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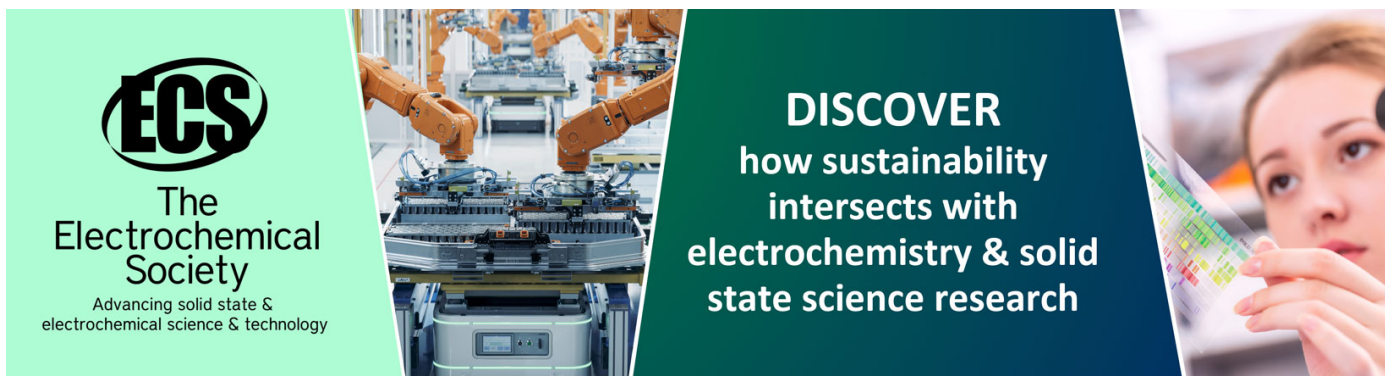
Charm Mixing and CP violation at LHCb

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Charm Mixing and CP violation at LHCb

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Abstract. The LHCb experiment has collected the world's largest sample of charmed hadrons. This sample is used to measure $D^0 - \bar{D}^0$ mixing and to search for direct and indirect CP violation, and its sensitivity is now approaching the Standard Model expectations. In this document, the most recent LHCb results on CP violation in charm sector and on charm mixing are reported.

1. Introduction

CP violation (CPV) plays an important role in the understanding of particle physics and of the entire Universe. As the D^0 system is the only up-type quark system in which flavour oscillation and CPV can be observed, it offers a privileged window to look for New Physics beyond the Standard Model. Mixing is now well established at a level which is consistent with SM expectations, and has been measured with a high level of significance by LHCb [1]. Although time-integrated CP asymmetries in Singly-Cabibbo-Suppressed $D^0 \rightarrow h^+ h^-$ decays ($h = K, \pi$) have reached the remarkable precision of $O(0.1\%)$ [2], approaching the level of Standard Model expectations, CPV has not yet been observed in the charm sector [3]. Larger yields are therefore required to achieve a higher precision and tighter control of systematics uncertainties. 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. Because of the large production cross-section of charm hadrons at the LHC [5], the LHCb experiment can collect these large samples, playing a major role in charm CPV searches.

2. Direct CP violation

Direct CPV appears as a result of the interference among various terms in the decay amplitude. The CP asymmetry is defined as

$$A_{CP}(f) \equiv \frac{\Gamma(H \rightarrow f) - \Gamma(\bar{H} \rightarrow \bar{f})}{\Gamma(H \rightarrow f) + \Gamma(\bar{H} \rightarrow \bar{f})}, \quad (1)$$

where Γ is the decay rate of a particle H ($\bar{H}$) in the final state f ($\bar{f}$). The quantity measured in LHCb is $A_{\text{raw}} = \frac{N_H - N_{\bar{H}}}{N_H + N_{\bar{H}}}$, where N_H is the measured yield of $H \rightarrow f$ and $N_{\bar{H}}$ is the measured yield of $\bar{H} \rightarrow \bar{f}$ decays. This observable is related to the CP asymmetry by the expression, valid to first order, $A_{\text{raw}} \approx A_{CP} + A_{\text{prod}} + A_{\text{det}}$, where A_{prod} is the production asymmetry of the H particle and A_{det} is the detection asymmetry. The production asymmetry arises from the fact that the initial state pp is not CP -symmetric, and therefore the production cross section of a particle H is different from the production cross section of its anti-particle $\bar{H}$. The detection



asymmetry depends both on the magnet polarity (left-right detector asymmetry) and on differing detection efficiencies for particles and antiparticles, due to the different interaction cross-sections with detector material. To measure the CP asymmetry, production and detection asymmetries must be either measured or removed using control modes.

2.1. Measurement of ΔA_{CP} in $\Lambda_c^+ \rightarrow ph^+h^-$ decays

CP violation in charm baryons is a sector almost unexplored, therefore it is interesting to search for CPV even if very little is known about its magnitude. Recently, a measurement of CPV has been performed using $\Lambda_c^+ \rightarrow ph^+h^-$ decays, where h is either a kaon or a pion. The charge conjugate decays are implied throughout this document, unless explicitly specified. The analysis is performed using data collected during Run 1 (2011-2012), corresponding to an integrated luminosity of 3 fb^{-1} . To reduce the background, Λ_c^+ particles are selected using $\Lambda_b^0 \rightarrow \Lambda_c^\pm \mu^\pm X$, where X represents any unreconstructed particle, exploiting the long lifetime of Λ_b^0 baryons. In this case $A_{raw}(ph^+h^-) = A_{CP}(ph^+h^-) + A_{prod}(\Lambda_b^0) + A_{det}(\mu) + A_{det}(ph^+h^-)$, where $A_{prod}(\Lambda_b^0)$ is the production asymmetry of the Λ_b^0 , $A_{det}(\mu)$ is the detection asymmetry of the muon and $A_{det}(ph^+h^-)$ is the detection asymmetry of the final state. To subtract production and detection asymmetries, the quantity

$$\Delta A_{CP} = A_{raw}(pK^+K^-) - A_{raw}(p\pi^+\pi^-) \quad (2)$$

is measured. This quantity is equal to the difference between the two CP asymmetries if the kinematic distributions of the two final state are equal. Therefore the kinematic spectra of $p\pi^+\pi^-$ final state has been weighted to match the pK^+K^- final state. The weight function has been provided for the comparison with theoretical predictions. To extract the number of $\Lambda_c^\pm$ decays, a fit to the ph^+h^- mass distribution is performed, as shown in Fig. 1.

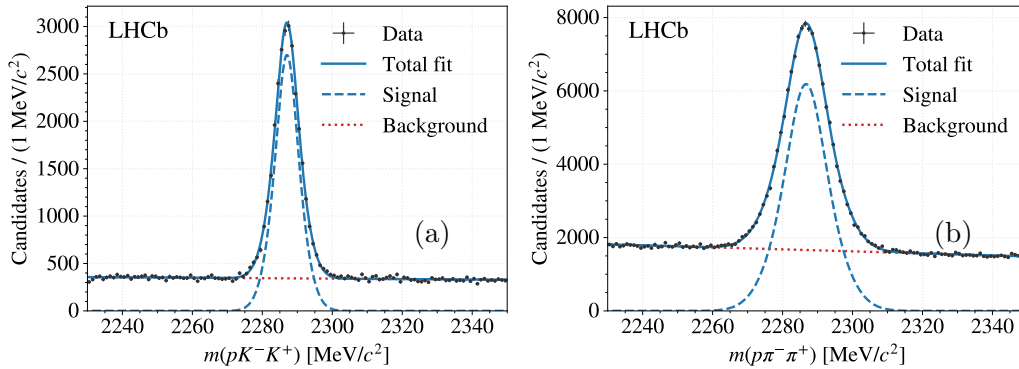


Figure 1. Fit to the ph^-h^+ invariant mass spectra from the fully selected (a) $\Lambda_c^+ \rightarrow pK^+K^-$ and (b) $\Lambda_c^+ \rightarrow p\pi^+\pi^-$ datasets summed over all data-taking conditions.

The final result is [6]

$$\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61)\%,$$

where the first uncertainty is statistical and the second is systematic. The main source of systematic uncertainty is the limited size of the simulated sample which is used to extract the phase space efficiency model.

2.2. Measurement of A_{CP} in $D^0 \rightarrow K_S^0 K_S^0$ decays

The $D^0 \rightarrow K_S^0 K_S^0$ decay is a promising discovery channel for CPV in charm. A prediction based on the Standard Model gives an upper limit for the CP asymmetry of about 1% [7]; further

enhancements could result from contributions from physics beyond the Standard Model. This quantity has already been measured by the CLEO collaboration [8], by the Belle collaboration [9], and by the LHCb collaboration [10] using Run 1 data. All the measurements are compatible with the hypothesis of no CPV . Here a new LHCb measurement, performed using data collected in the first two years of Run 2 ($\sqrt{s} = 13\text{TeV}$, integrated luminosity $\sim 2\text{ fb}^{-1}$), is presented. A sample of flavour-tagged $D^0 \rightarrow K_S^0 K_S^0$ decays has been obtained by selecting D^{*+} candidates coming directly from the primary pp interaction, with subsequent decay $D^{*+} \rightarrow D^0 \pi^+$. The sign of the tag pion, *i.e.* the pion in this decay, gives the flavour of the accompanying D^0 , and $D^0 - \bar{D}^0$ mixing is negligible at this level of precision. Candidate K_S^0 decays are reconstructed in the $\pi^+ \pi^-$ decay channel. In LHCb tracks are classified according to the subdetectors crossed. In particular particles traversing the full tracking system are called "long" tracks, while tracks reconstructed in all the tracking stations but not in the vertex-detector are called "downstream" tracks. In this analysis two samples are used: the LL sample, with both K_S^0 reconstructed from long tracks, and the LD sample, with one K_S^0 reconstructed from long tracks and the other one reconstructed from downstream tracks. The two samples are analysed separately because of the different mass resolution. The production asymmetry of the D^{*+} and the detection asymmetry of the tag pion are removed using the $D^0 \rightarrow K^+ K^-$ as a calibration channel. The raw asymmetry is extracted by fitting the $\Delta m = m(D^{*+}) - m(D^0)$ distribution. The result, obtained by performing a simultaneous maximum likelihood fit to the separate D^{*+} and D^{*-} unbinned Δm distributions, is [11]

$$A_{CP}(K_S^0 K_S^0) = (4.2 \pm 3.4 \pm 1.0)\%,$$

where the first uncertainty is statistical and the second is systematic. The fitted Δm distributions for the D^{*+} decays and the "magnet up" polarity are shown in Fig. 2. Combining this result

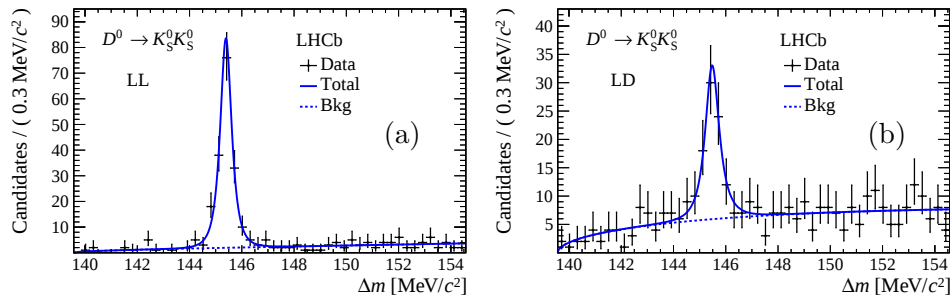


Figure 2. Fits to Δm distributions of $D^0 \rightarrow K_S^0 K_S^0$ candidates for the "magnet up" polarity. The fit to (a) $D^{*+} \rightarrow D^0 \pi^+$ candidates for the LL sample and the fit to (b) $D^{*+} \rightarrow D^0 \pi^+$ candidates for the LD sample are shown.

with the previous LHCb measurement on the Run 1 dataset, the asymmetry value obtained is

$$A_{CP}(K_S^0 K_S^0) = (2.0 \pm 2.9 \pm 1.0)\%,$$

therefore no evidence of CPV is found.

2.3. Measurement of A_{CP} in $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ decays

Recently, the LHCb collaboration has performed the first observation of the rarest charm decays so far [12], the $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and the $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$ decays. The branching ratio is in agreement with the Standard Model expectations and now the measurement of angular and CP

asymmetries has been performed, using data collected from 2011 to 2016 ($\sim 5 \text{ fb}^{-1}$ of integrated luminosity). With the current precision, these asymmetries are predicted to be negligible within the Standard Model, but they could reach the level of a few percent in some New Physics models [13, 14]. The D^0 mesons are tagged using $D^{*+} \rightarrow D^0 \pi^+$ decays. To subtract the D^{*+} production asymmetry and the tag pion detection asymmetry, the $D^0 \rightarrow K^+ K^-$ decay is used as a calibration channel. The CP asymmetry is determined through an unbinned maximum-likelihood fits to the $m(h^+ h^- \mu^+ \mu^-)$ distributions of the selected candidates, weighted with the inverse of the per-candidate phase-space-dependent efficiency. The asymmetries are measured both integrated and as a function of the dimuon mass, to test also regions away from the peaks of the resonances, which are more sensitive to the highly suppressed short-distance $c \rightarrow u \mu^+ \mu^-$ flavor-changing neutral-current process. The results for the integrated CP asymmetries are [15]

$$A_{CP}(\pi^+ \pi^- \mu^+ \mu^-) = (4.9 \pm 3.8 \pm 0.7)\% \quad A_{CP}(K^+ K^- \mu^+ \mu^-) = (0 \pm 11 \pm 2)\%$$

where the first uncertainty is statistical and the second is systematic. These measurements, as well as the asymmetries in each dimuon-mass region, are consistent with zero, as shown in Fig. 3. The main systematic uncertainty arise from the accuracy of the efficiency correction and from the uncertainty on the cancellation of production and detection asymmetries.

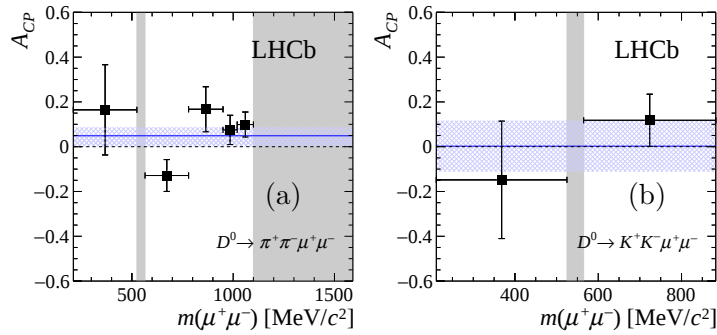


Figure 3. Measured value of A_{CP} values in the dimuon-mass regions for (a) the $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and (b) the $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$ decays. The horizontal shaded blue band corresponds to the measurement integrated in the full dimuon-mass range, with the hatched area representing the $\pm 1\sigma$ band.

3. Mixing and indirect CP violation with $D^0 \rightarrow K^- \pi^+$ decays

The $D^0 - \bar{D}^0$ mixing has been observed for the first time by a single experiment at LHCb in the decay time dependent ratio $D^0 \rightarrow K^+ \pi^-$ to $D^0 \rightarrow K^- \pi^+$ decay rates [16], where the D^0 meson is tagged using $D^{*+} \rightarrow D^0 \pi^+$ and $D^{*-} \rightarrow \bar{D}^0 \pi^-$ decays. A new measurement of the mixing parameters has been performed using data collected by LHCb from 2011 through 2016, corresponding to an integrated luminosity of 5 fb^{-1} . The time dependent ratio of the wrong-sign (WS) $D^0 \rightarrow K^+ \pi^-$ decays to right-sign (RS) $D^0 \rightarrow K^- \pi^+$ decays, which is dominated by a Cabibbo-Favored amplitude, can be written, in the limit of a slow mixing rate ($|x| \ll 1$, $|y| \ll 1$) as

$$R(t) = R_D + \sqrt{R_D} y' + \frac{x'^2 + y'^2}{4} \frac{t^2}{\tau^2}, \quad (3)$$

where R_D is the ratio of Doubly-Cabibbo-Suppressed to Cabibbo-Favored amplitude, $x' = x \cos \delta + y \sin \delta$ and $y' = y \cos \delta - x \sin \delta$, δ is the strong phase difference between Doubly-Cabibbo-Suppressed and Cabibbo-Favored amplitudes, x and y are the mixing parameters and t/τ is the D^0 decay time expressed in units of the average D^0 lifetime τ . The sample is split in

bins of decay time with approximatively the same number of selected RS decays. In each decay-time bin the yields of RS and WS decays is extracted by fitting the $D^0\pi^+$ mass distribution. The total yields, integrated over the decay time, are 1.77×10^8 and 7.22×10^5 for the RS and the WS decays respectively. The WS to RS ratio, corrected for possible biases in the selection efficiency, is measured independently for D^0 and $\bar{D}^0$ decays, as shown in Fig. 4.

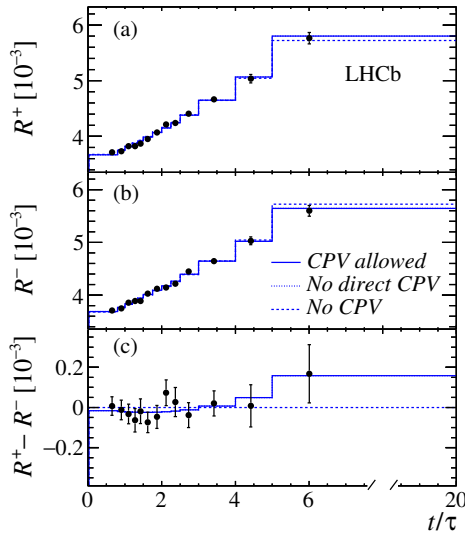


Figure 4. Efficiency-corrected ratios of WS-to-RS yields for (a) D^{*+} decays, (b) D^{*-} decays, and (c) their differences as functions of decay time in units of D^0 lifetime. Projections of fits allowing for (dashed line) no CPV , (dotted line) no direct CPV , and (solid line) direct and indirect CPV are overlaid.

Three different hypothesis are tested: no CPV , CPV in the mixing but no direct CPV , and all kind of CPV allowed. Data are compatible with CP symmetry and the best values for the mixing parameters are [1] $R_D = (3.454 \pm 0.031) \times 10^{-3}$, $y' = (5.28 \pm 0.52) \times 10^{-3}$ and $x'^2 = (0.039 \pm 0.027) \times 10^{-3}$. The major systematic uncertainty arise from the presence of D^{*+} decays originating from b-hadron decays and not from the primary interaction.

4. Conclusions

The LHCb experiment has a key role in the search of CP violation in the charm sector. With the dataset collected until now, LHCb is reaching and even passing the upper bounds of Standard Model expectations. The additional samples, that will be collected in the last year of Run 2 and during the LHCb Upgrade, will allow to open a privileged door for studying the structure of the flavour dynamics.

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