PROCEEDINGS OF SCIENCE

Charm Physics at LHCb

Marianna Fontana[*†]
CERN
E-mail: marianna.fontana@cern.ch

An overview of the latest LHCb's measurements in the charm sector is presented. This includes measurements of angular and CP -violating observables, as well as spectroscopy and production studies in the charmed baryon sector.

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*Speaker.
†On behalf of the LHCb collaboration.

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1. Introduction

Processes involving K and $B_{(s)}$ mesons have always been regarded as the most interesting probe of flavour and CP violation. Indeed, within the standard model (SM) the largest flavour- and CP-violating effects reside in systems involving down-type quarks, where charged-current loops are dominated by the heavy top quark. However, the mixing of neutral D mesons probing flavour changing neutral currents (FCNC) between up-type quarks, could be affected by beyond-the-SM physics in fundamentally different ways to the down-type quarks. Hence, decays of D mesons represent a unique probe of new physics (NP) flavour effects, quite complementary to tests in K and $B_{(s)}$ systems. Since flavour- 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 NP 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 production measurements. In the following an overview of the most recent results is presented.

2. Measurement of angular and *CP* asymmetries in $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays

Particularly sensitive to NP contribution are the rare decays of multibody charm mesons. The branching fraction of $D^0 \to h^+h^-\mu^+\mu^-$ decays is dominated by Long Distance (LD) contributions ($\mathcal{O}(10^{-6})$), when the muons are originating from a resonance, while the Short Distance (SD) contributions, which in the SM proceeds through a FCNC, are only effective away from the vector meson regions ($\mathcal{O}(10^{-9})$). In addition to the search studies, multibody rare decays are particularly interesting to study CP and angular asymmetries, which could be enhanced by some NP effects up to $\mathcal{O}(1\%)$ level [1]. Among all the possible angular observables that can be constructed, the forward-backward asymmetry of the dimuon system (A_{FB}), and the triple-product asymmetry ($A_{2\phi}$), together with the CP asymmetry (A_{CP}) are considered to be promising probes for physics beyond the SM.

The $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays have been observed by the LHCb collaboration [2] and their branching fractions found to be in agreement with the SM predictions [3]. The angular and CP asymmetries have been then measured by the same collaboration using proton-proton (pp) collision data collected between 2011 and 2016 (~ 5 fb^{-1}). The analysis is performed using D^0 mesons originating from $D^{*+} \to D^0\pi^+$ decays. The charge of the pion from the D^{*+} decay determines the flavour of the neutral D meson at production. The signal is studied in regions of dimuon mass defined according to the known resonances. The asymmetries of the signal decays are determined through unbinned maximum-likelihood fits to the invariant-mass distributions of the $h^+h^-\mu^+\mu^-$ candidates, weighted with the inverse of the per-candidate phase-space-dependent efficiency. The asymmetries are measured both integrated and as a function of dimuon mass (Fig. 1).

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The integrated asymmetries are

$$A_{FB}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (3.3 \pm 3.7 \pm 0.6)\% \tag{2.1}$$

$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\% \tag{2.2}$$

$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (4.9 \pm 3.8 \pm 0.7)\% \tag{2.3}$$

$$A_{FB}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\% \tag{2.4}$$

$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) = (9 \pm 11 \pm 1)\% \tag{2.5}$$

$$A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%. \tag{2.6}$$

These measurements, as well as those in each dimuon-mass region, are consistent with zero and will help constraining scenarios of physics beyond the SM.

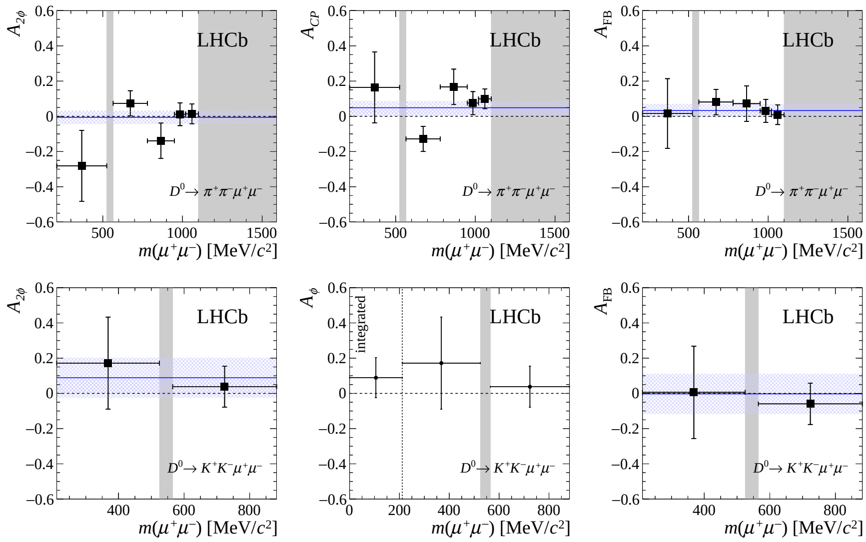

Figure 1: Signal asymmetries for (top) ($D^0 \to \pi^+\pi^-\mu^+\mu^-$) and bottom $D^0 \to K^+K^-\mu^+\mu^-$ decays as a function of the dimuon-mass.

3. Measurement of the time-integrated CP asymmetry in $D^0 \to K^0_S K^0_S$ decays

The $D^0 \to K^0_S K^0_S$ decay is a promising discovery channel for CP violation in charm decays. The LHCb collaboration used the 2015 and 2016 data samples collected in *pp* collisions at 13 TeV (~ 2 fb^{-1}) for this study [5]. A sample of flavour-tagged $D^0 \to K^0_S K^0_S$ decays is obtained by selecting D^{*+} mesons that are produced in the primary interaction, with the subsequent decay $D^{*+} \to D^0\pi^+$, where the charge of the pion identifies the flavour of the accompanying D^0 meson. The $K^0_S \to \pi^+\pi^-$ decays are reconstructed in two different categories: the first involving K^0_S mesons that decay early enough for the decay products to be reconstructed in the vertex detector (*Long*); and the second containing K^0_S candidates that decay downstream of the vertex detector (*Downstream*).

The experimentally measured quantity is the raw asymmetry, defined as the ratio between the difference and the sum of the $D^0 \to K^0_S K^0_S$ candidates tagged by positively and negatively charged pions. The number of signal decay is determined by means of a simultaneous unbinned maximum likelihood fit to the Δm distribution, the difference of the reconstructed invariant-mass of the D^{*+} and the D^0 candidates. The fit is shown in Fig. 2.

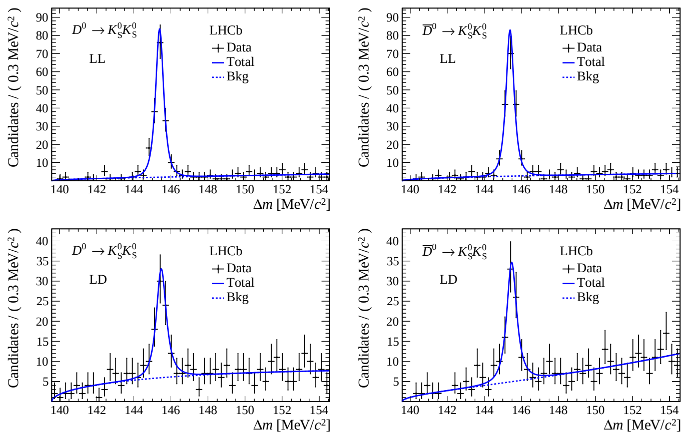

Figure 2: Fit results to Δm distributions of $D^0 \to K_S^0 K_S^0$ candidates. The fit to (Top left) $D^{*+} \to \bar{D}^0\pi^+$ and (Top right) $D^{*-} \to D^0\pi^-$ candidates for the Long-Long (LL) sample and the fit to (Bottom left) $D^{*+} \to \bar{D}^0\pi^+$ and (Bottom right) $D^{*-} \to D^0\pi^-$ candidates for the Long-Downstream (LD) sample are shown.

The raw asymmetry is related to the CP asymmetry by the expression $\mathscr{A}_{raw} \approx \mathscr{A}_{CP} + \mathscr{A}_{prod} + \mathscr{A}_{det}$, where $\mathscr{A}_{prod}$ is the $D^{*\pm}$ production asymmetry and $\mathscr{A}_{det}$ is the $\pi^\pm$ detection asymmetry. The decay $D^0 \to K^+K^-$ is used as calibration channel with the same production and tagging mechanism. The A_{CP} results for the different samples are combined and yield to

$$\mathscr{A}_{CP}(D^0 \to K_S^0 K_S^0) = (4.2 \pm 3.4 \pm 1.0)\%. \tag{3.1}$$

This result is compatible with the Run 1 measurement [6]. The average between the two measurements is

$$\mathscr{A}_{CP}(D^0 \to K_S^0 K_S^0) = (2.0 \pm 2.9 \pm 1.0)\% \tag{3.2}$$

which is compatible with the SM expectation [7] and with previous measurements.

4. Lifetime measurement of the doubly charmed baryon Ξ_{cc}^{++}

Weakly decaying baryons that contain two charm quarks provide a unique system for testing models of quantum chromodynamics. Recently, the LHCb collaboration observed a resonance in the $\Lambda_c^+ K^-\pi^+\pi^+$ final state consistent with expectations for the Ξ_{cc}^{++} baryon [8]. A measurement of its lifetime is critical to establish its nature and is also a necessary ingredient for theoretical predictions of branching fractions. The lifetime measurement has been performed using pp collision data, ~ 1.7 fb^{-1} of integrated luminosity, at 13 TeV [9]. The Ξ_{cc}^{++} baryon is reconstructed through the decay chain $\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$, $\Lambda_c^+ pK^-\pi^+$. The decay-time distribution is measured relative to that of a control mode with similar topology and known lifetime, the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ channel. An unbinned extended maximum-likelihood fits to the $\Lambda_c^+ K^-\pi^+\pi^+$ (Fig. 3 - Left) and $\Lambda_c^+\pi^-\pi^+\pi^-$

mass distributions is performed to determine the number of signal events. The Ξ_{cc}^{++} lifetime is measured by performing a weighted, unbinned maximum-likelihood fit to the background subtracted decay-time distribution of the selected sample (Fig. 3 - Right). This is the first measurement for the Ξ_{cc}^{++} lifetime and yields to

$$\tau_{\Xi_{cc}^{++}} = 0.256^{+0.024}_{-0.022}\ (\text{stat}) \pm 0.014\ (\text{syst})\ \text{ps} \tag{4.1}$$

which establishes the weakly decaying nature of this state.

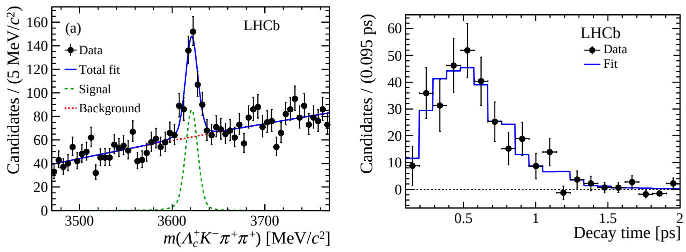

Figure 3: (Left) Invariant-mass distributions of $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates, with fit results shown. (Right) Background-subtracted decay-time distribution of selected $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ candidates.

5. First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

The recent observation by the LHCb collaboration [8] of a new state that is consistent with the doubly charmed baryon Ξ_{cc}^{++} has opened a new field of research studying the properties of baryons containing two heavy quarks. Searching for new decay modes is a critical step towards understanding the dynamics of weak decays of doubly heavy baryons. The process $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ has been predicted to have a sizable branching fraction [10], making it a promising final state in which to seek confirmation of the previous observation.

The same data sample of the measurement reported in the previous section has been used for this study [11]. The selection of $\Xi_{cc}^{++} \to \Xi_c^+(\to pK^-\pi^+)\pi^+$ is designed to be as similar as possible to that of $\Xi_{cc}^{++} \to \Lambda_c^+(\to pK^-\pi^+)K^-\pi^+\pi^+$ in [8], that is used as normalisation channel. The mass distribution of Ξ_{cc}^{++} candidates is fitted with an unbinned extended maximum-likelihood method (Fig. 4 - Left). The resulting signal yield is 91 ± 20, corresponding to a local statistical significance of 5.9 σ. The Ξ_{cc}^{++} mass is measured to be

$$m(\Xi_{cc}^{++}) = 3620 \pm 1.5\ (\text{stat}) \pm 0.4\ (\text{syst}) \pm 0.3(\Xi_c^+)\ \text{MeV}/c^2 \tag{5.1}$$

and is consistent with the previous result. The combination of the two measurements (Fig. 4 - Right) yields to $m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65\ (\text{stat}) \pm 0.31\ (\text{syst})\ \text{MeV}/c^2$. The ratio of branching fractions between the decay modes is measured to be

$$\mathscr{R}(\mathscr{B}) = \frac{\mathscr{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathscr{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathscr{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \times \mathscr{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009\ (\text{stat}) \pm 0.003\ (\text{syst}) \tag{5.2}$$

and it is consistent with the theoretical prediction, which, however, has large uncertainties.

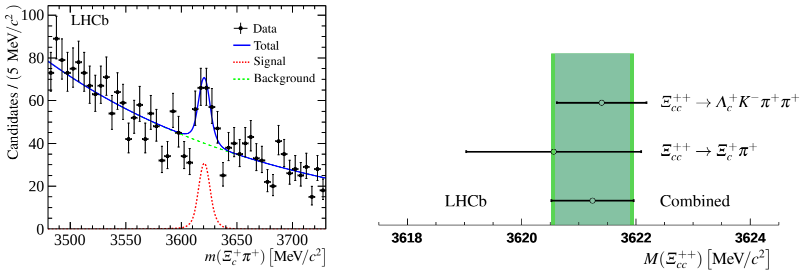

Figure 4: (Left) Invariant-mass distributions of $\Xi_c^+\pi^+$ candidates, with fit results shown. (Right) Measured Ξ_{cc}^{++} masses obtained with the decay modes $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+(\to pK^-\pi^+)\pi^+$ candidates, and the combined result.

6. Measurement of the Ω_c^0 baryon lifetime

While the charm-meson lifetimes have been measured precisely, the knowledge of charm-baryon lifetimes is much less accurate and can provide complementary information. The expected lifetime hierarchy should be [12]

$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}.$$

Current measurements [13] are consistent with this hierarchy. The least well measured lifetime is that of the Ω_c^0 baryon, with a value of (69 ± 12) fs obtained by fixed-target experiments using a small number of signal decays. A new measurement has been performed by the LHCb collaboration [14] using a sample of semileptonic $\Omega_b^- \to \Omega_c^0 \mu^- \overline{\nu}_\mu X$ with $\Omega_c^0 \to pK^-K^-\pi^+$ and X represents any additional undetected particles. The measurement uses (pp) collision data samples, collected by the LHCb experiment, corresponding to an integrated luminosity of 3.0 fb^{-1}. To reduce the uncertainties associated with systematic effects, the lifetime ratio between the Ω_c^0 and the D^+ meson is measured. The D^+ is detected in $B \to D^+(\to K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$. From a binned maximum-likelihood fit to the selected Ω_c^0 candidates (Fig. 5 - Left) yields are 978 ± 60, at least an order of magnitude larger than any previous sample used for Ω_c^0 lifetime measurement. The background subtracted decay-time distributions of the signal and the normalisations are fitted simultaneously (Fig. 5 - Right) to obtain a value of the lifetime of

$$\tau_{\Omega_c^0} = 268 \pm 21\ (\text{stat}) \pm 10\ (\text{syst}) \pm 2\ (D^+)\ \text{fs}. \tag{6.1}$$

This value is nearly four times larger than, and inconsistent with, the current world-average value.

7. Conclusions

Thanks to the world's largest, high-purity samples of charm meson and baryon decays collected during Run 1 and Run 2, LHCb is leading the charm physics field and has the potential to further improve the precision on many of the key observables in the next years. Major advances will be made in the close future since the full Run 2 data sample has not yet been fully analysed and additional data will be collected in the future with an upgraded LHCb detector.

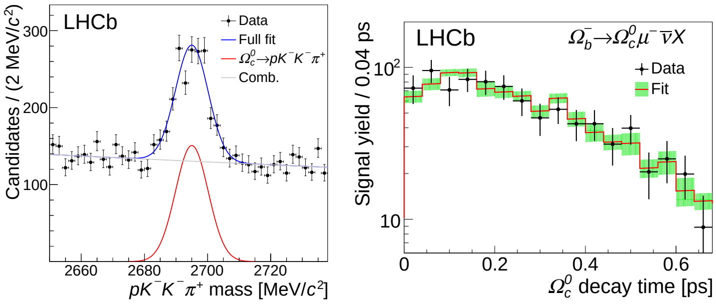

Figure 5: (Left) Invariant-mass distributions for Ω_c^0 candidates in $\Omega_b^- \to \Omega_c^0 \mu^- \overline{\nu}_\mu X$ decays. (Right) Decay-time spectra for $\Omega_b^- \to \Omega_c^0 \mu^- \overline{\nu}_\mu X$ events.

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