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CP violation and mixing in charm decays at LHCb

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The LHCb experiment has already collected an unprecedented sample of charmed particles from proton-proton collisions during the LHC Run 1 ($\sqrt{s} = 7$–8 TeV, 2010-2012) and the first part of Run 2 ($\sqrt{s} = 13$–14 TeV, 2015-2018). I present several new and recent measurements based on the Run 1 data sample, covering *CP* violation and mixing analyses in charm mesons. These measurements represent the highest precision tests of *CP* violation in the charm sector ever made, with all results currently consistent with *CP* conservation, and with standard model predictions.

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1. Introduction

The interactions and decays of particles containing a charm quark provide a unique testing ground for the standard model (SM), with sensitivity to discover new physics contributions currently inaccessible in direct searches. The neutral charm meson is the only up-type quark system which can exhibit flavour oscillations, which are heavily suppressed in the SM by a combination of GIM and CKM effects [1–3]. While oscillations are well established in the B and K systems, they have not yet been directly observed in D mesons (i.e., the measured mass difference is still consistent with zero) [4, 5]. On the other hand, the cancellation of SM amplitudes leads to predictions for charge-parity (*CP*) violation in oscillation which are both very small and precisely determined (see, e.g. Ref. [6]), giving high sensitivity to possible contributions from new physics effects. Furthermore, while *CP* violation in particle decay has been seen in several B and K channels, there is still no evidence for any such effects in the charm sector. As such, it is very important to provide new, precise measurements of charm oscillations and *CP* violation. The LHCb experiment is ideally suited for this task. For a theoretical overview of the topic, please see the proceedings from this conference (and references therein) from G. Martinelli and M. Ciuchini. Here I focus on the new and recent experimental results.

The LHCb detector [7, 8] 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 the analyses described in this document 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 of charged particles; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

There are two different sources of charm mesons at LHCb: those from charm quarks produced directly in the initial pp collision (prompt charm) and those produced via the decay of beauty hadrons (secondary charm). For studies of flavour oscillations and *CP* violation in the neutral charm system, the initial flavour of the D^0 at production can be determined either through the sign of the soft bachelor pion in the decay $D^{*\pm} \to D^0\pi^\pm$ (for prompt charm), or through the charge of the muon in a semileptonic decay $B \to \mu^\mp D^0 X$ (for secondary charm). For a sub-sample of the secondary data in which the B decays to $\mu^\mp D^{*\pm} X$, both tags are available (double-tagged).

2. Direct CP violation measurements

Direct *CP* violation is defined through the inequality $\Gamma(A \to f) \neq \Gamma(\bar{A} \to \bar{f})$, hence characterised by a decay rate differing from that of the *CP* conjugate process. While direct *CP* violation has been confirmed in many systems in the kaon and B systems [4], there is as yet no evidence for any such effects in the charm sector.

2.1 Two-body decays: $A_{\mathrm{CP}}(D^0 \to K^+K^-)$ and ΔA_{CP}

Time-integrated asymmetries in the decays $D^0 \to h^+h^-$ are defined by

$$A_{\mathrm{CP}}(h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\bar{D}^0 \to h^+h^-)}. \tag{2.1}$$

These quantities are expected to be small in the standard model, with potentially large contributions from a range of new physics models (see [9] and references therein for more details). The first experimental investigations into these quantities measured the difference between *CP* asymmetries for K^+K^- and $\pi^+\pi^-$ final states, $\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-)$, which retains the theoretical sensitivity to potential new physics contributions, but is experimentally simpler due to cancellation of instrumental and production asymmetries.

A new measurement of $A_{\mathrm{CP}}(K^+K^-)$ has been recently performed by the LHCb collaboration, using the complete 3 fb^{-1} data sample from 2011-2012, and with the initial flavour tagged using the soft pion from a $D^{*\pm}$ decay [9]. The *CP* asymmetry is related to the raw asymmetry A_{raw} in the number of reconstructed D^0 and $\bar{D}^0$ decays via

$$A_{\mathrm{CP}}(K^+K^-) = A_{\mathrm{raw}}(K^+K^-) - A_{\mathrm{P}}(D^{*+}) - A_{\mathrm{D}}(\pi_s^+), \tag{2.2}$$

where A_{P} and A_{D} represent production and detection asymmetries, respectively. These background asymmetries are cancelled by constructing a suitable combination of raw asymmetries from the signal channel and from three Cabibbo-favoured control channels where the *CP* asymmetry is assumed to be negligible:

$$\begin{aligned} A_{\mathrm{CP}}(K^+K^-) &= A_{\mathrm{raw}}(D^0 \to K^+K^-) - A_{\mathrm{raw}}(D^0 \to K^-\pi^+) + A_{\mathrm{raw}}(D^+ \to K^-\pi^+\pi^+) \\ &- A_{\mathrm{raw}}(D^+ \to \bar{K}^0\pi^+) + A_{\mathrm{D}}(\bar{K}^0). \end{aligned} \tag{2.3}$$

Here all D^0 channels are $D^{*\pm}$-tagged. This leaves a single remaining detector asymmetry for construcing a neutral kaon, which is well-known from previous LHCb measurements [10]. The cancellation is only valid if the initial and final state particles have the same kinematic distributions, which is ensured by appropriately reweighting the data, before computing the raw asymmetries using binned maximum likelihood fits.

Systematic uncertainties are assigned to account for the imperfect cancellation of background asymmetries (dominant), from the choice of fit model for signal and background components, and from the limited precision on the detection asymmetry of the neutral kaon. The final result is

$$A_{\mathrm{CP}}^{\mathrm{prompt}}(K^+K^-) = [0.14 \pm 0.15\ (\mathrm{stat.}) \pm 0.10\ (\mathrm{syst.})]\%, \tag{2.4}$$

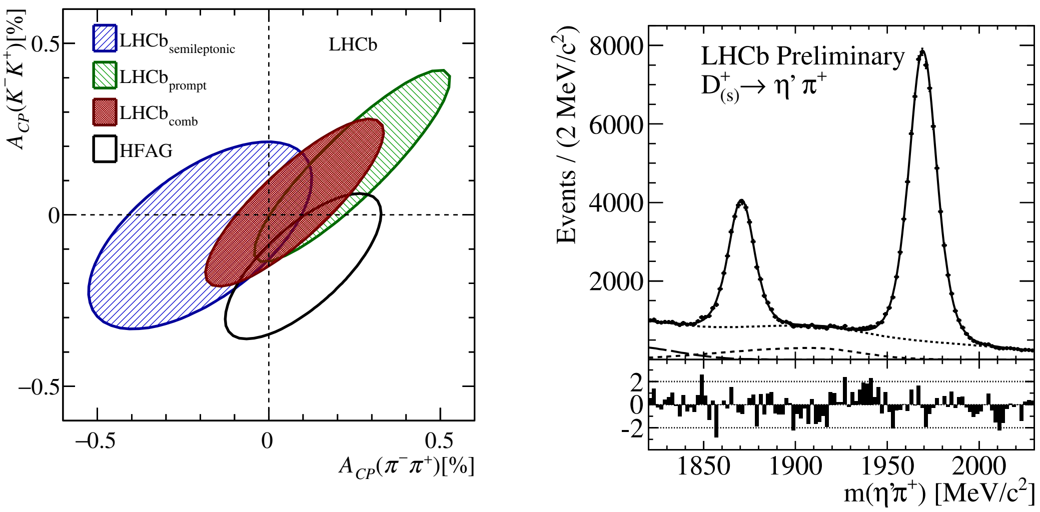
which is consistent with standard model expectations. This result can be combined with the corresponding measurement using μ-tagged D^0 candidates [11], yielding the value

$$A_{\mathrm{CP}}^{\mathrm{comb}}(K^+K^-) = [0.04 \pm 0.12\ (\mathrm{stat.}) \pm 0.10\ (\mathrm{syst.})]\%. \tag{2.5}$$

Finally, the measurements of $A_{\mathrm{CP}}(K^+K^-)$ and ΔA_{CP} can be combined to extract the corresponding *CP* asymmetry for the $\pi^+\pi^-$ channel

$$A_{\mathrm{CP}}^{\mathrm{comb}}(\pi^+\pi^-) = [0.07 \pm 0.14\ (\mathrm{stat.}) \pm 0.11\ (\mathrm{syst.})]\%, \tag{2.6}$$

with the full results of the combination shown on the $[A_{\mathrm{CP}}(\pi^+\pi^-), A_{\mathrm{CP}}(K^+K^-)]$ plane in Fig. 1a.



(a) Combined measurements of direct *CP* violation in $D^0 \to h^+h^-$ decays, using independent samples from prompt and semileptonic sources of charm mesons. The 68% confidence intervals are drawn, where the statistical and systematic uncertainties have been added in quadrature.

(b) Invariant mass distribution for $D^+_{(s)} \to \eta'\pi^+$ decays, where all kinematic bins have been combined. Peaking backgrounds from $D^+_{(s)} \to \phi_{3\pi}\pi^+$ are shown by the dashed (long-dashed) curves. The residuals (data - model)/uncertainty are shown in the lower pane.

Figure 1: Plots from two recent LHCb searches for direct *CP* violation: $A_{\mathrm{CP}}(D^0 \to K^+K^-)$ (left, Ref. [9]) and $A_{\mathrm{CP}}(D^\pm_{(s)} \to \eta'\pi^\pm)$ (right, Ref. [12]).

2.2 $D^+_{(s)} \to \eta'\pi^+$ decays

Given the current absence of a positive signal of *CP* violation in the charm sector, it is important to expand the search to include more experimentally challenging modes, including those with neutral final-state particles. The LHCb collaboration has recently searched for direct *CP* violation in decays of D^+ and D^+_s mesons to $\eta'\pi^+$, the first time such decays have been analysed at a hadron collider [12].

The standard model predicts *CP* asymmetries to be very small in these decays, at the level of 0.1% or less, with significant enhancements possible from a range of new physics models [13, 14]. The best existing measurements from Belle [15] and CLEO [16] have precision of order 1–2%. The LHCb data sample currently being collected will significantly improve sensitivity to contributions from new physics models in these decays. Further study of such $D \to PP$ decays will also help to test SU(3) predictions and flavour symmetry breaking.

The LHCb analysis uses the full 3 fb^{-1} data sample from 2011-2012, and reconstructs the signal $D^+_{(s)} \to \eta'\pi^+$ channel through the intermediate $\eta' \to \pi^+\pi^-\gamma$ decay. A total of ∼1.1M (∼6.6M) signal candidates are found for the $D^\pm_{(s)}$ channel.

As in the case of $A_{\mathrm{CP}}(K^+K^-)$ the *CP* asymmetry is related to the raw asymmetry, with additional terms arising from production and detection asymmetries, $A_{\mathrm{raw}} = A_{\mathrm{CP}} + A_{\mathrm{p}} + A_{\mathrm{d}}$. These background asymmetries are determined from Cabibbo-favoured control channels $D^+ \to K^0_S\pi^+$ and $D^+_s \to \phi\pi^+$, where the *CP* asymmetries are expected to be negligible, and are well constrained from external measurements by the Belle and D0 collaborations. To improve the cancellation of background asymmetries, all quantities are determined in bins of the bachelor pion kinematics. In addition, selection requirements are imposed to remove kinematic regions where reconstruction and particle identification of the bachelor pion have efficiencies with significant charge asymmetries. The raw asymmetries are determined via maximum likelihood fits to the data, simultaneous for positively and negatively charged D mesons. Figure 1b shows the $\eta'\pi^+$ mass distribution, combined over all kinematic bins.

The dominant source of systematic uncertainty arises from the limited knowledge of background components in the raw asymmetry fits. Various shapes are tested to model the combinatorial background, and the size of the peaking component from $D^+_{(s)} \to \phi_{3\pi}\pi^+$ decays. Smaller systematic uncertainties are assigned to account for contamination from non-prompt charm, possible asymmetries due to the trigger, and the limited precision of background asymmetries from the control channels. The final measurements of the CP asymmetries in the two channels are

$$A_{\rm CP}(D^\pm \to \eta'\pi^\pm) = [-0.61 \pm 0.72\,(\text{stat.}) \pm 0.55\,(\text{syst.}) \pm 0.12\ \ (\text{PDG})]\%, \tag{2.7}$$

$$A_{\rm CP}(D^\pm_s \to \eta'\pi^\pm) = [-0.82 \pm 0.36\,(\text{stat.}) \pm 0.24\,(\text{syst.}) \pm 0.27\ \ (\text{PDG})]\%, \tag{2.8}$$

where the final uncertainty is from the limited precision of $A_{\rm CP}$ for the control channels. These values are consistent with CP conservation, and with the standard model predictions, and improve significantly on the best existing measurements of these quantities.

2.3 Searching for local asymmetries in time-integrated $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays

CP violation requires that a process have interfering components from at least two amplitudes, in which both the strong and weak phases differ. The rich resonant structure of multibody charm decays leads to significant variation in strong phase over the final-state kinematic space. This presents the opportunity to search for local CP violation in specific kinematic regions, even if no global asymmetries are observed.

A new measurement from LHCb uses an unbinned, model-independent method to search for local CP violation in the final-state kinematic space of $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays [17]. This channel is dominated by the intermediate decays $D^0 \to a_1(1260)^+\pi^-$ with $a_1(1260)^+ \to \rho(770)^0\pi^+$, and $D^0 \to \rho(770)^0\rho(770)^0$, with CP violation expected below the 10^{-3} level in the standard model [18]. This analysis is mainly sensitive to direct CP violation, since mixing-driven effects have already been constrained by other channels to a level below the sensitivity of the current measurement.

This analysis uses the full 3 fb^{-1} data sample from 2011-2012, using $D^{*\pm}$-tagged candidates. Kinematic selections are chosen to minimise potential effects from instrumental asymmetries. The analysis method is insensitive to global background asymmetries, and any remaining contributions from instrumental effects are found to be negligible at the current level of experimental precision.

For a four-body decay, the final-state kinematics can be completely defined by five variables. In this analysis these are chosen to be those two- and three-pion invariant masses which exhibit the strongest resonant behaviour. The 'energy test' method is used to search for local CP asymmetries, in which a test metric T is constructed to compare the average phase-space separations of candidates, separately for two samples (e.g. D^0 and $\bar{D^0}$). This is analogous to measuring an electrical potential in a volume of mixed positive and negative charges. The test requires the choice of a suitable weighting function ψ_{ij} sensitive to the multidimensional phase-space separation d_{ij} of two candidates. This is chosen to be a Gaussian function $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$, with the tuneable scale δ chosen to be 0.5 GeV^2 based on sensitivity studies using simulated data.

The test metric averages to zero in the case of *CP* conservation. A full interpretation of the result relies on generating ensembles of pseudo-experiments in which the test statistic is computed after randomly assigning the flavour-tags of all data candidates. This allows a *p*-value to be determined for the consistency of the data with *CP* conservation. This process is computationally intensive, and takes advantage of GPU technology to significantly increase the number of permutations that can be generated.

Two separate measurements are made, one in which the two samples to be compared are defined purely by the initial D^0 flavour (sensitive to P-even asymmetries), and a second in which the samples are defined by both the D^0 flavour and the sign of a triple-product computed from the pion momenta (sensitive to P-odd asymmetries). The effects of asymmetric backgrounds, or of instrumental and production asymmetries, are assessed using dedicated control samples. In both cases, any possible contributions are found to be negligible with respect to the experimental sensitivity of the analysis. The choice of the distance scale $\delta = 0.5\ \mathrm{GeV}^2$ influences the final results, so values are reported for the range 0.3–0.7 GeV^2 in Ref. [17].

For the default case $\delta = 0.5\ \mathrm{GeV}^2$, the *p*-value for the P-even test is determined to be $(4.6 \pm 0.5)\%$, where the uncertainty is due to the limited number of pseudo-experiments generated. This is fully consistent with *CP* conservation. For the P-odd test, the *p*-value is found to be $(0.6 \pm 0.2)\%$, marginally consistent with *CP* conservation. This is the first application of the energy test in four-body decays, and the first extension of the method to investigate P-odd asymmetries.

3. D^0 mixing and CP violation

The oscillatory behaviour in the neutral charm system is characterised by two dimensionless mixing parameters, $x = \Delta M/\Gamma$, and $y = \Delta\Gamma/2\Gamma$, where ΔM and $\Delta\Gamma$ are the mass and decay width differences of the two mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle + q|\bar{D^0}\rangle$, and Γ is the average decay width [4]. The current world-average values are $x = (0.37 \pm 0.16)\%$, $y = (0.66\ ^{+0.07}_{-0.10})\%$ [5].

Mixing-induced *CP* violation is defined by two additional parameters, $|q/p|$ and $\phi \equiv \arg(q/p)$, both of which are consistent with *CP* conservation in the current world-average: $|q/p| = 0.91\ ^{+0.12}_{-0.08}$, $\phi = (-9.4\ ^{+11.9}_{-9.8})^\circ$ [5].

3.1 Wrong-sign $D^0 \to K^+\pi^-$ decays

The decay $D^0 \to K^+\pi^-$ is doubly-Cabibbo-suppressed (DCS), and denoted ‘wrong-sign’ in contrast to the ‘right-sign’ Cabibbo-favoured (CF) mode $D^0 \to K^-\pi^+$. It can proceed via two paths with comparable strengths, which gives high sensitivity to mixing and interference-induced *CP* violation. One path is the direct DCS decay, while the second proceeds via neutral meson oscillation followed by the CF decay $D^0 \to \bar{D^0} \to K^+\pi^-$. The oscillatory behaviour introduces a time-dependence into the wrong-sign rate, and hence into the experimentally simpler ratio $R(t)$ between the wrong-sign and right-sign decay rates. The mixing parameters (and mixing induced *CP* violation) can therefore be measured by analysing this time-dependence.

The LHCb collaboration has previously used this channel to make the first single-measurement observation of charm mixing, using $D^{*\pm}$-tagged candidates [19]. Here I report on a new measurement which uses double-tagged (DT) candidates $B \to \mu^{\mp} D^{*\pm} X$, $D^{*\pm} \to D^0 \pi^{\pm}$ to extend the reach to lower decay times, taking advantage of the lifetime-unbiased muon triggers [20].

For the case of small mixing parameters x and y, this ratio can be expressed as a quadratic function of the decay time in units of lifetime (t/τ):

$$R(t)^{\pm} = R_D^{\pm} + \sqrt{R_D^{\pm}} y'^{\pm} \left(\frac{t}{\tau}\right) + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} \cdot \left(\frac{t}{\tau}\right)^2 . \tag{3.1}$$

Here, the first term is due to the DCS decay (R_D is related to the magnitude of the ratio of DCS and CF amplitudes), the third term is due to mixing, and the second term arises from interference between the two paths. The parameters x' and y' are related to the mixing quantities x and y by a rotation through the strong phase for this decay. The superscript $+$ $(-)$ denotes the quantity for the D^0 ($\bar{D}^0$) case, which allows *CP* violation to be measured in both mixing $[(x'^{+}, y'^{+}) \neq (x'^{-}, y'^{-})]$ and in decay ($R_D^{+} \neq R_D^{-}$).

Using the full 3 fb^{-1} data sample from 2011-2012, and following standard selection requirements, around 1.7M (6.7K) right- (wrong-) sign candidates are reconstructed. Candidates used in the published $D^{*\pm}$-tagged analysis [19] are removed to simplify the combination of measurements. The yields of both samples are measured in five bins of decay time, using maximum likelihood fits to the $D^0\pi^-$ invariant mass in which the narrow $D^{*\pm}$ peak provides excellent signal purity. The measured value of $R(t)$ in each bin must then be corrected to account for contamination from backgrounds from prompt and semileptonic charm, and for differences in the detection asymmetries for $K^-\pi^+$ and $K^+\pi^-$ final states.

Once all corrections have been included, the $R(t)$ distribution is fitted to extract the parameters of interest. Three approaches are taken with differing *CP* violation (CPV) hypotheses: no CPV included; no direct CPV included (but CPV in mixing allowed); all CPV allowed. The projections for all three hypotheses are shown in Fig. 2a. No evidence for any *CP* violation is found, and the fit parameters from the *CP*-conserving fit are

$$R_D = [3.48 \pm 0.10\,(\text{stat.}) \pm 0.01\,(\text{syst.})] \cdot 10^{-3}, \tag{3.2}$$

$$x' = [0.28 \pm 3.10\,(\text{stat.}) \pm 0.11\,(\text{syst.})] \cdot 10^{-4}, \tag{3.3}$$

$$y' = [4.60 \pm 3.70\,(\text{stat.}) \pm 0.18\,(\text{syst.})] \cdot 10^{-3}. \tag{3.4}$$

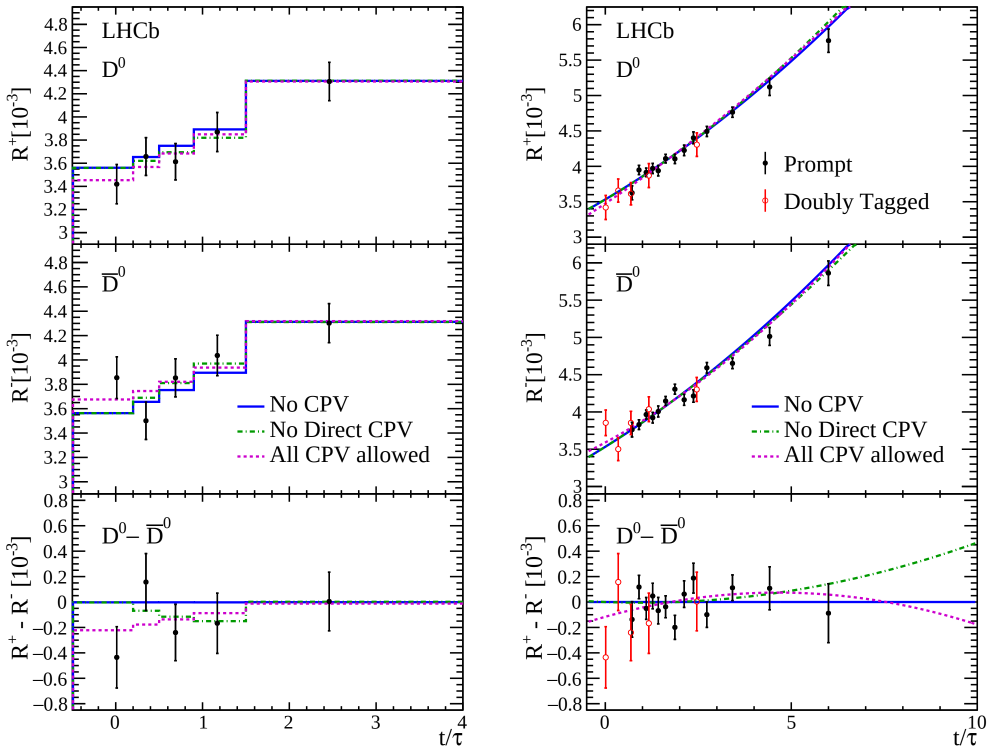
These results are inconsistent with the no-mixing hypothesis at the 4.6σ level. The uncertainties are dominated by the limited sample size, with the leading systematic uncertainty assigned to account for the effect of asymmetries in prompt charm backgrounds.

The data from this double-tagged sample, and from the published $D^{*\pm}$-tagged analysis, are used together in a combined $R(t)$ fit, yielding the following result (left: combination; right: Ref. [19] only):

$$R_D = (3.533 \pm 0.054) \cdot 10^{-3} \qquad [\text{cf. } (3.568 \pm 0.066) \cdot 10^{-3}], \tag{3.5}$$

$$x' = (0.36 \pm 0.43) \cdot 10^{-4} \qquad [\text{cf. } (0.55 \pm 0.49) \cdot 10^{-4}], \tag{3.6}$$

$$y' = (5.23 \pm 0.84) \cdot 10^{-3} \qquad [\text{cf. } (4.8 \pm 1.0) \cdot 10^{-3}]. \tag{3.7}$$



(a) Double-tagged sample (b) Combination with Ref. [19]

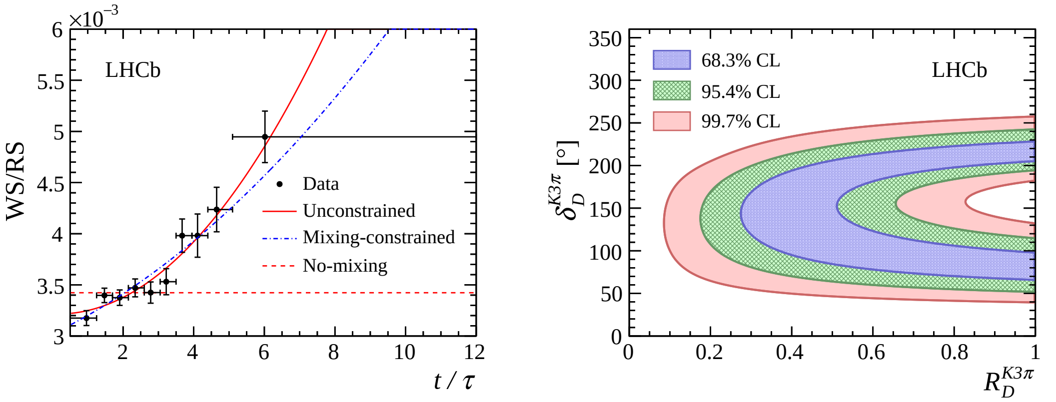
Figure 2: $R(t)$ fit projections from the wrong-sign $D^0 \to K^+\pi^-$ analysis [20], using double-tagged candidates (left) and combining with the existing data from the $D^{*\pm}$-tagged analysis in Ref. [19] (right). In each case, the upper pane shows results for D^0, the middle for $\bar{D}^0$, and the lower for the difference between the two samples. The different lines show the results of three fits under different CPV hypotheses.

where statistical and systematic uncertainties have been combined in quadrature. The fit projections are shown in Fig. 2b. Including the DT data reduces uncertainties on the earlier measurement by up to 20%, despite the fact that this is only an increase of 2.5% in sample size. The additional gain is due to the improved coverage at low decay times, and also benefits from improved signal purity in the DT sample.

3.2 Wrong-sign $D^0 \to K^+\pi^-\pi^-\pi^+$ decays

The analysis of the preceding section can in principle be repeated on the four body decay $D^0 \to K^+\pi^-\pi^-\pi^+$, giving yet another important experimental input into charm oscillations and *CP* violation. There are, however, key differences between the two channels. Firstly, the strong phases differ between the two- and four-body cases, since these are channel dependent. Secondly, the four-body case exhibits phase-space dependence: the analysis must either be performed as a function of this phase space, or else account for the effect of averaging the strong phase variations.

The $R(t)$ analysis of $D^0 \to K^+\pi^-\pi^-\pi^+$ has recently been performed by the LHCb collaboration [21], using $D^{*\pm}$-tagged candidates from the full 3 fb^{-1} data sample collected in 2011-2012.



(a) Wrong- to right-sign ratio $R(t)$ (points) overlaid with results of the fit to three different hypotheses (see text).

(b) Confidence level regions on the $R_D^{K3\pi} - \delta_D^{K3\pi}$ plane from the mixing constrained fit, required as inputs in measurements of the CKM angle γ.

Figure 3: Results from the analysis of wrong-sign $D^0 \to K^+\pi^-\pi^-\pi^+$ decays [21].

The analysis uses a phase-space integrated approach, which leads to the appearance of an additional coherence factor $R_D^{K3\pi}$ in the interference term. This quantity, along with the average strong phase $\delta_D^{K3\pi}$, and the phase-space averaged magnitude of the ratio of DCS to CF decays $r_D^{K3\pi}$, is required as an input in measurements of the CKM angle γ. The $R(t)$ fit is therefore performed using two distinct approaches: a standard fit to extract the charm mixing parameters, and a second fit with the mixing parameters constrained to the world-average values, which provides improved constraints on the γ inputs.

From a sample of ∼42K wrong-sign signal candidates, the fit without mixing constraints gives 8.2σ significance for charm mixing, observed for the first time in this channel. The fit projection is shown in Fig. 3a, and the measured values for the different decay-time coefficients are:

$$\begin{aligned} r_D^{K3\pi} &= [5.67 \pm 0.12] \cdot 10^{-2}, && (3.8)\\ R_D^{K3\pi} \cdot y'_{K3\pi} &= [0.3 \pm 1.8] \cdot 10^{-3}, && (3.9)\\ \frac{1}{4}(x^2 + y^2) &= [4.8 \pm 1.8] \cdot 10^{-5}, && (3.10) \end{aligned}$$

where the uncertainties are the combination in quadrature of those from statistical (dominant) and systematic components. The main systematic uncertainties are from the limited knowledge of backgrounds, contamination from secondary decays, and the precision on the charge-dependent efficiency over the final-state phase-space.

From the mixing-constrained fit, the parameters required as inputs to measurements of γ are measured with a precision comparable to that from CLEO-c [22], with confidence level regions shown in Fig. 3b. A preliminary combination shows that the uncertainties on $R_D^{K3\pi}$ and $\delta_D^{K3\pi}$ will reduce by approximately 50% when including the new LHCb measurement.

3.3 CP violation in mixing: two measurements of A_Γ

For decays of D^0 mesons into *CP* eigenstates f, the time-dependent *CP* asymmetry can be approximated as

$$A_{\rm CP}(t) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D^0} \to f)} \approx a_{\rm dir} + a_{\rm ind}\left(\frac{t}{\tau}\right), \tag{3.11}$$

where the constant term is proportional to direct *CP* violation, and the linear term is driven by *CP* violation in mixing and interference. Experimentally, the linear term is easier to constrain, as it is robust against time-integrated charge asymmetries (e.g. production asymmetries, and many instrumental effects). For small *CP* violation, the linear coefficient is approximately $a_{\rm ind} \approx -A_\Gamma$, where

$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\bar{D^0} \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D^0} \to f)}, \tag{3.12}$$

and $\hat{\Gamma}$ is the effective decay width. Neglecting direct *CP* violation, A_Γ can be expressed in terms of the underlying mixing and CPV parameters, leading to the approximate relation $A_\Gamma \approx -x\sin\phi$.

There are therefore two ways of extracting A_Γ, either by measuring effective lifetimes for D^0 and $\bar{D^0}$ and calculating the asymmetry in Eq. (3.12), or by fitting the time-dependent ratio to extract the linear coefficient in Eq. (3.11). The LHCb experiment has recently performed separate measurements using these two approaches over the same data sample, using $D^{*\pm}$-tagged candidates, and K^+K^- and $\pi^+\pi^-$ final states. For both analyses, the main experimental challenge is in accounting for residual time-dependent asymmetries, which arise due to correlations between the decay time and the kinematics of the soft pion from the $D^{*\pm}$ decay. The two approaches use different techniques to mitigate these effects, but both use the control channel $D^0 \to K^-\pi^+$ to validate the corrections. For this channel a pseudo-A_Γ can be computed, which is zero by construction.

The first analysis [23] computes the ratio $A_{\rm CP}(t)$ and performs a binned decay time fit to a linear function to extract A_Γ. The analysis uses the full 3 fb^{-1} data sample collected in 2011-2012, and proceeds via several steps. After implementing selections designed to avoid candidates from kinematic regions with large charge asymmetries, the data are divided into decay time bins with approximately equal yields. In each bin, backgrounds are removed using a sideband subtraction technique in the variable $\delta M \equiv M(D^0\pi^\pm) - M(D^0)$. The data then undergo a symmetrisation process to cancel the residual charge asymmetries from detector effects, following which the distributions of production angle and track curvature for the soft pion are consistent for D^0 and $\bar{D^0}$. Before this procedure, the control channel has a significant asymmetry, $A_\Gamma(K\pi) = (0.041 \pm 0.010)\%$, which becomes consistent with zero after symmetrisation, $A_\Gamma(K\pi) = (0.016 \pm 0.010)\%$.

Systematic uncertainties are assigned for various aspect of the analysis. The most important account for imperfect background removal, the effect of neglecting contamination from secondary decays in the fit, and the limits of the charge symmetrisation procedure. The final results for both final states are

$$A_\Gamma(K^+K^-, \text{via Eq. (3.11)}, 3~\text{fb}^{-1}) = (-0.30 \pm 0.32 \pm 0.14)\cdot 10^{-3}, \tag{3.13}$$
$$A_\Gamma(\pi^+\pi^-, \text{via Eq. (3.11)}, 3~\text{fb}^{-1}) = (+0.46 \pm 0.58 \pm 0.16)\cdot 10^{-3}, \tag{3.14}$$
$$A_\Gamma(\text{comb., via Eq. (3.11)}, 3~\text{fb}^{-1}) = (-0.12 \pm 0.28 \pm 0.10)\cdot 10^{-3}, \tag{3.15}$$

where the first uncertainty is statistical and the second systematic. The third row is the combination of both channels, accounting for all correlations.

The second analysis [24] uses an unbinned decay time fit to extract the effective lifetimes of D^0 and $\bar{D}^0$, from which A_Γ is determined. In this case, the analysis uses only the 2 fb^{-1} collected during 2012, since the corresponding analysis of 2011 data has already been performed [25]. The fit proceeds via two steps: firstly the mass distributions $M(h^+h^-)$ and δM are fitted to extract per-candidate signal and background probabilities. Secondly, the decay time is fitted to extract the effective lifetime. In this second stage an additional variable, related to the separation between the primary interaction vertex and the D meson origin, is also fitted simultaneously to provide separation between charm from prompt and secondary sources. The fits are performed separately for D^0 and $\bar{D}^0$, and hence provide the required inputs to calculate A_Γ.

In this approach, the residual charge asymmetries from instrumental effects are removed on a per-candidate basis, using a data-driven ‘swimming’ method. For each candidate, the D^0 decay vertex position is adjusted incrementally and the event reconstruction and selection is repeated at each position: this produces a discrete map of the decay time acceptance for each candidate, which is used to correct the fit function used to model the decay time distributions. Following this procedure, the control channel has $A_\Gamma(K\pi) = (-0.007 \pm 0.015)\%$, consistent with zero as expected from an unbiased measurement.

The main systematic uncertainties in this case arise from the description of the combinatorial background, the effect of possible non-modelled correlations between fit variables, and the limited knowledge on the secondary contamination. The results for the 2012 data sample are:

$$A_\Gamma(K^+K^-, \text{via Eq. (3.12)}, 2\ \text{fb}^{-1}) = (-0.03 \pm 0.46 \pm 0.10) \cdot 10^{-3}, \tag{3.16}$$

$$A_\Gamma(\pi^+\pi^-, \text{via Eq. (3.12)}, 2\ \text{fb}^{-1}) = (+0.03 \pm 0.79 \pm 0.16) \cdot 10^{-3}, \tag{3.17}$$

which can be combined with the existing 2011 results [25], giving:

$$A_\Gamma(K^+K^-, \text{via Eq. (3.12)}, 3\ \text{fb}^{-1}) = (-0.14 \pm 0.37 \pm 0.10) \cdot 10^{-3}, \tag{3.18}$$

$$A_\Gamma(\pi^+\pi^-, \text{via Eq. (3.12)}, 3\ \text{fb}^{-1}) = (+0.14 \pm 0.63 \pm 0.15) \cdot 10^{-3}, \tag{3.19}$$

$$A_\Gamma(\text{comb., via Eq. (3.12)}, 3\ \text{fb}^{-1}) = (-0.07 \pm 0.32 \pm 0.11) \cdot 10^{-3}. \tag{3.20}$$

The final results from the two methods [Eq. (3.15), and Eq. (3.20)] are completely consistent, taking into account the known correlations between the statistical and systematic uncertainties. The measured values of A_Γ are compatible with *CP* conservation, and represent the most precise measurements of *CP* violation ever made in the charm sector.

4. Summary

The LHCb collaboration has performed several new and recent searches for *CP* violation in both the oscillation and decay of charm mesons, using a variety of different decays and analysis methods. All measurements to date are consistent with *CP* conservation, and give further evidence of the smallness of *CP* violation effects in the charm sector. With the continuing increase in yields collected in Run 2 and beyond, the improved detector and trigger capabilities provided by the LHCb upgrade, and the expansion to use new channels and methods, the next few years promise significantly improved sensitivity to CPV in charm, maximising the chance of observing the first hints of new physics signals.

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