Measurements of $CP$ Violation and Mixing in Charm Decays at LHCb

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During run I, the LHCb experiment at the LHC, CERN, collected 1.0 fb$^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV and 2.0 fb$^{-1}$ at $\sqrt{s} = 8$ TeV, yielding the world’s largest sample of decays of charmed hadrons. This sample is used to search for direct and indirect $CP$ violation in charm and to measure $D^0$ mixing parameters. Recent measurements from several complementary decay modes are presented.

1 Introduction

The LHCb detector is a forward-arm spectrometer, with pseudo-rapidity coverage $2 < \eta < 5$, specifically designed for high precision measurements of decays of $b$ and $c$ hadrons [1]. During run I, the experiment collected 1.0 fb$^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV and 2.0 fb$^{-1}$ at $\sqrt{s} = 8$ TeV, yielding the world’s largest sample of decays of charmed hadrons. This allows $CP$ violation and mixing in charm to be studied with unprecedented precision in many complementary decay modes. The Standard Model (SM) predicts $CP$ asymmetries to be $\mathcal{O}(10^{-3})$ or less in charm interactions [2, 3]; observation of significantly larger $CP$ violating effects could indicate new physics.

For a decay $D \to f$ and its $CP$ conjugate $\bar{D} \to \bar{f}$, with amplitudes $A_f$ and $\bar{A}_f$ respectively, direct $CP$ violation is quantified by $A_d = (|A_f|^2 - |\bar{A}_f|^2)/(|A_f|^2 + |\bar{A}_f|^2)$. For $D^0$ mesons, the mass eigenstates $|D_{1,2}\rangle$, with masses $m_{1,2}$ and widths $\Gamma_{1,2}$, are defined in terms of the flavour eigenstates, $|D_0\rangle$ and $|\bar{D}_0\rangle$, as $|D_{1,2}\rangle = p|D_0\rangle \pm q|\bar{D}_0\rangle$, with $p$ and $q$ complex, satisfying $|p|^2 + |q|^2 = 1$. The rate of mixing is quantified by $x \equiv 2(m_2 - m_1)/(\Gamma_1 + \Gamma_2)$ and $y \equiv (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2)$. $CP$ violation in mixing is quantified by $A_m \equiv (|q/p|^2 - |p/q|^2)/(|q/p|^2 + |p/q|^2)$ and the interference between mixing and decay (when $f = \bar{f}$) by $\lambda_f \equiv qA_f/pA_f = |qA_f/pA_f| e^{i\phi}$.

The flavour of the $D^0$ meson at production is determined using either $D^+ \to D^0 \pi^+_s$ decays, where the charge of the “soft pion”, $\pi_s$, track gives the $D^0$ flavour, or $B \to D^0 \mu^- X$ decays, where the charge of the $\mu$ track gives the $D^0$ flavour.

2 Multi-body $D$ decays

Multi-body $D$ decays are sensitive to $CP$ violation due to the interference of different resonances across the multi-body phase space. In $D^0 \to K^+K^-\pi^+\pi^-$ decays, triple products of final state particle momenta in the $D^0$ rest frame, defined as $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ and
Thus, no evidence for CP violation in this way, using 1 fb$^{-1}$ of data, for which the nominal binning scheme yields a p-value of 72%. Similarly, binning in the decay time of the D$^0$ candidates and performing the same test gives sensitivity to indirect CP violation. This yields a p-value of 72%, so there is no evidence for direct or indirect CP violation.

A complementary method for studying CP violation in multi-body D meson decays is to examine CP asymmetries across the multi-body phase space directly. Signal yields are obtained in bins of the multi-body phase space, and the test statistic $S_{CP} \equiv (N_i(D^0) - \alpha N_i(D^0))/\sqrt{\alpha(N_i(D^0) + N_i(D^0))}$, calculated in each bin $i$, where $\alpha \equiv N(D^0)/N(D^0)$ cancels any global production and detection asymmetries. A $\chi^2$ test for consistency across the phase space is performed, yielding a p-value of 74%. Similarly, binning in the decay time of the D$^0$ candidates and performing the same test gives sensitivity to indirect CP violation. This yields a p-value of 72%, so there is no evidence for direct or indirect CP violation.

3 CP violation in D$^\pm(s)$ → K$^0_s h^\pm$

The singly-Cabibbo-suppressed (SCS) decays D$^\pm$ → K$^0_s$K$^\pm$ and D$^\pm$ → K$^0_s$π$^\pm$ offer a means of measuring direct CP violation with high precision. The CP asymmetry is defined as
\[ A_{CP}^{D^+ \rightarrow K^0 S} = (\Gamma(D^+ \rightarrow K^0 h^+) - \Gamma(D^+ \rightarrow K^0 h^-)) / (\Gamma(D^+ \rightarrow K^0 h^+) + \Gamma(D^+ \rightarrow K^0 h^-)), \]
while the measured asymmetry is
\[ A_{CP}^{D^+ \rightarrow K^0 S} \equiv (N_{D^+ \rightarrow K^0 S}^{\text{signal}} - N_{D^+ \rightarrow K^0 S}^{\text{background}}) / (N_{D^+ \rightarrow K^0 S}^{\text{signal}} + N_{D^+ \rightarrow K^0 S}^{\text{background}}) \]
\[ \simeq A_{CP}^{D^+ \rightarrow K^0 S} + A_{\text{prod}}^{D^+ \rightarrow K^0 S} + A_{\text{det}}^{D^+ \rightarrow K^0 S}. \]

Here \( N_{\text{signal}} \) is the number of signal candidates of the given decay, \( A_{CP}^{D^+ \rightarrow K^0 S} \) is the production asymmetry of the \( D^+ \) meson, \( A_{\text{det}}^{D^+ \rightarrow K^0 S} \) is the detection asymmetry of the \( h^\pm \) meson, and \( A_{CP}^{D^+ \rightarrow K^0 S} \) is the combined detection and \( CP \) asymmetry of the \( K^0 \) meson. Assuming negligible \( CP \) violation in the Cabibbo-favoured (CF) decays \( D^+ \rightarrow K^0 S \), \( D^\pm \rightarrow K^0 S \pi^\pm \) and \( D^0 \rightarrow \phi \pi^\pm \), the production and detection asymmetries cancel in the double difference
\[ A_{CP}^{D^0 \rightarrow K^0 S} \equiv \left( A_{\text{meas}}^{D^0 \rightarrow K^0 S} - A_{\text{meas}}^{D^0 \rightarrow K^0 S} \right) - \left( A_{\text{meas}}^{K^0 \rightarrow S} - A_{\text{meas}}^{K^0 \rightarrow S} \right) - 2A_{K^0}, \]
\[ = A_{CP}^{D^0 \rightarrow K^0 S} + A_{\text{prod}}^{D^0 \rightarrow K^0 S} + A_{\text{det}}^{D^0 \rightarrow K^0 S}, \]
while the \( K^0 \) asymmetry is calculable, so the sum of the \( CP \) asymmetries can be measured. Similarly the individual \( CP \) asymmetries can be accessed using
\[ A_{CP}^{D^+ \rightarrow K^0 S} = \left( A_{\text{meas}}^{D^+ \rightarrow K^0 S} - A_{\text{meas}}^{D^+ \rightarrow K^0 S} \right) - \left( A_{\text{meas}}^{K^0 \rightarrow S} - A_{\text{meas}}^{K^0 \rightarrow S} \right) - A_{K^0}. \]
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Using 3 fb\(^{-1}\) of data the results thus obtained are
\[ A_{CP}^{D^+ \rightarrow K^0 S} = (+0.41 \pm 0.49(\text{stat}) \pm 0.26(\text{syst}))%, \]
\[ A_{CP}^{D^0 \rightarrow K^0 S} = (+0.03 \pm 0.17(\text{stat}) \pm 0.14(\text{syst}))%, \]
\[ A_{CP}^{D^0 \rightarrow K^0 S} = (+0.38 \pm 0.46(\text{stat}) \pm 0.17(\text{syst}))%. \]
These are the most precise measurements of their kind to date and show no evidence of \( CP \) violation.

## 4 Mixing and \( CP \) violation in \( D^0 \rightarrow h^+ h^-(\ell^-) \) decays

Decays of \( D^0 \rightarrow h^+ h^- h^- \) provide a means of measuring direct and indirect \( CP \) violation, as well as mixing, in the \( D^0 \) system. The measured \( CP \) asymmetry in \( D^0 \rightarrow K^+ K^- \) and \( D^0 \rightarrow \pi^+ \pi^- \) decays, flavour tagged using \( B \rightarrow D^0 \mu^- X \) decays, is \( A_{CP}^{D^0 \rightarrow h^+ h^-} = A_{CP}^{D^0 \rightarrow h^+ h^-} + A_{\text{det}}^{h^+ h^-} + A_{\text{prod}}^{h^+ h^-} \).

The \( \pi^+ \pi^- \) and \( K^+ K^- \) final states are \( CP \) eigenstates, so have no detection asymmetry. Defining \( \Delta A_{CP}^{D^0 \rightarrow h^+ h^-} = A_{CP}^{D^0 \rightarrow h^+ h^-} - A_{CP}^{D^0 \rightarrow K^+ K^-} - A_{CP}^{D^0 \rightarrow \pi^+ \pi^-} \), the \( CP \) asymmetry cancels. Similarly to the analysis described in Sec. 3, \( CP \) decays can be used to cancel nuisance asymmetries as \( A_{CP}^{D^0 \rightarrow K^+ K^-} = A_{\text{meas}}^{D^0 \rightarrow K^+ K^-} - A_{\text{meas}}^{D^0 \rightarrow \pi^+ \pi^-} - A_{\text{det}}^{D^0 \rightarrow \pi^+ \pi^-} + A_{\text{det}}^{D^0 \rightarrow K^+ K^-} \), and \( A_{CP}^{D^0 \rightarrow \pi^+ \pi^-} \) can be calculated using the asymmetries of \( D^+ \rightarrow K^+ \pi^- \) and \( D^0 \rightarrow K^0_\pi^+ \) decays, and the known \( A_{K^0} \). The asymmetry \( A_{CP}^{D^0 \rightarrow \pi^+ \pi^-} \) can then be determined using \( A_{CP}^{D^0 \rightarrow \pi^+ \pi^-} = A_{CP}^{D^0 \rightarrow K^+ K^-} - \Delta A_{CP} \).
Using 3 fb\(^{-1}\) of data yields\(^9\)

\[
\Delta A_{CP} = (+0.14 \pm 0.16\text{(stat)} \pm 0.08\text{(syst)})\% ,
\]

\[
A_{CP}^{D^0 \rightarrow K^+K^-} = (-0.06 \pm 0.15\text{(stat)} \pm 0.10\text{(syst)})\% ,
\]

\[
A_{CP}^{D^0 \rightarrow \pi^+\pi^-} = (-0.20 \pm 0.19\text{(stat)} \pm 0.10\text{(syst)})\% .
\]

Indirect \(CP\) violation in \(D^0 \rightarrow K^+K^-\) and \(D^0 \rightarrow \pi^+\pi^-\) decays can be measured using

\[
A_{F} \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow f)} \approx \eta_{CP} \left[ \frac{1}{2}(A_{m} + A_{d})y \cos \phi - x \sin \phi \right].
\]

Here, \(\hat{\Gamma}\) is the inverse of the effective lifetime of the decay and \(\eta_{CP}\) is the \(CP\) eigenvalue of \(f\).

The effective lifetimes are measured directly using a data-driven, per-candidate correction for the selection efficiency on 1 fb\(^{-1}\) of data, yielding\(^10\)

\[
A_{F}(\pi\pi) = (+0.033 \pm 0.010\text{(stat)} \pm 0.014\text{(syst)})\% ,
\]

\[
A_{F}(KK) = (-0.035 \pm 0.062\text{(stat)} \pm 0.012\text{(syst)})\% .
\]

Thus, no evidence for direct or indirect \(CP\) violation in \(D^0 \rightarrow h^+h^-\) decays is found.

Mixing in the \(D^0\) system is measured using the ratio of the decay rates of “wrong sign” \(D\)CS \(D^0 \rightarrow K^+\pi^-\) to “right sign” \(CP\) \(D^0 \rightarrow K^-\pi^+\) as a function of \(D^0\) decay time, as

\[
R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2,
\]

where \(R_D = \left|\frac{A_{DCS}}{A_{CP}}\right|^2\), \(x' = x \cos(\delta) + y \sin(\delta)\), \(y' = -x \sin(\delta) + y \cos(\delta)\), and \(\delta = \arg\left(\frac{A_{DCS}}{A_{CP}}\right)\).

Using 3 fb\(^{-1}\) of data yields\(^11\)

\[
x'^2 = (5.5 \pm 4.9) \times 10^{-5}, y' = (4.8 \pm 1.0) \times 10^{-3}, R_D = (3.568 \pm 0.066) \times 10^{-3}.
\]

Allowing for \(CP\) violation yields:

\[
A_D \equiv (R_D(D^0) - R_D(D^0))/R_D(D^0) - R_D(D^0) = (-0.7 \pm 1.9)\% ,
\]

\[
0.75 < |q/p| < 1.24, (68.3\% \text{ CL}).
\]

These are the most precise measurements of mixing in the \(D^0\) system and of \(CP\) violation in \(D^0 \rightarrow K^+\pi^-\) decays to date.

5 Conclusions

There is a rich programme of charm physics studies at the LHCb experiment, with many complementary measurements already performed using some or all the 3 fb\(^{-1}\) of data collected during run I. No evidence for \(CP\) violation has been found, though constraints of \(O(10^{-3})\) have been achieved in many decay modes. Mixing in the \(D^0\) system has also been measured to unprecedented precision. With run II shortly to begin, and the LHCb upgrade in the near future, there are great prospects for future measurements with precisions of \(O(10^{-4})\), which will tightly constrain, or potentially discover, new physics.

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