PROCEEDINGS OF SCIENCE

Mixing and CP violation in charm decays at LHCb

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LHCb has collected the world's largest sample of charmed hadrons. This sample is used to measure $D^0-\overline{D}^0$ mixing and to search for direct and indirect CP violation. New measurements from several decay modes are presented, as well as prospects for future sensitivities.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

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PoS(ICHEP2016)528

1. Introduction

The mass eigenstates of the neutral D meson system are not aligned with the flavor eigenstates, leading to particle-antiparticle oscillations, otherwise known as mixing. The system can be parameterized as

$$|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\overline{D}^0\rangle\,, \tag{1.1}$$

where p and q are complex coefficients satisfying $|p|^2+|q|^2=1$. Mixing is generally described by the unitless parameters

$$x = 2\frac{m_2-m_1}{\Gamma_1+\Gamma_2},\, y = \frac{\Gamma_2-\Gamma_1}{\Gamma_1+\Gamma_2}, \tag{1.2}$$

where $m_{1,2},\Gamma_{1,2}$ are the masses and widths of the mass eigenstates of the system. In the Standard Model, the expectations for both x and y are expected to be at or less than half a percent. Charge-parity violation (CPV) can manifest itself in the neutral D system in three ways. First, one can have CP violation in the decay of the D meson, known as direct CPV. There can also be the violation of CP in the oscillation rates of the D^0 to its antiparticle, corresponding to $\left|\frac{q}{p}\right| \neq 1$, or $\phi = \arg(q/p) \neq 0$. Finally, one can have CPV in the interference between mixing and decay. The final two are often referred to as indirect CPV. The standard model prediction of CPV in any case in this system is at or below 10^{-3}. Any deviation from these predictions would be a sign for possible new physics contributions.

Experimentally, direct CPV is accessible by measuring the raw asymmetry between the number of D^0 decays to a final state f, $D^0 \to f$, and the CP conjugate process $\overline{D}^0 \to \overline{f}$:

$$A_{\rm raw} = \frac{N(D^0\to f)-N(\overline{D}^0\to\overline{f})}{N(D^0\to f)+N(\overline{D}^0\to\overline{f})}. \tag{1.3}$$

The CP asymmetries are then extracted by controlling any other detection or production asymmetries which could enter. Mixing and indirect CPV are accessible by measuring the time dependence of the decays of the D^0 and $\overline{D}^0$ mesons separately and understanding the time evolution of their differences. We present two analyses searching for CPV in the neutral D meson system: the first searching for direct CPV in the decays of $D^0\to K^-K^+$ and subsequently $D^0\to\pi^-\pi^+$, and the second searching for mixing and CPV with the time dependent ratio of $D^0\to K^+\pi^-$ to $D^0\to K^-\pi^+$ decays. Both use the 3 fb^{-1} dataset collected by the LHCb experiment in 2011 and 2012 at center of mass energies $\sqrt{s}=7$ and 8 TeV.

2. Measurement of CP asymmetry in $D^0\to K^-K^+$ decays

LHCb had previously searched for direct CP violation in the decays of $D^0\to K^-K^+$ and $D^0\to\pi^-\pi^+$ originating from semileptonic b-hadron decays [1]. In this most recent analysis [2], the search for direct CPV is performed for D^0 mesons originating from $D^{*+}\to D^0\pi^+$ decays that originate directly from pp collisions. As LHCb is an experiment based at a hadron collider, there are non-negligible production and detection asymmetries which could bias the CPV measurement. Such asymmetries are assessed using the control channels $D^{*+}\to D^0\pi^+$, with $D^0\to K^-\pi^+$, $D^+\to K^-\pi^+\pi^+$, and $D^+\to\overline{K}^0\pi^+$. Unless explicitly stated, the inclusion of charge-conjugate decays is implied. By successive weightings of these datasets, all production asymmetries cancel, and the

CP asymmetry of the $D^0 \to K^- K^+$ decay is given by the difference in raw yields of this decay and the control channels, namely

$$\begin{aligned} A_{CP}(D^0 \to K^- K^+) =& A_{raw}(D^0 \to K^- K^+) - A_{raw}(D^{*+} \to D^0 \pi^+, D^0 \to K^- \pi^+) \\ &+ A_{raw}(D^+ \to K^- \pi^+ \pi^+) - A_{raw}(D^+ \to \overline{K}^0 \pi^+) + A_D(\overline{K}^0). \end{aligned} \tag{2.1}$$

The final term takes into account the differing cross-sections of K^0 and $\overline{K}^0$ with matter. By combining with the previous result for $\Delta A_{CP} = A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$, the *CP* asymmetry $A_{CP}(D^0 \to \pi^- \pi^+)$ is accessible. The measurement extracts both *CP* asymmetries and LHCb reconstructs roughly 5.5 million $D^0 \to K^- K^+$ candidates, 1 million $D^+ \to \overline{K}^0 \pi^+$ and greater than 35 million $D^0 \to K^- \pi^+$ and $D^+ \to K^- \pi^+ \pi^+$ candidates. The number of candidates is determined from an unbinned maximum likelihood fit to either the D^+ invariant mass or the $\delta m = m(D^0 \pi^+) - m(D^0)$. The D^0 and $\overline{D}^0$ samples are fit simultaneously to extract the raw asymmetry. The weighting method to cancel production and detection asymmetries uses a successive weighting procedure:

1. The $D^+ \to K^- \pi^+ \pi^+$ sample is weighted to match the kinematics of the $D^+ \to \overline{K}^0 \pi^+$ sample.

2. The $D^0 \to K^- \pi^+$ sample is weighted to match kinematics of the the $D^+ \to K^- \pi^+ \pi^+$ sample

3. The $D^0 \to K^- K^+$ sample is weighted to match the kinematics of the $D^0 \to K^- \pi^+$ sample

Weightings of previous steps are accounted for in each successive weighting step, and a step is repeated to improve agreement if necessary. The details of the weighting procedure are described in more detail in [2].

The extracted *CP* asymmetry for the $D^0 \to K^- K^+$ sample is measured to be

$$A_{CP}(D^0 \to K^- K^+) = (0.14 \pm 0.15 \pm 0.10)\,\%, \tag{2.2}$$

where the first uncertainty is statistical, and the second is systematic. The dominant systematic uncertainties come from the weighting configurations and the cancellation of nuisance asymmetries.

In combination with the previous ΔA_{CP} measurement [4], the value of the time integrated *CP* asymmetry in $D^0 \to \pi^- \pi^+$ is determined to be

$$A_{CP}(D^0 \to \pi^- \pi^+) = A_{CP}(D^0 \to K^- K^+) - \Delta A_{CP} = (0.24 \pm 0.15 \pm 0.11)\,\%. \tag{2.3}$$

Finally, the results are combined with those from the previous analysis from semileptonic *b*-hadron decays [1] including all correlations between the different samples. The resulting combination is

$$A_{CP}^{\text{comb}}(D^0 \to K^- K^+) = (0.04 \pm 0.12 \pm 0.10)\,\%, \tag{2.4}$$
$$A_{CP}^{\text{comb}}(D^0 \to \pi^- \pi^+) = (0.07 \pm 0.14 \pm 0.11)\,\%. \tag{2.5}$$

The comparison between the this measurement and the previous analysis is shown in Figure 1 The result is consistent with no *CP* violation.

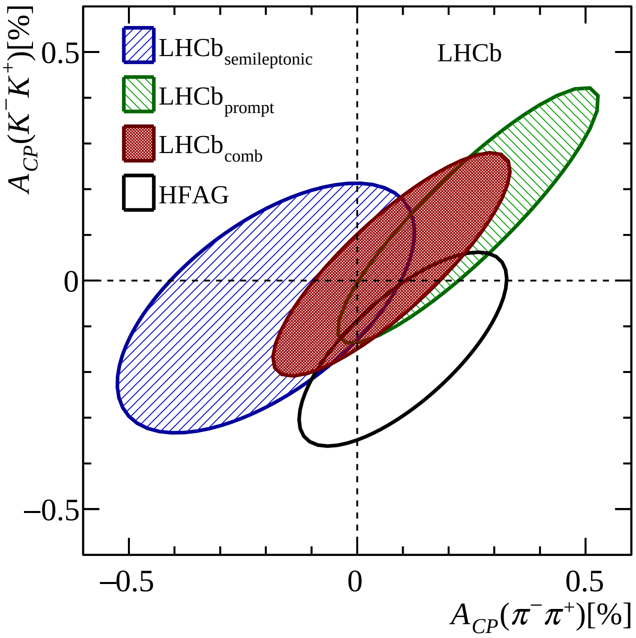

Figure 1: Contours corresponding to 68% confidence level this measurement (green), the previous measurement from semileptonic b-hadron decay [1] (blue), the average of the two measurements (red), and the comparison to the world average [3].

3. Search for mixing and *CP* violation with wrong-sign $D^0 \to K^\pm\pi^\mp$ from semileptonic b-hadron decays

Mixing and CPV in the D^0 system can be measured using the ratio of $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ decays, and corresponding charge-conjugate decays. The first decay is called "Right Sign" (RS), as it proceeds via Cabibbo favored (CF) tree level decays. The second decay is called "Wrong Sign" (WS), as the decay can either proceed directly to the final state via doubly-Cabibbo-suppressed (DCS) tree level decay, or the D^0 meson can first mix to the antiparticle $\overline{D}^0$, then proceed via Cabibbo favored decay. The time dependence of the WS to RS ratio, under the assumption of small x and y, can then be written as

$$R(t) = R_D + \sqrt{R_D}y'(t/\tau) + \frac{x'^2 + y'^2}{4}(t/\tau)^2. \tag{3.1}$$

The terms x' and y' are equal to x and y rotated by the strong phase difference $\delta_{K\pi}$ between DCS and CF decays. The parameter t is the measured D^0 decay time, τ is the mean D^0 lifetime, and R_D is the ratio of DCS to CF amplitudes. The first term of the equation is influenced only by the DCS/CF amplitudes, the last term is influenced purely by mixing, and the central term by an interference of the two. By measuring the WS/RS time dependent ratio separately for D^0 and $\overline{D}^0$ mesons, then taking the difference, one can directly access both direct CPV in the system which would represent an offset at $t = 0$, and indirect CPV, which would manifest itself as a difference in the time dependence of the two ratios. This is summarized by adding a charge to each of the fitted parameters

$$R^{\pm}(t) = R_D^{\pm} + \sqrt{R_D^{\pm}}y'^{\pm}(t/\tau) + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}(t/\tau)^2. \tag{3.2}$$

In the case of no CPV, $R^+ = R^-$, $y'^+ = y'^-$, and $(x'^+)^2 = (x'^-)^2$. In the case of no direct CPV, $R^+ = R^-$, and in the case of all CPV allowed, all parameters vary independently. We fit the data with each of these three assumptions.

Previously, LHCb measured the time dependent WS/RS ratio using D^0 mesons produced from prompt $D^{*+} \to D^0\pi^+$ decays [5]. This analysis [6] extends the previous analysis of Ref. [5] by considering decays originating from $\overline{B} \to D^{*+}\mu^- X$, with $D^{*+} \to D^0\pi^+$ and $D^0 \to K^{\pm}\pi^{\mp}$. As the D^0 meson originates from the decay of a b-hadron, the decay is largely unbiased by the trigger with respect to D^0 decay time and provides a complementary sample to that of the prompt D^* analysis by anchoring the measurement at low decay time. The flavor of the D^0 at production is tagged twice, once by the charge of the μ candidate originating from the b-hadron decay, and once by the charge of the pion originating from the D^* decay. Such a doubly-tagged (DT) sample provides an extremely clean WS and RS mass distribution. Candidates which enter both the DT and prompt samples are vetoed from the DT sample to ensure disjoint datasets and easier combination.

The number of RS and WS decays are extracted from a binned maximum likelihood fit to the D^{*+} invariant mass. The dataset contains roughly 1.7×10^6 RS and 6.7×10^3 WS doubly-tagged decays. The fit is performed in 5 bins of decay time with roughly equal populations of RS decays, and the WS and RS yields are extracted for events tagged at production as a D^0 and as a $\overline{D}^0$. The ratio of the yields of the DT sample, after accounting for efficiency corrections and including the effects of misidentification and combinatoric backgrounds is fit assuming the three hypotheses described above. The resulting fit is consistent with no CPV. The data are then fit simultaneously with that of the previous prompt result [5]. The projections of this fit are shown in Figure 2 and the fit results are shown in Table 1. In all cases, the data is consistent with no CPV, and the errors in the combined fit reduce by about 10 – 20% with the addition of the DT dataset, even though it is only about 3% of the size.

4. Conclusions and outlook

The searches for direct CPV in $D^0 \to K^-K^+$ and for mixing and CPV in WS $D^0 \to K\pi$ are both consistent with no CPV. With Run II of the LHC now underway, the LHCb detector is collecting data which will lead to more and more precise measurements of CPV in the system. Through 2015, LHCb has already reconstructed 4.6 billion charm decays [7], and more are on the way.

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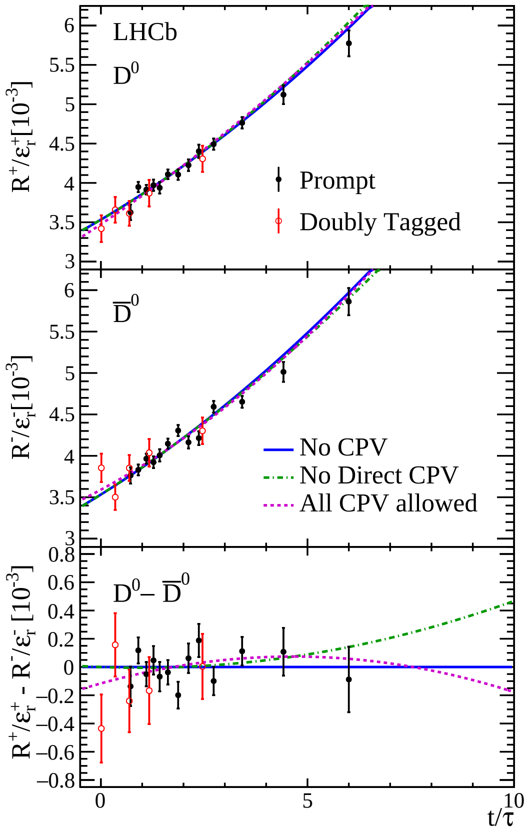

Figure 2: Efficiency-corrected projections of the simultaneous fit to the prompt [5] and DT datasets. The top plot shows the fit to candidates tagged as a D^0 at production, the center for candidates tagged as a $\overline{D}^0$, and the bottom shows the difference between the two fits.

Table 1: Parameters of the three simultaneous fits to the DT and prompt datasets. Included in the table is the previous prompt only result [5] for comparison.

Parameter	DT + Prompt	Prompt-only
	No CPV	
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067
$x'^2[10^{-5}]$	3.6 ± 4.3	5.5 ± 4.9
$y'[10^{-3}]$	5.23 ± 0.84	4.8 ± 0.9
χ^2/ndf	96.6/111	86.4/101
	No direct CPV	
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067
$(x'^+)^2\,[10^{-5}]$	4.9 ± 5.0	6.4 ± 5.6
$y'^+[10^{-3}]$	5.14 ± 0.91	4.8 ± 1.1
$(x'^-)^2\,[10^{-5}]$	2.4 ± 5.0	4.6 ± 5.5
$y'^-[10^{-3}]$	5.32 ± 0.91	4.8 ± 1.1
χ^2/ndf	96.1/109	86.0/99
	All CPV allowed	
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095
$(x'^+)^2\,[10^{-5}]$	1.1 ± 6.5	4.9 ± 7.0
$y'^+[10^{-3}]$	5.97 ± 1.25	5.1 ± 1.4
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090
$(x'^-)^2\,[10^{-5}]$	6.1 ± 6.1	6.0 ± 6.8
$y'^-[10^{-3}]$	4.50 ± 1.21	4.5 ± 1.4
χ^2/ndf	95.0/108	85.9/98

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