

First Measurement of the Decay-Time-Integrated CP Asymmetry in $B_s^0 \rightarrow D_s^- \pi^+$ Decays

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A measurement of the flavor-untagged decay-time-integrated CP asymmetry in the flavor-specific decay $B_s^0 \rightarrow D_s^- \pi^+$, $\langle A_{\text{untagged}}^s \rangle$, is performed using proton-proton collision data collected by the LHCb experiment between 2016 and 2018 at a center-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of 5.4 fb^{-1} . The CP asymmetry is measured in two D_s^- meson decay modes, $D_s^- \rightarrow K^- K^+ \pi^-$ and $D_s^- \rightarrow \pi^- \pi^+ \pi^-$. The combined result, $\langle A_{\text{untagged}}^s \rangle = (-1.4 \pm 5.9(\text{stat}) \pm 1.1(\text{syst})) \times 10^{-3}$, is consistent with the Standard Model expectation and provides a direct constraint on new physics in tree-level b -hadron decays.

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Decays of beauty mesons to open-charm mesons and an associated light hadron of the form $B_{(s)}^0 \rightarrow D_{(s)}^{(*)-} h^+$, where $h \in \{\pi, K\}$, are dominated by color-allowed, tree-level amplitudes proceeding through the $b \rightarrow c \bar{u} q$ quark transition, for $q \in \{d, s\}$. (Charge-conjugate modes are implied throughout, unless otherwise stated.) Theoretical predictions of their branching fractions in the Standard Model (SM), based on quantum chromodynamics factorisation, consistently disagree with experimental averages [1–7]. One possible explanation is physics beyond the SM (BSM), which may introduce an additional weak phase into the decay amplitude [8–11]. The interference of such a BSM amplitude with the SM amplitude can induce CP violation, dubbed direct CP violation, resulting in a small decay-rate asymmetry.

As the decay $B_s^0 \rightarrow D_s^- \pi^+$ is flavor specific (the corresponding wrong-sign decay $B_s^0 \rightarrow D_s^+ \pi^-$ is heavily suppressed) and proceeds only at tree level, direct CP violation is not possible in the SM as this would require interference with additional amplitudes. The flavor-specific CP asymmetry, i.e., the asymmetry of measuring CP -conjugate final states f and $\bar{f}$, is defined as a function of time, t , as

$$A_{\text{fs}}^s(t) \equiv \frac{\Gamma(\bar{B}_s^0(t) \rightarrow \bar{f}) - \Gamma(B_s^0(t) \rightarrow f)}{\Gamma(\bar{B}_s^0(t) \rightarrow \bar{f}) + \Gamma(B_s^0(t) \rightarrow f)}, \quad (1)$$

wherein Γ is the partial decay rate of a given state. This is equal to the CP asymmetry in B_s^0 – $\bar{B}_s^0$ mixing in the SM, denoted as a_{fs}^s for flavor-specific nonleptonic decays.

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This quantity has been measured in semileptonic decays, for which it is denoted by a_{sl}^s , as $a_{\text{sl}}^s = (-60 \pm 280) \times 10^{-5}$ [12], consistent with the SM prediction of $a_{\text{sl}}^s = (2.06 \pm 0.18) \times 10^{-5}$ [13].

The CP asymmetry of $B_s^0 \rightarrow D_s^- \pi^+$ decays can be measured as a decay-time-integrated flavor-untagged quantity, $\langle A_{\text{untagged}}^s \rangle$, to make use of the fast oscillation frequency of the B_s^0 meson and to circumvent the low efficiency to tag the initial B_s^0 flavor [14]. This is evaluated as

$$\langle A_{\text{untagged}}^s \rangle \approx A_{\text{dir}}^s - \frac{a_{\text{fs}}^s}{2}(1 - \rho_s), \quad (2)$$

wherein A_{dir}^s is a direct CP -asymmetry contribution from potential BSM effects, which can be up to $\mathcal{O}(10^{-2})$ [8], and $\rho_s \approx 0.001$ accounts for dilution from B_s^0 – $\bar{B}_s^0$ oscillation [8].

Experimentally, $\langle A_{\text{untagged}}^s \rangle$ can be measured from the raw asymmetry, A_{raw} , of observed $B_s^0 \rightarrow D_s^- \pi^+$ candidate yields, N , to final states $D_s^+ \pi^-$ and $D_s^- \pi^+$, obtained through fits to the decay-time-integrated invariant-mass distributions,

$$A_{\text{raw}} = \frac{N(D_s^+ \pi^-) - N(D_s^- \pi^+)}{N(D_s^+ \pi^-) + N(D_s^- \pi^+)}. \quad (3)$$

This asymmetry is subject to charge-dependent differences in detection efficiency, resulting in a detection asymmetry, A_{det} , which must be subtracted as

$$\langle A_{\text{untagged}}^s \rangle = A_{\text{raw}} - A_{\text{det}}. \quad (4)$$

The term A_{det} is determined from data using calibration and simulated samples. In this measurement, the decay-time-integrated B_s^0 production asymmetry is neglected, as this is diluted to $\mathcal{O}(10^{-5})$ by the fast B_s^0 – $\bar{B}_s^0$ oscillation frequency [14–16].

This Letter presents a measurement of the flavor-untagged decay-time-integrated CP asymmetry of $B_s^0 \rightarrow D_s^- \pi^+$ decays, $\langle A_{\text{untagged}}^s \rangle$, performed using proton-proton (pp) collision data collected by the LHCb experiment between 2016 and 2018 at a center-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of 5.4 fb^{-1} .

The LHCb detector [17,18] 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 elements of particular relevance to this analysis include: a silicon-strip vertex detector surrounding the pp interaction region that allows c and b hadrons to be identified from their characteristically long flight distance; a tracking system that provides a measurement of the momentum, p , of charged particles from their deflection by a large dipole magnet (the polarity of which is periodically reversed to reduce detection asymmetries); and two ring-imaging Cherenkov detectors that can discriminate between different species of charged hadrons.

The online event selection is performed by a trigger [19], which consists of a hardware stage, L0, based on information from the electromagnetic and hadronic (HCAL) calorimeter and muon systems, followed by two software stages, HLT1 and HLT2, which perform partial and full event reconstruction, respectively. At the L0 stage, events must contain a final-state hadron with greater transverse energy than a threshold varying between 3.46 and 3.70 GeV depending on the data-taking year according to the detector occupancy. A minimal spatial separation between final-state hadrons in the HCAL is required, such that energy deposits do not overlap. At the HLT1 stage, single or pairs of tracks are required to be significantly displaced from any primary pp interaction vertex (PV), as is indicative of a b hadron decay. Similarly, HLT2 requires a two-, three- or four-track secondary vertex (SV) with a significant displacement from any PV. A multivariate algorithm [20,21] is used to select those SVs consistent with the decay topology of a b hadron. Triggered events undergo a centralized, offline processing step and highly automated LHCb analysis productions deliver physics-analysis-ready data across the entire LHCb physics program [22,23].

Simulated samples are used to determine reconstruction and selection efficiencies and asymmetries, and shapes of invariant-mass distributions. In the simulation, pp collisions are generated using Pythia [24] with a specific LHCb configuration [25]. Decays of unstable particles are described by EvtGen [26], in which final-state radiation is generated using Photos [27]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [28] as described in Ref. [29]. These samples are corrected to account for known differences between data and simulation in the B_s^0 production kinematics and detector occupancy, and track-reconstruction, particle-identification, and trigger efficiencies.

The $B_s^0 \rightarrow D_s^- \pi^+$ decay is reconstructed by selecting D_s^- candidates through their decays to $K^- K^+ \pi^-$ and $\pi^- \pi^+ \pi^-$ final states, and combining them with a charged pion, referred to as the companion particle. Both final states are charge symmetric under the exchange of kaon or pion pairs. The invariant mass of all final-state particles, $m(h^- h^+ \pi^- \pi^+)$, is required to be within the range 5280–6000 MeV/ c^2 and the $h^- h^+ \pi^-$ invariant mass must lie within 30 MeV/ c^2 of the known D_s^- mass [30]. To separate the $B_s^0 \rightarrow D_s^- \pi^+$ signal from background sources with misidentified particles, particle identification (PID) requirements are applied using multivariate techniques that combine PID and tracking information from all LHCb subdetectors into two discriminants per particle species [31]. A loose PID requirement is applied on the companion track, since the $B_s^0 \rightarrow D_s^- \pi^+$ decay has a branching fraction roughly an order of magnitude larger than the misidentified $B_s^0 \rightarrow D_s^- K^+$ decay. The PID requirements on the D_s^- final-state tracks are optimized separately for the $D_s^- \rightarrow K^- K^+ \pi^-$ and $D_s^- \rightarrow \pi^- \pi^+ \pi^-$ decay modes. The $K^- K^+ \pi^-$ phase space is divided into three regions: $D_s^- \rightarrow \phi \pi^-$, $D_s^- \rightarrow K^*(892)^0 K^-$, and nonresonant, while the $\pi^- \pi^+ \pi^-$ phase space is split into $D_s^- \rightarrow f_0(980) \pi^-$ and nonresonant regions. Loose PID requirements are applied in resonant regions, where background contamination is low, while tight criteria are set in the nonresonant regions. In addition, dedicated vetoes are applied to suppress candidates from background contributions containing J/ψ and D^0 particles. Residual background components are modeled in the invariant-mass fit. After the selection, approximately 0.5% and 2.5% of events contain multiple candidates in the $D_s^- \rightarrow K^- K^+ \pi^-$ and $D_s^- \rightarrow \pi^- \pi^+ \pi^-$ final states, respectively. In these events, one candidate is retained arbitrarily, preferentially choosing candidates reconstructed in the $D_s^- \rightarrow K^- K^+ \pi^-$ final state where events remain reconstructed in both final states. This selection strategy differs from that of Ref. [14] in the specific PID requirements applied, in the requirement of hadron-pair separation in the HCAL, and in that a multivariate classifier was not used to suppress combinatorial background.

The total $B_s^0 \rightarrow D_s^- \pi^+$ yield and A_{raw} are determined from unbinned extended maximum-likelihood fits to $m(h^- h^+ \pi^- \pi^+)$ across both spectra, and A_{raw} is determined through a simultaneous fit to the $D_s^+ \pi^-$ and $D_s^- \pi^+$ invariant-mass distributions, where the models describing each component are shared across the invariant-mass distributions. Signal and background probability density functions (PDFs) for the invariant-mass fit are obtained from dedicated simulated and data samples, with the simulated samples corrected for the L0 and PID responses to better reflect the distributions observed in data. The L0 responses are calibrated using dedicated control samples of $D^{*+} \rightarrow D^0 \pi^+$ decays; the PID responses in simulation are

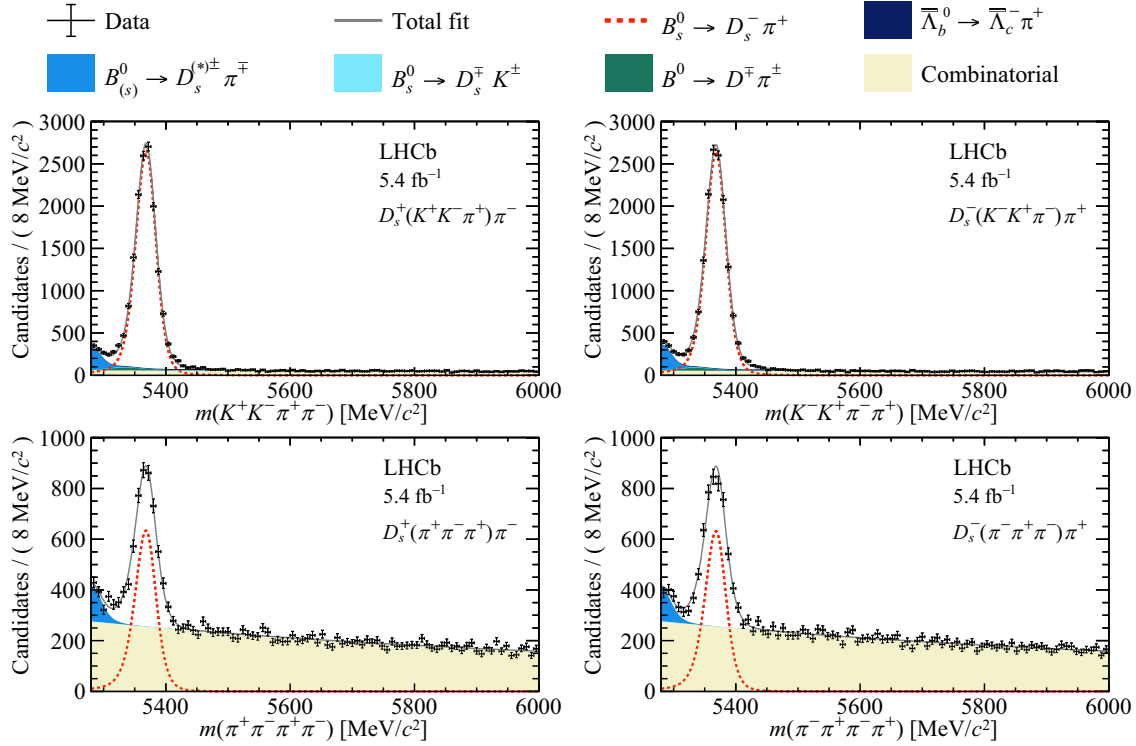


FIG. 1. Invariant-mass distributions of (left) $D_s^+ \pi^-$ and (right) $D_s^- \pi^+$ candidates, for the (top) $D_s^- \rightarrow K^- K^+ \pi^-$ and (bottom) $D_s^- \rightarrow \pi^- \pi^+ \pi^-$ decay modes, shown with the result of the invariant-mass fit.

calibrated using dedicated control samples of $D^{*+} \rightarrow D^0 \pi^+$ and $\Lambda \rightarrow p \pi^-$ decays [31].

As in Ref. [14], the $m(h^- h^+ \pi^- \pi^+)$ distribution for signal candidates is modeled as the sum of a modified Hypatia function with tails on both sides of the peak [32] and a Johnson S_U function [33], sharing a common peak position. Signal PDFs are determined from simulated $B_s^0 \rightarrow D_s^- \pi^+$ decays for each D_s^- final state separately. The PDF parameters are fixed in the fits to data, except for additive contributions to the peak position and width parameters, which account for resolution differences between data and simulation and are allowed to vary in the fit. The total $B_s^0 \rightarrow D_s^- \pi^+$ yield and A_{raw} are also allowed to vary in the fit.

The combinatorial background consists of random track combinations. It is modeled using two exponential functions derived from fits to the upper $m(h^- h^+ \pi^- \pi^+)$ sideband region, 5600–6800 MeV/c². In the baseline fit, all shape parameters are fixed except for the larger exponent, which is left free to account for possible differences between the upper sideband and the baseline fit region. The yield and asymmetry of the combinatorial background are determined directly from the data.

The background description closely follows Ref. [14] and includes fully reconstructed $B^0 \rightarrow D_s^+ \pi^-$ decays, $B_s^0 \rightarrow D_s^- K^+$ decays in which the kaon is misidentified as a pion, and partially reconstructed $B_s^0 \rightarrow D_s^{*-} \pi^+$ decays

where the neutral particle from $D_s^{*-} \rightarrow D_s^- \gamma / \pi^0$ decays is not reconstructed. Because of the similarity in the parametrization of $B^0 \rightarrow D_s^+ \pi^-$ and $B_s^0 \rightarrow D_s^{*-} \pi^+$ decays in the selected mass range, the two decays are represented by the same distribution, i.e., taking the $B^0 \rightarrow D_s^+ \pi^-$ shape as that of $B_s^0 \rightarrow D_s^- \pi^+$ decays and adjusting for the known mass difference between the B^0 and B_s^0 mesons [30]. Additional background contributions in the $D_s^- \rightarrow K^- K^+ \pi^-$ mode arise from $B^0 \rightarrow D^- \pi^+$ and $\bar{\Lambda}_b^0 \rightarrow \bar{\Lambda}_c^- \pi^+$ decays, where misidentification leads to the charm hadron being reconstructed as a D_s^- meson. The PDFs for these components are determined from simulation, with only the peak position and width parameters varying in the baseline fit, using the same additive shifts as the signal description. In the baseline fit, misidentified background asymmetries are fixed to zero to improve the stability of the fit, while the asymmetry of the component describing $B^0 \rightarrow D_s^+ \pi^-$ and $B_s^0 \rightarrow D_s^{*-} \pi^+$ decays, which contains many more events, is free to vary. The yields of $B_s^0 \rightarrow D_s^- K^+$ and $B^0 \rightarrow D^- \pi^+$ decays are fixed relative to the signal yields, corrected with their corresponding efficiencies from simulation and known branching fractions.

Distributions of invariant masses are shown in Fig. 1, along with the results of the mass fits. The charge-combined signal yields are 28940 ± 190 and 7270 ± 150 for the $D_s^- \rightarrow K^- K^+ \pi^-$ and $D_s^- \rightarrow \pi^- \pi^+ \pi^-$ decay modes, respectively. The measured value of A_{raw} is equal to

TABLE I. Contributions to A_{det} , averaged over magnet polarities and data-taking periods. The first uncertainties are statistical and the second are due to systematic sources. All values are given in percent.

Asymmetry (%)	$K^+K^-\pi^+\pi^-$	$\pi^+\pi^-\pi^+\pi^-$
A_{track}	$0.008 \pm 0.061 \pm 0.073$	$-0.010 \pm 0.023 \pm 0.029$
A_{sel}	$0.031 \pm 0.063 \pm 0.080$	$0.03 \pm 0.24 \pm 0.22$
A_{PID}	$0.021 \pm 0.088 \pm 0.057$	$0.08 \pm 0.34 \pm 0.17$
A_{L0}	$-0.169 \pm 0.056 \pm 0.007$	$0.00 \pm 0.21 \pm 0.02$
A_{det}	$-0.11 \pm 0.11 \pm 0.11$	$0.10 \pm 0.34 \pm 0.28$

$(-2.2 \pm 6.2) \times 10^{-3}$ for the $D_s^- \rightarrow K^-K^+\pi^-$ decay mode and $(-0.2 \pm 1.6) \times 10^{-2}$ for the $D_s^- \rightarrow \pi^-\pi^+\pi^-$ decay mode, where the uncertainties are statistical.

Following Eq. (4), the measured A_{raw} is corrected for detection asymmetries in the $D_s^+\pi^+$ and $D_s^+\pi^-$ final states, evaluated using calibration data and simulated samples. This is decomposed as a sum of four contributions: track reconstruction (A_{track}), kinematic and HCAL-based selection requirements (A_{sel}), particle-identification requirements (A_{PID}), and L0 requirements (A_{L0}). An additional contribution associated with the HLT1 requirements, A_{HLT1} , is estimated using a calibration sample of $D^+ \rightarrow K^-\pi^+\pi^+$ decays and found to be small. Its effect is therefore included as a systematic uncertainty on A_{sel} . Table I summarizes the measured values of the individual contributions to A_{det} , which are described in detail below.

For the $D_s^- \rightarrow K^-K^+\pi^-$ decay mode, the track reconstruction asymmetry is obtained as the sum of three components: the single-pion, combined two-track $K^-\pi^+$, and single-kaon track reconstruction asymmetries. For the $D_s^- \rightarrow \pi^-\pi^+\pi^-$ decay mode, the track reconstruction asymmetries of each final-state pion are combined, assuming each pion to be uncorrelated.

The term $A_{\text{track}}(\pi^-)$ is estimated from the asymmetry of efficiencies to fully reconstruct muons in bins of muon kinematics using samples of partially reconstructed $J/\psi \rightarrow \mu^+\mu^-$ decays with the tag-and-probe approach as described in Ref. [34]. One muon is reconstructed fully and the other reconstructed using limited detector information; the efficiency is estimated from the fraction of partially reconstructed muons, which can be matched to fully reconstructed muons, where numerator and denominator are obtained by maximum-likelihood fits to the dimuon invariant mass. The relative effect of hadronic interactions of pions with the detector material is assumed to have a small effect on $A_{\text{track}}(\pi^-)$. In contrast to pions, kaons have significant charge-asymmetric nuclear cross-sections, thus $A_{\text{track}}(K^-\pi^+)$ is determined from the raw asymmetries of prompt $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^+ \rightarrow K_S^0\pi^+$ decays, following the method described in Ref. [35]. Candidates are weighted such that the kinematics of the final state particles

in the $D^+ \rightarrow K^-\pi^+\pi^+$ ($D^+ \rightarrow K_S^0\pi^+$) decay reflect the kinematic distributions of the signal $D_s^- \rightarrow K^-K^+\pi^-$ (weighted $D^+ \rightarrow K^-\pi^+\pi^+$) sample. This kinematic weighting mitigates phase-space-dependent effects on the reconstruction efficiency.

The remaining terms are determined from charge-specific efficiencies of the corresponding requirements: A_{sel} from the efficiencies of the selection requirements in simulation, and A_{PID} by evaluating the per-event PID efficiencies in bins of the kinematics of each particle from calibration samples of $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ decays, where the charge of the companion pion identifies the charge of the kaon and pion originating from the D^0 meson, independently of PID requirements [31]. Similarly, A_{L0} , arising from the charge-dependent efficiencies of the L0 trigger to select light hadrons, is determined using reference $D^{*+} \rightarrow D^0\pi^+$ decays in which pions and kaons originating from the D^0 meson are well identified. The trigger efficiency is computed separately for the inner and outer HCAL regions in bins of transverse energy. As these contributions are evaluated using the same simulated samples, the corresponding statistical uncertainties are assumed to be fully correlated. The statistical uncertainty on A_{det} is thereby evaluated as the quadrature sum of the largest of these statistical uncertainties with the statistical uncertainty on A_{track} .

The systematic uncertainties on A_{raw} originate from imperfect modeling of the signal and background in the invariant-mass fits and from fixing misidentified background yields and their asymmetries. Each source is evaluated as the difference in A_{raw} relative to the baseline fit result after repeating the data fit accounting for each effect. For the signal model, an alternative parametrization using the sum of a Gaussian and a modified Gaussian function from Ref. [36] is employed. Similarly, the low-mass background systematic uncertainty is estimated by replacing the $B^0 \rightarrow D_s^+\pi^-$ shape with the $B_s^0 \rightarrow D_s^{*-}\pi^+$ model. Alternative fits are also performed allowing to vary within a Gaussian constraint all parameters fixed in the baseline fit, i.e., the fraction between the two exponential functions of the combinatorial background model, the fractions defining the $B_s^0 \rightarrow D_s^-K^+$ and $B^0 \rightarrow D^-\pi^+$ yields, and the misidentified background asymmetries. Individual contributions are assumed to be uncorrelated and combined in quadrature, resulting in systematic uncertainties of 4.9×10^{-4} and 1.3×10^{-4} for the $D_s^- \rightarrow K^-K^+\pi^-$ and $D_s^- \rightarrow \pi^-\pi^+\pi^-$ decay modes, respectively.

The systematic uncertainty on the detection asymmetry is estimated for each constituent term, as listed in Table I. For A_{track} , a systematic uncertainty is assigned for the differences between muon and pion tracking efficiency asymmetries due to pion-hadron interactions according to Ref. [37]. A systematic uncertainty on the pion tracking efficiency derived from $J/\psi \rightarrow \mu^+\mu^-$ decays is obtained by varying the fit model and binning scheme. The difference in

beam-crossing angles between the magnet-up and -down configurations may induce a magnet polarity- and phase-space-dependent contribution to A_{track} , for which a systematic uncertainty is estimated. Two different kinematic weighting schemes are used for the prompt $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^+ \rightarrow K_S^0 \pi^+$ samples in determining the combined two-track $K^- \pi^+$ asymmetry, and the resulting difference is assigned as a systematic uncertainty. The systematic uncertainty on A_{sel} is evaluated by comparing its value with and without per-event weights from PID and LO efficiencies. A systematic uncertainty from omitting the small A_{HLT1} is also assigned to A_{sel} by evaluating the impact of HLT1 on the raw asymmetry in reference samples of prompt $D^+ \rightarrow K^- \pi^+ \pi^+$ decays. A systematic uncertainty on A_{PID} is assigned by varying the PID selection requirements and the binning scheme applied to the calibration samples. The systematic uncertainty on A_{L0} is entirely due to the limited size of the available reference sample.

Studies are carried out to ensure the robustness of the measurement, in which the data sample is divided and the measurement repeated in each subsample. The data sample is divided into subsets according to the dipole magnet polarity, which is regularly changed during data-taking periods. The data are also divided by year of data taking, in bins of the B_s^0 meson and companion-pion momentum and pseudorapidity, and the resonant or nonresonant regions of the D_s^- phase space. The measurements of $\langle A_{\text{untagged}}^s \rangle$ are consistent between subsamples at the scale of the statistical uncertainties in each final state.

In conclusion, the first measurement of the flavor-untagged decay-time-integrated CP asymmetry in $B_s^0 \rightarrow D_s^- \pi^+$ decays is performed using pp collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of 5.4 fb^{-1} . The $B_s^0 \rightarrow D_s^- \pi^+$ decay is reconstructed in two D_s^- decay modes, $D_s^- \rightarrow K^- K^+ \pi^-$ and $D_s^- \rightarrow \pi^- \pi^+ \pi^-$. The measured asymmetries are

$$\langle A_{\text{untagged}}^s \rangle (K^- K^+ \pi^- \pi^+) = (-1.1 \pm 6.3 \pm 1.2) \times 10^{-3},$$

$$\langle A_{\text{untagged}}^s \rangle (\pi^- \pi^+ \pi^- \pi^+) = (-3 \pm 16 \pm 3) \times 10^{-3},$$

where the first uncertainty is statistical and the second systematic. The two results are combined as a mean weighted by the quadrature sums of uncertainties, yielding

$$\langle A_{\text{untagged}}^s \rangle (D_s^- \pi^+) = (-1.4 \pm 5.9 \pm 1.1) \times 10^{-3}.$$

This represents the first measurement of a decay-time-integrated CP asymmetry in hadronic $B_s^0 \rightarrow D_s^- \pi^+$ decays. The measurements of $\langle A_{\text{untagged}}^s \rangle$ in each final state, and their combination, are all consistent with the SM expectations and with the measured value of a_{sl}^s , and exclude generic BSM contributions that induce CP asymmetries

outside of the range -1.9 – 1.6% at the 95% confidence level.

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Data availability—Data associated to the plots in this publication are made available on the CERN Document Server in Ref. [38].

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- [1] S. Iguro and T. Kitahara, Implications for new physics from a novel puzzle in $\bar{B}_{(s)}^0 \rightarrow D_{(s)}^{(*)+} \{\pi^-, K^-\}$ decays, *Phys. Rev. D* **102**, 071701 (2020).
 - [2] M. Bordone, N. Gubernari, T. Huber, M. Jung, and D. van Dyk, A puzzle in $\bar{B}_{(s)}^0 \rightarrow D_{(s)}^{(*)+} \{\pi^-, K^-\}$ decays and extraction of the f_s/f_d fragmentation fraction, *Eur. Phys. J. C* **80**, 951 (2020).
 - [3] S. Meiser, D. van Dyk, and J. Virto, Towards a global analysis of the $b \rightarrow c\bar{u}q$ puzzle, *J. High Energy Phys.* **06** (2025) 19.

- [4] R. Fleischer and E. Malami, Revealing new physics in $\bar{B}_s^0 \rightarrow D_s^\mp K^\pm$ decays, *Eur. Phys. J. C* **83**, 420 (2023).
- [5] R. Fleischer and E. Malami, Using $B_s^0 \rightarrow D_s^\mp K^\pm$ decays as a portal to new physics, *Phys. Rev. D* **106**, 056004 (2022).
- [6] R. Fleischer, N. Serra, and N. Tuning, Tests of factorization and SU(3) relations in B decays into heavy-light final states, *Phys. Rev. D* **83**, 014017 (2011).
- [7] F.-M. Cai, W.-J. Deng, X.-Q. Li, and Y.-D. Yang, Probing new physics in class-I B -meson decays into heavy-light final states, *J. High Energy Phys.* **10** (2021) 235.
- [8] T. Gershon, A. Lenz, A. V. Rusov, and N. Skidmore, Testing the standard model with CP asymmetries in flavor-specific nonleptonic decays, *Phys. Rev. D* **105**, 115023 (2022).
- [9] T. Huber, S. Kränkl, and X.-Q. Li, Two-body non-leptonic heavy-to-heavy decays at NNLO in QCD factorization, *J. High Energy Phys.* **09** (2016) 112.
- [10] R. Fleischer and K. K. Vos, $B_s^0 - \bar{B}_s^0$ oscillations as a new tool to explore CP violation in $D_s^\pm$ decays, *Phys. Lett. B* **770**, 319 (2017).
- [11] I. Dunietz, R. Fleischer, and U. Nierste, In pursuit of new physics with B_s decays, *Phys. Rev. D* **63**, 114015 (2001).
- [12] S. Banerjee *et al.* (Heavy Flavor Averaging Group), Averages of b -hadron, c -hadron, and τ -lepton properties as of 2023, *Phys. Rev. D* **113**, 012008 (2026).
- [13] A. Lenz and G. Tetlalmatzi-Xolocotzi, Model-independent bounds on new physics effects in non-leptonic tree-level decays of B -mesons, *J. High Energy Phys.* **07** (2020) 177.
- [14] R. Aaij *et al.* (LHCb Collaboration), Precise determination of the $B_s^0 - \bar{B}_s^0$ oscillation frequency, *Nat. Phys.* **18**, 1 (2022).
- [15] R. Aaij *et al.* (LHCb Collaboration), First evidence of direct CP violation in charmless two-body decays of B_s^0 mesons, *Phys. Rev. Lett.* **108**, 201601 (2012).
- [16] R. Aaij *et al.* (LHCb Collaboration), Measurement of the flavour-specific CP -violating asymmetry a_{sl}^s in B_s^0 decays, *Phys. Lett. B* **728**, 607 (2014).
- [17] A. A. Alves Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, *J. Instrum.* **3**, S08005 (2008).
- [18] R. Aaij *et al.* (LHCb Collaboration), LHCb detector performance, *Int. J. Mod. Phys. A* **30**, 1530022 (2015).
- [19] R. Aaij *et al.*, Design and performance of the LHCb trigger and full real-time reconstruction in Run 2 of the LHC, *J. Instrum.* **14**, P04013 (2019).
- [20] V. V. Gligorov and M. Williams, Efficient, reliable and fast high-level triggering using a bonsai boosted decision tree, *J. Instrum.* **8**, P02013 (2013).
- [21] T. Likhomanenko, P. Ilten, E. Khairullin, A. Rogozhnikov, A. Ustyuzhanin, and M. Williams, LHCb topological trigger reoptimization, *J. Phys. Conf. Ser.* **664**, 082025 (2015).
- [22] N. Grieser *et al.*, The LHCb stripping project: Sustainable legacy data processing for high-energy physics, *Comput. Software Big. Sci.* **9**, 21 (2025).
- [23] A. Ahmed *et al.*, The LHCb sprucing and analysis productions, *Comput. Software Big. Sci.* **9**, 15 (2025).
- [24] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008), [arXiv:0710.3820](https://arxiv.org/abs/0710.3820); T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026, [arXiv:hep-ph/0603175](https://arxiv.org/abs/hep-ph/0603175).
- [25] I. Belyaev *et al.*, Handling of the generation of primary events in Gauss, the LHCb simulation framework, *J. Phys. Conf. Ser.* **331**, 032047 (2011).
- [26] D. J. Lange, The EvtGen particle decay simulation package, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [27] N. Davidson, T. Przedzinski, and Z. Was, PHOTOS interface in c++: Technical and physics documentation, *Comput. Phys. Commun.* **199**, 86 (2016).
- [28] J. Allison *et al.* (Geant4 Collaboration), Geant4 developments and applications, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006); S. Agostinelli *et al.* (Geant4 Collaboration), Geant4: A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [29] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranza, M. Pappagallo, and P. Robbe, The LHCb simulation application, Gauss: Design, evolution and experience, *J. Phys. Conf. Ser.* **331**, 032023 (2011).
- [30] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [31] R. Aaij *et al.*, Selection and processing of calibration samples to measure the particle identification performance of the LHCb experiment in Run 2, *Eur. Phys. J. Tech. Instr.* **6**, 1 (2019).
- [32] D. Martínez Santos and F. Dupertuis, Mass distributions marginalized over per-event errors, *Nucl. Instrum. Methods Phys. Res., Sect. A* **764**, 150 (2014).
- [33] N. L. Johnson, Systems of frequency curves generated by methods of translation, *Biometrika* **36**, 149 (1949).
- [34] R. Aaij *et al.* (LHCb Collaboration), Measurement of the track reconstruction efficiency at LHCb, *J. Instrum.* **10**, P02007 (2015).
- [35] A. Davis *et al.*, Measurement of the instrumental asymmetry for $K^-\pi^+$ -pairs at LHCb in Run 2, LHCb-PUB-2018-004, 2018.
- [36] R. Aaij *et al.* (LHCb Collaboration), Measurement of the CKM angle γ in $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D\pi^\pm$ decays with $D \rightarrow K_S^0 h^+ h^-$, *J. High Energy Phys.* **02** (2021) 169.
- [37] R. Aaij *et al.* (LHCb Collaboration), Measurement of the semileptonic CP asymmetry in $B^0 - \bar{B}^0$ mixing, *Phys. Rev. Lett.* **114**, 041601 (2015).
- [38] <https://cds.cern.ch/record/2956449>

R. Aaij³⁸, M. Abdelfatah⁶⁹, A. S. W. Abdelmotteleb⁵⁷, C. Abellan Beteta⁵¹, F. Abudinén⁵⁹, T. Ackernley⁶¹, A. A. Adefisoye⁶⁹, B. Adeva⁴⁷, M. Adinolfi⁵⁵, P. Adlarson⁸⁷, C. Agapopoulou¹⁴, C. A. Aidala⁸⁹, Z. Ajaltouni¹¹, S. Akar¹¹, K. Akiba³⁸, P. Albicocco²⁸, J. Albrecht^{19,b}, R. Aleksiejunas⁸¹, F. Alessio⁴⁹, P. Alvarez Cartelle^{56,47}, R. Amalric¹⁶, S. Amato³, J. L. Amey⁵⁵, Y. Amhis¹⁴, L. An⁶, L. Anderlini²⁷, M. Andersson⁵¹, P. Andreola⁵¹

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