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CP violation in the charm sector at LHCb

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Summary. — The copious amount of D mesons decays collected by the LHCb experiment opens the doors to measurements with sensitivities close to the Standard Model expectations for charm CP violation. The latest results on charm CP violation searches are reported. So far, no hint of CP violation has been found.

1. – Introduction

Charm physics is a unique probe to test the flavour sector in the Standard Model (SM). Charm hadrons provide the only sector involving up-type quarks where CP violation effects are expected to be observable, making it complementary to the B and K meson systems to study flavour structure in the Standard Model. Recently, with the huge data sample of D meson decays collected by the LHCb experiment, the current sensitivity reached in charm CP violation measurements is approaching (or even exceeds) the theoretical expectation for CP violation in charm, which is expected to be of the order of $\mathcal{O}(10^{-3})$ [1, 2].

The LHCb detector [3] 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 characteristically 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.

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2. – D-Mixing and CP violation formalism

The neutral D meson mass eigenstates $|D_{1,2}\rangle$ are linear combinations of the strong interaction eigenstates $|D^0\rangle$ and $|\overline{D}^0\rangle$,

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

$|D_{1,2}\rangle$ 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*, thus generating an *oscillation* of the flavour. These oscillations are controlled by the following two dimensionless parameters:

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

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 reported by the Heavy Flavor Averaging Group collaboration [4].

Three different types of CP violation are distinguished: CP violation in the decay, in the mixing and in the interference between decay and mixing. CP violation in the decay occurs when the probability of a D^0 decaying to a final state f is different from a $\overline{D}^0$ decay to $\overline{f}$. If the probability of a D^0 oscillating to $\overline{D}^0$ is different from the opposite process ($\overline{D}^0 \to D^0$) we speak of CP violation in the mixing: this occurs if $|q/p| \neq 1$. When a final state f can be reached both from D^0 and $\overline{D}^0$, there is an interference between the direct decay and the path proceeding through the mixing, which depends on the phase in the CKM matrix responsible for CP violation.

3. – Time-dependent CP-asymmetry

The CP violation of D^0 mesons could manifest itself with a different decay rate, Γ, for the D^0 and the $\overline{D}^0$ decaying to a final CP eigenstate, f. A useful observable to test this is the asymmetry

$$A_{CP}(t; f) = \frac{\Gamma(t; D^0 \to f) - \Gamma(t; \overline{D}^0 \to f)}{\Gamma(t; D^0 \to f) + \Gamma(t; \overline{D}^0 \to f)}. \tag{1}$$

Due to the slow mixing rate, eq. (1) is approximated as [5]

$$A_{CP}(t; f) \approx A_{CP}^{\mathrm{dir}} - \frac{t}{\tau} A_\Gamma, \tag{2}$$

where A_{CP}^{dir} is related to the direct CP violation (see next section), τ is the D^0 lifetime and A_Γ is the asymmetry between effective decay widths

$$A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\overline{D}^0 \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)} \approx \frac{y}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi - \frac{x}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi, \tag{3}$$

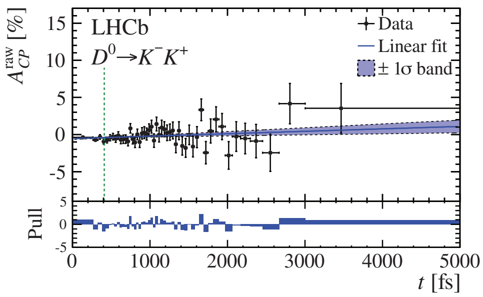

Fig. 1. – Raw CP asymmetry as function of D^0 decay time for $D^0 \to K^+K^-$ (left) and $D^0 \to \pi^+\pi^-$ right. Results of χ^2 fit to a straight line are reported in blue. The green dashed lines indicate the D^0 lifetime.

where the direct CP violation contribution has been neglected [2], $\phi = \arg((q\overline{A}_f)/(pA_f))$ where $\overline{A}_f(A_f)$ is the amplitude of $D^0 \to f(\overline{D}^0 \to f)$ decay and the effective decay widths is $1/\hat{\Gamma} \equiv \int t\Gamma(t)\,\mathrm{d}t/\int \Gamma(t)\mathrm{d}t$.

The time-dependent asymmetry has been measured by the LHCb collaboration in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ two-body decays. The flavour of D^0 mesons is inferred from the charge of the muon in semileptonic $B \to D^0\mu^- X$ decays. In total 2.34×10^6 $D^0 \to K^+K^-$ and 0.79×10^6 $D^0 \to \pi^+\pi^-$ decays are reconstructed in the full LHCb Run I data sample corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$. The raw asymmetry between D^0 and $\overline{D}^0$ yields is measured as function of the D^0 proper decay time, see fig. 1, and a χ^2 fit to a straight line model is performed to extracted the value of A_Γ. The results are

$$\begin{aligned} A_\Gamma(K^+K^-) &= (-0.134 \pm 0.077^{+0.026}_{-0.034})\%, \\ A_\Gamma(\pi^+\pi^-) &= (-0.092 \pm 0.145^{+0.025}_{-0.033})\%, \end{aligned} \tag{4}$$

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

4. – Time-integrated CP asymmetries

CP violation can be tested also in the time-independent term of the decay rates asymmetry $A_{CP}^{\rm dir}$, which is related to the direct CP violation in the decay, see eq. (2). Experimentally the raw asymmetry between the number of reconstructed D^{*+} and D^{*-} is measured (strong $D^{*+} \to D^0\pi^+$ decays are used to infer the flavour of D^0 mesons):

$$\begin{aligned} A_{\rm raw}(f) &= \frac{N(D^{*+} \to D^0(\to f)\pi^+) - N(D^{*-} \to \overline{D}^0(\to f)\pi^-)}{N(D^{*+} \to D^0(\to f)\pi^+) + N(D^{*-} \to \overline{D}^0(\to f)\pi^-)} \\ &\approx A_{CP}(f) + A_{\rm det}(\pi) + A_{\rm prod}(D^{*+}). \end{aligned} \tag{5}$$

$A_{\rm det}(\pi)$ is the detection asymmetry for the tagging pion and $A_{\rm prod}(D^{*+})$ is the production asymmetry for the D^{*+}.

Measuring $A_{\rm det}(\pi)$ and $A_{\rm prod}(D^{*+})$ with a sensitivity of $\mathcal{O}(10^{-3})$ is experimentally challenging. Thus, to achieve such a precision the difference between the CP asymmetry

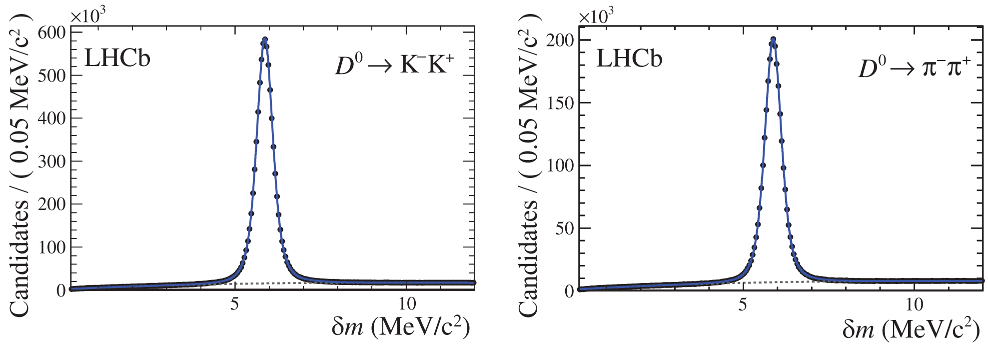

Fig. 2. – $\Delta m \equiv m(D^{*+}) - m(D^0)$ distribution for $D^0 \to K^+K^-$ decays (left) and for $D^0 \to \pi^+\pi^-$ decays (right).

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 in the difference, giving ΔA_{CP}:

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx A_{\mathrm{raw}}(K^+K^-) - A_{\mathrm{raw}}(\pi^+\pi^-). \tag{6}$$

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

$$\Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%, \tag{7}$$

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.

5. – Summary

The large amount of D^0 meson decays collected by the LHCb experiment during the Run I allow to reach sensitivities close to the Standard Model expectation for charm CP violation (below $\mathcal{O}(10^{-3})$). Soon the remaining measurements with the Run I data sample will be completed, and then with the enormous charm samples collected by LHCb in the current Run II new exciting measurements in the charm sector are expected.

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