collaboration], Phys. Rev. Lett. 96, 151801 (2006) [arXiv:hep-ex/0601205].