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Measurement of the $D^{\pm}$ production asymmetry in 7 TeV pp collisions ☆

LHCb Collaboration

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ABSTRACT

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

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

is measured in bins of pseudorapidity η and transverse momentum p_T within the acceptance of the LHCb detector. The result is obtained with a sample of $D^+ \to K^0_S\pi^+$ decays corresponding to an integrated luminosity of 1.0 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 $2.0 < p_T < 18.0$ 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 $D^+ \to K^0_S\pi^+$ decay is negligible. No significant dependence on η or p_T is observed.

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 $\sigma_{c\bar{c}} = 1230 \pm 190$ μb and $\sigma_{b\bar{b}} = 74 \pm 14$ μb at $\sqrt{s} = 7$ 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

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

for cross-sections $\sigma(D^{\pm})$, is determined with a sample of $D^+ \to K^0_S\pi^+$, $K^0_S \to \pi^+\pi^-$ decays.[1] 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^0_S, 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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[1] Charge conjugate decays are implied throughout this Letter unless stated otherwise.

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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 1×10^{-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 μm 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 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 $D^+ \to K^0_S\pi^+$, $K^0_S \to \pi^-\pi^+$ 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^0_S candidates. Only those K^0_S candidates with $p_T > 700$ MeV/c and invariant mass within 35 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^0_S 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^0_S mesons that decay well within the VELO are used. This creates a bias towards short

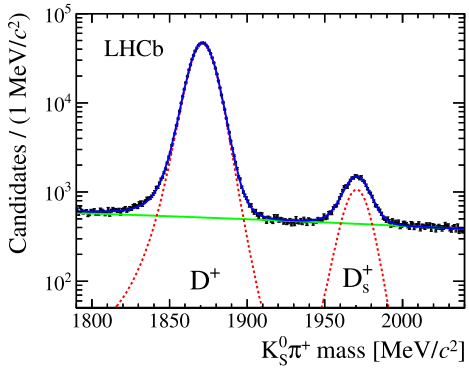

Fig. 1. Mass distribution of selected $K^0_S\pi^+$ candidates. The data are represented by symbols with error bars. The dashed curves indicate the signal and the $D_s^+ \to K^0_S\pi^+$ decays, the lower solid line represents the background shape, and the upper solid line shows the sum of all fit components.

K^0_S decay times. Both the K^0_S 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 dataset used to determine the charge asymmetry in the tracking efficiency (see Section 6). The daughters of the K^0_S must have $p > 2$ GeV/c and $p_T > 250$ MeV/c. Impact parameter requirements are used to ensure that both the K^0_S candidate and its daughter tracks do not originate at any primary vertex (PV) in the event, and the K^0_S decay vertex must be at least 10 mm downstream of the PV with which it is associated. The bachelor pion must have $p > 5$ GeV/c and $p_T > 500$ 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 $p_T > 1$ 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 $D^+ \to K^0_S\pi^+$ 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^0_S 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 $K^0_S\pi^+$ candidates remain.

4. Yield determination

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

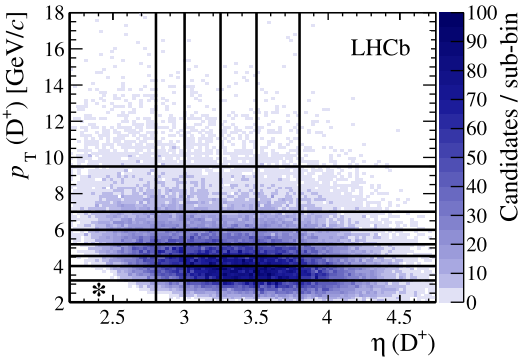

Fig. 2. Background-subtracted distribution of transverse momenta p_T versus pseudorapidity η for selected $D^+ \to K^0_S\pi^+$ candidates in a signal region of $1845 < m < 1890$ MeV/c^2. The bin marked with an asterisk is excluded from the weighted average over the production asymmetries in the bins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

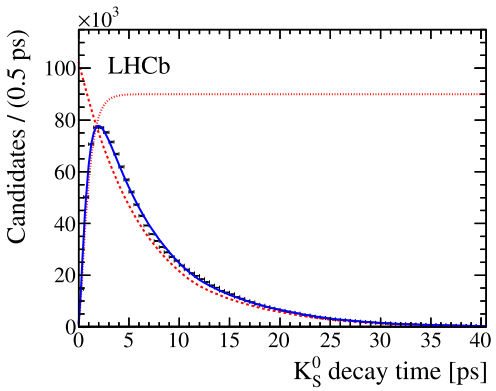

Fig. 3. Observed K^0_S decay time distribution within the LHCb acceptance. The data points are fitted with an empirical function (solid curve). This contains a component for the upper decay time acceptance, due mainly to the requirement that the K^0_S decays inside the VELO (dashed curve) and a component 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.

bins are shown in Fig. 2. The shapes of the $D^+_{(s)} \to K^0_S\pi^+$ mass peaks are described by 'Cruijff' functions [21],

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

with the measured masses defined by the free parameter μ, the widths by σ_L and σ_R, and the tails by α_L and α_R. The parameters α_L and σ_L are used for $m < \mu$ and α_R and σ_R for $m > \mu$. The background is fitted with a straight line plus an additional Gaussian component to account for background from $D^+_s \to K^0_S\pi^+\pi^0$ decays. The yield of the latter is consistent with zero in most p_T, η 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 $D^\pm_{(s)}$, 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 $D^+ \to K^0_S\pi^+$ decay [22]. The bias on A_P due to the CPV depends on the decay time acceptance $F(t)$ of the K^0_S meson, according to

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

where ϵ parameterises the indirect CPV in neutral kaon mixing, Γ_S and Γ_L are the decay widths of the K^0_S and K^0_L respectively, and Δm is their mass difference [23,24]. Direct CPV and terms of order ϵ^2 are neglected. To determine the decay time acceptance, the K^0_S decay time is fitted with an empirical function shown in Fig. 3. All of the K^0_S candidates used in this analysis decay inside the VELO with an average measured lifetime of 6.97 ± 0.02 ps, which is much shorter than the nominal K^0_S lifetime of 89.5 ps. Using $\Re(\epsilon) = 1.65 \times 10^{-3}$ [20] in Eq. (4), we obtain $A_\epsilon = (2.831^{+0.003}_{-0.004}) \times 10^{-4}$ for the CPV in the neutral kaon system, where the uncertainty quoted is statistical only. This value is 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 η 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 ϕ and two bins of pion momentum with a control sample of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$ decays in the same dataset [7]. The average efficiency asymmetry ratios $\epsilon_{\pi^+}/\epsilon_{\pi^-}$ in that sample were found to be 0.9914 ± 0.0040 for magnet-up data and 1.0045 ± 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 η bin are averaged with equal weights to obtain the production asymmetries in two-dimensional bins of p_T and η, given in Table 1. Any left–right asymmetries that differ between the signal $D^+ \to K^0_S\pi^+$ decay and the $D^0 \to K^-\pi^+\pi^-\pi^+$ 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 η 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 η. 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 $D^+ \to K^0_S\pi^+$ yields and that due to the tagged $D^0 \to K^-\pi^+\pi^-\pi^+$ sample used to calculate the pion efficiencies. Summing these in quadrature, we obtain

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

The production asymmetry as a function of p_T and η 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, η) 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)	η					
	(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 ± 2.5	-2.2 ± 1.2	-0.4 ± 0.8	-0.4 ± 0.7	-1.2 ± 0.6	-1.2 ± 0.5
(3.20, 4.00)	-0.4 ± 0.9	-0.4 ± 0.7	-0.4 ± 0.5	-1.1 ± 0.5	$+0.1 \pm 0.5$	-1.2 ± 0.5
(4.00, 4.55)	$+0.1 \pm 0.8$	-1.0 ± 0.8	-1.3 ± 0.6	-2.0 ± 0.6	-0.1 ± 0.6	-2.1 ± 0.7
(4.55, 5.20)	-1.6 ± 0.7	-0.6 ± 0.8	-0.5 ± 0.6	-0.7 ± 0.6	-1.6 ± 0.6	-2.0 ± 0.8
(5.20, 6.00)	-0.5 ± 0.7	-0.8 ± 0.8	$+0.2 \pm 0.7$	-0.3 ± 0.7	-0.6 ± 0.7	-1.2 ± 0.9
(6.00, 7.00)	-1.4 ± 0.8	$+0.5 \pm 1.0$	-0.9 ± 0.9	-0.6 ± 0.9	-0.7 ± 0.9	-1.6 ± 1.2
(7.00, 9.50)	-0.4 ± 0.8	-0.4 ± 1.1	-0.2 ± 1.1	$+1.7 \pm 1.1$	-1.4 ± 1.1	$+1.2 \pm 1.4$
(9.50, 18.00)	-0.6 ± 1.3	$+1.8 \pm 2.3$	-2.5 ± 2.2	$+1.8 \pm 2.4$	$+1.1 \pm 2.5$	-7 ± 11

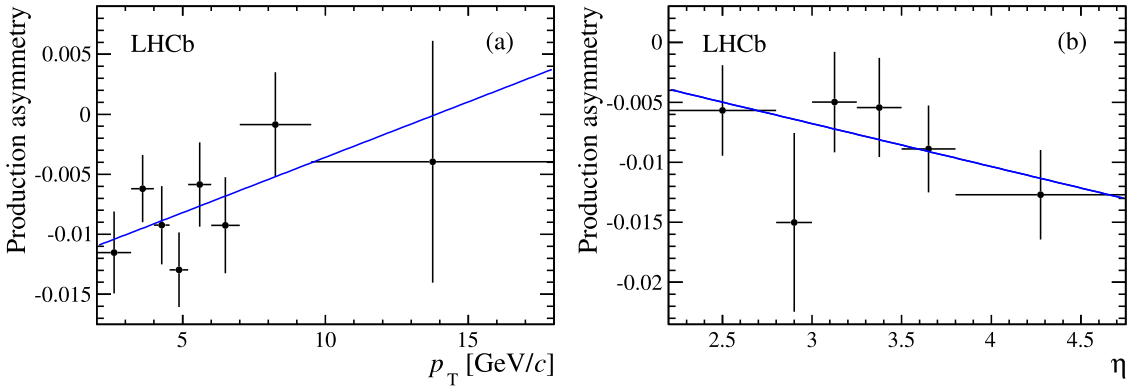

Fig. 4. Production asymmetry as a function of (a) transverse momentum p_T and (b) pseudorapidity η. The straight line fits have slopes of $(0.09 \pm 0.07) \times 10^{-2}$ (GeV/c)$^{-1}$ and (-0.36 ± 0.28)%, and values of χ^2 per degree of freedom of 5.5/6 and 2.2/4, respectively. The error bars include 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 ± 0.41)% and (-0.85 ± 0.34)%, respectively.

7. Systematic uncertainties

The sources of systematic uncertainty are summarised in Table 2. The dominant uncertainty of 1.5×10^{-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 $D^+ \to K^-\pi^+\pi^+$ decay. To mimic the charge-unbiased sample of $D^+ \to K^0_S\pi^+$ decays which are triggered by a K^0_S 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 $D^+ \to K^-\pi^+\pi^+$ 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 $D^+_s \to \phi\pi^+$ 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 ± 0.3)%. This quantity is combined with the B^0 production asymmetry, which is estimated to be (-1.0 ± 1.3)% [25], to determine the systematic uncertainty.

Certain selection criteria differ between the $D^+ \to K^0_S\pi^+$ signal sample and the $D^0 \to K^-\pi^+\pi^-\pi^+$ 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 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 $D^0 \to K^-\pi^+\pi^-\pi^+$ 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 $D^+ \to K^0_S\pi^+$ sample, and asymmetric backgrounds such as that from $D^+_s \to K^0_S K^+$ 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 1.8×10^{-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 2.1×10^{-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.

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R. Aaij [38], C. Abellan Beteta [33,n], A. Adametz [11], B. Adeva [34], M. Adinolfi [43], C. Adrover [6], A. Affolder [49], Z. Ajaltouni [5], J. Albrecht [35], F. Alessio [35], M. Alexander [48], S. Ali [38], G. Alkhazov [27], P. Alvarez Cartelle [34],

A.A. Alves Jr.[22], S. Amato[2], Y. Amhis[36], L. Anderlini[17,f], J. Anderson[37], R.B. Appleby[51], O. Aquines Gutierrez[10], F. Archilli[18,35], A. Artamonov[32], M. Artuso[53], E. Aslanides[6], G. Auriemma[22,m], S. Bachmann[11], J.J. Back[45], C. Baesso[54], W. Baldini[16], R.J. Barlow[51], C. Barschel[35], S. Barsuk[7], W. Barter[44], A. Bates[48], Th. Bauer[38], A. Bay[36], J. Beddow[48], I. Bediaga[1], S. Belogurov[28], K. Belous[32], I. Belyaev[28], E. Ben-Haim[8], M. Benayoun[8], G. Bencivenni[18], S. Benson[47], J. Benton[43], A. Berezhnoy[29], R. Bernet[37], M.-O. Bettler[44], M. van Beuzekom[38], A. Bien[11], S. Bifani[12], T. Bird[51], A. Bizzeti[17,h], P.M. Bjørnstad[51], T. Blake[35], F. Blanc[36], C. Blanks[50], J. Blouw[11], S. Blusk[53], A. Bobrov[31], V. Bocci[22], A. Bondar[31], N. Bondar[27], W. Bonivento[15], S. Borghi[48,51], A. Borgia[53], T.J.V. Bowcock[49], C. Bozzi[16], T. Brambach[9], J. van den Brand[39], J. Bressieux[36], D. Brett[51], M. Britsch[10], T. Britton[53], N.H. Brook[43], H. Brown[49], A. Büchler-Germann[37], I. Burducea[26], A. Bursche[37], J. Buytaert[35], S. Cadeddu[15], O. Callot[7], M. Calvi[20,j], M. Calvo Gomez[33,n], A. Camboni[33], P. Campana[18,35], A. Carbone[14,c], G. Carboni[21,k], R. Cardinale[19,i], A. Cardini[15], H. Carranza-Mejia[47], L. Carson[50], K. Carvalho Akiba[2], G. Casse[49], M. Cattaneo[35], Ch. Cauet[9], M. Charles[52], Ph. Charpentier[35], P. Chen[3,36], N. Chiapolini[37], M. Chrzaszcz[23], K. Ciba[35], X. Cid Vidal[34], G. Ciezarek[50], P.E.L. Clarke[47], M. Clemencic[35], H.V. Cliff[44], J. Closier[35], C. Coca[26], V. Coco[38], J. Cogan[6], E. Cogneras[5], P. Collins[35], A. Comerma-Montells[33], A. Contu[52,15], A. Cook[43], M. Coombes[43], G. Corti[35], B. Couturier[35], G.A. Cowan[36], D. Craik[45], S. Cunliffe[50], R. Currie[47], C. D'Ambrosio[35], P. David[8], P.N.Y. David[38], I. De Bonis[4], K. De Bruyn[38], S. De Capua[51], M. De Cian[37], J.M. De Miranda[1], L. De Paula[2], P. De Simone[18], D. Decamp[4], M. Deckenhoff[9], H. Degaudenzi[36,35], L. Del Buono[8], C. Deplano[15], D. Derkach[14], O. Deschamps[5], F. Dettori[39], A. Di Canto[11], J. Dickens[44], H. Dijkstra[35], P. Diniz Batista[1], M. Dogaru[26], F. Domingo Bonal[33,n], S. Donleavy[49], F. Dordei[11], A. Dosil Suárez[34], D. Dossett[45], A. Dovbnya[40], F. Dupertuis[36], R. Dzhelyadin[32], A. Dziurda[23], A. Dzyuba[27], S. Easo[46,35], U. Egede[50], V. Egorychev[28], S. Eidelman[31], D. van Eijk[38], S. Eisenhardt[47], R. Ekelhof[9], L. Eklund[48], I. El Rifai[5], Ch. Elsasser[37], D. Elsby[42], A. Falabella[14,e], C. Färber[11], G. Fardell[47], C. Farinelli[38], S. Farry[12], V. Fave[36], V. Fernandez Albor[34], F. Ferreira Rodrigues[1], M. Ferro-Luzzi[35], S. Filippov[30], C. Fitzpatrick[35], M. Fontana[10], F. Fontanelli[19,i], R. Forty[35], O. Francisco[2], M. Frank[35], C. Frei[35], M. Frosini[17,f], S. Furcas[20], A. Gallas Torreira[34], D. Galli[14,c], M. Gandelman[2], P. Gandini[52], Y. Gao[3], J.-C. Garnier[35], J. Garofoli[53], P. Garosi[51], J. Garra Tico[44], L. Garrido[33], C. Gaspar[35], R. Gauld[52], E. Gersabeck[11], M. Gersabeck[35], T. Gershon[45,35], Ph. Ghez[4], V. Gibson[44], V.V. Gligorov[35], C. Göbel[54], D. Golubkov[28], A. Golutvin[50,28,35], A. Gomes[2], H. Gordon[52,*], M. Grabalosa Gándara[33], R. Graciani Diaz[33], L.A. Granado Cardoso[35], E. Graugés[33], G. Graziani[17], A. Grecu[26], E. Greening[52], S. Gregson[44], O. Grünberg[55], B. Gui[53], E. Gushchin[30], Yu. Guz[32], T. Gys[35], C. Hadjivasiliou[53], G. Haefeli[36], C. Haen[35], S.C. Haines[44], S. Hall[50], T. Hampson[43], S. Hansmann-Menzemer[11], N. Harnew[52], S.T. Harnew[43], J. Harrison[51], P.F. Harrison[45], T. Hartmann[55], J. He[7], V. Heijne[38], K. Hennessy[49], P. Henrard[5], J.A. Hernando Morata[34], E. van Herwijnen[35], E. Hicks[49], D. Hill[52], M. Hoballah[5], P. Hopchev[4], W. Hulsbergen[38], P. Hunt[52], T. Huse[49], N. Hussain[52], D. Hutchcroft[49], D. Hynds[48], V. Iakovenko[41], P. Ilten[12], J. Imong[43], R. Jacobsson[35], A. Jaeger[11], M. Jahjah Hussein[5], E. Jans[38], F. Jansen[38], P. Jaton[36], B. Jean-Marie[7], F. Jing[3], M. John[52], D. Johnson[52], C.R. Jones[44], B. Jost[35], M. Kaballo[9], S. Kandybei[40], M. Karacson[35], T.M. Karbach[35], I.R. Kenyon[42], U. Kerzel[35], T. Ketel[39], A. Keune[36], B. Khanji[20], Y.M. Kim[47], O. Kochebina[7], V. Komarov[36,29], R.F. Koopman[39], P. Koppenburg[38], M. Korolev[29], A. Kozlinskiy[38], L. Kravchuk[30], K. Kreplin[11], M. Kreps[45], G. Krocker[11], P. Krokovny[31], F. Kruse[9], M. Kucharczyk[20,23,j], V. Kudryavtsev[31], T. Kvaratskheliya[28,35], V.N. La Thi[36], D. Lacarrere[35], G. Lafferty[51], A. Lai[15], D. Lambert[47], R.W. Lambert[39], E. Lanciotti[35], G. Lanfranchi[18,35], C. Langenbruch[35], T. Latham[45], C. Lazzeroni[42], R. Le Gac[6], J. van Leerdam[38], J.-P. Lees[4], R. Lefèvre[5], A. Leflat[29,35], J. Lefrançois[7], O. Leroy[6], T. Lesiak[23], Y. Li[3], L. Li Gioi[5], M. Liles[49], R. Lindner[35], C. Linn[11], B. Liu[3], G. Liu[35], J. von Loeben[20], J.H. Lopes[2], E. Lopez Asamar[33], N. Lopez-March[36], H. Lu[3], J. Luisier[36], H. Luo[47], A. Mac Raighne[48], F. Machefert[7], I.V. Machikhiliyan[4,28], F. Maciuc[26], O. Maev[27,35], J. Magnin[1], M. Maino[20], S. Malde[52], G. Manca[15,d], G. Mancinelli[6], N. Mangiafave[44], U. Marconi[14], R. Märki[36], J. Marks[11], G. Martellotti[22], A. Martens[8], L. Martin[52], A. Martín Sánchez[7], M. Martinelli[38], D. Martinez Santos[35], D. Martins Tostes[2], A. Massafferri[1], R. Matev[35], Z. Mathe[35], C. Matteuzzi[20], M. Matveev[27], E. Maurice[6], A. Mazurov[16,30,35,e], J. McCarthy[42], G. McGregor[51], R. McNulty[12], M. Meissner[11], M. Merk[38], J. Merkel[9], D.A. Milanes[13], M.-N. Minard[4],

J. Molina Rodriguez [54], S. Monteil [5], D. Moran [51], P. Morawski [23], R. Mountain [53], I. Mous [38], F. Muheim [47], K. Müller [37], R. Muresan [26], B. Muryn [24], B. Muster [36], J. Mylroie-Smith [49], P. Naik [43], T. Nakada [36], R. Nandakumar [46], I. Nasteva [1], M. Needham [47], N. Neufeld [35], A.D. Nguyen [36], T.D. Nguyen [36], C. Nguyen-Mau [36,o], M. Nicol [7], V. Niess [5], N. Nikitin [29], T. Nikodem [11], A. Nomerotski [52,35], A. Novoselov [32], A. Oblakowska-Mucha [24], V. Obraztsov [32], S. Oggero [38], S. Ogilvy [48], O. Okhrimenko [41], R. Oldeman [15,35,d], M. Orlandea [26], J.M. Otalora Goicochea [2], P. Owen [50], B.K. Pal [53], A. Palano [13,b], M. Palutan [18], J. Panman [35], A. Papanestis [46], M. Pappagallo [48], C. Parkes [51], C.J. Parkinson [50], G. Passaleva [17], G.D. Patel [49], M. Patel [50], G.N. Patrick [46], C. Patrignani [19,i], C. Pavel-Nicorescu [26], A. Pazos Alvarez [34], A. Pellegrino [38], G. Penso [22,l], M. Pepe Altarelli [35], S. Perazzini [14,c], D.L. Perego [20,j], E. Perez Trigo [34], A. Pérez-Calero Yzquierdo [33], P. Perret [5], M. Perrin-Terrin [6], G. Pessina [20], K. Petridis [50], A. Petrolini [19,i], A. Phan [53], E. Picatoste Olloqui [33], B. Pie Valls [33], B. Pietrzyk [4], T. Pilař [45], D. Pinci [22], S. Playfer [47], M. Plo Casasus [34], F. Polci [8], G. Polok [23], A. Poluektov [45,31], E. Polycarpo [2], D. Popov [10], B. Popovici [26], C. Potterat [33], A. Powell [52], J. Prisciandaro [36], V. Pugatch [41], A. Puig Navarro [36], W. Qian [4], J.H. Rademacker [43], B. Rakotomiaramanana [36], M.S. Rangel [2], I. Raniuk [40], N. Rauschmayr [35], G. Raven [39], S. Redford [52], M.M. Reid [45], A.C. dos Reis [1], S. Ricciardi [46], A. Richards [50], K. Rinnert [49], V. Rives Molina [33], D.A. Roa Romero [5], P. Robbe [7], E. Rodrigues [48,51], P. Rodriguez Perez [34], G.J. Rogers [44], S. Roiser [35], V. Romanovsky [32], A. Romero Vidal [34], J. Rouvinet [36], T. Ruf [35], H. Ruiz [33], G. Sabatino [22,k], J.J. Saborido Silva [34], N. Sagidova [27], P. Sail [48], B. Saitta [15,d], C. Salzmann [37], B. Sanmartin Sedes [34], M. Sannino [19,i], R. Santacesaria [22], C. Santamarina Rios [34], R. Santinelli [35], E. Santovetti [21,k], M. Sapunov [6], A. Sarti [18,l], C. Satriano [22,m], A. Satta [21], M. Savrie [16,e], P. Schaack [50], M. Schiller [39], H. Schindler [35], S. Schleich [9], M. Schlupp [9], M. Schmelling [10], B. Schmidt [35], O. Schneider [36], A. Schopper [35], M.-H. Schune [7], R. Schwemmer [35], B. Sciascia [18], A. Sciubba [18,l], M. Seco [34], A. Semennikov [28], K. Senderowska [24], I. Sepp [50], N. Serra [37], J. Serrano [6], P. Seyfert [11], M. Shapkin [32], I. Shapoval [40,35], P. Shatalov [28], Y. Shcheglov [27], T. Shears [49,35], L. Shekhtman [31], O. Shevchenko [40], V. Shevchenko [28], A. Shires [50], R. Silva Coutinho [45], T. Skwarnicki [53], N.A. Smith [49], E. Smith [52,46], M. Smith [51], K. Sobczak [5], F.J.P. Soler [48], F. Soomro [18,35], D. Souza [43], B. Souza De Paula [2], B. Spaan [9], A. Sparkes [47], P. Spradlin [48], F. Stagni [35], S. Stahl [11], O. Steinkamp [37], S. Stoica [26], S. Stone [53], B. Storaci [38], M. Straticiuc [26], U. Straumann [37], V.K. Subbiah [35], S. Swientek [9], M. Szczekowski [25], P. Szczypka [36,35], T. Szumlak [24], S. T'Jampens [4], M. Teklishyn [7], E. Teodorescu [26], F. Teubert [35], C. Thomas [52], E. Thomas [35], J. van Tilburg [11], V. Tisserand [4], M. Tobin [37], S. Tolk [39], D. Tonelli [35], S. Topp-Joergensen [52], N. Torr [52], E. Tournefier [4,50], S. Tourneur [36], M.T. Tran [36], A. Tsaregorodtsev [6], P. Tsopelas [38], N. Tuning [38], M. Ubeda Garcia [35], A. Ukleja [25], D. Urner [51], U. Uwer [11], V. Vagnoni [14], G. Valenti [14], R. Vazquez Gomez [33], P. Vazquez Regueiro [34], S. Vecchi [16], J.J. Velthuis [43], M. Veltri [17,g], G. Veneziano [36], M. Vesterinen [35], B. Viaud [7], I. Videau [7], D. Vieira [2], X. Vilasis-Cardona [33,n], J. Visniakov [34], A. Vollhardt [37], D. Volyanskyy [10], D. Voong [43], A. Vorobyev [27], V. Vorobyev [31], H. Voss [10], C. Voß [55], R. Waldi [55], R. Wallace [12], S. Wandernoth [11], J. Wang [53], D.R. Ward [44], N.K. Watson [42], A.D. Webber [51], D. Websdale [50], M. Whitehead [45], J. Wicht [35], D. Wiedner [11], L. Wiggers [38], G. Wilkinson [52], M.P. Williams [45,46], M. Williams [50,p], F.F. Wilson [46], J. Wishahi [9], M. Witek [23], W. Witzeling [35], S.A. Wotton [44], S. Wright [44], S. Wu [3], K. Wyllie [35], Y. Xie [47,35], F. Xing [52], Z. Xing [53], Z. Yang [3], R. Young [47], X. Yuan [3], O. Yushchenko [32], M. Zangoli [14], M. Zavertyaev [10,a], F. Zhang [3], L. Zhang [53], W.C. Zhang [12], Y. Zhang [3], A. Zhelezov [11], L. Zhong [3], A. Zvyagin [35]

[1] *Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*
[2] *Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*
[3] *Center for High Energy Physics, Tsinghua University, Beijing, China*
[4] *LAPP, Université de Savoie, CNRS/IN2P3, Annecy-Le-Vieux, France*
[5] *Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[6] *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[7] *LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France*
[8] *LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France*
[9] *Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[10] *Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
[11] *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[12] *School of Physics, University College Dublin, Dublin, Ireland*
[13] *Sezione INFN di Bari, Bari, Italy*
[14] *Sezione INFN di Bologna, Bologna, Italy*
[15] *Sezione INFN di Cagliari, Cagliari, Italy*
[16] *Sezione INFN di Ferrara, Ferrara, Italy*

[17] Sezione INFN di Firenze, Firenze, Italy
[18] Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy
[19] Sezione INFN di Genova, Genova, Italy
[20] Sezione INFN di Milano Bicocca, Milano, Italy
[21] Sezione INFN di Roma Tor Vergata, Roma, Italy
[22] Sezione INFN di Roma La Sapienza, Roma, Italy
[23] Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
[24] AGH University of Science and Technology, Kraków, Poland
[25] National Center for Nuclear Research (NCBJ), Warsaw, Poland
[26] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
[27] Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
[28] Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
[29] Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
[30] Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
[31] Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
[32] Institute for High Energy Physics (IHEP), Protvino, Russia
[33] Universitat de Barcelona, Barcelona, Spain
[34] Universidad de Santiago de Compostela, Santiago de Compostela, Spain
[35] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[36] Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[37] Physik-Institut, Universität Zürich, Zürich, Switzerland
[38] Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
[39] Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
[40] NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
[41] Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
[42] University of Birmingham, Birmingham, United Kingdom
[43] H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
[44] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[45] Department of Physics, University of Warwick, Coventry, United Kingdom
[46] STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
[47] School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[48] School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[49] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[50] Imperial College London, London, United Kingdom
[51] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[52] Department of Physics, University of Oxford, Oxford, United Kingdom
[53] Syracuse University, Syracuse, NY, United States
[54] Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil [q]
[55] Institut für Physik, Universität Rostock, Rostock, Germany [r]

* Corresponding author.
E-mail address: hamish.gordon@cern.ch (H. Gordon).
[a] P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.
[b] Università di Bari, Bari, Italy.
[c] Università di Bologna, Bologna, Italy.
[d] Università di Cagliari, Cagliari, Italy.
[e] Università di Ferrara, Ferrara, Italy.
[f] Università di Firenze, Firenze, Italy.
[g] Università di Urbino, Urbino, Italy.
[h] Università di Modena e Reggio Emilia, Modena, Italy.
[i] Università di Genova, Genova, Italy.
[j] Università di Milano Bicocca, Milano, Italy.
[k] Università di Roma Tor Vergata, Roma, Italy.
[l] Università di Roma La Sapienza, Roma, Italy.
[m] Università della Basilicata, Potenza, Italy.
[n] LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
[o] Hanoi University of Science, Hanoi, Viet Nam.
[p] Massachusetts Institute of Technology, Cambridge, MA, United States.
[q] Associated to Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil.
[r] Associated to Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany.