MIXING AND CP VIOLATION IN CHARM MESONS AT LHCb*

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In 2019, LHCb reported the first observation of direct CP violation in the charm sector. As of yet indirect CP violation has not been observed but measurements of this and mixing is essential to our understanding of the Standard Model. We report on the latest measurements of CP violation and mixing in charm mesons from LHCb and present prospects for future measurements.

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1. Introduction

Charge-Parity (CP) violation is a key requirement for the generation of the baryon–antibaryon asymmetry in the early Universe. Although CP violation has been observed in a range of physics processes, it has only recently been observed in the decay of charm mesons at the LHCb [1]. Despite this observation of direct CP violation, indirect CP violation remains elusive.

2. Mixing and CP violation in charm

Mixing occurs because the mass eigenstates $|D_{1,2}\rangle$ of the neutral mesons are a superposition of the flavour eigenstates $|D^0\rangle$ and $|\bar{D}^0\rangle$

$$|D_{1,2}\rangle = p\left|D^0\right\rangle \pm q\left|\bar{D}^0\right\rangle , \tag{1}$$

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where the two complex coefficients satisfy $|p|^2 + |q|^2 = 1$. From this, the time evolution of the flavour eigenstates is given by

$$\left|D^0(t)\right\rangle = g_+(t)\left|D^0\right\rangle + \frac{q}{p}g_-(t)\left|\bar{D}^0\right\rangle , \tag{2}$$

$$\left|\bar{D}^0(t)\right\rangle = \frac{p}{q}g_-(t)\left|D^0\right\rangle + g_+(t)\left|\bar{D}^0\right\rangle , \tag{3}$$

where

$$g_\pm(t) = \mathrm{e}^{-iMt}\mathrm{e}^{i\Gamma t/2}\left[{}^{\cos}_{\sin}\left(-i(x+iy)\Gamma t/2\right)\right] . \tag{4}$$

Mixing is governed by the mixing parameters, x and y, found in Eq. (4), where

$$x = \frac{m_2 - m_1}{2\Gamma} \quad \text{and} \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} . \tag{5}$$

CP violation can occur predominantly through three mechanisms: direct CP violation, where $|\bar{A}_{\bar{f}}/A_f| \neq 1$; CP violation in mixing, where $|q/p| \neq 1$; and CP violation in interference between mixing and decay, where $\phi \equiv \arg\left(\frac{q\bar{A}_{\bar{f}}}{pA_f}\right) \neq 0$.

3. Observation of CP violation at the LHCb

In 2019, the LHCb Collaboration reported on the first observation of CP violation in the charm sector [1], with a significance of 5.3σ.

The analysis measured CP violation in decays of the D^0 to a pair of pions or kaons ($D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$) [1]. Two production methods of the D^0 were considered. The first is prompt production where the D^0 originates from a D^{*+} at the primary vertex ($D^{*+} \to D^0\pi^+$). This sample is also referred to as the pion tagged sample as the initial flavour of the D^0 is determined from the soft pion charge. The second is semileptonic where the D^0 originates from a B meson ($B^- \to D^0\mu^-\bar{\nu}_\mu X$). This sample is also referred to as the muon tagged sample as the initial flavour of the D^0 is determined from the charge of the muon. The used data sample is that collected by LHCb during Run 2 of the LHC. In total 44 million prompt and 9 million semileptonic $D^0 \to K^+K^-$ decays are used; and 14 million prompt and 3 million semileptonic $D^0 \to \pi^+\pi^-$ are used.

CP violation is observed by measuring the relative difference of the widths of the D mesons to the respective final states

$$A_{\mathrm{CP}} = \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\bar{D}^0 \to \bar{f}\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\bar{D}^0 \to \bar{f}\right)} . \tag{6}$$

[1] Unless specified, charge conjugation is implied throughout.

However what is measured at the LHCb is

$$A_{\mathrm{raw}} \equiv \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}} \,. \tag{7}$$

This is not the same as A_{CP}, and A_{raw} can be approximated as

$$A_{\mathrm{raw}} \sim A_{\mathrm{CP}} + A_{\mathrm{prod}} + A_{\mathrm{det}} \,, \tag{8}$$

where A_{prod} is the production asymmetry that accounts for any asymmetries in the production of D^0 mesons relative to $\bar{D}^0$, and A_{det} is the detection asymmetry due to different reconstruction efficiencies between positive and negative tagging pions and muons.

To a very accurate approximation, A_{prod} and A_{det} are independent of the final state when the kinematics of the final state is identical. A multidimensional re-weighting procedure is applied to match the kinematics of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ final states.

Therefore, by measuring the difference between A_{CP} for the K^+K^- and $\pi^+\pi^-$ final states, we obtain

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{raw}}\left(K^-K^+\right) - A_{\mathrm{raw}}\left(\pi^-\pi^+\right) \,. \tag{9}$$

The difference of time-integrated CP asymmetries of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays is measured. The results are

$$\Delta A_{\mathrm{CP}}^{\pi-\mathrm{tagged}} = [-18.2 \pm 3.2\,(\mathrm{stat.}) \pm 0.9\,(\mathrm{syst.})] \times 10^{-4} \,, \tag{10}$$

$$\Delta A_{\mathrm{CP}}^{\mu-\mathrm{tagged}} = [-9 \pm 8\,(\mathrm{stat.}) \pm 5\,(\mathrm{syst.})] \times 10^{-4} \,. \tag{11}$$

Both measurements are in good agreement with the world average and previous LHCb results. By making a full combination with previous LHCb measurements [2, 3], the following value of ΔA_{CP} is obtained:

$$\Delta A_{\mathrm{CP}} = (-15.4 \pm 2.9) \times 10^{-4} \,. \tag{12}$$

This value differs from zero by more than 5.3 standard deviations and hence constitutes the first observation of CP violation in the decay of charm hadrons.

4. Latest LHCb measurements

Since the first observation of CP violation in the charm hadron by LHCb, there has been a variety of further measurements of CP violation and mixing in the charm sector.

4.1. Mixing and CP violation in $D^0 \to K_S^0\pi^+\pi^-$

Using 2.3×10^6 $D^0 \to K_\mathrm{S}^0\pi^+\pi^-$ prompt and semileptonic decays collected during Run 1 of the LHC, the LHCb Collaboration measured the mixing parameters in charm decays [4]. The observables are defined as

$$x_\mathrm{CP} = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right], \tag{13}$$

$$\Delta x = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right], \tag{14}$$

$$y_\mathrm{CP} = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right], \tag{15}$$

$$\Delta y = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]. \tag{16}$$

In the limit of CP symmetry (*i.e.* $\phi = 0$ and $|p/q| = 1$), then $x, y = x_\mathrm{CP}, y_\mathrm{CP}$ and $\Delta x, \Delta y = 0$. Therefore, any significant discrepancies between x, y and $x_\mathrm{CP}, y_\mathrm{CP}$ would indicate CP violation.

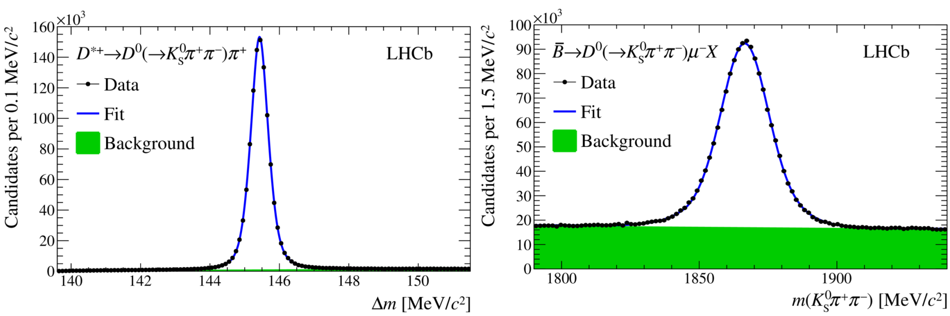

Fig. 1. Invariant mass fits for prompt (left) and semileptonic (right) decays of $D^0 \to K_\mathrm{S}^0\pi^+\pi^-$.

The measured values are

$$x_\mathrm{CP} = [2.7 \pm 1.6\,(\mathrm{stat.}) \pm 0.4\,(\mathrm{syst.})] \times 10^{-3}, \tag{17}$$

$$y_\mathrm{CP} = [7.4 \pm 3.6\,(\mathrm{stat.}) \pm 1.1\,(\mathrm{syst.})] \times 10^{-3}, \tag{18}$$

$$\Delta x = [-0.53 \pm 0.70\,(\mathrm{stat.}) \pm 0.22\,(\mathrm{syst.})] \times 10^{-3}, \tag{19}$$

$$\Delta y = [0.6 \pm 1.6\,(\mathrm{stat.}) \pm 0.3\,(\mathrm{syst.})] \times 10^{-3}, \tag{20}$$

and from this, we can derive

$$x = \left(2.7^{+1.7}_{-1.5}\right) \times 10^{-3}. \tag{21}$$

Finally, when this measurement is combined with the world average, there is evidence of a mass difference between the neutral charm-meson eigenstates

$$x = \left(3.9^{+1.1}_{-1.2}\right) \times 10^{-3} . \tag{22}$$

4.2. Time-dependent CP violation in $D^0 \to h^+h^-$

Using 5.4 fb^{-1} of data taken during Run 2 (2015–2016) of the LHCb detector, decays of $D^0 \to \pi^+\pi^-/K^+K^-$ from semileptonic decays of the B meson were used to measure the time-dependent CP violation parameter A_Γ [5]. The definition of A_Γ is

$$\begin{aligned} A_{\mathrm{CP}}(f,t) &= \frac{\Gamma\left(D^0 \to f,t\right) - \Gamma\left(\bar{D}^0 \to f,t\right)}{\Gamma\left(D^0 \to f,t\right) + \Gamma\left(\bar{D}^0 \to f,t\right)} \\ &\approx a_{\mathrm{CP}}^{\mathrm{dir}}(f) - \frac{t}{\tau_{D^0}} A_\Gamma(t) . \end{aligned} \tag{23}$$

Standard Model predictions state $A_\Gamma \approx 3.5 \times 10^{-5}$ [6].

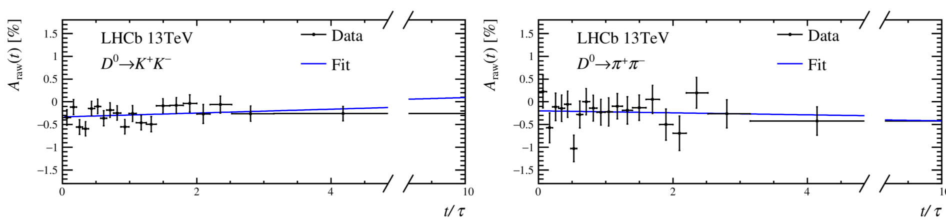

Fig. 2. Measurement of A_Γ using Run 2 semileptonic decays of $D^0 \to \pi^+\pi^-/K^+K^-$ [5].

When combined with Run 1 results [2, 3], we obtain

$$A_\Gamma\left(K^+K^-\right) = (-4.4 \pm 2.3 \pm 0.6) \times 10^{-4} , \tag{24}$$

$$A_\Gamma\left(\pi^+\pi^-\right) = (2.5 \pm 4.3 \pm 0.7) \times 10^{-4} . \tag{25}$$

5. Outlook for LHCb

The outlook for the physics programme of LHCb is very promising. Run 3 will begin in 2022 and provide 5–10 times the sensitivity to direct and indirect CP violation in charm. For decay-dependent CP violation in particular, effects not deriving from the Standard Model could be highlighted. A new detector and trigger system will help with much greater efficiency in some channels and hopefully provide greater statistics.

Looking ahead to Upgrade II, this will come with a huge gain in statistics and allow measurements with incredible precision of the CP violation parameters. Figure 3 shows the potential precision q/p that is expected at the end of data taking at the LHCb [7].

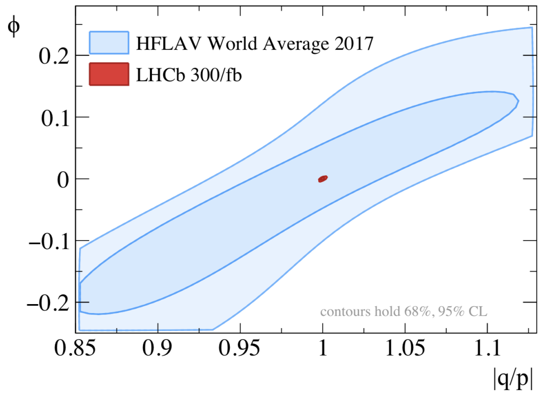

Fig. 3. Potential precision of CP violation parameters measurements.

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