Search for CP Violation in $D_s^+ \to K_S^0 \pi^+$, $D^+ \to K_S^0 K^+$, and $D^+ \to \phi \pi^+$ Decays

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A search for charge-parity (CP) violation in Cabibbo-suppressed $D_s^+ \to K_S^0 \pi^+$, $D^+ \to K_S^0 K^+$, and $D^+ \to \phi \pi^+$ decays is reported using proton-proton collision data, corresponding to an integrated luminosity of 3.8 fb$^{-1}$, collected at a center-of-mass energy of 13 TeV with the LHCb detector. High-yield samples of kinematically and topologically similar Cabibbo-favored $D_s^+$ decays are analyzed to subtract nuisance asymmetries due to production and detection effects, including those induced by CP violation in the neutral kaon system. The results are

$$A_{CP}(D_s^+ \to K_S^0 \pi^+) = (1.3 \pm 1.9 \pm 0.5) \times 10^{-3},$$
$$A_{CP}(D^+ \to K_S^0 K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3},$$
$$A_{CP}(D^+ \to \phi \pi^+) = (0.05 \pm 0.42 \pm 0.29) \times 10^{-3},$$

where the first uncertainties are statistical and the second systematic. They are the most precise measurements of these quantities to date, and are consistent with CP symmetry. A combination with previous LHCb measurements, based on data collected at 7 and 8 TeV, is also reported.

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Violation of charge-parity (CP) symmetry arises in the standard model (SM) of particle physics through the complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1,2]. CP violation is well established in $K$- and $B$-meson systems [3–7], and has been observed only recently in charm decays [8]. CP violation in charm decays can arise from the interference between tree- and loop-level diagrams through Cabibbo-suppressed $c \to d u$ and $c \to s u$ transition amplitudes. In the loop-level processes, contributions from physics beyond the SM may arise that can lead to additional sources of CP violation [9]. However, the expected SM contribution is difficult to compute due to the presence of low-energy strong-interaction effects, with current predictions spanning several orders of magnitude [9–13]. A promising handle to determine the origin of possible CP-violation signals are correlations between CP asymmetries in flavor $SU(3)$ related decays [14–22]. Particularly interesting in this respect are $D_s^+$ and $D^+$ decays to two-body (or quasi-two-body) final states, such as $D_s^+ \to K_S^0 \pi^+$, $D^+ \to K_S^0 K^+$, and $D^+ \to \phi \pi^+$. (The inclusion of charge-conjugate processes is implied throughout this Letter, unless stated otherwise.) Searches for CP violation in these modes have been performed by the CLEO [23], BABAR [24,25], Belle [26–28], and LHCb [29,30] collaborations. No evidence for CP violation has been found within a precision of a few per mille.

This Letter presents measurements of CP asymmetries in $D_s^+ \to K_S^0 \pi^+$, $D^+ \to K_S^0 K^+$, and $D^+ \to \phi \pi^+$ decays performed using proton-proton collision data collected with the LHCb detector between 2015 and 2017 at a center-of-mass energy of 13 TeV, and corresponding to an integrated luminosity of 3.8 fb$^{-1}$. In the presence of a $K_S^0$ meson in the final state, a CP asymmetry is expected to be induced by $K^0\bar{K}^0$ mixing [31]. This effect is well known and predictable, allowing for a precise measurement of CP violation in the charm-quark transition. The $D^+ \to \phi \pi^+$ decay is reconstructed with the $\phi \to K^+ K^-$ mode. Several intermediate states contribute to the $D^+ \to K^+ K^- \pi^+$ decay amplitude [32]. In this Letter, no attempt is made to separate them through an amplitude analysis, and the measurement is performed by simply restricting the $K^+ K^-$ pair to the mass region around the $\phi(1020)$ resonance.

The CP asymmetry of a $D_s^+$ meson decaying to the final state $f^+$ is defined as

$$A_{CP}(D_s^+ \to f^+) \equiv \frac{\Gamma(D_{(s)}^+ \to f^+) - \Gamma(D_{(s)}^- \to f^-)}{\Gamma(D_{(s)}^+ \to f^+) + \Gamma(D_{(s)}^- \to f^-)},$$

where $\Gamma$ is the partial decay rate. If CP symmetry is violated in the decay, $A_{CP} \neq 0$. An experimentally
The convenient quantity to measure is the “raw” asymmetry of the observed yields $N$, 
\[
A(D_{(s)}^+ \rightarrow f^+) = \frac{N(D_{(s)}^+ \rightarrow f^+) - N(D_{(s)}^- \rightarrow f^-)}{N(D_{(s)}^+ \rightarrow f^+) + N(D_{(s)}^- \rightarrow f^-)}. \tag{2}
\]

The raw asymmetry can be approximated as 
\[
A(D_{(s)}^+ \rightarrow f^+) \approx A_{CP}(D_{(s)}^+ \rightarrow f^+) + A_P(D_{(s)}^+) + A_D(f^+), \tag{3}
\]

where $A_P(D_{(s)}^+)$ is the asymmetry of the $D_{(s)}^+$-meson production cross section [33,34] and $A_D(f^+)$ is the asymmetry of the reconstruction efficiency for the final state $f^+$. When $f^+ = K_S^0 h^+$ (with $h = K, \pi$), the detection asymmetry receives contributions from the $h^+$ hadron (indicated as companion hadron in the following), $A_D(h^+)$, and from the neutral kaon, $A_D(K^0)$. Relevant instrumental effects contributing to $A_D(h^+)$ may include differences in interaction cross sections with matter and from their propagation in the detector being affected by the presence of $CP$ violation in the $K^0$-$\bar{K}^0$ system. When $f^+ = \phi(K^+K^-)\pi^+$, the detection asymmetry is mostly due to the charged pion, as the contributions from the oppositely charged kaons cancel to a good precision.

The detection and production asymmetries are canceled by using the decays $D^+ \rightarrow K_S^0\pi^+$, $D^+_s \rightarrow K_S^0 K^+$, and $D^+_s \rightarrow \phi\pi^+$, which proceed through the Cabibbo-favored $c \rightarrow s d u$ transition. In the SM, these decays are expected to have $CP$ asymmetries that are negligibly small compared to the Cabibbo-suppressed modes, when effects induced by the neutral kaons are excluded [31,35]. Hence, their raw asymmetries can be approximated as in Eq. (3), but with $A_{CP} = 0$. The $CP$ asymmetries of the decay modes of interest are determined by combining the raw asymmetries as follows:

\[
A_{CP}(D^+_s \rightarrow K_S^0\pi^+) \approx A(D^+_s \rightarrow K_S^0\pi^+) - A(D^+_s \rightarrow \phi\pi^+), \tag{4}
\]

\[
A_{CP}(D^+ \rightarrow K_S^0 K^+) \approx A(D^+ \rightarrow K_S^0 K^+) - A(D^+ \rightarrow K_S^0\pi^+) - A(D^+_s \rightarrow K_S^0 K^+) + A(D^+_s \rightarrow \phi\pi^+), \tag{5}
\]

\[
A_{CP}(D^+ \rightarrow \phi\pi^+) \approx A(D^+ \rightarrow \phi\pi^+) - A(D^+ \rightarrow K_S^0\pi^+). \tag{6}
\]

where the contribution from $A_D(K^0)$ is omitted and should be subtracted from any of the measured asymmetries where it is present.

The LHCb detector [36,37] is a single-arm forward spectrometer designed for the study of particles containing $b$ or $c$ quarks. The detector elements that are particularly relevant to this analysis are a silicon-strip vertex detector that allows for a precise measurement of the impact parameter, i.e., the minimum distance of a charged-particle trajectory to a $pp$ interaction point (primary vertex), a tracking system that provides a measurement of the momentum of charged particles, two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons, and a calorimeter system that is used for the identification of photons, electrons and hadrons. The polarity of the magnetic field is periodically reversed during data-taking to mitigate the differences between reconstruction efficiencies of oppositely charged particles.

The online event selection is performed by a trigger, which consists of a hardware stage followed by a two-level software stage. In between the two software stages, an alignment and calibration of the detector is performed in near real-time and their results are used in the trigger [38]. Events with candidate $D^+_s$ decays are selected by the hardware trigger by imposing either that one or more $D^+_s$ decay products are associated with large transverse energy deposits in the calorimeter or that the accept decision is independent of the $D^+_s$ decay products (i.e., it is caused by other particles in the event). In the first level of the software trigger, one or more $D^+_s$ decay products must have large transverse momentum and be inconsistent with originating from any primary vertex. In the second level, the candidate decays are fully reconstructed using kinematic, topological and particle-identification criteria. The $D^+_s \rightarrow K_S^0 h^+$ candidates are made by combining charged hadrons with $K_S^0 \rightarrow \pi^+\pi^-$ candidates that decay early enough for the final-state pions to be reconstructed in the vertex detector. This requirement suppresses to a negligible level possible $CP$-violation effects due to interference between Cabibbo-favored and doubly Cabibbo-suppressed amplitudes with neutral-kaon mixing in the control-sample decays $D^+ \rightarrow K_S^0\pi^+$ and $D^+_s \rightarrow K_S^0 K^+$ [35].

The $D^+_s$ candidates reconstructed in the trigger are used directly in the offline analysis [39,40]. The candidates with a $K_S^0$ meson in the final state are further selected offline using an artificial neural network (NN), based on the multilayer perceptron algorithm [41], to suppress background due to random combinations of $K_S^0$ mesons and hadrons not originating from a $D^+_s \rightarrow K_S^0 h^+$ decay. The quantities used in the NN to discriminate signal from combinatorial background are the $K_S^0$ candidate momentum, the transverse momenta of the $D^+_s$ candidate and of the companion hadron, the angle between the $D^+_s$ candidate momentum...
and the vector connecting the primary and secondary vertices, the quality of the secondary vertex, and the track quality of the companion hadron. The NN is trained using signal and background data samples, obtained with the sPlot method [42], from a $\mathcal{O}(1\%)$ fraction of candidates randomly sampled. In the $D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+}$ case, thanks to similar kinematics, background-subtracted $D^{+} \rightarrow K_{S}^{0}\pi^{+}$ decays are exploited as a signal proxy to profit from the $D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+}$ case, and the $\Lambda_{c}^{+} \rightarrow \phi\pi^{+}$ decay, where the proton is misidentified as a pion, when the signal is the $D^{+} \rightarrow \phi\pi^{+}$ decay. These are all reduced to a negligible level using particle-identification requirements and kinematic vetos.

Fiducial requirements are imposed to exclude kinematic regions that induce a large asymmetry in the companion-hadron reconstruction efficiency. These regions occur because low momentum particles of one charge at large (small) angles in the bending plane may be deflected out of the detector acceptance (into the noninstrumented beam pipe region), whereas particles with the other charge are more likely to remain within the acceptance. About 78%, 93%, and 94% of the selected candidates are retained by these fiducial requirements for $D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+}$, $D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+}$, and $D_{s}^{+} \rightarrow \phi\pi^{+}$ decays, respectively.

Detection and production asymmetries may depend on the kinematics of the involved particles. Therefore, the cancellation provided by the control decays is accurate only if the kinematic distributions agree between any pair of signal and control modes, or pair of control modes entering Eqs. (4)–(6). Differences are observed, and the ratio between background-subtracted [42] signal and control sample distributions of transverse momentum, azimuthal angle and pseudorapidity are used to define candidate-by-candidate weights. The background-subtracted candidates of the control decays are weighted such that their distributions agree with those of the signal using an iterative procedure. The process consists of calculating the weights in each one-dimensional distribution of the weighting variables and repeating the procedure until good agreement is achieved among all the distributions. For the measurements of the $D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+}$ and $D^{+} \rightarrow \phi\pi^{+}$ $CP$ asymmetries, the $D_{s}^{+} \rightarrow \phi\pi^{+}$ and $D^{+} \rightarrow K_{S}^{0}\pi^{+}$ control samples are weighted so that the $D_{s}^{+}$ meson and companion-pion kinematic distributions agree with their respective signal samples to cancel the $D_{s}^{+}$ production and companion-pion detection asymmetries. In the case of the $A_{CP}(D^{+} \rightarrow K_{S}^{0}\pi^{+})$ measurement, the $D^{+}$ kinematic distributions of the $D^{+} \rightarrow K_{S}^{0}\pi^{+}$ sample are weighted to those of the $D^{+} \rightarrow K_{S}^{0}\pi^{+}$ signal to cancel the $D^{+}$ production asymmetry, and the $K^{+}$ distributions of the $D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+}$ decays are weighted to those of the $D^{+} \rightarrow K_{S}^{0}\pi^{+}$ signal to cancel the kaon detection asymmetry. The $D^{+} \rightarrow K_{S}^{0}\pi^{+}$ and $D_{s}^{+} \rightarrow K_{S}^{0}\pi^{+}$ control decays then introduce their own additional nuisance asymmetries, which need to be corrected for using the $D^{+} \rightarrow \phi\pi^{+}$ control decay. Hence, the $D_{s}^{+}$ and companion-pion kinematic distributions of the $D_{s}^{+} \rightarrow \phi\pi^{+}$ sample are made to agree with those of the $D_{s}^{+} \rightarrow K_{S}^{0}K^{+}$ and $D^{+} \rightarrow K_{S}^{0}\pi^{+}$ samples, respectively, to cancel the $D_{s}^{+}$ production and companion-pion detection asymmetries.
Simultaneous least-squares fits to the mass distributions of weighted $D_{(s)}^+$ and $D_{(s)}^-$ candidates determine the raw asymmetries for each decay mode considered. To avoid experimenter bias, the raw asymmetries of the Cabibbo-suppressed signals were shifted by unknown offsets sampled uniformly between $-1\%$ and $1\%$, such that the results remained blind until the analysis procedure was finalized. In the fits, the signal and control decays are modeled as the sum of a Gaussian function to describe the core of the peaks, and a Johnson $S_U$ distribution [43], which accounts for the asymmetric tails. The combinatorial background is described by the sum of two exponential functions. All shape parameters are determined from the data. In each fit, signal and control decays share the same shape parameters apart from a mass shift, which accounts for the known difference between the $D_S^+$ and $D^+$ masses [32], and a relative scale factor between the peak widths, which is also determined from the data. The means and widths of the peaks, as well as all background shape parameters, are allowed to differ between $D_{(s)}^+$ and $D_{(s)}^-$ decays. The projections of the fits to the combined $D_{(s)}^+$ and $D_{(s)}^-$ data are shown in Fig. 2. The samples contain approximately 600 thousand $D_S^+ \to K_S^0\pi^+$, 5.1 million $D^+ \to K_S^0 K^+$, and 53.3 million $D^+ \to \phi\pi^+$ signal candidates, together with approximately 30.5 million $D^+ \to K_S^0\pi^+$, 6.5 million $D_S^+ \to K_S^0 K^+$, and 107 million $D_S^+ \to \phi\pi^+$ control decays.

The raw asymmetries are, where relevant, corrected for the relative-kaon detection asymmetry. The net correction is estimated following Ref. [44] to be $(+0.084 \pm 0.005)\%$ for $A_{CP}(D_S^+ \to K_S^0\pi^+)$, $(-0.086 \pm 0.005)\%$ for $A_{CP}(D^+ \to K_S^0 K^+)$, and $(-0.068 \pm 0.004)\%$ for $A_{CP}(D^+ \to \phi\pi^+)$, where the uncertainty is dominated by the accuracy of the detector modeling in the simulation. The asymmetries are combined following Eqs. (4)–(6) to obtain $A_{CP}(D_S^+ \to K_S^0\pi^+) = (1.3 \pm 1.9) \times 10^{-3}$, $A_{CP}(D^+ \to K_S^0 K^+) = (-0.09 \pm 0.65) \times 10^{-3}$, $A_{CP}(D^+ \to \phi\pi^+) = (0.05 \pm 0.42) \times 10^{-3}$, where the uncertainties are only statistical.

Several sources of systematic uncertainty affecting the measurement are considered as reported in Table I. The dominant contribution is due to the assumed shapes in the mass fits. This is evaluated by fitting with the default model large sets of pseudoexperiments where alternative models that describe data equally well are used in generation. For $A_{CP}(D_S^+ \to K_S^0\pi^+)$ and $A_{CP}(D^+ \to K_S^0 K^+)$, the second leading contribution is due to the residual

**TABLE I.** Summary of the systematic uncertainties (in units of $10^{-3}$) on the measured quantities. The total is the sum in quadrature of the different contributions.

<table>
<thead>
<tr>
<th>Source</th>
<th>$A_{CP}(D_S^+ \to K_S^0\pi^+)$</th>
<th>$A_{CP}(D^+ \to K_S^0 K^+)$</th>
<th>$A_{CP}(D^+ \to \phi\pi^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit model</td>
<td>0.39</td>
<td>0.44</td>
<td>0.24</td>
</tr>
<tr>
<td>Secondary decays</td>
<td>0.30</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>Kinematic differences</td>
<td>0.09</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Neutral kaon asymmetry</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Charged kaon asymmetry</td>
<td>0.08</td>
<td>0.09</td>
<td>0.15</td>
</tr>
<tr>
<td>Total</td>
<td>0.51</td>
<td>0.48</td>
<td>0.29</td>
</tr>
</tbody>
</table>
uniformly distributed; the lowest (largest) \( p \) value is 4\% (86\%). Therefore, the observed variations in results are consistent with statistical fluctuations and no additional systematic. No evidence for \( CP \) violation in these decays is found. More precise measurements of these asymmetries can be expected when the data already collected by LHCb in 2018 are included in a future analysis, and when much larger samples will become available at the upgraded LHCb detector [46].

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