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Charm physics at LHCb

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Summary. — An overview of the latest LHCb's measurements in the charm physics sector is presented. This includes searches for rare decays, measurements of direct and indirect *CP*-violating observables and precise determination of mixing parameters using "wrong-sign" $D^0 \to K^+\pi^-$ decays.

PACS `13.20.Fc` – Decays of charmed mesons.
PACS `13.25.Ft` – Decays of charmed mesons.
PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.

1. – Introduction

Processes involving K and $B_{(s)}$ mesons have always been regarded as the most interesting probe of flavor and *CP* violation. Indeed, within the standard model the largest flavor- and *CP*-violating effects reside in systems involving down-type quarks, where charged-current loops dominated by the heavy top quark communicate the symmetry violation. However, while these properties hold in the standard model, there is no good reason for them to be true if new physics is present at the electroweak scale. In particular, it is quite plausible that new-physics contributions affect mostly the up-type sector, possibly in association with the mechanism responsible for the large top mass [1]. Hence, decays of D mesons represent a unique probe of new-physics flavor effects, quite complementary to tests in K and B systems.

Since flavor- and *CP*-violating processes in the charm sector are much more suppressed than in K and $B_{(s)}$ sectors, huge and clean samples of D decays are needed to search for possible new-physics contributions. These can currently be accessed only at hadron-collider experiments. LHCb has therefore a broad programme of charm physics, which includes searches for rare decays, studies of *CP* violation and mixing, as well as spectroscopy and measurements of production cross-sections.

In the following an overview of the most recent results is presented.

2. – Rare decays

The LHCb collaboration has recently published several searches for rare charm decays using the sample of pp collisions, corresponding to $1\,\mathrm{fb}^{-1}$ of integrated luminosity, collected during 2011 [2]:

$$\begin{aligned}\mathcal{B}(D^0 \to \mu^+\mu^-) &< 6.8\times10^{-9} \text{ at 95\% CL},\\ \mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &< 6.7\times10^{-7} \text{ at 95\% CL},\\ \mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) &< 8.3\times10^{-8} \text{ at 95\% CL},\\ \mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) &< 4.1\times10^{-7} \text{ at 95\% CL}.\end{aligned}$$

In all cases the measurements are several orders of magnitude above the standard-model predictions, but, improving existing limits from the B-factories by about a factor of fifty, provide more stringent constraint on possible new-physics models [3].

3. – Direct CP violation

Direct CP violation occurs when the magnitudes of a given decay amplitude is different from the magnitude of the amplitude for the corresponding CP-conjugated decay. The early evidence for large direct CP violation in singly-Cabibbo-suppressed D^0 decays to two charged hadrons [4] has not been confirmed by later results based on the data sample collected during 2011 [5, 6]. Recently, LHCb reported an updated measurement of the difference between time-integrated CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays, $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$, using the full Run I data set, corresponding to $3\,\mathrm{fb}^{-1}$ of integrated luminosity [7]. In this analysis, neutral D mesons are reconstructed from a semileptonic b-hadron decay, so that the flavor at production time can be determined by the charge of the accompanying charged lepton. Together with ΔA_{CP}, the analysis also measures the individual CP asymmetries, $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$, by subtracting spurious detector and production asymmetries with control samples of Cabibbo-favored D decays where CP violation can be neglected. The results,

$$\begin{aligned}\Delta A_{CP} &= [+0.14 \pm 0.16(\text{stat.}) \pm 0.08(\text{stat.})]\,\%,\\ A_{CP}(K^+K^-) &= [-0.06 \pm 0.15(\text{stat.}) \pm 0.10(\text{stat.})]\,\%,\\ A_{CP}(\pi^+\pi^-) &= [-0.20 \pm 0.19(\text{stat.}) \pm 0.10(\text{stat.})]\,\%,\end{aligned}$$

further increase the consistency of the available data with the hypothesis of CP symmetry in two-body charm decays [8], as also shown in fig. 1.

In addition to two-body final states, LHCb also exploits multi-body decays to search for CP violation. These are particularly interesting as they offer the opportunity to study effects localized in phase space, providing sensitivity to phenomena that might be "washed out" in global decay rate asymmetries. LHCb performed searches for local CP asymmetries in Cabibbo-suppressed three-body $D^+ \to \pi^+\pi^-\pi^+$ [10] and four-body $D^0 \to \pi^+\pi^-\pi^+\pi^-$ and $D^0 \to K^+K^-\pi^+\pi^-$ decays [11], using the data collected during 2011. Neutral D mesons are here reconstructed using the $D^{*+} \to D^0\pi^+$ decay, so that the production flavor is determined by the charge of the accompanying pion. In all cases, local CP violation is searched using a model-independent binned method, while for the D^+ case also an unbinned technique has been developed, providing consistent

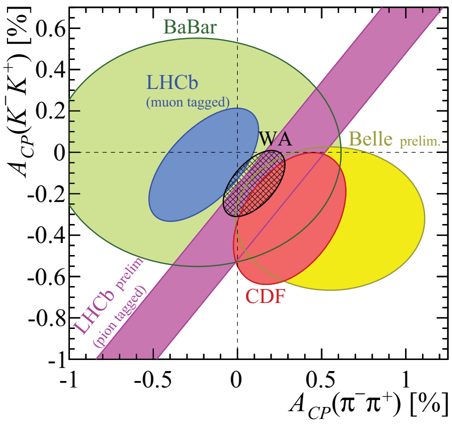

Fig. 1. – Overview of 68% CL contours from measurements of *CP*-violating asymmetries in D^0 decays to two charged hadrons [5,7,9]. The world average (WA) neglects any effect from indirect *CP* violation.

results [10]. The binned method divides the multi-body phase space into n independent volumes ("bins") and defines an asymmetry significance for each as

$$S_{CP}^i = \frac{N^i(D) - \alpha N^i(\overline{D})}{\sqrt{N^i(D) + \alpha^2 N^i(\overline{D})}},$$

where N^i is the number of candidates in the bin i and $\alpha = \sum_i N^i(D)/\sum_i N^i(\overline{D})$ is used to remove any global asymmetry. This procedure makes the search insensitive to global *CP* asymmetries, but also to any unwanted production and/or detection asymmetry that does not vary across the phase space. In absence of local *CP* violation, S_{CP}^i would be distributed as a normal distribution. The no-*CP*-violation hypothesis is tested by computing a p-value from $\chi^2 = \sum_i \left(S_{CP}^i\right)^2$ with $n-1$ degrees of freedom. Different binning schemes are tested and p-values are found to exceed 50%, 40% and 9% in the $D^+ \to \pi^+\pi^-\pi^+$, $D^0 \to \pi^+\pi^-\pi^+\pi^-$ and $D^0 \to K^+K^-\pi^+\pi^-$ cases, respectively.

4. – Mixing and indirect CP violation

Building upon the previous measurement of charm mixing parameters in $D^0 \to K^+\pi^+$ decays [12], LHCb performed an updated measurement of charm mixing and searched for time-dependent *CP* violation using the full data sample consisting of $3\,\mathrm{fb}^{-1}$ of integrated luminosity collected during Run I [13]. *CP* violation in $D^0 - \overline{D}^0$ mixing is searched by comparing the decay-time-dependent ratio of "wrong-sign" $D^{*+} \to D^0(\to K^+\pi^-)\pi^+$ to "right-sign" $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ rates with the corresponding ratio for the charge-conjugate processes. In the limit of $|x|, |y| \ll 1$, and assuming negligible *CP* violation, the decay-time dependence of this ratio is approximated by

$$R(t) \approx R_D + \sqrt{R_D}\; y' \;\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2,$$

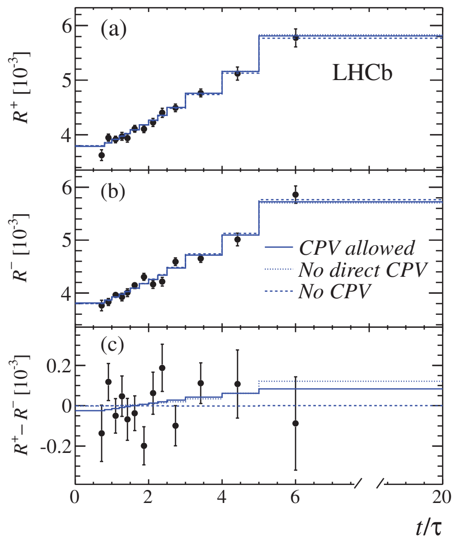

Fig. 2. – Ratios of wrong-sign to right-sign yields for (a) D^0 decays, (b) $\overline{D}^0$ decays, and (c) their differences as functions of decay time in units of D^0 lifetime. Projections of fits allowing for (dashed line) no *CP* violation, (dotted line) no direct *CP* violation, and (solid line) full *CP* violation are overlaid. The abscissa of the data points corresponds to the average decay time over the bin; the error bars indicate the statistical uncertainties.

where τ is the average D^0 lifetime. The parameters x' and y' depend linearly on the mixing parameters as $x' \equiv x\cos\delta + y\sin\delta$ and $y' \equiv y\cos\delta - x\sin\delta$. The parameter R_D and the strong phase δ are related to the decay amplitudes as $\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\overline{D}^0 \to K^+\pi^-) = -\sqrt{R_D}e^{-i\delta}$. Allowing for *CP* violation, the rates $R^+(t)$ and $R^-(t)$ of initially produced D^0 and $\overline{D}^0$ mesons are functions of independent sets of mixing parameters ($R_D^\pm$, $x'^{2\pm}$, $y'^\pm$), where $x'^\pm = |q/p|^{\pm1}(x'\cos\phi \pm y'\sin\phi)$ and $y'^\pm = |q/p|^{\pm1}(y'\cos\phi \mp x'\sin\phi)$ and ϕ is the relative week phase between q/p and $\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\overline{D}^0 \to K^+\pi^-)$. Direct *CP* violation would produce a difference between R_D^+ and R_D^-, which can be quantified by the direct *CP* asymmetry $A_D = (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$. Violation of *CP* symmetry either in mixing ($|q/p| \neq 1$) or in the interference between mixing and decay amplitudes ($\phi \neq 0$) are usually referred to as indirect *CP* violation and would result in differences between (x'^{2+}, y'^+) and (x'^{2-}, y'^-). The measured RS-to-WS ratios as a function of time, shown in fig. 2, are consistent with *CP* conservation as no difference between $R^+(t)$ and $R^-(t)$ is found. This translates into the world's most precise bounds on $|q/p|$ and A_D from a single experiment:

$$0.75 < |q/p| < 1.24 \text{ at } 68.3\% \text{ CL}, \qquad A_D = (-0.7 \pm 1.9)\%.$$

Assuming *CP* conservation, the mixing parameters are measured to be $x'^2 = (5.5 \pm 4.9) \times 10^{-5}$, $y' = (4.8 \pm 1.0) \times 10^{-3}$, and $R_D = (3.568 \pm 0.066) \times 10^{-3}$. The reported interval and uncertainties include both statistical and systematic components.

Indirect *CP* violation is also searched by measuring the asymmetry between the effective lifetimes of D^0 and $\overline{D}^0$ mesons decaying into *CP* eigenstates [14], such as $D^0 \to h^+h^-$

decays with $h = K$ or π:

$$A_\Gamma = \frac{\hat{\tau}(\overline{D}^0 \to h^+h^-) - \hat{\tau}(D^0 \to h^+h^-)}{\hat{\tau}(\overline{D}^0 \to h^+h^-) + \hat{\tau}(D^0 \to h^+h^-)} \approx \frac{y}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi - \frac{x}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi.$$

The sample of neutral D mesons from a $D^{*+} \to D^0\pi^+$ decays collected during 2011 is fit with a multi-dimensional unbinned likelihood to separate the signal from the relevant backgrounds and determine the value of A_Γ. The measured values, separately for the two final states, are consistent with zero and thus with CP symmetry:

$$A_\Gamma(D^0 \to K^+K^-) = [-0.35 \pm 0.62(\text{stat.}) \pm 0.12(\text{stat.})] \times 10^{-3},$$
$$A_\Gamma(D^0 \to \pi^+\pi^-) = [+0.33 \pm 1.06(\text{stat.}) \pm 0.14(\text{stat.})] \times 10^{-3}.$$

These are the world's most precise measurement of this quantity to date. No difference between the two final states is observed, as expected from Standard Model predictions.

5. – Conclusions

Thanks to the world's largest, high-purity samples of charm decays collected during Run I in both hadronic and (semi)leptonic final states, LHCb has already shown its potential to substantially improve the precision on all the key observables of the charm physics sector in the next years. Major advances will be made in the coming months since the full Run I data sample has not yet been fully analyzed and additional data will soon be collected in the forthcoming LHC runs.

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