Measurement of CP Violation in $B^0 \to D^+D^-$ Decays

R. Aaij et al.
(LHCb Collaboration)

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The CP violation observables $S$ and $C$ in the decay channel $B^0 \to D^+D^-$ are determined from a sample of proton-proton collisions at center-of-mass energies of 7 and 8 TeV, collected by the LHCb experiment and corresponding to an integrated luminosity of 3 fb$^{-1}$. The observable $S$ describes CP violation in the interference between mixing and the decay amplitude, and $C$ parametrizes direct CP violation in the decay. The following values are obtained from a flavor-tagged, decay-time-dependent analysis: $S = -0.54^{+0.17}_{-0.16}(\text{stat}) \pm 0.05(\text{syst})$, $C = 0.26^{+0.18}_{-0.17}(\text{stat}) \pm 0.02(\text{syst})$. These values provide evidence for CP violation at a significance level of 4.0 standard deviations. The phase shift due to higher-order standard model corrections is constrained to a small value of $\Delta \phi = -0.16^{+0.19}_{-0.21}$ rad.

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signal samples and on background samples formed from \( B^0 \) candidates at high invariant masses (> 5500 MeV/c\(^2\)), and exploit observables related to the kinematics of the decay, PID information, and track and vertex quality. The requirements on the boosted decision tree classifier outputs are chosen to optimize the precision of both \( CP \) observables \( S \) and \( C \).

To separate the remaining background from the signal a fit to the \( D^+D^- \) invariant mass distribution is performed to calculate signal candidate weights via the \( sPlot \) technique [25]. The mass fit is performed simultaneously in four categories, split by the data-taking period (7, 8 TeV) and the number of kaons in the final state. The probability density function (PDF) used to parametrize the mass distribution consists of four contributions: signal, \( B^0 \to D^+D^- \), combinatorial background, and a component that includes both \( B^0 \to D_s^0 D^- \) and \( B_s^0 \to D^-D^0 \) decays. The signal is modeled by the sum of three Crystal Ball functions [26] with a common mean. The parameters of the tails (two towards lower and one towards higher mass) and the three widths are determined from simulated samples. To account for differences in the mass resolution in simulation and data, the width parameters are multiplied by a common scale factor, which is free to vary in the fit to data. The \( B^0 \to D^+D^- \) component shares all shape parameters with the signal PDF except for the peak position, which is constrained by the known value of the difference between the \( B^0 \) and the \( B_s^0 \) masses [22]. Each peak in the \( B^0 \to D_s^+ D^- \) and \( B_s^0 \to D^-D^0 \) component is described by the sum of two Crystal Ball functions (one with a tail towards lower and one with a tail towards higher masses) whose parameters are taken from simulation. The widths and the \( B^0 \) peak position are free to vary in the fit while the \( B^0 \) peak offset is constrained in the same way as that of the \( B^0 \to D^+D^- \) component. The combinatorial background is parametrized with an exponential function, with separate exponents used for the final states with two or three kaons. Partially reconstructed \( B^0 \to D^+D^- \) decays with \( D^{*+} \) and \( D^{*0} \) mesons are described by the sum of two Crystal Ball functions (one with a tail towards lower and one with a tail towards higher masses) whose parameters are taken from simulation. The widths and the \( B^0 \) peak position are free to vary in the fit while the \( B^0 \) peak offset is constrained in the same way as that of the \( B^0 \to D^+D^- \) component. The combinatorial background is parametrized with an exponential function, with separate exponents used for the final states with two or three kaons. Partially reconstructed \( B^0 \to D^+D^- \) decays with \( D^{*+} \) and \( D^{*0} \) mesons are described by the sum of two Crystal Ball functions (one with a tail towards lower and one with a tail towards higher masses) whose parameters are taken from simulation.
referred to as the mistag probability. Two classes of flavor-tagging algorithms are used: opposite-side (OS) and same-side (SS) taggers [27–29]. In $b\bar{b}$ pair production, the dominant source of $b$ hadrons at LHCb, the signal $B^0$ meson is accompanied by a second $b$ hadron. The OS taggers determine the flavor of the signal by examining the decay products of this second $b$ hadron. The information from the decay products consists of the charge of muons or electrons produced in semileptonic decays, the charge of kaons from $b \to c \to s$ transitions, the charge of charm hadrons from $b \to c$ transitions, and the net charge of all decay products. The SS taggers analyze pions and protons related to the hadronization process of the $B^0$ meson. This is the first analysis to use the LHCb SS proton and OS charm taggers, and the first to use the new SS pion tagger.

The outputs of all OS algorithms are combined into an overall OS tagging decision and mistag estimate, and the same is done for the SS algorithms. The mistag estimates $\eta \in \{\eta_{OS}, \eta_{SS}\}$ are calibrated using linear functions $\omega(\eta|d)$, so that $\eta$ on average matches the true mistag probability $\omega$, which depends on the true production flavor $d$ of the $B^0$ meson. The calibration studies are performed with a sample of $B^0 \to D^+_s D^-$ decays, for which the final state determines the flavor of the $B^0$ at decay. Since the calibration and signal channels are kinematically very similar, the calibration can be applied to the signal channel without further corrections. To ensure that the same calibration is valid for both, the same selection is used as for the signal decay with one $D^+ \to K^- K^+ \pi^+$, apart from requiring that the $K^- K^+ \pi^+$ invariant mass lie within 25 MeV/$c^2$ of the known $D^+_s$ mass [22] and dropping the vetoes against misidentified backgrounds. Background is subtracted from the calibration sample via the sPlot technique [25]. The tagging calibration parameters are determined from a fit to the decay time and tag distributions of $B^0 \to D^+_s D^-$ candidates, in which the detection asymmetry, the production asymmetry of the $B^0$ mesons, and the flavor-specific semileptonic asymmetry $a^d_M$ are taken into account. Here, the detection asymmetry describes the difference in reconstruction efficiency between the $D^+_s D^-$ and $D^+_s D^+$ final states, and $A_F \equiv [\sigma(B^0) - \sigma(B^0)]/\sqrt{\sigma(B^0) + \sigma(B^0)}$, where $\sigma$ denotes the production cross section inside the LHCb acceptance. The values of all these parameters are fixed according to the latest LHCb measurements [30,31], and their uncertainties are treated as sources of systematic uncertainty on the calibration parameters. Further systematic uncertainties are assigned due to the calibration method, the dependence of the efficiency on decay time, the decay time resolution, and the background subtraction. More details on the calibration studies are given in Ref. [32].

In the $B^0 \to D^+ D^-$ signal data sample, the correlation between the OS and the SS mistag estimates is found to be negligible. A small correlation of the mistag probability with decay time is seen; this is neglected in the main fit but considered as a source of systematic uncertainty.

The effective tagging efficiency is the product of the probability for reaching a tagging decision, $\epsilon_{\text{tag}} = (87.6 \pm 0.8)\%$, and the square of the effective dilution $D = 1 - 2\omega = (30.3 \pm 1.1)\%$. Its value is $\epsilon_{\text{tag}} D^2 = (8.1 \pm 0.6)\%$, the highest effective tagging efficiency to date in tagged $CP$ violation measurements at LHCb thanks to the improved flavor-tagging algorithms and the kinematic properties of the selected $B^0 \to D^+ D^-$ decays.

The $CP$ violation observables $S$ and $C$ are determined from a multidimensional fit to the background-subtracted tag and decay time distributions of the tagged $B^0 \to D^+ D^-$ candidates; a projection of the decay time distribution summed over the nonzero tag decisions is shown in Fig. 1(b). The conditional PDF describing the reconstructed decay time $t'$ and tag decisions $d' = (d'_{\text{OS}}, d'_{\text{SS}})$, given a per-event decay time resolution $\sigma_t$ and per-event mistag probability estimates $\tilde{\eta} = (\tilde{\eta}_{\text{OS}}, \tilde{\eta}_{\text{SS}})$, is
observables are studied with pseudoexperiments. The AP and where ρ is the true decay time, d is the true production flavor, A_p is the production asymmetry, and \( P(d|\vec{d}, \vec{\eta}) \) is a two-dimensional binomial PDF describing the distribution of tagging decisions given \( \vec{\eta} \) and d. Normalization factors are omitted for brevity. In the fit, the mass difference \( \Delta m \) and the lifetime \( \tau \) are constrained to their known values within uncertainties [22]. The production asymmetry \( A_p \) is constrained separately for the 7 and 8 TeV samples to the common mean. All parameters of the resolution model are determined from simulation. The average decay time resolution in data is 49 fs. The function \( \epsilon(t') \) describes the efficiency for all reconstruction and selection steps as a function of the reconstructed decay time. It is represented by cubic splines [33], with the spline coefficients left unconstrained in the fit.

The statistical uncertainties are estimated using the bootstrap method [34]. Individual bootstrap samples are drawn from the candidates in data that pass the full selection; the analysis procedure described above, consisting of the mass fit, background subtraction, and decay time fit, is then applied to obtain the values of the CP observables for each such sample. Two-sided 68% confidence intervals, with equal tail probabilities on either side, are obtained from the distributions of fitted parameters in the bootstrapped samples. To account for the uncertainties of the flavor-tagging calibration parameters, which are fixed in the likelihood fit, further pseudexperiments are generated in which these flavor-tagging calibration parameters are varied within their combined statistical and systematic uncertainties. The results are then used to correct the uncertainties from the bootstrapping procedure.

The CP observables are measured to be \( S = -0.54^{+0.17}_{-0.16} \) and \( C = 0.26^{+0.18}_{-0.17} \) with a correlation coefficient of \( \rho = 0.48 \). The decay-time-dependent signal yield asymmetry \( (N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0}) \), where \( N_{B^0} \) is the number of \( B^0 \rightarrow D^+D^- \) decays with a \( B^0 \) flavor tag, and \( N_{\bar{B}^0} \) the number with a \( B^0 \) tag, is shown in Fig. 2.

Several sources of systematic uncertainties on the CP observables are studied with pseudexperiments. The largest systematic uncertainty arises from neglecting backgrounds in which the final state contains only one charm meson, such as \( B^0 \rightarrow D^-K^-\pi^+ \). The yield of these backgrounds is estimated to be about 2% of the signal yield and their impact is assessed by assuming that they maximally violate CP symmetry and have the eigenvalue opposite to the signal mode. This leads to a systematic uncertainty of ±0.05 on \( S \) and ±0.013 on \( C \). Further systematic uncertainties on \( S \) are related to the assumption \( \Delta\Gamma = 0 \), and to the modeling of the dependence of the efficiency on decay time (±0.007). For \( C \) the second largest systematic uncertainty of ±0.007 is due to neglecting the correlation between the invariant mass and the decay time. Additional systematic uncertainties arise from the decay time resolution, from the uncertainty on the knowledge of the length scale, from the parametrization of the mass model, and from uncertainties on the \( B^0 \) production asymmetry and mass difference \( \Delta m \). The total systematic uncertainty, calculated as the sum in quadrature of all contributions, is ±0.05 for \( S \) and ±0.02 for \( C \), with a correlation coefficient of \( \rho = -0.69 \).

In conclusion, a measurement of the CP observables \( S \) and \( C \) in the decay channel \( B^0 \rightarrow D^+D^- \) is performed. Using the full data sample collected by the LHCb experiment during Run 1, which corresponds to a total integrated luminosity of 3 fb\(^{-1} \), they are determined to be

\[
S = -0.54^{+0.17}_{-0.16} \text{(stat)} \pm 0.05 \text{(syst)},
\]

\[
C = 0.26^{+0.18}_{-0.17} \text{(stat)} \pm 0.02 \text{(syst)}
\]

with a statistical correlation coefficient of \( \rho = 0.48 \). This result excludes the conservation of CP symmetry by 4.0 standard deviations. It is compatible with the previous measurement by the BABAR experiment of \( S = -0.63 \pm 0.36 \pm 0.05 \) and \( C = -0.07 \pm 0.23 \pm 0.03 \) [12] while being significantly more precise. A proper evaluation of the compatibility with the result from the Belle experiment [13] could not be performed due to its non-Gaussian
uncertainties. The result presented here corresponds to 
\[ \sin(\phi_1 + \Delta \phi) = 0.56^{+0.16}_{-0.17} \] 
which constrains the phase shift to the world’s most precise value of \[ \Delta \phi = -0.16^{+0.19}_{-0.21} \text{ rad} \], and thus implies only a small contribution from higher-order standard model corrections.

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