Mixing and CP violation in Charm decays at LHCb

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Two measurements of mixing and CP violation in charm decays performed at the LHCb experiment are presented. The former is a measurement of the mixing observable $y_{\text{CP}} - y_{\text{CP}}^K$ in two-body $D^0$ decays, while the latter is a search for direct CP violation in $D_{(s)}^+ \rightarrow \eta^0 \pi^+$ decays.

I. INTRODUCTION

In the Standard Model (SM), mixing and CP violation in charm are highly suppressed, due to the smallness of the CKM matrix elements involved in these processes and to the GIM mechanism. Measurements of mixing and CPV in charm provide good sensitivity to beyond SM operators that couples to up-type quarks only.

The $D^0$ mass eigenstates can be written as linear combinations of flavour eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, where $p$ and $q$ are complex parameters. Oscillations are characterized by two parameters: the differences in mass, $x \equiv (m_1 - m_2)/\Gamma$, and in decay width, $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$, between the $D^0$ mass eigenstates (here $\Gamma$ is the average decay width of the $D^0$ mass eigenstates). If CP is violated, then the oscillation probabilities for $D^0$ and $\bar{D}^0$ mesons can differ.

In recent years significant progress has been made in this research field, mainly due to the large samples of charmed hadron decays collected by the LHCb experiment. The first observation of a non-zero value of the $y$ parameter dates back to 2010 by BaBar and Belle collaborations [1] and today we are approaching a 3% relative precision on its world-averaged value [3]. The first observation of a non-zero value of $x$, instead, was achieved only in 2021 from the LHCb collaboration [4]. Moreover, in 2019 the LHCb collaboration announced the first observation of CP violation in charm decays [5], achieved looking at the difference of the time-integrated CP asymmetries of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays, $\Delta A_{\text{CP}} \equiv A_{\text{CP}}(K^+K^-) - A_{\text{CP}}(\pi^+\pi^-)$. However, the large theoretical uncertainty on nonperturbative QCD effects, which might contribute to enhance $CP$ violation, does not allow to unequivocally establish if this observation is compatible or not with the SM. Further measurements are crucial to shed light on CP violation theoretical interpretation in the up-type quarks sector.

In these proceedings, two recent LHCb measurements of mixing and CP violation in charm decays are presented: a measurement of the mixing observable $y_{\text{CP}} - y_{\text{CP}}^K$ in two-body $D^0$ meson decays and a search for direct CP violation in $D_{(s)}^+ \rightarrow \eta^0 \pi^+$ decays.

II. MEASUREMENT OF THE CHARM MIXING PARAMETER $y_{\text{CP}}$ WITH $D^0 \rightarrow h^+h^-$ DECAYS

The $y_{\text{CP}}$ mixing observable is defined based on $D^0$ two-body decay rates. As shown in Fig. 1, the self-conjugate final states $D^0 \rightarrow f$, with $f = K^-K^+$ or $\pi^-\pi^+$, undergo a Cabibbo-suppressed decay either directly of after mixing, while the $K^-\pi^+$ final state is dominated by the Cabibbo-favoured amplitude, since the contribution following mixing is suppressed by the subsequent doubly Cabibbo-suppressed decay. The time-dependent decay rates can be described by exponential functions with an effective decay width. The non-zero value of $y$ introduces a shift between the two decay modes. The departure from unity of the ratio of the effective decay widths of $D^0 \rightarrow f$ and $D^0 \rightarrow K^-\pi^+$ is the target observable:

$$\frac{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow K^-\pi^+) + \Gamma(\bar{D}^0 \rightarrow K^+\pi^-)} - 1 \simeq y_{\text{CP}}^f - y_{\text{CP}}^K.$$  

At the current experimental sensitivity, final-state dependent contributions and $CP$ violation effects can be neglected, hence $y_{\text{CP}}^f$ is equal to $y$. The correction term $y_{\text{CP}}^K$ is approximately equal to $\sqrt{R_{Dy}} \simeq 6\% \ y$, [6] where $R_{D}$ is the ratio of the branching fractions of the doubly Cabibbo-suppressed $D^0 \rightarrow K^+\pi^-$ decay to the Cabibbo-favoured $D^0 \rightarrow K^-\pi^+$ decay.

The observable of interest is measured through an

FIG. 1: Sketches of the interfering amplitudes of $D^0$ two-body decays.

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exponential fit to the ratio
\[
R^f(t) = \frac{N(D^0 \rightarrow f,t)}{N(D^0 \rightarrow K^-\pi^+,t)} \propto \exp\left(-\frac{y_{CC}^f}{\tau_{CP}} t\right)
\]
\[
\propto e^{-\left(y_{CC}^{f,t}/\tau_{DP}\right)t} \cdot \frac{\epsilon(f,t)}{\epsilon(K^-\pi^+,t)}, \tag{2}
\]
where \( \tau_{DP} \) is the lifetime of the \( D^0 \) meson and \( \epsilon(X) \) is the time-dependent efficiency of the \( X \) decay mode.

This measurement is performed using proton-proton (pp) collision collected at the LHCb experiment at a centre-of-mass energy of 13 TeV during Run 2 (2015–2018), corresponding to an integrated luminosity of 6 fb\(^{-1}\). The \( D^0 \) meson is required to come from a \( D^{*+} \rightarrow D^0\pi^+ \) decay, such that the flavour of the \( D^0 \) is determined from the charge of the slow pion.

**Efficiency equalization** Trigger requirements are applied to the \( D^0 \) daughters tracks, on kinematic observables such as momentum and pseudorapidity. Applying these requirement to different final states, with different kinematic distributions, introduces discrepancies between the time-dependent efficiency of these final states. In order to equalize these efficiencies, a procedure called *kinematic matching* is applied. It consists in computing new kinematic variables, called *matched* variables, designed to have the same distribution for the \( D^0 \rightarrow f \) decays and \( D^0 \rightarrow K^-\pi^+ \) decay, so that if a selection on these variables is applied, the efficiency is equal for both final states. To compute the matched kinematic variables for a \( D^0 \rightarrow K^-K^+ \) decay, the momentum of the daughter particles in the \( D^0 \) centre-of-mass frame, which is 791 MeV/c for a \( D^0 \rightarrow K^-K^+ \) decay, is changed to 861 MeV/c (the value for a \( D^0 \rightarrow K^-\pi^+ \) decay).

To remove the effect of the trigger requirements, tighter requirements are applied on the matched kinematic variables. Figure 2 shows an example of how the new thresholds are determined to ensure that both \( D^0 \rightarrow K^-K^+ \) and \( D^0 \rightarrow K^-\pi^+ \) decays are selected with the same efficiency.

The different interaction with the matter of kaons compared to pions, as well as particle identification requirements, produce efficiency discrepancies that cannot be removed by the kinematic matching. To remove these residual discrepancies, the \( p_t \), \( \eta \) and \( \rho \) distributions of the \( D^{+} \) mesons of \( D^0 \rightarrow f \) decays are weighted to the corresponding distributions of \( D^0 \rightarrow K^-\pi^+ \) decay, using a gradient-boosted reweighting algorithm from the *hep_ml* library [8].

This efficiency equalization is validated with simulated samples and also on data, through a cross-check observable,
\[
R^{CC}(t) = \frac{N(D^0 \rightarrow \pi^-\pi^+,t)}{N(D^0 \rightarrow K^-K^+,t)} \propto \exp\left(-\frac{y_{CC}^{\pi\pi}}{\tau_{DP}} t\right) \cdot \frac{\epsilon(\pi^-\pi^+,t)}{\epsilon(K^-K^+,t)}, \tag{3}
\]
where \( y_{CC}^{\pi\pi} \) is expected to be zero in the SM and is measured to be \( y_{CC}^{\pi\pi} = (-0.44 \pm 0.53) \times 10^{-3} \).

**Yield determination and main backgrounds** The combinatorial background, mainly due to random slow pion, is the main background in the data sample. In order to disentangle the signal yield from this background, a binned \( \chi^2 \) fit is performed, in bins of \( D^0 \) decay time, to the \( \Delta m = m(h^-h^+\pi^+_{tag}) - m(h^-h^+) \) observable, where \( m(h^-h^+\pi^+_{tag}) \) is the mass of the \( D^{*+} \) candidate and \( m(h^-h^+) \) is the mass of the \( D^0 \) candidate. Most of the uncertainty related to the \( D^0 \) mass resolution is cancelled in the subtraction, considerably improving the mass resolution. The signal model consists of the sum of three Gaussian and of a Johnson SU [9] functions, while the combinatorial background is modelled with this empirical function
\[
P_{BKG}(\Delta m|m_0,\alpha) \equiv \frac{1}{\mathcal{I}_B} \cdot \sqrt{\frac{\Delta m^2}{m_0^2} - 1} \cdot \exp\left(-\alpha \left(\frac{\Delta m^2}{m_0^2} - 1\right)\right). \tag{4}
\]

The signal yields, integrated over all decay-time bins, amount to 70 million, 18 million, and 6 million decays, respectively for the \( D^0 \rightarrow K^-\pi^+ \), \( D^0 \rightarrow K^-K^+ \) and \( D^0 \rightarrow \pi^-\pi^+ \) decay channels.

The second main background contribution comes from \( D^{*+} \) mesons that are not produced at the interaction vertex, but that rather come from a \( B^0 \) or \( B^+ \) decay. The reconstructed decay time of those candidates is biased toward larger values, diluting the mixing effects. To reduce this background, a requirement on the \( D^0 \) impact parameter with respect to the its interaction vertex, is applied. The fraction of residual background is fitted with simulated templates in the 2D-variables space of the \( D^0 \) impact parameter and decay time. Then the decay-time bias from the residual background is estimated with the LHCb simulation, and subtracted.
III. MEASUREMENT OF CP ASYMMETRIES IN D_{(s)} \rightarrow \eta^{(')} \pi^{+} DECAYS

The goal of this analysis is the measurement of the time-integrated CP asymmetry of the singly Cabibbo-suppressed D^{+} \rightarrow \eta^{(')} \pi^{+} decay, while simultaneously measuring the Cabibbo-favoured D_{s}^{+} \rightarrow \eta^{(')} \pi^{+} decay. Singly Cabibbo-suppressed decay channels are of particular interest because CP violation may manifest due to the interference of tree level amplitudes. No evidence for CP violation has been observed in these decay channels by the CLEO [10, 11], Belle [12, 13] and LHCb [14, 15] collaborations.

Also this measurement is performed using pp-collision data collected at the LHCb experiment at a centre-of-mass energy of 13 TeV during Run 2 (2015-2018), corresponding to an integrated luminosity of 6 fb^{-1}. Both \eta and \eta^{'} mesons are reconstructed in the \gamma \pi^{-} \pi^{+} final state. The two charged pions allow the decay vertex to be reconstructed, which is crucial to reduce the combinatorial background. The CP asymmetry is defined as

\[ A_{CP}(D_{(s)}^{+} \rightarrow f^{+}) \equiv \frac{\Gamma(D_{(s)}^{+} \rightarrow f^{+}) - \Gamma(D_{(s)}^{-} \rightarrow f^{-})}{\Gamma(D_{(s)}^{+} \rightarrow f^{+}) + \Gamma(D_{(s)}^{-} \rightarrow f^{-})}, \]

where \Gamma is the partial decay width to the final state of interest \( f \). For each of the analysed final states, the measured experimental observable is the raw asymmetry,

\[ A_{raw}(D_{(s)}^{+} \rightarrow f^{+}) \equiv \frac{N(D_{(s)}^{+} \rightarrow f^{+}) - N(D_{(s)}^{-} \rightarrow f^{-})}{N(D_{(s)}^{+} \rightarrow f^{+}) + N(D_{(s)}^{-} \rightarrow f^{-})}, \]

where \( N \) refer to the measured yield. For small asymmetries, a first-order approximation can be used:

\[ A_{raw}(D_{(s)}^{+} \rightarrow f^{+}) \approx A_{CP}(D_{(s)}^{+} \rightarrow f^{+}) \approx A_{prod}(D_{(s)}^{+}) + A_{det}(f^{+}). \]

Therefore, to extract the CP asymmetry value from the raw asymmetry, we have to correct for the production asymmetry and the detection asymmetry. The production asymmetry is defined as

\[ A_{prod}(D_{(s)}^{+}) \equiv \frac{\sigma(D_{(s)}^{+}) - \sigma(D_{(s)}^{-})}{\sigma(D_{(s)}^{+}) + \sigma(D_{(s)}^{-})}, \]

where \( \sigma(D_{(s)}^{\pm}) \) is the production cross-section of the \( D_{(s)}^{+} \) and \( D_{(s)}^{-} \) mesons, which differ at the LHC, because of the CP asymmetric initial state, pp. The detection asymmetry is defined as

\[ A_{det}(f^{+}) \equiv \frac{\epsilon(f^{+}) - \epsilon(f^{-})}{\epsilon(f^{+}) + \epsilon(f^{-})}, \]

where \( \epsilon(f^{\pm}) \) is the detection efficiency of the final state \( f^{+} \) and \( f^{-} \). These two values can differ due to the different interaction with matter of particles and antiparticles. In our case of study, the detection asymmetry is fully due to the pion in the \( D_{(s)}^{+} \rightarrow \eta^{(')} \pi^{\pm} \) decay.
decay, because the $\eta^{(i)}$ final state, $\gamma\pi^-\pi^+$ is $CP$ symmetric. In order to subtract these nuisance asymmetries, the raw asymmetry of the control channels are subtracted. These control channels have identical contributions from production and detection asymmetries, but have a negligible, or precisely known, $CP$ asymmetry. The control samples consist of the Cabibbo-favoured $D_s^+ \to \phi\pi^+$ decays, where $A_{CP}$ is assumed negligible in the SM, and the singly Cabibbo-suppressed $D^+ \to \phi\pi^+$ decay, where $A_{CP}(D^+ \to \phi\pi^+) = (0.5 \pm 5.1) \times 10^{-4}$ has been previously measured by the LHCb collaboration [16]. The $\phi$ meson is reconstructed in the self-conjugate $K^-K^+$ final state.

The experimental observables are

\[
A_{CP}(D^+ \to \eta^{(i)}\pi^+) =
= A_{raw}(D^+ \to \eta^{(i)}\pi^+) - A_{raw}(D^+ \to \phi\pi^+)
+ A_{CP}(D^+ \to \phi\pi^+),
A_{CP}(D_s^+ \to \eta^{(i)}\pi^+) =
= A_{raw}(D_s^+ \to \eta^{(i)}\pi^+) - A_{raw}(D_s^+ \to \phi\pi^+). \tag{10}
\]

**Determination of the raw asymmetry** The main background in the sample is combinatorial background. In order to determine the raw asymmetry, signal yields need to be extracted and disentangled from this background. To do this, a binned maximum-likelihood fit is performed simultaneously in the 3D variable space [$m(\eta^{(i)}\pi^+), m(\eta^{(i)}\pi^-), m(\gamma\pi^-\pi^+)$]. Both the signal and combinatorial background are modeled with empirical functions. The $D_s^\pm$ and $D_s^\mp$ signal models are Johnson SU[9] functions in the $m(\eta^{(i)}\pi^+)$ variable. A quadratic dependence on $m(\gamma\pi^-\pi^+)$ is allowed for the mean and the width, while $\Delta m \equiv m(D_s^+) - m(D_s^-)$ linearly depends on it. The two Johnson SU parameters that mainly determine the asymmetry and kurtosis of the distribution are shared between $D_s^+$ and $D_s^-$ and between positively and negatively charged candidates. The model for the combinatorial background is a third-order Chebyshev polynomial in the $m(\eta^{(i)}\pi^\pm)$ variable, independent in each bin of $m(\gamma\pi^-\pi^+)$. The $D_s^0$ is misreconstructed as a photon. The shape of this background is fixed from simulation. Figures 4 and 5 show the $m(\eta^{(i)}\pi^\pm)$ and $m(\gamma\pi^-\pi^+)$ distributions with the fit results superimposed.

**Control channel yields extraction** Due to the absence of neutral particles, the control channels have much less background. To correctly subtract nuisance asymmetries, the kinematics distribution (transverse momentum and pseudorapidity of $D_s^\pm$ and tagging pion) of the control channels have to be weighted to those of the signal channels in the $m(\eta^{(i)}\pi^\pm)$ distributions. The control channels are subtracted using the $sPlot$ technique [17], using $m(\eta^{(i)}\pi^\pm)$ as discriminating variable.

**Final results** The final value of $A_{CP}$ after the combination with previous LHCb measurements using different $\eta$ final states [13] or independent data samples [14] are:

\[
A_{CP}(D^+ \to \eta\pi^+) = (0.13 \pm 0.50 \pm 0.18)\% \tag{11}
A_{CP}(D^+ \to \eta'\pi^+) = (0.43 \pm 0.17 \pm 0.10)\% \tag{12}
A_{CP}(D_s^+ \to \eta\pi^+) = (0.48 \pm 0.42 \pm 0.17)\% \tag{13}
A_{CP}(D_s^+ \to \eta'\pi^+) = (-0.04 \pm 0.11 \pm 0.09)\%.
\]
where the first uncertainty is statistical, and the second is systematic. The results are compatible with the conservation of the $CP$ symmetry. For the $D^+ \to \eta\pi^+$, $D^+ \to \eta'\pi^+$ and $D_s^+ \to \eta'\pi^+$ decay channels, this is the most precise measurement to date.

IV. FUTURE PROSPECTS

We have just barely started to approach the SM upper limits for $CP$ violation in charm decays. LHCb–Upgrade I started in 2022 and over 23 (50) fb$^{-1}$ of integrated luminosity are expected to be collected by the end of Run 3 (4) in 2025 (2032). Moreover, the new LHCb data acquisition and trigger system will help to increase the reconstruction efficiency per fb$^{-1}$, in particular for hadronic charm decays [19]. This large amount of data will allow for a significant improvement in the accuracy of mixing and $CP$-violation measurements in the charm sector.

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