Results and prospects for Charm Physics at LHCb

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Precision measurements in charm physics offer a window into a unique sector of potential New Physics interactions. LHCb is well equipped to take advantage of the enormous production cross-section of charm mesons in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV. The measurement of the \( D^0 - \bar{D}^0 \) mixing parameters and the search for CP-violation in the charm sector are key physics goals of the LHCb programme. The first CP violation measurements in the charm sector, with 37 pb\(^{-1} \) of data collected in 2010, are discussed. The study of \( D^+ \to K^- K^+ \pi^+ \) decays shows no indication of CP violation. The measurement of the proper time asymmetry in the time dependent analysis of \( D^0 \to K^- K^+ \) and \( D^0 \to K^- K^+ \) is evaluated to be \( A_T = (-5.9 \pm 5.9_{\text{stat}} \pm 2.4_{\text{syst}}) \). The difference of CP asymmetry in the time integrated rates of \( D^0 \to K^- K^+ \) and \( D^0 \to \pi^- \pi^+ \) decays is measured to be \((-0.28 \pm 0.70_{\text{stat}} \pm 0.25_{\text{syst}}) \% \).

1. Introduction

LHCb \[1\], an experiment at the Large Hadron Collider (LHC), is dedicated to the study of \( b \) and \( c \) flavour physics. The abundance of charm particles produced in LHC offers an unprecedented opportunity for high precision measurements in the charm sector, including measurements of CP violation and \( D^0 - \bar{D}^0 \) mixing. The high performance of LHCb detectors allows this potential to be fully exploited.

The detector is a single-arm forward spectrometer covering the geometrical region where heavy flavour particles, at LHC energy, are mostly produced. A silicon micro-strip vertex detector (VELO) provides, with high precision, the position of the primary vertex and those of the decay of long-lived particles. Other elements of the LHCb tracking system include a silicon strip detector (TT) located in front of a dipole magnet and three station detector downstream of the magnet, composed of a silicon micro-strip detector (IT) in the inner part and by straw drift chambers (OT) in the outer region. Charged hadron identification is made through two ring-imaging Cherenkov detectors (RICH). The calorimeter system identifies high transverse energy hadron, electron and photon candidates and provides information for the trigger. The particle identification system is completed by five muon stations that provide fast information for the trigger and muon tagging.

CP violation in \( D \) decay processes has not yet been observed. In the SM, indirect CP violation in the charm sector is expected to be highly suppressed, less than \( \mathcal{O}(10^{-3}) \), and universal between CP eigenstates. While, direct CP violation can be larger in SM dependent on the final state: CKM dynamics can produce direct CPV asymmetries in single Cabibbo suppressed \( D^\pm \) decays of the order of \( 10^{-3} \) or less \[2\]. Both asymmetries can be enhanced by New Physics in principle up to \( \mathcal{O}(1\%) \) \[3\].

In 2010 LHCb recorded a total integrated luminosity of 37 pb\(^{-1} \). This provides a charm sample large enough to be able already to make several competitive measurements. The expected integrated luminosity of more than 1 fb\(^{-1} \) foreseen in 2011 will offer the opportunity to improve the world knowledge of \( D \) mixing and CP violation. The results of search for direct and indirect CP violation in the charm sector on data taken in 2010 by LHCb are presented here. In particular, the search for direct CP violation in singly Cabibbo suppressed (SCS) decay \( D^+ \to K^- K^+ \pi^+ \), the measurement of indirect CP violation in \( D^0 \) mixing in two body hadronic charm decays, and the search for CP asymmetry in the time integrated rates of \( D \) mesons into 2 body SCS decays are illustrated.

2. Search for CP violation in \( D^+ \to K^- K^+ \pi^+ \) decays

An independent analysis is performed to search for direct CP violation in the singly Cabibbo suppressed decay \( D^+ \to K^- K^+ \pi^+ \). The search consists of a direct comparison between the \( D^+ \) and the \( D^- \) Dalitz plots on a bin-by-bin basis. The Dalitz plot is divided into bins and for each bin a local CP asymmetry variable is defined:

\[
S_{CP}^i = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}} , \quad \text{with} \quad \alpha = \frac{N_{tot}(D^+)}{N_{tot}(D^-)},
\]

where \( N^i(D^+) \) and \( N^i(D^-) \) are the numbers of \( D^\pm \) decays in the \( i \)th bin and \( \alpha \) is the ratio between the total \( D^+ \) and \( D^- \) yields. The parameter \( \alpha \) is a correction to account for global asymmetries that are constant across the Dalitz plot.
Figure 1: Mass spectra of $K^-K^+\pi^+$. The signal mass windows and sidebands (lower, middle and upper) are labelled.

In the absence of local asymmetries, the $S_{CP}^i$ values are distributed according to a Gaussian distribution with zero mean and unit width. CPV signals are, therefore, deviations from this behaviour. The comparison between the $D^+$ and the $D^-$ Dalitz plots is made by a $\chi^2$ test \cite{4}. The $\chi^2$ is defined as $\chi^2 \equiv \sum(S_{CP}^i)^2$ and the number of degrees of freedom ($ndof$) is the number of bins minus one. Hence the probability value (p-value) measures the confidence level that the difference between $D^+$ and $D^-$ Dalitz plots is driven only by statistical fluctuations.

Different binning schemes are considered to obtain the highest sensitivity to various types of CPV. The bin scheme was optimized taking into account that we have no sensitivity if CP asymmetries change sign within a bin and we have a reduced sensitivity if only a small part of a large bin has any CP violation in it.

The technique relies on careful accounting for local asymmetries that could be induced by sources such as the different production mechanisms for $D^+$ and $D^-$, the difference in the K-nucleon inelastic cross-section, differences in the reconstruction or trigger efficiencies, left-right detector asymmetries, etc. The existence of these local asymmetries are investigated using the Cabibbo favoured control channels, $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+_s \rightarrow K^-K^+\pi^+\pi^+$. No CP violation is expected in these channels. The first control mode, $D^+ \rightarrow K^-\pi^+\pi^+$, has an order of magnitude greater branching ratio than the Cabibbo suppressed signal mode and is more sensitive to detector effects since there is no cancellation between $K^+$ and $K^-$. The second control mode, $D^+_s \rightarrow K^-K^+\pi^+\pi^+$, is similar to the signal mode in terms of resonant structure, statistics, kinematics, detector effects and backgrounds. Similarly, the method is also applied in the sidebands (shown in Fig. 1) of the second control channel to investigate possible asymmetries due to the contamination of the background. Another source of asymmetries could come from a charge asymmetry from the parent $B$ in the $B \rightarrow D(K^-K^+\pi^+)X$ decays. The effect of secondary charm is investigated by dividing the data set by the impact parameter $1^{\text{IP}}$ significance ($\chi^2_{IP}$) to have samples with different contamination from secondary charm. All these tests are fully consistent with no asymmetry, thus the method is determined to be very robust against systematic effects.

The data sample used in this analysis corresponds to approximately 35 pb$^{-1}$ collected in 2010. The signal

Table I: The p-values for consistency with no CPV for the $D^0 \rightarrow K^-K^+\pi^+$ decay mode for data with different magnet polarities

| Magnet Polarity | p-value |
|-----------------|---------|
| Up              | 6.0%    |
| Down            | 28.5%   |
| Combined        | 12.7%   |

$^1$ The IP is the minimum distance of approach with respect to the primary vertex. The $\chi^2_{IP}$ is formed by using the hypothesis that the IP is equal to zero.
sample consist of about 370k candidates. The global asymmetries parameter \( \alpha \) is measured to be 0.984±0.003. Fig. 1 shows the invariant mass of \( K^−K^+\pi^+ \) for the analysed data sample. The following two bin schemes are used on the signal data: the first scheme (Uniform) uses an uniform grid of equal size bins; the second type (Adaptive) takes into account the non uniform event distribution due to the \( \phi \) \( \pi^+ \) and \( K^∗(892)^0K^- \) modes. This second scheme has bins of variable size, aiming for a uniform population in all the bins. For each bin the significance \( S_{\Delta m}^i \) of the difference in \( D^+ \) and \( D^- \) population is computed as defined in Eq. 1 and the \( \chi^2/ndof \) is calculated to obtain the p-value. The data with opposite magnet polarities are combined to cancel left-right asymmetries.

The obtained p-values, summarized in Table \( \chi \) indicate no evidence for CPV \( \chi \). This result is also supported by the result of the Gaussian fit of \( S_{\Delta m} \), that have mean and width consistent with 0 and 1, respectively. The results for the Uniform bin scheme are shown in Fig. 2.

### 3. Measurement of indirect CP violation in \( D^0 \) mixing

A measurement of the indirect CP violation in \( D^0 \) mixing can be performed in the study of two-body hadronic charm decays. It can be evaluated by the asymmetry of the proper-time \( \tau \) of flavour-tagged decays:

\[
A_\tau \equiv \frac{\tau (D^0 \rightarrow K^-K^+) - \tau (D^0 \rightarrow K^+K^-)}{\tau (D^0 \rightarrow K^-K^+) + \tau (D^0 \rightarrow K^+K^-)} = \frac{1}{2} A_M y \cos \phi - x \sin \phi,
\]

where \( x = \frac{\Delta m}{\Delta \Gamma} \) and \( y = \frac{\Delta \Gamma}{\Delta m} \) are the mixing parameters and \( \phi \) is the CP violating weak phase. \( A_M \) is defined by the parameterization \( R_{m}^{\pm 2} = | q/p |^{1/2} = 1 \pm A_M \) with the assumption that \( R_m \) is close to unity and where \( q \) and \( p \) are parameters that define the mass eigenstates in terms of the flavour eigenstates.

A measurement of \( A_\tau \) differing significantly from zero would be a measurement of indirect CP violation as it requires a non-zero value for \( A_M \) or \( \phi \).

The signal yield and the background contribution are extracted from fits to the reconstructed invariant mass alone. Due to the abundance of charm decays, the selection has been designed to achieve maximal purity, with a background rate of the order of a few percent. The main component of the background is due to the secondary charm, i.e. \( D \) mesons produced from large hadron decays. This kind of background is not distinguishable by the invariant mass distribution. The secondaries have larger impact parameter with respect to the primary vertex than the prompts as a secondary \( D \) no longer has to point back to the primary vertex. Thus this background can be reduced by a selection based on the topology but it can not be completely suppressed. Hence a statistical separation is required. We use the variable \( \ln (\chi^2_P) \), because it is an easier quantity to parameterise than \( IP \) directly. For the secondary charm, the \( IP \) depends on the \( B \) flight distance. The form of the consequent \( \ln (\chi^2_P) \) dependence on proper-time is extracted from the simulation, and the parameters of this dependence are evaluated in the fit procedure.

Since this analysis is sensitive to the proper time dependence of the acceptance, particular attention is paid to requirements that could bias this distribution. A correction of these lifetime biasing effects is needed to properly
extract $A_\Gamma$ via absolute lifetime measurements. The heavy flavour selection implies some criteria which bias the measured proper time distribution. These biasing selections are unavoidable and have to be applied already at trigger level to suppress background from the large number of particles produced promptly in the proton-proton collisions. One example in the LHCb selection of heavy flavour decays is the request of a minimum impact parameter of the daughters. A correction of these lifetime biases has to be computed to properly evaluate the lifetime to determine $A_\Gamma$.

This analysis uses a data driven approach to evaluate the proper time acceptance, that describes the selection efficiency as a function of the $D^0$ proper time. The method evaluates the proper-time acceptance on a per event basis by a so-called ‘swimming’ algorithm, which was originally developed at CDF [6, 7] and is now being applied at LHCb [8–10]. In this method the acceptance function is evaluated by moving the primary vertices (and thus varying the proper time for the $D^0$ candidate). For each primary vertex position the software trigger decision and the offline selection are re-evaluated. Consequently the proper-time acceptance function for each event is determined as a sum of step functions, indicating when the event would be selected or not selected.

The measurement of $A_\Gamma$ is performed via absolute lifetime measurements obtained by a simultaneous fit of proper time and $\ln(\chi^2_{IP})$ including the acceptance function evaluated by the swimming method. Fig. 3 shows an example of the projection of the $\ln(\chi^2_{IP})$ for $D^0 \to K^- K^+$ decays.

The measurement is based on a data sample equivalent to 28 ± 3 pb$^{-1}$ of data taken in 2010. The number of candidates selected is about 15k for each flavour tag, $D^0$ and $\bar{D}^0$. The flavour tagging of $D^0$ decays is done by reconstructing the decay $D^{*+} \to D^0 \pi_s^+$, where the charge of the slow pion ($\pi_s$) determines the flavour of the $D^0$ at production.

The method was validated on a control measurement using decays to the Cabibbo favoured decay $D \to K \pi$. The combinatorial background contribution is ~ 1% for the control channel and ~ 3% for $D \to K K$ decays. In the 2010 data sample only low statistics were available in the mass sidebands. Hence it was not possible to model the background shape, and the background contribution is neglected in the time dependent fit and it is taken into account in the systematic uncertainties.

In the control channel the result for the lifetimes, averaged between $D^0 \to K^- \pi^+$ and $\bar{D}^0 \to K^+ \pi^-$, is $\tau(D^0) = 410.3 \pm 0.9$ fs, where the uncertainty is statistical only. This is in agreement with the current world average [12]. The lifetime asymmetry has been determined as $A_\Gamma^{K\pi} = (-0.9 \pm 2.2^{stat} \pm 1.6^{syst}) \cdot 10^{-3}$, which is consistent with zero in accordance with the expectation.

The measured lifetime is an effective lifetime since the fitted distribution includes also mistagged events, in which the $D^0$ is associated with a random slow pion. The mistag rates are assumed to be independent of the final state and are extracted from the favoured $D \to K \pi$ decays which offer higher statistical precision. This rate is evaluated by the fit of the difference between the mass of $D^*$ and $D^0$ ($\Delta m$) to be 1.8%. This has been neglected in the control channel as it is very small, but it is applied in the evaluation of $A_\Gamma$. The distribution of the $\Delta m$ between the $D^*$ and $D^0$ is shown in Fig. 4.

The results of the lifetime fit of $D^0 \to K^- K^+$ and $\bar{D}^0 \to K^+ K^+$ are shown in Fig. 5. The asymmetry is evaluated from these lifetimes to be [11]:

$$A_\Gamma = (-5.9 \pm 5.9^{stat} \pm 2.1^{syst}) \cdot 10^{-3}.$$  

(3)
Figure 4: $\Delta m$ mass difference between the reconstructed $D^*$ and $D$ candidates. The data are shown as points, the total fit as a solid line and the random background as dashed line.

Figure 5: Lifetime fit projection of $D^0 \rightarrow K^- K^+$ candidates on the left and $\bar{D}^0 \rightarrow K^- K^+$ candidates on the right on a logarithmic scale. The data are shown as points, the total fit (blue), the prompt signal (red), and the secondary signal (pink).

This result is consistent with zero and hence shows no evidence of CP violation and is in agreement with the current world average [12]. The main contributions to the systematic error are due to neglecting the combinatorial background and to the separation of prompt and secondary charm decays. The systematic uncertainty is expected to be significantly reduced by an improved treatment of the background events, which will be possible for the data taken in 2011.

4. Search for CP asymmetry in the time integrated decay rates of $D$ mesons

LHCb is searching for evidence of new sources of CP asymmetry in the time-integrated decay rates of $D$ mesons. The asymmetry is defined as

$$A_{CP}^{\text{RAW}}(f) = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow f)} = \frac{N(D^{*+} \rightarrow D^0(f)\pi^+) - N(D^{*-} \rightarrow \bar{D}^0(f)\pi^-)}{N(D^{*+} \rightarrow D^0(f)\pi^+) + N(D^{*-} \rightarrow \bar{D}^0(f)\pi^-)},$$

where $N(X)$ refers to the number of reconstructed events of decay $X$ after background subtraction. The raw time integrated asymmetries of $D^0$ and $\bar{D}^0$ decays are considered separately using the $D^*$ decay slow pion tagging method explained above.

The raw asymmetries may be written as a sum of various components, coming from both physics and detector
effects:

\[ A_{CP}^{RAW}(f)^* = A_{CP}(f) + A_{D}(f) + A_{P}(D^*) , \]  

where \( A_{CP}(f) \) is the physics CP asymmetry, \( A_{D}(f) \) the detection asymmetry of the \( D^0 \), \( A_{P}(\pi_s) \) the detection asymmetry of the soft pion and \( A_{P}(D^*) \) the production asymmetry.

Taking the asymmetry difference of the two final state \((A_{RAW}(f)^* - A_{RAW}(f'))^*\) the production and soft pion detection asymmetries will cancel. Moreover, for a two body decay of a spin-0 particle to a self-conjugate final state, there is no \( D^0 \) detector efficiency asymmetry contribution, i.e. \( A_{D}(K^-K^+) = A_{D}(\pi^-\pi^+) = 0 \). Due to possible production and detection asymmetries, the measurement of time-integrated CP asymmetry independently in \( D^0 \to KK \) and \( D^0 \to \pi\pi \) is challenging.

We can however measure the difference in time-integrated CP asymmetry \( \Delta A_{CP} \) between \( D^0 \to KK \) and \( D^0 \to \pi\pi \).

\[ A_{CP}^{RAW}(KK)^* = A_{CP}(KK) + A_{D}(\pi_s) + A_{P}(D^{*+}) , \]  

\[ A_{CP}^{RAW}(\pi\pi)^* = A_{CP}(\pi\pi) + A_{D}(\pi_s) + A_{P}(D^{*+}) , \]  

\[ \Delta A_{CP}^{RAW} = A_{RAW}(KK)^* - A_{CP}^{RAW}(\pi\pi)^* = A_{CP}(KK) + A_{CP}(\pi\pi) . \]  

No dependence remains on production or detection efficiencies, so this observable is extremely robust against systematic biases.

In a proton-proton collider machine the production of heavy-flavour hadrons need not be CP symmetric in a given region of phase space. Possible variations of both selectivity efficiency and production and detection asymmetry as a function of \( p_T \) and \( \eta \) could generate second-order yield asymmetries that do not cancel out in our formalism. \( A_{CP}^{RAW} \) extraction is performed in bins of \( \eta \) and \( p_T \) chosen such that the statistics are approximately constant within each bin. The binning is chosen to take into account the potential variation of production or detection asymmetries in these variables that differ for the two final states, such as those that may be induced in the selection by e.g. particle identification requirements.

A binned maximum likelihood fit to the spectrum of the mass difference between \( D^* \) and \( D^0 \) is used to evaluate the yields. Examples of the fit are shown in Fig. The data sample has an integrate luminosity of 37 pb\(^{-1}\). The total signal yield is 116k tagged \( D^0 \to K^-K^+ \) and 36k tagged \( D^0 \to \pi^-\pi^+ \). The background of mis-reconstructed \( D^0 \) decays that peaks in the mass difference is estimated from the mass sideband to be at the sub-percent level. The effect enters the asymmetry calculation at second order, \( O(10^{-4}) \), and can be neglected.

Systematic uncertainties are assigned by repeating the analysis with an alternative description of the mass spectra line-shapes; with different fit windows for the \( D^0 \) mass; with all candidates, choosing one candidate randomly in events containing multiple candidates; and comparing with the result obtained with no \( (p_T,\eta) \) binning. The full change in result is taken as a systematic uncertainty and all uncertainties are added in quadrature. No source of limiting systematic bias has been identified. These uncertainties are expected to be reduced by exploiting the much larger statistics that will be available.

A value of \( \Delta A_{CP} \) is determined in each measurement bin using the result from \( A_{RAW}(K^-K^+)^* \) and \( A_{RAW}(\pi^-\pi^+)^* \). These values are found to be consistent throughout the \( (p_T,\eta) \) space, as well as for the
two trigger periods and for both settings of the magnet polarity. A weighted average is therefore performed to yield the result $\Delta A_{CP} = (-0.28 \pm 0.70 \pm 0.25)\%$ [13]. This result is approaching the sensitivity of CPV measurements performed by the B-factories in these decay modes [14, 15], but not yet at the level of CDF’s recent measurement [16].

The time-integrated CP asymmetry $\Delta A_{CP}$ between the final states $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ has two contributions: a direct and an indirect component, $a_{CP}^{dir}$ and $a_{CP}^{ind}$, respectively. However, its time dependence has to be taken into account, leading to a non-cancellation if the two final states are reconstructed with a different mean proper time. Thus, the physics asymmetry of each final state may be written at first order as [17]

$$\Delta A_{CP} \approx a_{CP}^{dir}(\pi^- \pi^+) + \frac{\Delta < t >}{\tau} a_{CP}^{ind},$$

(9)

where $\Delta < t >$ denotes the difference of the mean proper time of the two final states and $\tau$ is the true $D^0$ lifetime. Although the measured value of $\Delta A_{CP}$ includes a residual 10% of the mode independent indirect CP asymmetry, $\Delta A_{CP}$ is primarily sensitive to direct CPV. Thus the measurement of $\Delta A_{CP}$ and $A_T$ are complementary in the search for CP violation. The current knowledge of these measurements leads to an agreement with the no CP violation hypothesis with a C.L. of 20% [18].

5. Conclusion

The first measurements at LHCb for search for CP violation in the charm sector are competitive with the results of the B-factories, even though only a total integrated luminosity of 37 pb$^{-1}$ collected in 2010 is used. The search for direct CP violation in $D^+ \rightarrow K^- K^+ \pi^+ \pi^-$ decays with a method based on the study of Dalitz plots indicate no evidence of CP violation. The measurement of indirect CP violation is performed on singly Cabibbo suppressed two-body charm decays through the study of the asymmetry of the proper-time. It is evaluated to be $A_T = (-5.9 \pm 5.9_{\text{stat}} \pm 2.1_{\text{syst}})$. The time-integrated CP asymmetries of $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays is measured to be $\Delta A_{CP} = (-0.28 \pm 0.70 \pm 0.25)\%$. In addition to these measurements, many others are underway, e.g. in 2-body decays the measurement of the mixing parameters using doubly Cabibbo-suppressed $D^0 \rightarrow K^+ \pi^-$ decays. Significant improvements in the precision is expected with the large data set collected in 2011 with an expected integrated luminosity of about 1 fb$^{-1}$.

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