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Measurements of CP violation in charm decays at LHCb

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The copious amount of D-meson decays collected by the LHCb experiment, opens the doors to measurements with sensitivities close to the Standard Model expectations for CP violation in charm. Latest results on CP violation searches at the LHCb experiment are reported. No hint of CP violation has been found so far.

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1. Introduction

Charm physics is a unique probe to test the flavour sector in the Standard Model (SM), being the charm quark the only up-type quark where the flavour mixing can occur. Thus, the precise exploration of the charm sector is totally complementary to the same studies carried on *B*- and *K*-meson systems, providing a unique window for improving our knowledge of the flavour structure within the SM. Charm physics can be used to search for physics beyond the SM, as a matter of fact the New Physics could couple to the up-sector only, resulting masked in the well-known *B*- and *K*-meson systems, although the large experimental effort done in the past. The current experimental sensitivity achieved in charm measurements is definitively approaching (or even exceeding) the theoretical expectation for *CP* violation in charm $\mathcal{O}(10^{-3})$ [1, 2, 3], and the LHCb experiment, by collecting huge data samples of D decays $\mathcal{O}(10^7)$, plays a leading role in the game.

The LHCb detector [4] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector elements that are particularly relevant to charm analyses are: a silicon-strip vertex detector surrounding the pp interaction region that allows c- and b-hadrons to be identified from their typicall long flight distance; a tracking system that provides a measurement of momentum, p, of charged particles; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons.

2. D^0–$\overline{D}^0$ system

The neutral meson mass eigenstates $|D_{1,2}\rangle$ are linear combinations of the strong interaction eigenstates $|D^0\rangle$ and $|\overline{D}^0\rangle$, $|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\overline{D}^0\rangle$,where $|D_{1,2}\rangle$ have masses $m_{1,2}$ and widths $\Gamma_{1,2}$. The complex coefficients p and q satisfy the equation $|p|^2 + |q|^2 = 1$. This mixing permits, during the time-evolution, that a $|D^0\rangle$ can turn into $|\overline{D}^0\rangle$ and *vice-versa*, generating an *oscillation* between the flavour. This oscillations are controlled by the following two dimensionless parameters: $x = (m_1 - m_2)/\Gamma$ and $y = (\Gamma_1 - \Gamma_2)/(2\Gamma)$, where $\Gamma = (\Gamma_1 + \Gamma_2)/2$ is the average width. The current experimental average values of x and y are $x = (0.37 \pm 0.16)\%$ and $y = (0.66^{+0.07}_{-0.10})\%$ (*CPV*-allowed) as report by the Heavy Flavor Averaging Group collaboration [5].

Three different types of *CP* violation are possible: *CP* violation in decay, in mixing and in interference. The *CP* violation in the decay, occurs when the probability of a D^0 decaying to a final state f is different from that one of a $\overline{D}^0$ decay to $\overline{f}$. If the probability of a D^0 oscillating to $\overline{D}^0$ is different from the probability of the opposite process ($\overline{D}^0 \to D^0$), *CP* violation in the mixing occurs, resulting in $|q/p| \neq 1$. When a final state f can be reached both from D^0 and $\overline{D}^0$, the interference between the direct decay and the path proceeding through the mixing can happen, providing the necessary phases for a manifestation of *CP* violation.

3. Charm-mixing in D^0-multibody decay

The first observation (by a single experiment) of the D^0-mixing has been performed using $D^0 \to K^-\pi^+$ decays [6]. Here the first measurement of such phenomenon is reported by studying multi-body decays of the D^0 meson. The analysis uses the full Run I data sample, corresponding to 3fb^{-1} of integrated luminosity, recorded by the LHCb experiment in 2011 and 2012 [7]. The, so-called, right sign (RS) $D^0 \to K^-\pi^+\pi^-\pi^+$ decays and the wrong-sign (WS) $D^0 \to K^+\pi^-\pi^+\pi^-$ decays are reconstructed[1]. A time-dependent analysis is performed measuring the ratio (at the second order in t/τ) of the WS decay mode to the RS mode:

$$R(t) = \frac{\Gamma(t;D^0 \to K^+\pi^-\pi^+\pi^-)}{\Gamma(t;D^0 \to K^-\pi^+\pi^-\pi^+)} \approx r_D^2 - r_D R_D \cdot y' \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2, \tag{3.1}$$

where t is the proper decay-time of the D^0 meson, τ is D^0 lifetime, and r_D gives the phase space averaged ratio of DCS to CF amplitudes. The parameters y' and R_D are defined by $y' \equiv y\cos\delta^{K3\pi} - x\sin\delta^{K3\pi}$, where $\delta^{K3\pi}$ is the average strong phase difference, $R_D e^{i\delta^{K3\pi}} \equiv \langle\cos\delta\rangle + i\langle\sin\delta\rangle$ where δ is the phase difference of the ratio of the DCS to the CF amplitude, averaged over phase space. The D-meson flavour at the production is determined by reconstructing the strong decay chain $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$, where the pion charge tags the flavour. In total, 11×10^6 of $D^0 \to K^-\pi^+\pi^-\pi^+$ and 42×10^3 of $D^0 \to K^+\pi^-\pi^+\pi^-$ decays are reconstructed and the mass difference between the D^{*+} mass and the D^0 mass is reported in Fig. 1. The ratio of eq. (3.1) is shown in Fig. 1 (right); the no-mixing hypothesis is rejected at 8.2σ level. This represents the first observation of the D^0-$\overline{D}^0$ oscillations in a four-body decay. In addition, the values r_D and $R_D \cdot y'$ are measured (unconstrained): $r_D = (5.67 \pm 0.12) \times 10^{-2}$, $R_D \cdot y' = (0.3 \pm 1.8) \times 10^{-3}$, which are the most precise determination to date.

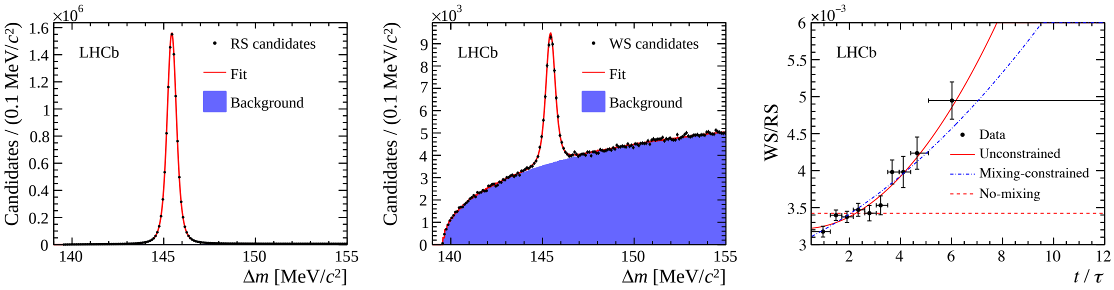

Figure 1: $\Delta m \equiv m(D^{*+}) - m(D^0)$ distribution for right-sign decays (left) and for wrong-sign decays (middle). Ratio of RS to WS decays with the results of the unconstrained (solid), mixing-constrained (dashed/dotted), and no-mixing (dashed) fits superimposed. In mixing-constrained fit the parameters x and y are constrained to the world average values [5].

4. Time-dependent *CP*-asymmetry

The *CP* violation of D^0 mesons could manifest itself into a different decay rate, Γ, for the D^0 and the $\overline{D}^0$ to a certain final state, f. An useful observable to test this at high precision level is the time-dependent asymmetry:

$$A_{CP}(t;f) = \frac{\Gamma(t;D^0 \to f) - \Gamma(t;\overline{D}^0 \to f)}{\Gamma(t;D^0 \to f) + \Gamma(t;\overline{D}^0 \to f)}. \tag{4.1}$$

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[1] Charge conjugated decays are implied.

Due to the slow mixing rate, equation (4.1) can be approximated [8] at the first order as

$$A_{CP}(t;f) \approx A_{CP}^{\text{dir}} - \frac{t}{\tau} A_\Gamma, \tag{4.2}$$

where A_{CP}^{dir} denotes the direct *CP* violation (see next section), τ is the D^0 lifetime, and the linear decay-time term A_Γ is related to mixing parameters by the following epression

$$A_\Gamma \approx (A_{CP}^{\text{mix}}/2 - A_{CP}^{\text{dir}}) y \cos\phi - x \sin\phi, \tag{4.3}$$

where $A_{CP}^{\text{mix}} = |q/p|^2 - 1$ describes the *CP* violation in the mixing. The weak phase ϕ describes *CP* violation in the interference between mixing and decay. The D^0-meson decays into K^+K^- and $\pi^+\pi^-$ final states are reconstructed in the decay of B-mesons, $B \to D^0\mu^- X$, where the charge of the muon is used to infer the flavour of the D^0. In total 2.34×10^6 $D^0 \to K^+K^-$ and 0.79×10^6 $D^0 \to \pi^+\pi^-$ are reconstructed in the full LHCb Run I data sample of 3fb^{-1}. The raw asymmetry of these yields as function of the D^0 decay time is measured. Then, from a straight line fit, the value of A_Γ is measured to be [8]:

$$\begin{aligned} A_\Gamma(K^+K^-) &= (-0.134 \pm 0.077^{+0.026}_{-0.034})\%, \\ A_\Gamma(\pi^+\pi^-) &= (-0.092 \pm 0.145^{+0.025}_{-0.033})\%; \end{aligned} \tag{4.4}$$

where the first uncertainties are statistical and the second systematic. These results are in agreement with the hypothesis of no *CP* violation.

5. Time-integrated *CP* asymmetries

The time-independent term of decay rates asymmetry, as reported in eq. (4.2), is related to the direct *CP* violation, therefore a measurement of the time-integrated *CP* asymmetry, is desirable, although it is entangled to the mixing component. Experimentally, the raw asymmetry can be measured by counting the number of reconstructed D^{*+} and D^{*-} decays (strong $D^{*\pm}$ decays are used to infer the flavour of D^0 mesons) as follows:

$$\begin{aligned} A_{\text{raw}}(f) &= \frac{N(D^{*+} \to D^0(\to f)\pi^+) - N(D^{*-} \to \overline{D}^0(\to f)\pi^-)}{N(D^{*+} \to D^0(\to f)\pi^+) + N(D^{*-} \to \overline{D}^0(\to f)\pi^-)} \\ &\approx A_{CP}(f) + A_{\text{det}}(\pi) + A_{\text{prod}}(D^{*+}), \end{aligned} \tag{5.1}$$

where $A_{\text{det}}(\pi)$ is the detection asymmetry for the tagging pion and $A_{\text{prod}}(D^{*+})$ is the production asymmetry for the D^{*+}. Measuring $A_{\text{det}}(\pi)$ and $A_{\text{prod}}(D^{*+})$ with a sensitivity of $\mathcal{O}(10^{-3})$ is experimentally challenging, thus, to achieve such a precision the difference between the *CP* asymmetry of the $D^0 \to K^+K^-$ decays and the $D^0 \to \pi^+\pi^-$ decays is exploited. In this way, the D^{*+} production asymmetry and the detection asymmetry of tagging pions cancel out in the difference, giving ΔA_{CP}:

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-). \tag{5.2}$$

About 7.7×10^6 $D^0 \to K^+K^-$ decays and 2.5×10^6 $D^0 \to \pi^+\pi^-$ are reconstructed, in the full Run I data sample of LHCb, corresponding to 3fb^{-1}, as shown in Fig. 2. The measured value of ΔA_{CP} is found to be [9]:

$$\Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%, \tag{5.3}$$

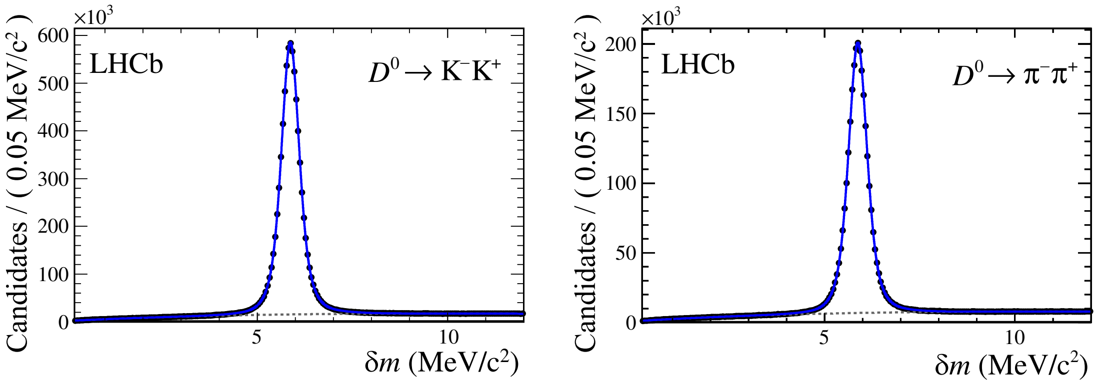

Figure 2: $\Delta m \equiv m(D^{*+}) - m(D^0)$ distribution for $D^0 \to K^+K^-$ decays (left) and for $D^0 \to \pi^+\pi^-$ decays (right).

where the first uncertainty is statistical and the second one is systematic. The results is compatible with the no-*CP*-violation hypothesis and represents the most precise determination to date of this observable.

6. Conclusion

The large amount of *D*-meson decays collected by the LHCb experiment, in Run I, allows reaching sensitivities close to the SM expectation for charm *CP* violation, in certain cases already even below $\mathcal{O}(10^{-3})$. Enormous samples of charm decays will be collected by LHCb in the current Run II and in the future LHCb-Upgrade. This will provide the unique opportunity to study more deeply the dynamics of charm decays, increasing our knowledge of SM and our sensitivity to possible virtual contribution from new particles.

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