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Measurement of the $D_{\pm}$ production asymmetry in 7 TeV $pp$ collisions

LHCb Collaboration

**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 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 $D^+ \rightarrow K_S^0 \pi^+$ 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 $\sigma_{c\bar{c}} = 1230 \pm 190 \mu b$ and $\sigma_{b\bar{b}} = 74 \pm 14 \mu b$ 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 $D^+$ 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.\(^1\) 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 $K_S^0$, 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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\(^1\) 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 $\mu$m for tracks with high transverse momentum $p_T$. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photons, electrons 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 $D^+ \rightarrow K^0_S\pi^+$, $K^0_S \rightarrow \pi^+\pi^-$ 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 $K^0_S$ 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 $K^0_S$ 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 $D^+ \rightarrow K^0_S\pi^+$ 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 $\eta$ using binned likelihood fits to the distribution of the $K^0_S\pi^+$ mass m. The
The production asymmetry as a function 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

$$A_{P} = (-0.96 \pm 0.26 \text{ (stat.)})\%.$$
dependently of the signal decay, i.e. by a track that does not
metries introduced by the trigger. Events which are triggered in-
between D± decays is

Table 1
| PT ( GeV/c) | η |
|-------------|---|
| (2.00, 3.20) | (2.20, 2.80) | (2.80, 3.00) | (3.00, 3.25) | (3.25, 3.50) | (3.50, 3.80) | (3.80, 4.75) |
| −0.0 ± 2.5 | −2.2 ± 1.2 | −0.4 ± 0.8 | −0.4 ± 0.7 | −1.2 ± 0.6 | −1.2 ± 0.5 |
| −0.4 ± 0.9 | −0.4 ± 0.7 | −0.4 ± 0.5 | −1.1 ± 0.5 | +0.1 ± 0.6 | −1.2 ± 0.5 |
| +0.1 ± 0.8 | −1.0 ± 0.8 | −1.3 ± 0.6 | −2.0 ± 0.6 | −0.1 ± 0.6 | −21.0 ± 0.7 |
| −1.6 ± 0.7 | −0.6 ± 0.8 | −0.5 ± 0.6 | −0.7 ± 0.6 | −1.6 ± 0.6 | −2.0 ± 0.8 |
| −0.5 ± 0.7 | −0.8 ± 0.8 | +0.2 ± 0.7 | −0.3 ± 0.7 | −0.6 ± 0.7 | −1.2 ± 0.9 |
| −1.4 ± 0.8 | +0.5 ± 1.0 | −0.9 ± 0.9 | −0.6 ± 0.9 | −0.7 ± 0.9 | −1.6 ± 1.2 |
| −0.4 ± 0.8 | −0.4 ± 1.1 | −0.2 ± 1.1 | +1.7 ± 1.1 | −1.4 ± 1.1 | +1.2 ± 1.4 |
| −0.6 ± 1.3 | +1.8 ± 2.3 | −2.5 ± 2.2 | +1.8 ± 2.4 | +1.1 ± 2.5 | −7 ± 11 |

The sources of systematic uncertainty are summarised in Ta-
ble 2. The dominant uncertainty of 1.5 × 10−3 is due to asym-
metries introduced by the trigger. Events which are triggered in-
dependently 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 produc-
tion asymmetry, and would bias the measurement of it. This was
studied with a control sample of the abundant D± → K−π+π−
declays. To mimic the charge-unbiased sample of D± → K±π±
declay which are triggered by a K± 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± → K−π+π− decays is
then compared to that in the much larger sample of candidates
that are triggered independently of the signal decay. The differ-
ence in raw charge asymmetry between these two samples,
(1.5 ± 0.4) × 10−3, is a measure of the scale of the bias. Unlike
the signal, the K−π+π− 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± → φπ± 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 B0
production asymmetry, which is estimated to be (−1.0 ± 1.3)% [25],
to determine the systematic uncertainty.

Certain selection criteria differ between the D± → K±π± signal
sample and the D0 → K−π+π− 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 pT.
Pions in the signal sample must have pT > 500 MeV/c while those
in the control sample must have pT > 300 MeV/c. A systematic
uncertainty is calculated by estimating the proportion of signal
candidates with 300 < pT < 500 MeV/c and multiplying this frac-
tion by the difference between the charge asymmetries in the low
pT 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
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 Ta-
ble 2. The dominant uncertainty of 1.5 × 10−3 is due to asym-
metries introduced by the trigger. Events which are triggered in-
dependently of the signal decay, i.e. by a track that does not
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Pions in the signal sample must have pT > 500 MeV/c while those
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uncertainty is calculated by estimating the proportion of signal
candidates with 300 < pT < 500 MeV/c and multiplying this frac-
tion by the difference between the charge asymmetries in the low
pT 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

Table 2
Summary of absolute values of systematic uncertainties on Aτ. For the binned
production asymmetries given in Table 1, all uncertainties except that on the re-
construction 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 |
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 $D^+ \rightarrow K^0\pi^+$ sample, and asymmetric backgrounds such as that from $D^+ \rightarrow K^0\pi^+$ 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 there is no evidence for it to be observed at the $B$-factories [27,13]. If we allow 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 $2.0 < p_T < 18.0 \text{ GeV}/c$ and $2.20 < \eta < 4.75$, excluding the region with $2.0 < p_T < 3.2 \text{ GeV}/c$, $2.20 < \eta < 2.80$, 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 consistent 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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