

**Original citation:**

LHCb Collaboration (Including: Back, J. J., Craik, D., Dossett, D., Gershon, T. J., Harrison, P. F., Kreps, Michal, Latham, Thomas, Pilar, T., Poluektov, Anton, Reid, M. M., Coutinho, R. S., Whitehead, M. (Mark) and Williams, M. P.). (2013) Measurement of the D<sup>+</sup>/<sub>-</sub> production asymmetry in 7 TeV pp collisions. Physics Letters B, Volume 718 (Number 3). pp. 902-909. ISSN 0370-2693

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# Measurement of the $D^\pm$ production asymmetry in 7 TeV $pp$ collisions <sup>☆</sup>

LHCb Collaboration

## ARTICLE INFO

### Article history:

Received 16 October 2012

Accepted 12 November 2012

Available online 19 November 2012

Editor: L. Rolandi

## ABSTRACT

The asymmetry in the production cross-section  $\sigma$  of  $D^\pm$  mesons,

$$A_P = \frac{\sigma(D^+) - \sigma(D^-)}{\sigma(D^+) + \sigma(D^-)},$$

is measured in bins of pseudorapidity  $\eta$  and transverse momentum  $p_T$  within the acceptance of the LHCb detector. The result is obtained with a sample of  $D^+ \rightarrow K_S^0 \pi^+$  decays corresponding to an integrated luminosity of  $1.0 \text{ fb}^{-1}$ , collected in  $pp$  collisions at a centre of mass energy of 7 TeV at the Large Hadron Collider. When integrated over the kinematic range  $2.0 < p_T < 18.0 \text{ GeV}/c$  and  $2.20 < \eta < 4.75$ , the production asymmetry is  $A_P = (-0.96 \pm 0.26 \pm 0.18)\%$ . The uncertainties quoted are statistical and systematic, respectively. The result assumes that any direct  $CP$  violation in the  $D^+ \rightarrow K_S^0 \pi^+$  decay is negligible. No significant dependence on  $\eta$  or  $p_T$  is observed.

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## 1. Introduction

The Large Hadron Collider (LHC) offers an excellent opportunity to study heavy flavour physics. The rate of production of  $c\bar{c}$  and  $b\bar{b}$  pairs is substantial in the forward region close to the beam direction. The associated cross-sections were measured at the LHCb experiment in the forward region to be  $\sigma_{c\bar{c}} = 1230 \pm 190 \mu\text{b}$  and  $\sigma_{b\bar{b}} = 74 \pm 14 \mu\text{b}$  at  $\sqrt{s} = 7 \text{ TeV}$  [1,2].

Direct production of  $c\bar{c}$  pairs at the LHC occurs almost entirely via QCD and electroweak processes that do not discriminate between  $c$  and  $\bar{c}$  quarks. However, in hadronization the symmetry is broken by the presence of valence quarks, which introduce several processes that distinguish between  $c$  and  $\bar{c}$  quarks [3–5]. For example, a  $c$  quark could couple to valence quarks to form a charmed baryon, leaving an excess of  $\bar{c}$  quarks. These would hadronize to create an excess of  $D^-$  mesons over  $D^+$  mesons. Furthermore, the kinematic distributions of charmed hadrons and their antiparticles can differ, introducing production asymmetries in local kinematic regions. Analogous production asymmetries in the strange sector are well-established at the LHC, and are seen to be large at high rapidity [6]. However, no evidence for a  $D_s^+$  production asymmetry was found in a recent study [7].

Searches for  $CP$  violation (CPV) in charmed hadron decays can be used to probe for evidence of physics beyond the Standard Model [8]. Direct CPV is measured using time-integrated observables, and is of particular interest following evidence for CPV in

two-body  $D^0$  decays reported by LHCb [9] and subsequently by CDF [10]. In order to understand the origin of this effect, more precise measurements of  $CP$  asymmetries in a suite of decay modes are required. Production asymmetries have the same experimental signature as direct CPV effects and are potentially much larger than the  $CP$  asymmetries to be determined. This problem can sometimes be avoided by taking the difference in asymmetry between two decay modes with a common production asymmetry [9] or by studying the difference in kinematic distributions of multi-body decays [11]. However, these methods result in a reduction in statistical power and are not applicable to all final states. It is therefore important to measure production asymmetries directly.

In this Letter, the  $D^\pm$  production asymmetry, defined as

$$A_P = \frac{\sigma(D^+) - \sigma(D^-)}{\sigma(D^+) + \sigma(D^-)}, \quad (1)$$

for cross-sections  $\sigma(D^\pm)$ , is determined with a sample of  $D^+ \rightarrow K_S^0 \pi^+$ ,  $K_S^0 \rightarrow \pi^+ \pi^-$  decays.<sup>1</sup> As there are no charged kaons in the final state, the detector biases in this decay are simpler to understand than those in other  $D^+$  decays with higher branching fractions. The  $K_S^0$ , a pseudoscalar particle, has a charge-symmetric decay, and the charge asymmetry in the pion efficiency at LHCb has been measured previously for the 2011 data sample [7]. However, there is the possibility of CPV in the decay. The expected CPV in the  $D^+$  decay, due to the interference of the Cabibbo-favoured

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<sup>1</sup> Charge conjugate decays are implied throughout this Letter unless stated otherwise.

and doubly Cabibbo-suppressed amplitudes, is defined by the charge asymmetry in the partial widths  $\Gamma(D^\pm)$ ,

$$A_{CP} = \frac{\Gamma(D^+) - \Gamma(D^-)}{\Gamma(D^+) + \Gamma(D^-)}. \quad (2)$$

$A_{CP}$  is negligible in the Standard Model: a simple consideration of the CKM matrix leads to a value of at most  $1 \times 10^{-4}$  depending on the strong phase difference between the two amplitudes [12]. Since both amplitudes are at tree level, no enhancement of CPV due to new physics is expected. The current world-best measurement of  $A_{CP}$ , by the Belle Collaboration, is consistent with zero:  $(0.024 \pm 0.094 \pm 0.067)\%$  [13]. On the other hand, CPV in the neutral kaon system induces an asymmetry which must be considered. This will be discussed further in Section 5.

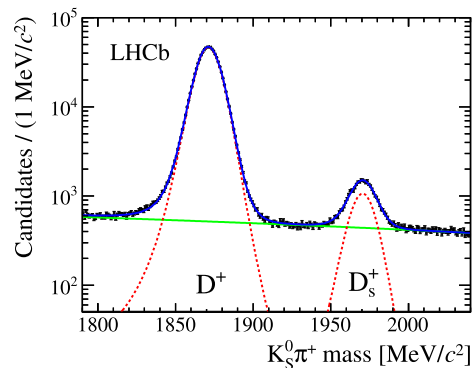
## 2. Detector description

The LHCb detector [14] 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 (VELO) surrounding the  $pp$  interaction region, a large-area silicon-strip detector located upstream of a dipole magnet of reversible polarity with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift-tubes placed downstream. The combined tracking system has a momentum resolution  $\Delta p/p$  that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and an impact parameter (IP) resolution of 20  $\mu\text{m}$  for tracks with high transverse momentum  $p_T$ . Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and pre-shower 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 trigger consists of a hardware stage, based on information from the calorimeter and muon systems, an inclusive software stage, which uses the tracking system, and a second software stage that exploits the full event information.

## 3. Dataset and selection

The data sample used in this analysis corresponds to  $1.0 \text{ fb}^{-1}$  of  $pp$  collisions taken at a centre of mass energy of 7 TeV at the Large Hadron Collider in 2011. The polarity of the LHCb magnetic field was changed several times during the run, and approximately half of the data were taken with each polarity, referred to as ‘magnet-up’ and ‘magnet-down’ data hereafter. To optimise the event selection and estimate efficiencies, 12.5 million  $pp$  collision events containing  $D^+ \rightarrow K_S^0 \pi^+$ ,  $K_S^0 \rightarrow \pi^- \pi^+$  decays were simulated with PYTHIA 6.4 [15] with a specific LHCb configuration [16]. Decays of hadronic particles are described by EVTGEN [17]. The interactions of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [18] as described in Ref. [19].

Pairs of oppositely charged tracks with a pion mass hypothesis are combined to form  $K_S^0$  candidates. Only those  $K_S^0$  candidates with  $p_T > 700 \text{ MeV}/c$  and invariant mass within 35  $\text{MeV}/c^2$  of the nominal value [20] are retained. Surviving candidates are then combined with a third charged track, the bachelor pion, to form a  $D^+$  candidate, with the mass of the  $K_S^0$  candidate constrained to its nominal value in a kinematic fit. Each of the three pion tracks must be detected in the VELO, so only those  $K_S^0$  mesons that decay well within the VELO are used. This creates a bias towards short



**Fig. 1.** Mass distribution of selected  $K_S^0 \pi^+$  candidates. The data are represented by symbols with error bars. The dashed curves indicate the signal and the  $D_s^+ \rightarrow K_S^0 \pi^+$  decays, the lower solid line represents the background shape, and the upper solid line shows the sum of all fit components.

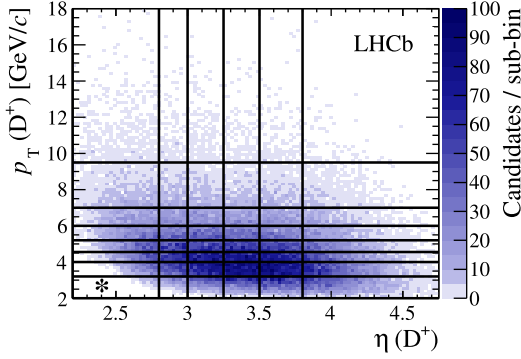
$K_S^0$  decay times. Both the  $K_S^0$  and  $D^+$  candidates are required to have acceptable vertex fit quality.

Further requirements are applied in order to reduce the background and to align the selection of bachelor pions with the tracking efficiency (see Section 6). The daughters of the  $K_S^0$  must have  $p > 2 \text{ GeV}/c$  and  $p_T > 250 \text{ MeV}/c$ . Impact parameter requirements are used to ensure that both the  $K_S^0$  candidate and its daughter tracks do not originate at any primary vertex (PV) in the event, and the  $K_S^0$  decay vertex must be at least 10 mm downstream of the PV with which it is associated. The bachelor pion must have  $p > 5 \text{ GeV}/c$  and  $p_T > 500 \text{ MeV}/c$ , be positively identified as a pion rather than as a kaon, electron or muon, and must not come from any PV. In addition, fiducial requirements are applied as in Ref. [9] to exclude regions with large tracking efficiency asymmetry. All three tracks must have an acceptable track fit quality. The  $D^+$  candidate is required to have  $p_T > 1 \text{ GeV}/c$ , to point to a PV (suppressing  $D$  from  $B$  decays), and to have a decay time significantly greater than zero. After these criteria are applied, the remaining background is mostly from random combinations of tracks. The invariant mass distribution of selected candidates is shown in Fig. 1.

In selected events, a trigger decision may be based on part or all of the  $D^+$  signal candidate, on other particles in the event, or both. The second stage of the software trigger is required to find a fully reconstructed candidate which meets the criteria to be a signal  $D^+ \rightarrow K_S^0 \pi^+$  decay. To control potential charge asymmetries introduced by the hardware trigger, two possibilities, not mutually exclusive, are allowed. The hardware trigger decision must be based on one or both of the  $K_S^0$  daughter tracks, or on a particle other than the decay products of the  $D^+$  candidate. In both cases, the inclusive software trigger must make a decision based on one of the three tracks that form the  $D^+$ . For the first case, it is explicitly required that the same track activated the hardware trigger, and therefore this is independent of the  $D^+$  charge. The second possibility does not depend directly on the  $D^+$  charge, but an indirect dependence could be introduced if the probability for particles produced in association with the signal candidate to activate the trigger differs between  $D^+$  and  $D^-$ . This will be discussed further in Section 7. After applying the selection and trigger requirements, 1,031,068  $K_S^0 \pi^+$  candidates remain.

## 4. Yield determination

The signal yields are measured in 48 bins of  $p_T$  and  $\eta$  using binned likelihood fits to the distribution of the  $K_S^0 \pi^+$  mass  $m$ . The



**Fig. 2.** Background-subtracted distribution of transverse momenta  $p_T$  versus pseudorapidity  $\eta$  for selected  $D^+ \rightarrow K_S^0 \pi^+$  candidates in a signal region of  $1845 < m < 1890$  MeV/ $c^2$ . The bin marked with an asterisk is excluded from the weighted average over the production asymmetries in the bins used to obtain the final result.

bins are shown in Fig. 2. The shapes of the  $D_{(s)}^+ \rightarrow K_S^0 \pi^+$  mass peaks are described by ‘Cruiff’ functions [21],

$$f(m) \propto \exp\left(\frac{-(m - \mu)^2}{2\sigma_{L,R}^2 + (m - \mu)^2\alpha_{L,R}}\right) \quad (3)$$

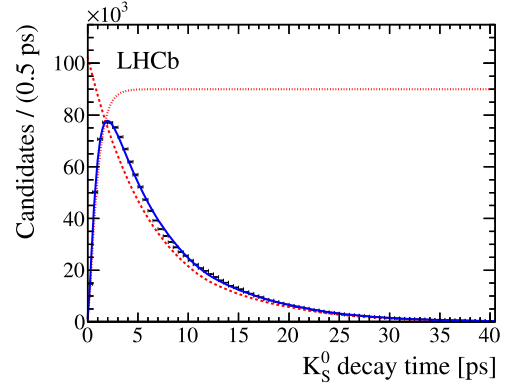
with the measured masses defined by the free parameter  $\mu$ , the widths by  $\sigma_L$  and  $\sigma_R$ , and the tails by  $\alpha_L$  and  $\alpha_R$ . The parameters  $\alpha_L$  and  $\sigma_L$  are used for  $m < \mu$  and  $\alpha_R$  and  $\sigma_R$  for  $m > \mu$ . The background is fitted with a straight line plus an additional Gaussian component to account for background from  $D_s^+ \rightarrow K_S^0 \pi^+ \pi^0$  decays. The yield of the latter is consistent with zero in most  $p_T$ ,  $\eta$  bins. The fit is performed simultaneously over four subsamples ( $D^+$  magnet-up,  $D^+$  magnet-down,  $D^-$  magnet-up, and  $D^-$  magnet-down data) with the masses and yields of the  $D_{(s)}^\pm$ , and the yield of background, allowed to vary independently in the four subsamples. All other parameters are shared. The charge asymmetries are then determined from the yields. The results are cross-checked with a sideband subtraction procedure under the assumption of a linear background.

## 5. Effect of CP violation in the neutral kaon system

CP violation in the neutral kaon system can affect the observed asymmetry in the  $D^+ \rightarrow K_S^0 \pi^+$  decay [22]. The bias on  $A_P$  due to the CPV depends on the decay time acceptance  $F(t)$  of the  $K_S^0$  meson, according to

$$A_\epsilon \sim 2\Re(\epsilon) \times \left[ 1 - \frac{\int_0^\infty F(t) e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} (\cos \Delta m t - \frac{\Im(\epsilon)}{\Re(\epsilon)} \sin \Delta m t) dt}{\int_0^\infty F(t) e^{-\Gamma_S t} dt} \right], \quad (4)$$

where  $\epsilon$  parameterises the indirect CPV in neutral kaon mixing,  $\Gamma_S$  and  $\Gamma_L$  are the decay widths of the  $K_S^0$  and  $K_L^0$  respectively, and  $\Delta m$  is their mass difference [23,24]. Direct CPV and terms of order  $\epsilon^2$  are neglected. To determine the decay time acceptance, the  $K_S^0$  decay time is fitted with an empirical function shown in Fig. 3. All of the  $K_S^0$  candidates used in this analysis decay inside the VELO with an average measured lifetime of  $6.97 \pm 0.02$  ps, which is much shorter than the nominal  $K_S^0$  lifetime of 89.5 ps. Using  $\Re(\epsilon) = 1.65 \times 10^{-3}$  [20] in Eq. (4), we obtain  $A_\epsilon = (2.831_{-0.004}^{+0.003}) \times 10^{-4}$  for the CPV in the neutral kaon system, where the uncertainty quoted is statistical only. This value is



**Fig. 3.** Observed  $K_S^0$  decay time distribution within the LHCb acceptance. The data points are fitted with an empirical function (solid curve). This contains a component for the upper decay time acceptance, due mainly to the requirement that the  $K_S^0$  decays inside the VELO (dashed curve) and a component for the lower decay time acceptance, due to the selection cuts (dotted curve). These are shown scaled by arbitrary factors. The CPV is not sensitive to the fine details of the distribution, so the fit quality is not important.

subtracted from the measured production asymmetry and a systematic uncertainty equal to its central value is assigned.

## 6. Results

In order to convert the measured charge asymmetries in the 48 bins of  $p_T$  and  $\eta$  into production asymmetries, a correction for the asymmetry in the pion reconstruction efficiency is made. This asymmetry was evaluated previously in eight bins of pion azimuthal angle  $\phi$  and two bins of pion momentum with a control sample of  $D^{*+} \rightarrow D^0 \pi^+$ ,  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$  decays in the same dataset [7]. The average efficiency asymmetry ratios  $\epsilon_{\pi^+}/\epsilon_{\pi^-}$  in that sample were found to be  $0.9914 \pm 0.0040$  for magnet-up data and  $1.0045 \pm 0.0034$  for magnet-down data.

After the correction is applied, the resulting asymmetries for magnet-up and magnet-down data in each  $D^+$   $p_T$  and  $\eta$  bin are averaged with equal weights to obtain the production asymmetries in two-dimensional bins of  $p_T$  and  $\eta$ , given in Table 1. Any left–right asymmetries that differ between the signal  $D^+ \rightarrow K_S^0 \pi^+$  decay and the  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$  control channel will cancel in this average.

Reconstruction and selection efficiencies from the simulation are used to calculate binned efficiency-corrected yields. These are used to weight the production asymmetries in the average over the  $p_T$  and  $\eta$  bins. The result is an asymmetry for  $D^+$  produced in the LHCb acceptance. The same weighting technique is applied to obtain production asymmetries as one-dimensional functions of  $p_T$  and  $\eta$ . The bin marked with an asterisk in Fig. 2 has a high cross-section but is mostly outside the acceptance and so it is excluded from the average. After subtracting the contribution from CPV in the kaon system, the production asymmetry is  $(-0.96 \pm 0.19 \pm 0.18)\%$ . The uncertainties are the statistical errors on the  $D^+ \rightarrow K_S^0 \pi^+$  yields and that due to the tagged  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$  sample used to calculate the pion efficiencies. Summing these in quadrature, we obtain

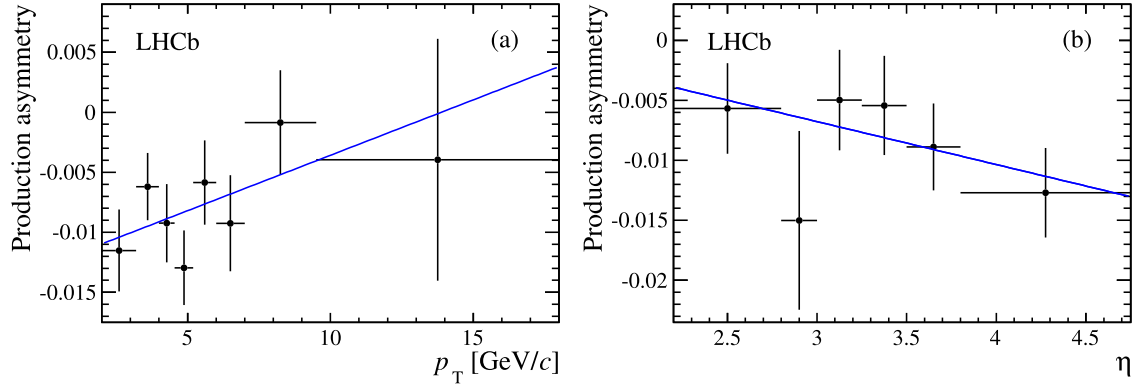
$$A_P = (-0.96 \pm 0.26 \text{ (stat.)})\%.$$

The production asymmetry as a function of  $p_T$  and  $\eta$  is given in Fig. 4. No significant dependence of the asymmetry on these variables is observed. As a cross-check, the average production asymmetry is calculated for magnet-up and magnet-down data

**Table 1**

Production asymmetry for  $D^+$  mesons, in percent, in  $(p_T, \eta)$  bins, for  $2.0 < p_T < 18.0$  GeV/c and  $2.20 < \eta < 4.75$ . The uncertainties shown are statistical only; the systematic uncertainty is 0.17% (see Table 2).

$p_T$ (GeV/c)	$\eta$					
	(2.20, 2.80)	(2.80, 3.00)	(3.00, 3.25)	(3.25, 3.50)	(3.50, 3.80)	(3.80, 4.75)
(2.00, 3.20)	$-0.0 \pm 2.5$	$-2.2 \pm 1.2$	$-0.4 \pm 0.8$	$-0.4 \pm 0.7$	$-1.2 \pm 0.6$	$-1.2 \pm 0.5$
(3.20, 4.00)	$-0.4 \pm 0.9$	$-0.4 \pm 0.7$	$-0.4 \pm 0.5$	$-1.1 \pm 0.5$	$+0.1 \pm 0.5$	$-1.2 \pm 0.5$
(4.00, 4.55)	$+0.1 \pm 0.8$	$-1.0 \pm 0.8$	$-1.3 \pm 0.6$	$-2.0 \pm 0.6$	$-0.1 \pm 0.6$	$-2.1 \pm 0.7$
(4.55, 5.20)	$-1.6 \pm 0.7$	$-0.6 \pm 0.8$	$-0.5 \pm 0.6$	$-0.7 \pm 0.6$	$-1.6 \pm 0.6$	$-2.0 \pm 0.8$
(5.20, 6.00)	$-0.5 \pm 0.7$	$-0.8 \pm 0.8$	$+0.2 \pm 0.7$	$-0.3 \pm 0.7$	$-0.6 \pm 0.7$	$-1.2 \pm 0.9$
(6.00, 7.00)	$-1.4 \pm 0.8$	$+0.5 \pm 1.0$	$-0.9 \pm 0.9$	$-0.6 \pm 0.9$	$-0.7 \pm 0.9$	$-1.6 \pm 1.2$
(7.00, 9.50)	$-0.4 \pm 0.8$	$-0.4 \pm 1.1$	$-0.2 \pm 1.1$	$+1.7 \pm 1.1$	$-1.4 \pm 1.1$	$+1.2 \pm 1.4$
(9.50, 18.00)	$-0.6 \pm 1.3$	$+1.8 \pm 2.3$	$-2.5 \pm 2.2$	$+1.8 \pm 2.4$	$+1.1 \pm 2.5$	$-7 \pm 11$



**Fig. 4.** Production asymmetry as a function of (a) transverse momentum  $p_T$  and (b) pseudorapidity  $\eta$ . The straight line fits have slopes of  $(0.09 \pm 0.07) \times 10^{-2}$  (GeV/c) $^{-1}$  and  $(-0.36 \pm 0.28)\%$ , and values of  $\chi^2$  per degree of freedom of 5.5/6 and 2.2/4, respectively. The error bars include only the statistical uncertainty on the  $D^+$  signal sample and are uncorrelated within a given plot.

**Table 2**

Summary of absolute values of systematic uncertainties on  $A_p$ . For the binned production asymmetries given in Table 1, all uncertainties except that on the reconstruction efficiency apply, giving a combined systematic uncertainty of 0.17%.

Systematic effect	Uncertainty (%)
Trigger asymmetries	0.15
$D$ from $B$	0.04
Selection criteria	0.05
Running conditions	0.04
Pion efficiency	0.02
Fitting	0.04
Kaon $CP$ violation	0.03
Weights (reconstruction efficiency)	0.05
Total including uncertainty on weights	0.18

separately, and found to be fully consistent:  $(-1.07 \pm 0.41)\%$  and  $(-0.85 \pm 0.34)\%$ , respectively.

## 7. Systematic uncertainties

The sources of systematic uncertainty are summarised in Table 2. The dominant uncertainty of  $1.5 \times 10^{-3}$  is due to asymmetries introduced by the trigger. Events which are triggered independently of the signal decay, i.e. by a track that does not form part of the signal candidate, could be triggered by particles produced in association with the  $D^+$  meson. If this occurs, the asymmetry in this sample would be correlated with the production asymmetry, and would bias the measurement of it. This was studied with a control sample of the abundant  $D^+ \rightarrow K^- \pi^+ \pi^+$  decay. To mimic the charge-unbiased sample of  $D^+ \rightarrow K_S^0 \pi^+$  decays which are triggered by a  $K_S^0$  daughter, we choose the kaon and one pion at random and require that the trigger decision be based on one of these tracks. This is close to being charge-symmetric between  $D^+$  and  $D^-$  candidates, with some residual effects due to

differences in material interaction between  $K^+$  and  $K^-$  mesons. The raw asymmetry in this subsample of  $D^+ \rightarrow K^- \pi^+ \pi^+$  decays is then compared to that in the much larger sample of candidates that are triggered independently of the signal decay. The difference in raw charge asymmetry between these two samples,  $(1.5 \pm 0.4) \times 10^{-3}$ , is a measure of the scale of the bias. Unlike the signal, the  $K^- \pi^+ \pi^+$  decay also includes a component due to the  $K^+/K^-$  asymmetry, and therefore this is treated as a systematic uncertainty rather than a correction. This is cross-checked with other control samples such as  $D_S^+ \rightarrow \phi \pi^+$  and the uncertainty is found to be conservative.

Further systematic uncertainties arise from the contamination of the prompt sample by  $D$  candidates that originate from  $B$  decays. The yield of these is calculated using the measured cross-sections [1,2], branching ratios, and efficiencies determined from the simulation. The fraction of  $D$  candidates from  $B$  decays is found to be  $(1.2 \pm 0.3)\%$ . This quantity is combined with the  $B^0$  production asymmetry, which is estimated to be  $(-1.0 \pm 1.3)\%$  [25], to determine the systematic uncertainty.

Certain selection criteria differ between the  $D^+ \rightarrow K_S^0 \pi^+$  signal sample and the  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$  decays used to determine the asymmetry in the pion efficiencies. The charge asymmetry is found to depend weakly on the value of the requirement on the pion  $p_T$ . Pions in the signal sample must have  $p_T > 500$  MeV/c while those in the control sample must have  $p_T > 300$  MeV/c. A systematic uncertainty is calculated by estimating the proportion of signal candidates with  $300 < p_T < 500$  MeV/c and multiplying this fraction by the difference between the charge asymmetries in the low  $p_T$  region and the average.

The difference in signal yields per  $\text{pb}^{-1}$  of integrated luminosity between magnet-up and magnet-down data is used to determine a systematic uncertainty for changes in running conditions that could impair the cancellation of detector asymmetries achieved

by averaging over the magnet polarities. There is also a systematic uncertainty on the pion efficiency asymmetry associated with the determination of the yields of  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$  decays. The error associated with the mass fit is determined by comparing fitted and sideband-subtracted results. The CPV in the neutral kaon decay, discussed in Section 5, is also included as a systematic uncertainty.

Other systematic effects such as regeneration in the neutral kaon system [26], second order effects due to the kinematic binning of the  $D^+ \rightarrow K_S^0 \pi^+$  sample, and asymmetric backgrounds such as that from  $D_s^+ \rightarrow K_S^0 K^+$  with the kaon misidentified as a pion, were considered but found to be negligible. When taking the average asymmetry weighted by the efficiency-corrected yield in each bin, the limited number of simulated events leads to an uncertainty on the reconstruction efficiency and hence on the per-bin weights. This does not contribute to the uncertainty on the individual asymmetries given in Table 1, which are calculated without using the simulation. A quadratic sum yields an overall systematic uncertainty of  $1.8 \times 10^{-3}$ .

In principle, CPV in the charm decay could occur via the interference of Cabibbo-favoured and doubly Cabibbo-suppressed amplitudes, but this is strongly suppressed by the CKM matrix and no evidence for it has been observed at the  $B$ -factories [27,13]. If we allowed for the possibility of new physics or large unexpected enhancements of the Standard Model CPV in these tree-level  $D^+$  decays, the uncertainty on the null result found at Belle [13] would increase the total systematic uncertainty to  $2.1 \times 10^{-3}$ .

## 8. Conclusions

Evidence for a charge asymmetry in the production of  $D^+$  mesons is observed at LHCb. In the kinematic range  $2.0 < p_T < 18.0$  GeV/ $c$  and  $2.20 < \eta < 4.75$ , excluding the region with  $2.0 < p_T < 3.2$  GeV/ $c$ ,  $2.20 < \eta < 2.80$ , the average asymmetry is

$$A_P = (-0.96 \pm 0.26 \pm 0.18)\%$$

where the first uncertainty is statistical and the second is systematic. The result is inconsistent with zero at approximately three standard deviations. There is no evidence for a significant dependence on  $p_T$  or pseudorapidity at the present level of precision. The bias on the measured asymmetry due to  $CP$  violation in kaon decays has been calculated and found to be almost negligible for this dataset. These results are consistent with expectations [5] and lay the foundations for searches for  $CP$  violation in Cabibbo suppressed  $D^+$  decays.

## Acknowledgements

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 and Region Auvergne (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); SCSR (Poland); ANCS/IFA (Romania); MinES, Rosatom, RFBR and NRC “Kurchatov Institute” (Russia); MinECo,

XuntaGal and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); NSF (USA). We also acknowledge the support received from the ERC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), CIEMAT, IFAE and UAB (Spain), GridPP (United Kingdom). We are thankful for the computing resources put at our disposal by Yandex LLC (Russia), as well as to the communities behind the multiple open source software packages that we depend on.

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## References

- [1] R. Aaij, et al., Prompt charm production in  $pp$  collisions at  $\sqrt{s} = 7$  TeV, LHCb-CONF-2010-013.
- [2] LHCb Collaboration, R. Aaij, et al., Phys. Lett. B 694 (2010) 209, arXiv:1009.2731.
- [3] E. Norrbin, Heavy quark production asymmetries, arXiv:hep-ph/9909437.
- [4] E. Norrbin, R. Vogt, Bottom production asymmetries at the LHC, in: Proceedings of the CERN 1999 Workshop on SM Physics (and More) at the LHC, arXiv:hep-ph/0003056.
- [5] E. Norrbin, T. Sjöstrand, Eur. Phys. J. C 17 (2000) 137, arXiv:hep-ph/0005110.
- [6] LHCb Collaboration, R. Aaij, et al., JHEP 1108 (2011) 034, arXiv:1107.0882.
- [7] LHCb Collaboration, R. Aaij, et al., Phys. Lett. B 713 (2012) 186, arXiv:1205.0897.
- [8] Y. Grossman, A.L. Kagan, Y. Nir, Phys. Rev. D 75 (2007) 036008, arXiv:hep-ph/0609178.
- [9] LHCb Collaboration, R. Aaij, et al., Phys. Rev. Lett. 108 (2012) 111602, arXiv:1112.0938.
- [10] CDF Collaboration, T. Aaltonen, et al., Phys. Rev. Lett. 109 (2012) 111801, arXiv:1207.2158.
- [11] LHCb Collaboration, R. Aaij, et al., Phys. Rev. D 84 (2011) 112008, arXiv:1110.3970.
- [12] I.I. Bigi, H. Yamamoto, Phys. Lett. B 349 (1995) 363, arXiv:hep-ph/9502238.
- [13] Belle Collaboration, B. Ko, et al., Phys. Rev. Lett. 109 (2012) 021601, arXiv:1203.6409; Belle Collaboration, B. Ko, et al., Phys. Rev. Lett. 109 (2012) 119903 (Erratum).
- [14] LHCb Collaboration, A.A. Alves Jr., et al., JINST 3 (2008) S08005.
- [15] T. Sjöstrand, S. Mrenna, P. Skands, JHEP 0605 (2006) 026, arXiv:hep-ph/0603175.
- [16] I. Belyaev, et al., in: Nuclear Science Symposium Conference Record (NSS/MIC), IEEE, 2010, p. 1155.
- [17] D.J. Lange, Nucl. Instrum. Meth. A 462 (2001) 152.
- [18] GEANT4 Collaboration, J. Allison, et al., IEEE Trans. Nucl. Sci. 53 (2006) 270; GEANT4 Collaboration, S. Agostinelli, et al., Nucl. Instrum. Meth. A 506 (2003) 250.
- [19] M. Clemencic, et al., J. Phys.: Conf. Ser. 331 (2011) 032023.
- [20] Particle Data Group, J. Beringer, et al., Phys. Rev. D 86 (2012) 010001.
- [21] BaBar Collaboration, P. del Amo Sanchez, et al., Phys. Rev. D 82 (2010) 051101, arXiv:1005.4087.
- [22] S. Bianco, F. Fabbri, D. Benson, I. Bigi, Riv. Nuovo Cim. 26 (7) (2003) 1, arXiv:hep-ex/0309021.
- [23] Y. Grossman, Y. Nir, JHEP 1204 (2012) 002, arXiv:1110.3790.
- [24] CPLEAR Collaboration, A. Apostolakis, et al., Eur. Phys. J. C 18 (2000) 41.
- [25] LHCb Collaboration, R. Aaij, et al., Phys. Rev. Lett. 108 (2012) 201601, arXiv:1202.6251.
- [26] J. Roehrig, et al., Phys. Rev. Lett. 38 (1977) 1116.
- [27] BaBar Collaboration, P. del Amo Sanchez, et al., Phys. Rev. D 83 (2011) 071103, arXiv:1011.5477.

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Hopchev<sup>4</sup>, W. Hulsbergen<sup>38</sup>, P. Hunt<sup>52</sup>, T. Huse<sup>49</sup>, N. Hussain<sup>52</sup>, D. Hutchcroft<sup>49</sup>, D. Hynds<sup>48</sup>, V. Iakovenko<sup>41</sup>, P. Ilten<sup>12</sup>, J. Imong<sup>43</sup>, R. Jacobsson<sup>35</sup>, A. Jaeger<sup>11</sup>, M. Jahjah Hussein<sup>5</sup>, E. Jans<sup>38</sup>, F. Jansen<sup>38</sup>, P. Jaton<sup>36</sup>, B. Jean-Marie<sup>7</sup>, F. Jing<sup>3</sup>, M. John<sup>52</sup>, D. Johnson<sup>52</sup>, C.R. Jones<sup>44</sup>, B. Jost<sup>35</sup>, M. Kaballo<sup>9</sup>, S. Kandybei<sup>40</sup>, M. Karacson<sup>35</sup>, T.M. Karbach<sup>35</sup>, I.R. Kenyon<sup>42</sup>, U. Kerzel<sup>35</sup>, T. Ketel<sup>39</sup>, A. Keune<sup>36</sup>, B. Khanji<sup>20</sup>, Y.M. Kim<sup>47</sup>, O. Kochebina<sup>7</sup>, V. Komarov<sup>36,29</sup>, R.F. Koopman<sup>39</sup>, P. Koppenburg<sup>38</sup>, M. Korolev<sup>29</sup>, A. Kozlinskiy<sup>38</sup>, L. Kravchuk<sup>30</sup>, K. Kreplin<sup>11</sup>, M. 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