Indirect $CP$ violation results and HFAG averages

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The current status of the search for indirect $CP$ violation in the neutral D meson system at the B-factories and at LHCb is reported. The indirect $CP$ asymmetry search is performed by the measurement of the proper-time asymmetry ($A_\Gamma$) in decays of $D^0 \bar{D}^0$ mesons to $CP$ eigenstates, $K^-K^+$ and $\pi^\pm\pi^\mp$, and by $y_{CP}$, the ratio between the effective lifetime measured in decay to a $CP$ eigenstate and that to the mixed eigenstate $K\pi$. All results are consistent with the no $CP$ violation hypothesis. The latest world averages for mixing and $CP$ asymmetry in the charm sector evaluated by the Heavy Flavour Averaging Group are presented. The no mixing hypothesis is excluded at more than 12 standard deviations. The search for direct and indirect $CP$ violation in the charm sector is consistent with no $CP$ violation at 2.0% confident level.

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Introduction

The charm sector is a promising field to probe for the effect of physics beyond the Standard Model (SM). The study of neutral D mesons offers a unique opportunity to access up-type quarks in flavour-changing neutral current (FCNC) processes. In the SM, indirect $CP$ violation in the charm sector is expected to be highly suppressed, less than $O(10^{-3})$, and at first order independent of the final state. Direct $CP$ violation can be larger in SM and depends on the final state [1]. Both asymmetries can be enhanced by New Physics in principle up to $O(1\%)$ [2, 3, 4]. The charm-mixing process has recently been observed for the first time unambiguously in single measurements [5, 6]. Charge Parity ($CP$) violation, on the other hand, has yet not been observed. Evidences of direct $CP$ violation by measuring the difference of $CP$ asymmetries in singly-Cabibbo suppressed two-body decays have been reported by the LHCb and CDF experiments [7, 8], but it has not been confirmed by the most recent measurements [9, 10].

Flavour mixing occurs when the mass eigenstates ($|D_{1,2}\rangle$) differ from the flavour eigenstates and they can be written as linear combinations of the flavour eigenstates $|D_{1,2}\rangle = p |D^0\rangle \pm q |D^\ast 0\rangle$, with complex coefficients $p$ and $q$ which satisfy $|p|^2 + |q|^2 = 1$. The mixing parameters are defined as $x \equiv (m_1 - m_2)/\Gamma$ and $y \equiv (\Gamma_1 - \Gamma_2)/(2\Gamma)$, where $m_1$, $m_2$, $\Gamma_1$ and $\Gamma_2$ are the masses and the decay widths for $D_1$ and $D_2$, respectively, and $\Gamma = (\Gamma_1 + \Gamma_2)/2$. The phase convention is chosen such that $CP|D^0\rangle = -|D^\ast 0\rangle$. In the absence of $CP$ violation $q/p = 1$, $D_1$ is $CP$-even and $D_2$ is $CP$-odd.

Three types of $CP$ violating effects can be distinguished. Firstly $CP$ violation in decays occurs when the decay amplitude differs for particle and anti-particle: $|A_f/A_f^\ast| = 1 + A_d$ where $A_d$ is the contribution from direct $CP$ asymmetry. Secondly, $CP$ violation in mixing occurs when $q$ and $p$ differ ($|q/p| = 1 \pm A_m$ where $A_m$ is the mixing $CP$ contribution). Finally, $CP$ violation contribution appears due to the interference between mixing and decay amplitudes when $\phi \equiv \arg[qA_f/pA_f]$. The $CP$ direct and indirect asymmetries can be defined as

$$a_{CP}^{dir} \equiv -1/2 A_d$$

$$a_{CP}^{ind} \equiv -A_m/2 y \cos \phi + x \sin \phi.$$  \hspace{1cm} (1) (2)

From the study of the lifetime of $CP$ eigenstates and mixed eigenstates one can extract information about the mixing and $CP$ violation as they would modify the decay time distribution of $CP$ eigenstates. One of the interesting parameters is $y_{CP}$ which is defined as the ratio of the lifetime of the mixed eigenstate and a $CP$ eigenstate where the final state $(f)$ is $K^-K^+$ or $\pi^-\pi^+$,

$$y_{CP} = \frac{\tau(D^0 \rightarrow K^-\pi^+)}{\tau(D^0 \rightarrow f)} - 1 \approx \left(1 - \frac{1}{8} A_m^2\right) y \cos \phi - \frac{1}{2} A_m x \sin \phi.$$
In case of no CP violation $y_{CP}$ is equal to the $y$ mixing parameter. On the other hand, if $y_{CP}$ differs from the $y$ this is a sign of CP violation.

The other interesting parameter that one can extract from the lifetime measurements of CP eigenstates is $A_\Gamma$ defined as

$$A_\Gamma = \frac{\tau(D^0 \to f) - \tau(D^0 \to f)}{\tau(D^0 \to f) + \tau(D^0 \to f)} \approx \frac{1}{2} (A_m + A_d) y \cos \phi - x \sin \phi A_m$$

A measurement of $A_\Gamma$ differing significantly from zero is a manifestation of CP violation as it requires a non-zero value for $A_m$, $A_d$ or $\phi$. BaBar determines the parameter $\Delta Y$ instead of $A_\Gamma$ which is written as $\Delta Y = (1 + y_{CP}) A_\Gamma$. The SM predicts $A_\Gamma$ to be smaller than $10^{-4}$ while physics beyond the SM estimate $A_\Gamma$ up to $10^{-2}$.

The difference in the two final states ($K^- K^+$, $\pi^- \pi^+$) can be evaluated as

$$\Delta A_\Gamma (f(KK) - f(\pi\pi)) \approx \Delta A_d y \cos \phi + (A_m + A_d) y \Delta \cos \phi - x \Delta \sin \phi$$

Assuming both $x$ and $y$ of $\mathcal{O}(10^{-2})$, $\cos \phi = 1$ and direct CP violation at the level of $A_d/2 \approx 1\%$ would lead to a difference of the per mille. The B-factories neglect terms of $\mathcal{O}(10^{-4})$, hence they do not consider any difference between the final states. While LHCb quotes the results for the two final states, $K^- K^+$ and $\pi^- \pi^+$, separately.

## 2 Experimental measurements

The measurement of $A_\Gamma$ requires the flavour tagging of the $D^0$-$\bar{D}^0$. This is obtained using a $D^*$ sample where the $D^*$ is promptly decaying at the primary vertex into $D^0$ and a charged pion. The charge of the pion (usually called slow pion due to its low momentum compared to the pions of $D^0$ daughters) determines univocally the $D^0$ flavour.

Several types of background are found in $D^*$ samples: combinatorial background, specific background coming from mis- or partially reconstructed events, and association of a true $D^0$ with a random slow pion. The combinatorial background can be determined using the side band of the $D^0$ invariant mass. While the decays that could contribute to the specific background are studied deeply using simulated samples to determine the shape in the mass distribution, the yields are determined in the fit procedure. The latest type of background can be studied using $\Delta m$ defined as the difference of invariant mass of $D^*$ and $D^0$.

### 2.1 Measurements at the B-factories

The BaBar and Belle experiments use a similar procedure to determine the CP parameters. After a selection based on track and vertex quality, on particle identification...
(PID) and on variables that remove D candidates originating B decays, an unbinned maximum likelihood fit of \( D^0 \) invariant mass determines the background and optimizes the selection on the \( D^0 \) invariant mass and \( \Delta m \). Purities better than 98\% for \( K^-K^+ \) and 93\% for \( \pi^-\pi^+ \) are achieved. Both experiments use the full data sample collected. The total data sample contains a few hundred thousand candidates for KK, about a hundred thousand for \( \pi\pi \) and few million candidates for the Cabibbo favoured mode K\( \pi \).

At BaBar, the effective lifetimes and the parameters \( y_{CP} \) and \( \Delta Y \) are evaluated by simultaneous fit of seven samples: five tagged samples and two untagged samples for KK and K\( \pi \). The results are [11]:

\[
\begin{align*}
y_{CP} &= (0.72 \pm 0.18_{stat} \pm 0.12_{syst})\% \\
\Delta Y &= (0.09 \pm 0.26_{stat} \pm 0.06_{syst})\%
\end{align*}
\]

The result of \( y_{CP} \) shows an evidence for mixing at 3.3 \( \sigma \) and the \( \Delta Y \) parameter is compatible with 0. Thus no CP asymmetry is observed.

At Belle experiment a simultaneous binned maximum likelihood fit to all 5 tagged samples is performed to extract the effective lifetimes, \( y_{CP} \) and \( A_{\Gamma} \). The data are divided into two independent data sets due to the different vertex detector used during data taking. In addition it has been found that the \( D^0 \) lifetime has a dependence on the \( D^0 \) polar angle in the central mass frame due to dependence of the lifetime resolution function. Thus it is needed to perform the fit in bins of polar angle (\( \theta \)). The weighted average of these measurements results to be [12]:

\[
\begin{align*}
y_{CP} &= (1.11 \pm 0.22_{stat} \pm 0.11_{syst})\% \\
A_{\Gamma} &= (0.03 \pm 0.20_{stat} \pm 0.08_{syst})\%
\end{align*}
\]

The \( y_{CP} \) measurement shows a mixing at 4.5\( \sigma \). No sign of CP violation is observed as the value of \( A_{\Gamma} \) is compatible with zero.

### 2.2 The measurements at LHCb

The measurements at LHCb are performed using 1 fb\(^{-1}\) of data from a sample of \( pp \) collisions at a centre-of-mass energy of 7 TeV collected in 2011. The main selection is applied at the trigger level on the momentum, PID and impact parameter (IP) of the \( D^0 \) daughters. Only few additional offline requirements, e.g. on the track quality and on the \( \Delta m \) window, are applied.

The data sample contains almost five millions of \( K^-K^+ \) candidates and 1 million of \( \pi^-\pi^+ \). A purity of 93.6\% (91.2 \%) for KK (\( \pi\pi \)) is obtained in a region of two
standard deviations of the signal peak and $\Delta m$. The data sample is split into four independent sets depending on the magnet polarity and on two run periods due to different detector alignment and calibration conditions. The fit to determine the effective lifetime is performed independently for each data set, each flavour tag and each decay mode.

The signal yield and the background contribution are extracted from simultaneous unbinned likelihood fits of the $D^0$ invariant mass and $\Delta m$ that allow to distinguish the different background sources. One example of the mass fit results is shown in Fig. 1. The only background that is not distinguishable by the mass fit is the one due to the secondary charm. The secondaries have larger impact parameter with respect to the primary vertex than the prompt candidates as a secondary $D$ does not usually point back to the primary vertex. Thus this background can be reduced by a selection based on the topology but it can not be completely suppressed. The variable $\ln (\chi^2_{IP})$ is used. It is defined as the difference in $\chi^2$ of a given primary interaction vertex reconstructed with and without the considered particle.

The measurement of $A_T$ is performed by the measurements of the effective lifetime obtained by a simultaneous fit of proper time and $\ln (\chi^2_{IP})$. For the evaluation of the effective lifetime an acceptance correction is applied because of the bias of the measured proper-time distribution due to the trigger event selection. The acceptance is determined using a data driven method, the so-called swimming algorithm [13, 14, 15, 16]. Figure 2 shows an example of the lifetime projection for $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays.

The method is validated on a control measurement using decays to the Cabibbo favoured decay $D^0 \rightarrow K \pi$. The lifetime asymmetry is determined to be consistent with zero in accordance with the expectation.

An alternative method is used to perform $A_T$ measurement on the same data.

Figure 1: On the left, the $D^0$ invariant mass and on the right the $\Delta m$ mass difference between the reconstructed $D^*$ and $D^0$ candidates. The data are shown as points.
Figure 2: Lifetime fit projection of $D^0 \rightarrow K^-K^+$ (on the left) and $D^0 \rightarrow \pi^-\pi^+$ (on the right) candidates. The data are shown as points.

$A_\Gamma$ is evaluated by the measurement of the ratio of $D^0$ and $\bar{D}^0$ yields which can be written as

$$R(t, t + \Delta t) \approx \frac{N_{\bar{D}^0}}{N_{D^0}} \left(1 + \frac{2A_\Gamma t}{\tau_{KK}}\right) \frac{1 - e^{-\Delta t/\tau_{KK}}}{1 - e^{-2\Delta t/\tau_{KK}}}$$

where $\tau_{KK} = \tau_{K\pi}/(1 + y_{CP})$ is taken from the world average value of this quantity. By simultaneous unbinned maximum likelihood fits to the $D^0$ mass, $\Delta m$ and $\chi^2_{IP}$ one can extract the yields in each time bin. The evolution of the $D^0$ $\bar{D}^0$ yield ratio for the $K^-K^+$ and $\pi^-\pi^+$ samples are shown in Fig. 3.

The two methods are tested in many simplified simulated experiments. From several cross checks no dependence or bias, e.g. on $D^0$ kinematics or multi-PV events, are observed.

Several sources of systematics are considered, the main ones are due to the decay-time acceptance correction and due to the background description. The first is assessed by testing the sensitivity to artificial biases applied to the per-event acceptance function. The second is assessed through pseudo-experiments with varied background levels and varied generated distributions while leaving the fit model unchanged. The systematics contributions are summarized in Table 1.

The results of the four subsets are found to be in agreement with each other for the nominal fit and the $A_\Gamma$ measurements from the two methods yield consistent results. The resulting value of $A_\Gamma$ for the two final states evaluated by the main method is

$$A_{\Gamma}^{KK} = (-0.35 \pm 0.62_{\text{stat}} \pm 0.12_{\text{syst}}) \times 10^{-3}$$
$$A_{\Gamma}^{\pi\pi} = (0.33 \pm 1.06_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-3}.$$  \[5\]
Figure 3: Evolution of the of $D^0$-$\bar{D}^0$ yield ratio with decay time for $D^0 \to K^-K^+$ decays (on the left) and for $D^0 \to \pi^-\pi^+$ decays (on the right) with the two data-taking periods shown with different symbols. The line shows the linear fit to extract $A_\Gamma$ for the alternative method.

Table 1: Summary of systematic uncertainties, given as multiples of $10^{-3}$.

| Source                  | $A^{KK}_\Gamma$ | $A^{\pi\pi}_\Gamma$ |
|-------------------------|-----------------|---------------------|
| Part. rec. backgrounds  | ±0.02           | ±0.00               |
| Charm from B decays     | ±0.07           | ±0.07               |
| Other backgrounds       | ±0.02           | ±0.04               |
| Acceptance function     | ±0.09           | ±0.11               |
| Total systematic uncertainty | ±0.12       | ±0.14               |
| Total statistical uncertainty | ±0.62         | ±1.06               |

The results for both final states are consistent with zero and hence no evidence of $CP$ violation is obtained. They are also in agreement with the current world average.

3 The Heavy Flavour Averaging Group averages

The Heavy Flavour Averaging Group (HFAG) [18] provides averages for heavy flavour quantities. In particular, the Charm Physics sub-group provides averages for the $D^0$-$\bar{D}^0$ mixing and $CP$ violation parameters by combining measurements from different experiments.

The new world average of $A_\Gamma$, shown in Fig. 4, is $-0.014 \pm 0.052\%$. Thanks to the contribution of the latest measurement at per mille level by LHCb, its accuracy has been increased by more than a factor 3.
In addition, HFAG uses a global $\chi^2$-based fit of all 41 experimental observables from Belle, BaBar, CDF, CLEO and LHCb experiments to extract the theoretical parameters describing the mixing and $CP$ violation in the charm sector. Correlations among observables are accounted for by using covariance matrices provided by the experimental collaborations. Errors are assumed to be Gaussian, and systematic uncertainties among different experiments are assumed uncorrelated unless specific correlations have been identified. The fit is performed considering three different $CP$ violation assumptions: no $CP$ violation in the charm sector, allowing indirect $CP$ asymmetry contribution but no direct $CP$ violation, and allowing both direct and indirect $CP$ violation. The results presented include the latest measurements of the mixing parameters and search of $CP$ violation in the double-Cabibbo suppressed 2-body decays at LHCb [17, 6], and the latest mixing measurement at CDF [19]. All fit results are listed in Fig. 5.

Confidence contour plots in $(x, y)$ and $(|q/p|, \phi)$ planes are obtained by letting, for any point in the two-dimensional plane, all other fitted parameters take their preferred values. The resulting 1$\sigma$-5$\sigma$ contours are shown in Fig. 6 for the $CP$-conserving case and in Fig. 7 for the $CP$ violation case. In the latter fit, the no-mixing point $(x, y) = (0, 0)$ is excluded at more than 12 $\sigma$. The no $CP$ violation point $(|q/p|, \phi) = (1, 0)$ is within 1$\sigma$ with a confidence level (C.L.) at 48%. Thus the data are consistent with $CP$ conservation in mixing and in the interference between mixing and decay.

A nice way to visualize the status of search of $CP$ violation in the charm sector is plotting the direct $CP$ asymmetry by Eq. 1 versus the indirect $CP$ asymmetry defined.
Figure 5: Results of the mixing and CP violating parameters by the global fit for different assumptions concerning CP violation.

| Parameter     | No CPV | No direct CPV | CPV-allowed in DCS decays | CPV-allowed 95% CL Interval |
|---------------|--------|---------------|---------------------------|-----------------------------|
| $x$ (%)       | 0.53 $^{+0.36}_{-0.17}$ | 0.43 $^{+0.15}_{-0.16}$ | 0.39 $^{+0.16}_{-0.17}$ | [0.03, 0.68]               |
| $y$ (%)       | 0.67 ± 0.09 | 0.65 ± 0.08 | 0.67 ± 0.07 | [0.50, 0.81]               |
| $\delta_{K^\pi}$ (°) | 14.0 $^{+9.3}_{-10.5}$ | 11.2 $^{+10.2}_{-11.8}$ | 12.5 $^{+9.4}_{-11.0}$ | [-13.2, 30.5]               |
| $R_D$ (%)     | 0.350 ± 0.004 | 0.349 ± 0.004 | 0.349 ± 0.004 | [0.342, 0.357]             |
| $A_D$ (%)     | –         | –             | –             | [-3.0, 1.0]                 |
| $|q/p|$        | –         | 1.01 ± 0.01   | 0.91 $^{+0.11}_{-0.09}$ | [0.76, 1.14]               |
| $\phi$ (°)   | –         | $^{−0.3}_{+0.5}$ | $^{−10.8}_{+12.3}$ | $^{−37.4}_{+9.9}$         |
| $\delta_{K^{*\pi}}$ (°) | 19.6 $^{+22.8}_{−23.4}$ | 23.6 $^{+22.7}_{−24.2}$ | 26.8 $^{+24.2}_{−24.5}$ | $^{−21.5, 74.7}$         |
| $A_{K}$       | –         | $^{−0.16}_{+0.13}$ | $^{−0.15}_{+0.14}$ | $^{−0.43, 0.12}$         |
| $x_{12}$ (%)  | –         | 0.43 $^{+0.15}_{−0.16}$ | 0.43 $^{+0.15}_{−0.16}$ | [0.10, 0.71]             |
| $y_{12}$ (%)  | –         | 0.65 ± 0.08 | 0.65 ± 0.08 | [0.49, 0.80]               |
| $\phi_{12}$ (°) | –         | 1.0 $^{+2.0}_{−1.7}$ | 1.0 $^{+2.0}_{−1.7}$ | [−3.0, 7.8]               |

Figure 6: Two-dimensional contours for the mixing parameters (x, y), for the no CP violation assumption.

by Eq. 2. The direct contribution is mainly determined by the $\Delta A_{CP}$ measurements [7, 8, 9, 10]. The measurements of $A_{F}$ determines the indirect contribution, the contribution due to the direct CP violation to $A_{F}$ measurement is neglected. The results are shown in Fig. 8. The new world averages are $a^{dir}_{CP} = (0.015 \pm 0.052)\%$ and $a^{ind}_{CP} = (−0.033 \pm 0.120)\%$. These values are consistent with no CP violation at 2.0% confident level.
Figure 7: Two-dimensional contours for the parameters \((x, y)\) (left) and \((-q/p, \phi)\) (right), allowing for \(CP\) violation.

Figure 8: The combination plot shows the indirect asymmetry versus the direct contribution. The bands represent ±1σ intervals. The point of no \(CP\) violation (0,0) is shown as a filled circle, and two-dimensional 68% C.L., 95% C.L., and 99.7% C.L. regions are plotted as ellipses with the best fit value as a cross indicating the one-dimensional uncertainties in their centre.

4 Conclusion

The search for indirect \(CP\) violation in 2-body decays at the B-factories and at LHCb are consistent with \(CP\) conservation. The \(A_\Gamma\) measurements at LHCb for the two \(CP\)
eigenstates are in agreement with each other and compatible with zero, as predicted by the SM at this level of precision. HFAG combination excludes the no mixing hypothesis at more than 12 $\sigma$. The search of direct and indirect $CP$ violation in the charm sector is consistent with no $CP$ violation at 2.0% confident level. The next measurements at LHCb, and later from Belle II and LHCb upgrade will allow to deploy deeply the $CP$ violation search in the charm sector.

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