CP Violation measurements in B→DX decays at LHCb

Agnieszka Oblakowska-Mucha¹ (on behalf of the LHCb Collaboration)

¹AGH University of Science and Technology,
Faculty of Physics and Applied Computer Science,
Al. Mickiewicza 30, 30-059 Krakow, Poland

E-mail: Agnieszka.Mucha@agh.edu.pl

Abstract. Measurements of CP violation are a core part of the LHCb physics programme and provide sensitivity to angles of the CKM matrix as well as searching for evidence of physics beyond the Standard Model. A summary of recent B→DX results from LHCb are presented, including the time-dependent B⁰ → D⁺π⁻ analysis which profits from the largest flavour tagged sample analysed by LHCb, the world’s first observation of the B⁺ → DₛKK and the world’s most precise (first) measurements of the CP asymmetry in B⁻ → D₋(s)D⁰ decays.

1. Introduction
Precise measurements of CP violation and searches for rare decays have a high potential for discovering effects of New Physics. CP violation and rare decays are sensitive to new particles and couplings in an indirect way that probes an energy scale beyond the collision energy of the LHC.

The rich family B→DX decays, where the B meson decays into a charm meson and an additional hadron, are considered. As a hadron X pion, kaon (also vector particles) or another charm meson are considered. The decays contain the b → c transition together with b → u, thus are sensitive to the CKM angle γ. The CP violating parameters from B → DX are obtained in the interference between different amplitudes leading to the same particles in the final state. The available precision of LHCb extends the potential of B→DX measurements to higher order processes, also including loop diagrams. Apart from the CKM angle γ measurements, decays from the B→DX family provide valuable information for the searches of the physics beyond the Standard Model (BSM).

2. Detector requirements for multi-body B decays
The LHCb experiment is currently the only project that is able to precisely study the heavy flavor quark sector and thanks to the very large b quark production cross-section in high energy proton collisions, has the largest samples of beauty hadrons ever collected. More than 2×10¹² b̅b pairs were produced in proton-proton collisions in the LHCb during Run I data taking period (years 2010-2012) with the cross-section σ_b̅b = (72.0 ± 0.3 ± 6.8) µb at centre-of-mass energy √s =7 TeV and integrated luminosity 3 fb⁻¹ [1]. This number was doubled after the increase of energy to √s =13 TeV during the ongoing Run II period (2015-2018). Due to huge number of events produced, an effective on-line event selection is required where the rate is reduced by a first level hardware trigger (L0) and further by two software high level triggers (HLT). This selects interesting events by means of high transverse energy and momentum signatures. The HLT performs a reconstruction of the tracks in the event in real time and runs a mixture of exclusive and inclusive selection algorithms.
The $B \to DX$ decay channels result in at least four particles in the final state and require precise tracking for momentum and mass determination and excellent vertex resolution to measure impact parameters and to achieve good decay time resolution.

The LHCb spectrometer (Figure 1) is a single-arm forward spectrometer covering the pseudorapidity range $2\eta<5$. Its forward geometry exploits the dominant heavy flavor production mechanism at the LHC since the $b\bar{b}$ pair production in proton-proton collisions at the LHC is spatially correlated and occurs predominantly at small angles with respect to the beam axis.

The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (Vertex Locator) surrounding the proton-proton interaction region, one silicon-strip detector before the magnet (TT), and three tracking stations behind the magnet (T1-T3). The tracking system provides a measurement of charged particle momentum with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c. A decay time resolution of about 50 fs is obtained at LHCb thanks to the accurate measurement of production and decay vertices [1].

Two ring-imaging Cherenkov detectors (RICH) provide efficient identification of charged particles with momenta up to 100 GeV/c. Photons, electrons and hadrons are identified by a calorimeter system. Muons are detected by a system (M1-M5). A complete description of the LHCb spectrometer can be found in [3].

3. CP violation in $B^0 \to D^+\pi^\pm$ decays

Measurements of CP violation in tree-level $B^0 \to D^+\pi^\pm$ decays are sensitive to the combination $(2\beta + \gamma)$ that comes from the transitions: $b \to c\bar{u}d$ and $\bar{b} \to \bar{u}cd$. The weak phase $2\beta$ is related to the amplitude of the $B^0 - \bar{B}^0$ oscillations, whereas sensitivity to $\gamma$ comes from the interference between amplitudes leading to the same final state. Phases $\beta$ and $\gamma$ are angles of the Cabibbo-Kobayashi-Maskawa (CKM) matrix expressed by: $\beta = \arg(-\frac{V_{cb}^\dagger V_{ub}}{V_{ub}V_{cb}^\dagger})$, $\gamma = \arg(-\frac{V_{ud}^\dagger V_{ub}}{V_{ub}V_{cd}^\dagger})$.

Decay-time-dependent CP asymmetries are measured in the decay rates as a function of tagged $B^0$ decay time:

$$I_{B^0\to f(f')} t \propto e^{-\Gamma t} \left[ 1 + C_f (f) \cos(\Delta m t) - S_f (f) \sin(\Delta m t) \right],$$

where $C_f (f)$ and $S_f (f)$ are CP-violating observables given by: $C_f = -C_\delta = \frac{1-r_{D\pi}^2}{1+r_{D\pi}^2}$, $S_f = \frac{2r_{D\pi} \sin(\delta - (2\beta + \gamma))}{1+r_{D\pi}^2}$. $\Delta m$ is the $B^0 - \bar{B}^0$ oscillation frequency and $\Gamma$ is the average $B^0$ decay width, $\delta$ describes the CP-conserving phase difference. The sensitivity to CP asymmetries is limited by the ratio of the interfering amplitudes: $r_{D\pi} = \frac{|A_0(B^0 \to D^+ \pi^-)|}{|A_0(B^0 \to D^- \pi^+)|} \approx 0.2$, thus $|C_f| \approx 1$.

The measurement is performed using a dataset corresponding to an integrated luminosity of $3 \text{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 7\text{ TeV}$. Signal events are selected by reconstructing $D^- \to K^- \pi^+\pi^-$ candidates accompanied by a pion or kaon. $B^0$ candidates should have decay time larger than 0.2 ps and a momentum vector aligned with the vector from the production vertex to the $B^0$ decay vertex. A boosted
decision tree is used to increase the signal purity. Finally, according to the particle identification information, the samples of \( B^0 \rightarrow D^+ \pi^\pm \) and \( B^0 \rightarrow D^\mp K^\pm \) decays are identified and fitted simultaneously.

The \( B^0 \rightarrow D^\mp K^\pm \) channel is used to control the cross-feed from misidentification. The mass distribution of \( B^0 \rightarrow D^\mp \pi^\pm \) candidates is displayed in figure 2a. The fit consists of the signal together with partially reconstructed decays and combinatorial background.

A combination of tagging algorithms is used to determine the flavor of the candidate \( B \) at production. They are based on the study of the particles produced together with the signal \( B \) candidate or exploit the second \( B \) meson produced in the same collision. The effective tagging efficiency is \( (5.59 \pm 0.01)\% \). The tagged \( B^0 \rightarrow D^\mp \pi^\pm \) signal yield is found to be \( 479 \, 000 \pm 700 \) and number of background events is \( 34 \, 000 \pm 300 \) [4].

The \( CP \)-violating observables are determined from a multidimensional, maximum likelihood fit to the unbinned decay time distribution of the signal candidates. The probability density function (PDF) describes the signal decay to the final state \( D^\mp \pi^- \) or \( D^\mp \pi^+ \) at the reconstructed time \( t \). The distribution of the decay time with the overlaid fit projection is shown in figure 2b. The following parameters are determined: \( S_f = 0.058 \pm 0.021 \) (stat) \( \pm 0.011 \) (syst) and \( S_f = 0.038 \pm 0.021 \) (stat) \( \pm 0.007 \) (syst). The values are in agreement and are more precise than the previous measurements. Taking external measurements of \( \beta \) and \( r_{\pi \pi} \) the intervals for \( \gamma \) are determined to be: \( \gamma \in [5, 86] \) \( \cup [185, 266] \) at 68\% C.L.

These are in agreement with the value obtained with other methods [5].

![Figure 2](image_url)  
Figure 2. a) Mass distribution of \( B \) candidates. b) Decay time distribution for tagged \( B \) candidates. The solid blue (dark) line is the projection of the signal PDF, the red (faint) dotted curve describes the efficiency function in arbitrary units.

### 4. First observation of \( B^+ \rightarrow D_s^+ K^+ K^- \) decays

The decay \( B^+ \rightarrow D_s^+ K^+ K^- \) is mediated by \( \bar{b} \rightarrow \bar{u} \) transition and is suppressed in the SM. The branching fraction for this decay was previously unknown. The pseudo-two body decay \( B^+ \rightarrow D_s^+ \phi \) proceeds dominantly via the annihilation diagram and requires the wave function of the incoming quarks to overlap to form the virtual \( W^+ \) boson. The decay is further suppressed due to the small value of the CKM element \( V_{ub} \). The SM predictions, using input from lattice calculations, are in the range \( \mathcal{B}_{SM} \sim (1 - 7) \times 10^{-7} \). Additional diagrams can arise in extensions of the SM, such as SUSY with R-parity violation, enhancing the branching fraction and producing large \( CP \) asymmetries. This makes the \( B^+ \rightarrow D_s^+ \phi \) decay a promising place to search for new physics beyond the SM.

This measurement analyzes data collected by the LHCb experiment during Run I (\( \sqrt{s} = 7 - 8 \) TeV, integrated luminosity 3 fb\(^{-1}\)) and data from Run II corresponding to an integrated luminosity of 1.8 fb\(^{-1}\) at \( \sqrt{s} = 13 \) TeV. The decay \( B^+ \rightarrow D_s^+ D^0 \) is used for normalisation. Candidates are reconstructed with \( D_s^+ \) decaying to \( K^- K^+ \pi^- \) with additional two charged kaons originating from the same vertex,
well separated from primary vertex. Decays $B^+ \to D_{s}^+ \phi$ are reconstructed with $\phi \to K^+ K^-$. Most of the candidates should fulfill the requirement that $|\cos \theta_K| > 0.4$, where $\theta_K$ is the angle between the kaon and $B$ momenta in $\phi$ rest frame.

The mass distribution of $B^+ \to D_{s}^+ K^+ K^-$ and the fit including all the relevant background components is presented in figure 3a. The fit gives $N(B^+ \to D_{s}^+ K^+ K^-) = 443 \pm 29$ candidates. The branching fraction is: $\mathcal{B}(B^+ \to D_{s}^+ K^+ K^-) = (7.1 \pm 0.5(stat) \pm 0.6(syst) \pm 0.7(norm)) \times 10^{-6}$. This is the first observation of this decay mode.

No significant peak is found in the $\phi$ region (see figure 3b). The fit to the $B^+ \to D_{s}^+ \phi$ candidates finds $N(B^+ \to D_{s}^+ \phi) = 5.3 \pm 6.7$ and $N(B^+ \to D_{s}^+ K^+ K^-) = 65 \pm 10$ events which are consistent with the $B^+ \to D_{s}^+ K^+ K^-$ measurement. The limit of: $\mathcal{B}(B^+ \to D_{s}^+ \phi) < 4.2 \times 10^{-7}$ is set on the branching fraction at 95% confidence level [6].

Figure 3. a) Mass distribution of $B^+ \to D_{s}^+ K^+ K^-$ candidates. b) Mass distribution of $B^+ \to D_{s}^+ \phi$ candidates.

5. B decays to two open charm mesons

The decays of charged and neutral $B$ mesons to two charm mesons proceed via tree- and loop-level amplitudes. The $CP$ asymmetry in the decay of the $B^-$ meson is defined as:

$$A^{CP}(B^- \to D_{s}^- D^0) \equiv \frac{\Gamma(B^- \to D_{s}^- D^0) - \Gamma(B^+ \to D_{s}^+ \bar{D}^0)}{\Gamma(B^- \to D_{s}^- D^0) + \Gamma(B^+ \to D_{s}^+ \bar{D}^0)}$$

and is expected to be small but nonzero in the SM. Since the interference is driven by a loop diagram, new physics contribution can enhance the observed asymmetry.

The following results are based on a data sample from proton-proton collisions that correspond to an integrated luminosity of 3 fb$^{-1}$ at energy $\sqrt{s} = 7.8$ TeV. This analysis provides the world-largest sample of the Cabibbo suppressed $B^- \to D^- \bar{D}^0$ decays.

Charm mesons are reconstructed in the following decays: $D^0 \to K^- \pi^+$, $D^0 \to K^- \pi^+ \pi^+ \pi^-$, $D^+ \to K^- \pi^+ \pi^+$, and $D_{s}^+ \to K^+ K^- \pi^+$. The mass distribution of $B^+ \to D_{s}^+ \bar{D}^0$ candidates with $D^0 \to K^- \pi^+$ decays is shown in figure 4. The signal yields and raw asymmetries (defined as a difference between the number of candidates for $B^-$ and $B^+$ decays, divided by their sum) are determined by fitting data to a model including components for the signal decays, a background from $B \to K K \pi D$ and combinatorial background. The $CP$ asymmetry is determined from the raw asymmetry as $A_{r_{raw}} = A_{CP} - (A_P + A_D)^1$.

1 The production asymmetry $A_P$ occurs due to different production rate of $B^0$ and $\bar{B}^0$. Detector asymmetry $A_D$ arises from tracking, trigger, and identification asymmetries and because of different $K^\pm$ interaction cross-sections with the detector material. $A_P$ and $A_D$ are determined in additional analyses.
which was determined to be: \( A_p + A_d = (-1.4 \pm 0.5\%) \) for \( B^- \to D_s^- D^0 \), and \( A_p + A_d = (-0.3 \pm 0.4\%) \) for \( B^0 \to D^- D^0 \) decay [7].

The obtained value yields: \( A^{CP}(B^- \to D_s^- D^0) = (-0.4 \pm 0.5(stat) \pm 0.5(syst))\% \), is the first, however without statistical significance, \( CP \) asymmetry measurement in this decay. The determined asymmetry: \( A^{CP}(B^0 \to D^- D^0) = (2.3 \pm 2.7(stat) \pm 0.4(syst))\% \) is more than a factor two more precise than the past measurements.

6. Summary and prospects for Run II measurements

The huge cross-section for \( b \bar{b} \) production in proton-proton interactions at the LHC energies and excellent performance of the LHCb spectrometer opened the possibility to observe rare and multibody decays of \( B \) mesons. Amongst them are \( B \) decays to charm mesons, which are key measurements for the CKM \( \gamma \) angle determinations but provides also important insights into New Physics searches.

The measurement of \( CP \)-violating observables in time-dependent decay rates in flavor-tagged \( B^0 \to D^+ \pi^\pm \) decays is a unique achievement at a hadron collider and provides valuable input to the LHCb \( \gamma \) combination [5].

The first observation of the decay \( B^+ \to D_s^+ K^- \) was established and the search for the annihilation decay \( B^+ \to D_s^+ \phi \) was performed. A limit on the branching fraction for \( B^+ \to D_s^+ \phi \) was set.

The first attempt of the \( CP \) asymmetry measurement in \( B^- \to D_s^- D^0 \) decays was performed using LHCb data. The precision of \( A^{CP}(B^0 \to D^- D^0) \) was improved with respect to previous measurements. No evidence of \( CP \) violation in both \( B^- \to D^- D^0 \) decays is found.

New results with a factor of 4 more data from Run II will become available in the future, greatly improving the precision and breadth of results from \( B \to DX \) decays at LHCb.

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