Published for SISSA by Springer

Received: *August 27, 2015*
Accepted: *September 14, 2015*
Published: *October 8, 2015*

Measurement of the time-integrated CP asymmetry in $D^0 \to K^0_S K^0_S$ decays

The LHCb collaboration

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Abstract: The time-integrated CP asymmetry in the decay $D^0 \to K^0_S K^0_S$ is measured using $3\,\text{fb}^{-1}$ of proton-proton collision data collected by the LHCb experiment at centre-of-mass energies of 7 and 8 TeV. The flavour of the D^0 meson is determined by use of the decay $D^{*+} \to D^0\pi^+$ and its charge conjugate mode. The result is

$$\mathcal{A}_{CP} = -0.029 \pm 0.052 \pm 0.022\,,$$

where the first uncertainty is statistical and the second systematic. The result is consistent with Standard Model expectations and improves the uncertainty with respect to the only previous measurement of this quantity by more than a factor of three.

Keywords: CP violation, Charm physics, Flavor physics, Hadron-Hadron Scattering

ArXiv ePrint: 1508.06087

doi:10.1007/JHEP10(2015)055

Contents

1 Introduction

In the Standard Model, *CP* violation in charm decays is expected to be small and hence potentially sensitive to contributions from New Physics. Although measurements of the time-integrated *CP* asymmetry in D^0 decays to pairs of charged mesons showed hints of *CP* asymmetry at the level of 0.7 %, the combined results are not yet conclusive [1–5]. Of particular interest, both for the search of New Physics and for the understanding of penguin contributions, are decays of D^0 mesons into a pair of neutral mesons, such as the decay $D^0 \to K^0_S K^0_S$ [6, 7].[1] If the *CP* asymmetry in D^0 decays to charged mesons is confirmed and assuming moderate breaking of the SU(3) flavour symmetry, the *CP* asymmetry of this mode could be of $\mathcal{O}(1\,\%)$ or even larger [6]. From a more recent Standard Model based analysis of the contributing amplitudes, a 95 % confidence level upper limit of 1.1 % for direct *CP* violation in the decay $D^0 \to K^0_S K^0_S$ has been derived [7]. The single previous measurement gave $\mathcal{A}_{CP} = (23 \pm 19)\,\%$ [8].

Here, we present the first result from the LHCb collaboration on *CP* violation in the decay $D^0 \to K^0_S K^0_S$. The measurement is based on D^0 mesons originating from $D^{*+} \to D^0\pi^+$ decays, where the flavour of the D^0 meson can be inferred from the charge of the "slow" pion from the D^{*+} decay. Throughout this document, D^{*+} stands for $D^*(2010)^+$. As a control channel, the decay $D^0 \to K^-\pi^+$ is used to estimate production and detection asymmetries. The analysis uses $3\,\text{fb}^{-1}$ of proton-proton collision data collected with the LHCb detector in 2011 and in 2012, at centre-of-mass energies of 7 TeV and 8 TeV, respectively.

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[1] The inclusion of charge-conjugate processes is implied throughout this article.

2 Detector and simulation

The LHCb detector [9, 10] 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 includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of momentum, p, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV.[2] The minimum distance of a track to a primary vertex (PV), the impact parameter, is measured with a resolution of $(15 + 29/p_{\mathrm{T}})$ μm, where p_{T} is the component of the momentum transverse to the beam, in GeV. The polarity of the dipole magnet is reversed regularly throughout the data-taking period, which allows to determine and correct for charge asymmetries due to the detector geometry.

Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The online event selection is performed by a trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

In the simulation, pp collisions are generated using PYTHIA [11, 12] with a specific LHCb configuration [13]. Decays of hadronic particles are described by EVTGEN [14], in which final state radiation is generated using PHOTOS [15]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [16, 17] as described in ref. [18].

3 Selection

Signal decays are reconstructed in the decay mode $D^{*+} \to D^0\pi^+$ with $D^0 \to K^0_{\mathrm{S}}K^0_{\mathrm{S}}$ and $K^0_{\mathrm{S}} \to \pi^+\pi^-$ [19]. To collect as many $D^0 \to K^0_{\mathrm{S}}K^0_{\mathrm{S}}$ decays as possible, events from all available physics triggers are considered. Candidate events are accepted if the four pions assigned to the K^0_{S} decays are sufficient to trigger the event or if the rest of the event, without the slow pion from the D^* decay, satisfies a trigger condition. Excluding the slow pion from the trigger decision minimises any bias on the CP asymmetry due to the trigger.

The $K^0_{\mathrm{S}} \to \pi^+\pi^-$ decays are reconstructed in two different categories: the first involves K^0_{S} mesons that decay early enough for the daughter pions to be reconstructed in the vertex detector; the second contains K^0_{S} mesons that decay later such that daughter track segments are only reconstructed in the tracking detectors downstream of the vertex detector. These categories are referred to as *long* (L) and *downstream* (D), respectively. The less abundant long category has better momentum and vertex resolution than the downstream category.

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[2] We use natural units where $c = 1$.

Categories	Description
LL	both K^0_S are of category long and *not* selected by the dedicated trigger
LD	one K^0_S is long, the other one is downstream
DD	both K^0_S are downstream
LLtrig	both K^0_S are of category long and selected by the dedicated trigger

Table 1. Definition of candidate categories.

As the final state contains two K^0_S mesons, there are three possible combinations labeled LL, LD, and DD. A dedicated software trigger selection for the $D^0 \to K^0_\mathrm{S} K^0_\mathrm{S}$ decay was implemented in 2012. As this trigger only accepts signal candidates composed of two long K^0_S, a fourth D^0 category, LLtrig, is defined where the dedicated trigger accepted the signal candidate. The four categories are listed in table 1.

The decay vertex of the D^0 candidate is reconstructed from the pion trajectories, constraining the K^0_S mass to its known value [20] and the D^0 flight direction to point to a PV [19]. To reduce the contamination from the decay $D^0 \to K^0_\mathrm{S}\pi^+\pi^-$, only candidates with significant decay times for both K^0_S decays are accepted. This requirement has a signal efficiency of over 99 %. The D^0 candidate is combined with a pion to produce a D^* candidate. Fiducial cuts are applied on the kinematic properties of this slow pion to remove regions where the detection charge asymmetry is large. A cut on the invariant mass of the $K^0_\mathrm{S} K^0_\mathrm{S}$ system of $\pm 20\,\mathrm{MeV}$ around the known value of the D^0 mass is applied. The efficiency of this cut is 98 % in all categories, except for DD, where it is 94 %. Candidates are further selected by requiring the difference between the D^{*+} and D^0 candidate masses, $\Delta m \equiv m_{D^*} - m_{D^0}$, to be less than 155 MeV.

To further reduce combinatorial background a multivariate analysis (MVA) method [21, 22] is used. It is based on a rule-based learner applying the methods of bagging [23] and instance weighting (see, e.g., refs. [24, 25]). Separate samples have been used for training and testing, where simulated events have been used as signal proxy, while the background sample was a mixture of data from D^0 sidebands (the mass ranges $1764.84 - 1844.84\,\mathrm{MeV}$ and $1884.84 - 1964.84\,\mathrm{MeV}$) and simulation. Kinematic quantities, decay time variables, geometric quantities, and fit quality variables are used as input to the MVA. The selection of variables and the training have been done separately for the different categories. For the MVA optimisation, the figure of merit $S/\sqrt{S+B}$ is used, where S is the expected number of signal candidates in the signal region defined by a $\pm 1.5\,\mathrm{MeV}$ window around the known Δm value [20], while B is the number of background candidates in the signal region. The optimal points have signal efficiencies of 95 %, 51 %, 47 %, and 37 %, and background retentions of 50 %, 0.33 %, 0.40 %, and 0.73 % for LLtrig, LL, LD, and DD, respectively. The large background retention for the LLtrig category is due to the fact that the dedicated trigger intrinsically has a much lower background level. The control channel $D^0 \to K^-\pi^+$ is selected by cuts on kinematic quantities, vertex quality variables, geometric quantities, and decay time variables. In addition, the same mass requirements and fiducial cuts on the slow pion are applied as in case of the signal channel. Due to the large number of control

Category	N^+	N^-	$\mathcal{A}_{CP}$
LL	86 ± 11	86 ± 12	0.00 ± 0.09
LD	82 ± 14	83 ± 13	-0.00 ± 0.11
DD	29 ± 14	66 ± 14	-0.39 ± 0.23
LLtrig	96 ± 11	99 ± 11	-0.02 ± 0.08
combined			-0.029 ± 0.052

Table 2. Number of signal candidates and *CP* asymmetry obtained from the fits in the four categories.

channel candidates, which is much larger than needed for this analysis, 1 % of candidates are accepted at random.

4 Asymmetry measurement

The *CP* asymmetry is obtained as

$$\mathcal{A}_{CP} = \frac{N^+ - N^-}{N^+ + N^-} \tag{4.1}$$

for each category, where N^+ (N^-) is the yield determined from a fit to the data for a positive (negative) charge of the slow pion.

The yields are determined from an extended unbinned maximum likelihood fit to the Δm distribution. In the fit model, the signal is described by a sum of three Gaussian functions, where the two narrower ones are required to have the same mean value. The parameters of the narrowest Gaussian function and the mean value of the widest one are allowed to float, while the ratios between widths, as well as those between normalisations, of all three are constrained to the values found in the simulation. The background is parametrised by the product of an exponential function and a power law for the phase-space threshold at the pion mass

$$f_{\text{bg}} = C_{\text{bg}}(\Delta m - m_{\pi^+})^p e^{-(\Delta m - \mathrm{m}_{\pi^+})\alpha} \,. \tag{4.2}$$

Here C_{bg}, p and α are determined by the fit. Independent fits are performed for the four categories. In each category, the background parameters and the shape parameters of the signal component are shared between the two charges of the slow pion.

The Δm distribution for the control channel, summed over both charges of the slow pion with the fit function overlaid is shown in figure 1. Figures 2 and 3 show the Δm distributions and the fit for each of the four categories and the two slow-pion charges. Table 2 lists the yields from the nominal fits and the resulting asymmetries. To obtain the final result, the asymmetries of the four signal categories are combined by taking the weighted mean.

5 Systematic uncertainties

The main sources of systematic effects are due to production and detection asymmetries and possible biases in the signal extraction method. The systematic uncertainty related

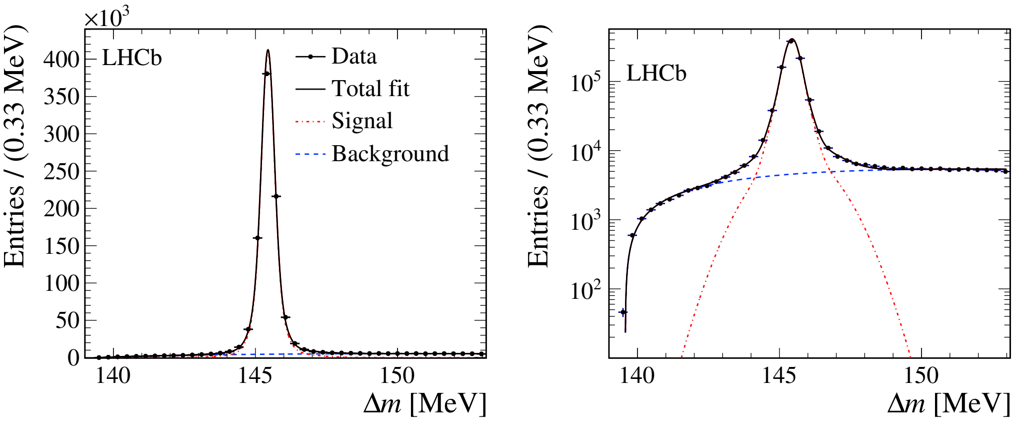

Figure 1. Distribution of Δm for the control channel $D^0 \to K^-\pi^+$ in (left) linear and in (right) logarithmic scale. The solid (black) line corresponds to the total fit, the dashed (blue) line corresponds to the background, and the dash-dotted (red) line represents the signal contribution.

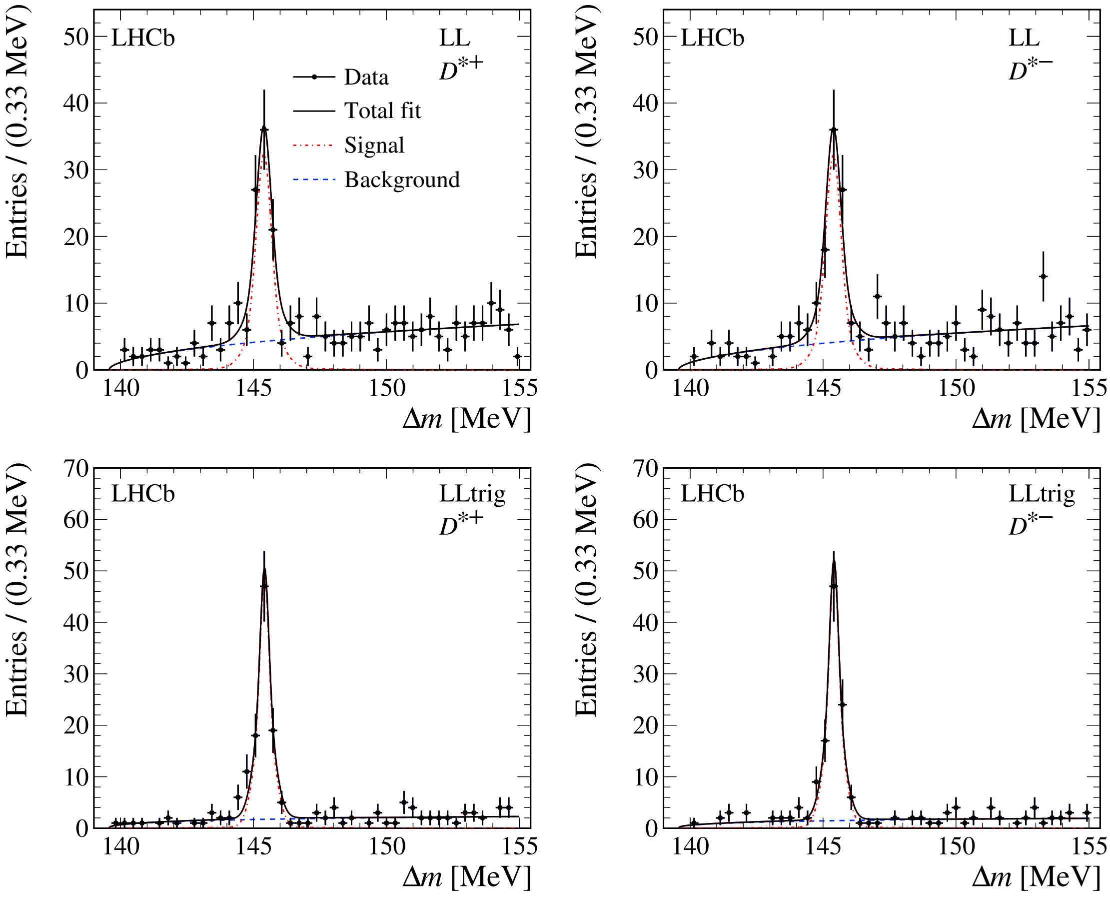

Figure 2. Distributions of Δm split into (left) D^{*+}, (right) D^{*-} and (top) LL, (bottom) LLtrig, including the fit function. The solid (black) line corresponds to the total fit, the dashed (blue) line corresponds to the background, and the dash-dotted (red) line represents the signal contribution.

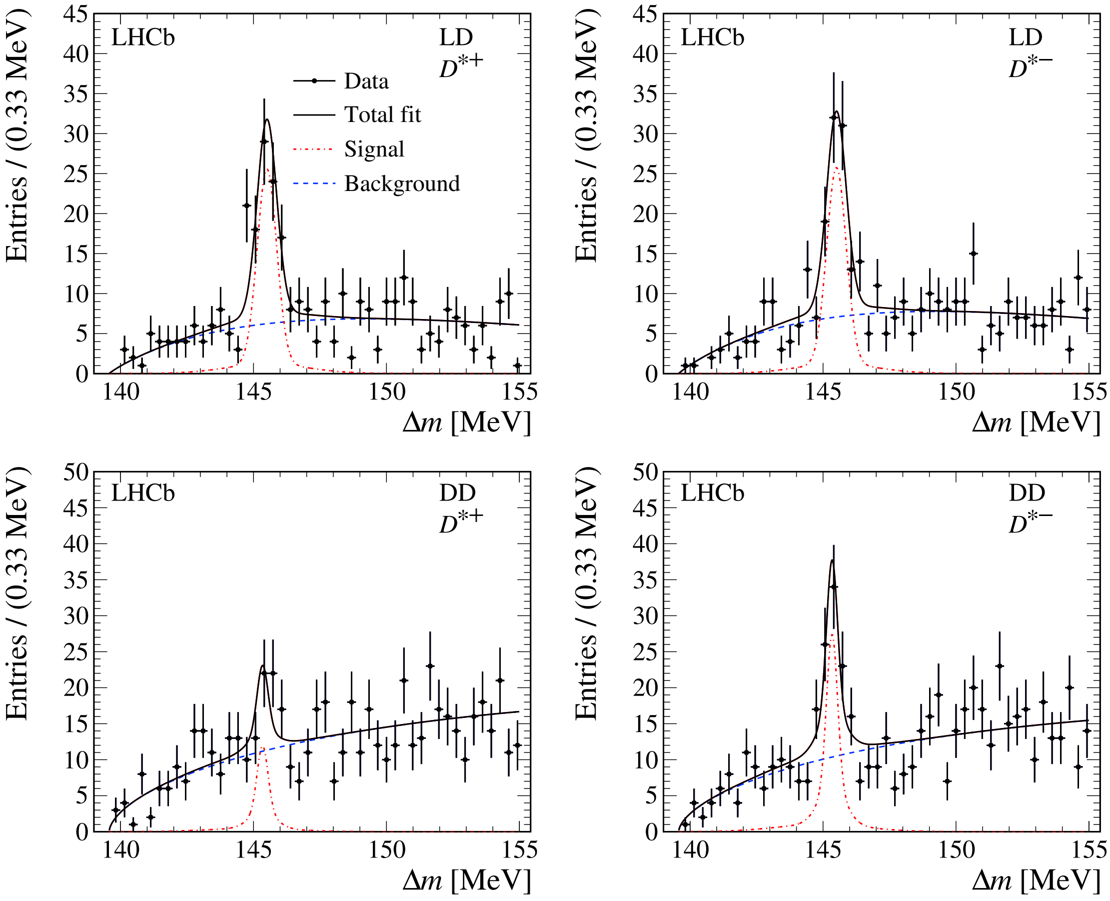

Figure 3. Distributions of Δm split into (left) D^{*+}, (right) D^{*-} and (top) LD, (bottom) DD, including the fit function. The solid (black) line corresponds to the total fit, the dashed (blue) line corresponds to the background, while the dash-dotted (red) line represents the signal contribution.

to the signal extraction is estimated by comparing the nominal fit with an alternative one, where outside of the signal region of ±1.5 MeV around the known Δm-value, only the background component is fitted. The signal yield is obtained by subtracting the background extrapolated into the signal region from the total observed yield. For the combined *CP* asymmetry a difference of 0.019 is found, which is assigned as a systematic uncertainty.

The systematic effects that arise due to the slow pion charge asymmetry in the detector and a possible charge asymmetry of D^* production in pp collisions in the LHCb acceptance are determined using the control channel. However, the control channel contains charged kaons which introduce an additional detection asymmetry, as the interaction cross-sections of K^+ and K^- with the detector material are different. In ref. [26], the charged kaon detection asymmetry has been measured to be in the range 0.008 to 0.012. Assuming the pion detection asymmetry to be negligible, and including possible trigger effects, a correction of -0.010 ± 0.005 is applied to the observed asymmetry in the control channel, resulting in a corrected value of -0.009 ± 0.005. The absolute value of this number and its uncertainty are added in quadrature and assigned as a conservative estimate of the systematic uncertainty due to production and detection asymmetries.

Other checks have been performed but found to have statistically insignificant effects. These tests include the split into different trigger types, different run periods, and different magnet polarities. Also the effect of a possible difference in contamination by charm from beauty decays between signal and the control channel has been checked and found to be negligible. The total systematic uncertainty is calculated from the quadratic sum of the two dominant contributions, which come from the signal extraction (0.019) and the detection and production asymmetry (0.011), giving 0.022 for the total.

6 Result

The time-integrated *CP* asymmetry in the decay $D^0 \to K^0_S K^0_S$ is determined to be

$$\mathcal{A}_{CP} = -0.029 \pm 0.052 \pm 0.022\,,$$

where the first uncertainty is statistical and the second systematic. The result is consistent with no *CP* violation and with Standard Model expectations [7]. This is the single best measurement of this quantity to date, with an uncertainty more than three times smaller than the previous determination [8].

Acknowledgments

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 (France); BMBF, DFG, HGF and MPG (Germany); INFN (Italy); FOM and NWO (The Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FANO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (U.S.A.). The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom). We are indebted to the communities behind the multiple open source software packages on which we depend. We are also thankful for the computing resources and the access to software R&D tools provided by Yandex LLC (Russia). Individual groups or members have received support from EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union), Conseil général de Haute-Savoie, Labex ENIGMASS and OCEVU, Région Auvergne (France), RFBR (Russia), XuntaGal and GENCAT (Spain), Royal Society and Royal Commission for the Exhibition of 1851 (United Kingdom).

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