Precision Measurement of *CP* Violation and Branching Fractions in $B^{\pm} \to K_S^0 h^{\pm}$ ($h = \pi, K$) Decays and Search for the Rare Decay $B_c^{\pm} \to K_S^0 K^{\pm}$

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The decay $B^{\pm} \to K_S^0 \pi^{\pm}$, with a *CP* asymmetry expected to be close to zero in the standard model, is theoretically clean and sensitive to potential new physics. An analysis of the decays $B^{\pm} \to K_S^0 \pi^{\pm}$ and $B^{\pm} \to K_S^0 K^{\pm}$ is performed using proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1}. The *CP* asymmetries are determined to be $\mathcal{A}^{CP}(B^{\pm} \to K_S^0 \pi^{\pm}) = -0.028 \pm 0.009 \pm 0.009$ and $\mathcal{A}^{CP}(B^{\pm} \to K_S^0 K^{\pm}) = 0.118 \pm 0.062 \pm 0.031$, and the branching fraction ratio is measured to be $\mathcal{B}(B^{\pm} \to K_S^0 K^{\pm})/\mathcal{B}(B^{\pm} \to K_S^0 \pi^{\pm}) = 0.055 \pm 0.004 \pm 0.002$, where the first uncertainties are statistical and the second are systematic. These results are the most precise measurements of these quantities to date. A search for the rare decay $B_c^{\pm} \to K_S^0 K^{\pm}$ is also performed. No significant signal is observed, and the upper limit on the product of the branching fraction ratio $\mathcal{B}(B_c^{\pm} \to K_S^0 K^{\pm})/\mathcal{B}(B^{\pm} \to K_S^0 \pi^{\pm})$ and the fragmentation-fraction ratio f_c/f_u is set to be 0.015 (0.016) at the 90% (95%) confidence level.

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Charmless hadronic two-body decays of B mesons provide powerful probes of *CP* violation and rare processes, where deviations from standard model (SM) predictions could signal new physics in the flavor sector [1]. In particular, decays mediated by flavor-changing neutral currents offer a unique window into loop-level dynamics [2]. The $B^+ \to K_S^0 \pi^+$ decay, dominated by a single gluonic loop (penguin) amplitude with no tree-level contribution and only highly Cabibbo-Kobayashi-Maskawa–suppressed subleading terms, is among the theoretically cleanest channels in the $b \to d\bar{d}s$ sector [3–5]. Within the SM, its direct *CP* asymmetry is predicted to be very close to zero, making precision measurements a highly sensitive probe for potential deviations [3,6,7]. In such a theoretically clean channel, precision is the primary discriminator. Thus, advancing the experimental precision in this decay constitutes a critical step forward for testing the SM in a regime where theoretical uncertainties are minimal [8].

Complementing this, the decay $B^+ \to K_S^0 K^+$, proceeding via the doubly Cabibbo-Kobayashi-Maskawa–suppressed $b \to s\bar{s}d$ transition, provides a distinct probe of penguin and annihilation amplitudes. Theoretical predictions for its *CP* asymmetry exhibit strong model dependence, reflecting the intricate interplay between perturbative and nonperturbative QCD effects. Precision measurements here can discriminate between competing theoretical frameworks, such as perturbative QCD (pQCD) [3] and QCD factorization (QCDF) [4,5], and shed light on the role of poorly understood annihilation topologies. The rare decay $B_c^+ \to K_S^0 K^+$, which proceeds purely via weak annihilation, offers a unique opportunity to isolate and probe this latter contribution. Experimental constraints on such processes are particularly valuable given the strong theoretical uncertainties associated with annihilation contributions in nonleptonic heavy-meson decays.

The first studies of $B^+ \to K_S^0 \pi^+$ decays were performed by the *BABAR* [9] and Belle [10] collaborations. Subsequent LHCb results, based on proton-proton (pp) collision data collected during 2011–2012 (Run 1), measured the ratio of branching fractions $\mathcal{B}(B^+ \to K_S^0 K^+)/\mathcal{B}(B^+ \to K_S^0 \pi^+) = 0.064 \pm 0.009 \pm 0.004$, and the *CP* asymmetries $\mathcal{A}^{CP}(B^+ \to K_S^0 \pi^+) = -0.022 \pm 0.025 \pm 0.010$ and $\mathcal{A}^{CP}(B^+ \to K_S^0 K^+) = -0.21 \pm 0.14 \pm 0.01$ [11]. The Belle II experiment reported consistent results in Ref. [12]. This Letter presents updated measurements of *CP* asymmetries for both the $B^+ \to K_S^0 \pi^+$ and $B^+ \to K_S^0 K^+$ decays with significantly improved precision. The analysis uses a subset of Run 2 data, recorded by the LHCb experiment between 2016 and 2018 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1}. Taking advantage of the same data sample and analysis strategy, a search for the pure annihilation decay $B_c^+ \to K_S^0 K^+$ is also performed, providing a

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complementary probe of annihilation amplitudes. In order to avoid experimenter's bias, the results of the analyses were not examined until the full procedure had been finalized.

The LHCb detector [13,14] 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 used to collect the data for this analysis includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region [15], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 T m, and three stations of silicon-strip detectors and straw drift tubes [16] placed downstream of the magnet. The tracking system provides a measurement of the momentum, p, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c. The minimum distance of a track to a primary pp collision vertex (PV), the impact parameter, is measured with a resolution of $(15 + 29/p_{\mathrm{T}})$ μm, where p_{T} is the component of the momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [17]. Photons, electrons, and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, and electromagnetic and hadronic calorimeters. The online event selection is performed by a trigger [18], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. At the hardware stage, events are required to include a hadron with high transverse energy in the calorimeters. The software trigger requires a two- or three-track secondary vertex with a significant displacement from any PV.

Simulation is required to model the effects of the detector acceptance and the imposed selection requirements. In the simulation, pp collisions are generated using Pythia [19] with a specific LHCb configuration [20]. Decays of unstable particles are described by EvtGen [21], in which final-state radiation is generated using Photos [22]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [23] as described in Ref. [24].

The $B^+ \to K^0_{\mathrm{S}}\pi^+$ and $B^+ \to K^0_{\mathrm{S}}K^+$ candidates are formed by combining a $K^0_{\mathrm{S}} \to \pi^+\pi^-$ candidate decay with a charged track that is identified as a pion or kaon. Pions from K^0_{S} decays must satisfy $p > 2$ GeV/c and be incompatible with production at any PV. The K^0_{S} candidates are required to have $p > 8$ GeV/c, $p_{\mathrm{T}} > 1$ GeV/c, a small vertex-fit χ^2, a mass within ± 15 MeV/c^2 of the known K^0_{S} mass [25], and a significant separation of the decay vertex from all PVs, corresponding to a flight-distance significance larger than 2σ. Final-state pions and kaons must satisfy $p_{\mathrm{T}} > 1$ GeV/c and be inconsistent with PV origin. The B^+ candidates are selected with $p > 25$ GeV/c, and must have a high-quality vertex displaced from all PVs by at least 1 mm. Further background suppression is achieved by requiring significant displacement between the K^0_{S} decay vertex and the reconstructed B^+ vertex along the beam direction. Fiducial volume requirements are imposed to exclude B^+ candidates near detector acceptance boundaries where detection asymmetries are enhanced.

Verification of consistency between data and simulation and further background suppression is achieved, respectively, using a boosted decision tree classifier implemented via the AdaBoost algorithm [26] and a gradient boosted decision tree (BDTG) classifier [27], implemented via the TMVA toolkit [28]. Both algorithms use four classes of discriminating variables: kinematic properties including the B^+ candidate p_{T}; vertex-quality information including the K^0_{S} and B^+ vertex-fit χ^2 and the χ^2 of a kinematic refit assuming the B^+ originates from a PV [29]; lifetime-related information including the impact parameters of charged hadrons, K^0_{S}, and B^+ candidates as well as the B^+ flight distance from its PV; and isolation variables characterizing the B^+ candidate. The classifiers are trained using background from the upper B^+ mass sideband in data ($5600 < m_{B^+} < 6000$ MeV/c^2), and signal from simulated $B^+ \to K^0_{\mathrm{S}}\pi^+$ and $B^+ \to K^0_{\mathrm{S}}K^+$ decays. The simulation is corrected for differences with respect to data by using the $B^+ \to K^0_{\mathrm{S}}\pi^+$ channel, which has the largest signal yield. In this channel, a loose boosted decision tree selection is applied, and the background is statistically subtracted using the sPlot technique [30]. A gradient-boosting weighter is then used to adjust the simulated distributions to match the background-subtracted data. The following variables are considered for the matching: the B^+ candidate's p_{T}, η, cosine of the angle between momentum and flight direction, and decay time; the χ^2 of a kinematic refit of the B^+ decay; and the track multiplicity. Owing to the limited size of the $B^+ \to K^0_{\mathrm{S}}K^+$ sample, the correction derived from the $B^+ \to K^0_{\mathrm{S}}\pi^+$ sample is applied to both modes.

For the final selection stage, separate BDTG classifiers are trained and applied to both the $B^+ \to K^0_{\mathrm{S}}\pi^+$ and $B^+ \to K^0_{\mathrm{S}}K^+$ channels. The optimal BDTG output requirement is determined separately for $K^0_{\mathrm{S}}\pi^\pm$ and $K^0_{\mathrm{S}}K^\pm$ samples by maximizing the signal significance $N_{\mathrm{S}}/\sqrt{N_{\mathrm{S}} + N_{\mathrm{B}}}$. The expected background yield, N_{B}, is determined from the sideband data and extrapolated into the signal region ($5219.34 < m_{B^+} < 5339.34$ MeV/c^2), while the expected signal yield, N_{S}, is obtained from simulation. To further suppress specific peaking backgrounds, a set of dedicated mass vetoes is implemented. The $\Lambda \to p\pi^-$ veto, designed to suppress misidentified K^0_{S} candidates, is applied to both the $B^+ \to K^0_{\mathrm{S}}\pi^+$ and $B^+ \to K^0_{\mathrm{S}}K^+$ decay modes. Additionally, exclusively for the $B^+ \to K^0_{\mathrm{S}}K^+$ channel, two further mass vetoes are introduced: one to suppress cross feed from $B^+ \to K^0_{\mathrm{S}}\pi^+$ decays where the pion is misidentified as a kaon, and another to reject contributions from $B^+ \to D^0\pi^+$ decays with $D^0 \to K^-\pi^+$. These vetoes are optimized using both data and simulation.

The total signal yields and raw charge asymmetries for $B^+ \to K^0_S K^+$ and $B^+ \to K^0_S\pi^+$ decays are determined through a simultaneous unbinned extended maximum-likelihood fit to the $B^\pm$ mass distributions in the range $5000 < m_{B^+} < 5700\ \mathrm{MeV}/c^2$. The fit incorporates four samples: $B^+ \to K^0_S\pi^+$, $B^- \to K^0_S\pi^-$, $B^+ \to K^0_S K^+$, and $B^- \to K^0_S K^-$. Each mass distribution contains four distinct components that are modeled separately: signal, cross feed, partially reconstructed background, and combinatorial background. The signal component is parametrized using the sum of a modified Gaussian function with power-law tails on both sides (double-sided crystal ball, DSCB) [31] and a Gaussian function, with a common peak position. The ratio of widths of the DSCB and Gaussian components, and the tail parameters of the DSCB function, are fixed to values obtained from simulation.

Because of the residual misidentification between pions and kaons after imposing particle identification (PID) requirements, a small fraction of $B^+ \to K^0_S\pi^+$ decays may be mistakenly reconstructed as $K^0_S K^+$ candidates, and vice versa. The cross-feed components from $B^+ \to K^0_S K^+$ and $B^+ \to K^0_S\pi^+$ decays are both modeled with a DSCB function. Misidentification rates are then measured with a data-driven approach and applied as weights to the simulation sample. The cross-feed yields are constrained within statistical uncertainties to the values expected from the corresponding signal yields. Additional background contributions arise from partially reconstructed decays, predominantly from B^0, B^+, and B^0_s mesons decaying to open-charm modes, with smaller contributions from three-body charmless decays. These backgrounds are modeled using an ARGUS function [32] convolved with a Gaussian resolution function. The remaining combinatorial background is parametrized with a first-order polynomial function.

In the fit to data, the signal peak positions and widths are treated as free parameters, shared between B^+ and B^-. The width of the $B^+ \to K^0_S K^+$ signal is scaled relative to that of $B^+ \to K^0_S\pi^+$ using a simulation-derived factor. The peak shifts between signal and cross-feed components are also determined from simulation.

The raw charge asymmetry is defined as

$$\mathcal{A}^{\mathrm{raw}}_X \equiv \frac{N(B^- \to \bar{X}) - N(B^+ \to X)}{N(B^- \to \bar{X}) + N(B^+ \to X)}, \tag{1}$$

where $N(B^\pm \to \overset{(-)}{X})$ are the signal yields obtained from the fit. The mass distributions of the selected $B^\pm \to K^0_S\pi^\pm$ and $B^\pm \to K^0_S K^\pm$ candidates, along with the fit projections, are shown in Fig. 1. The total signal yields are

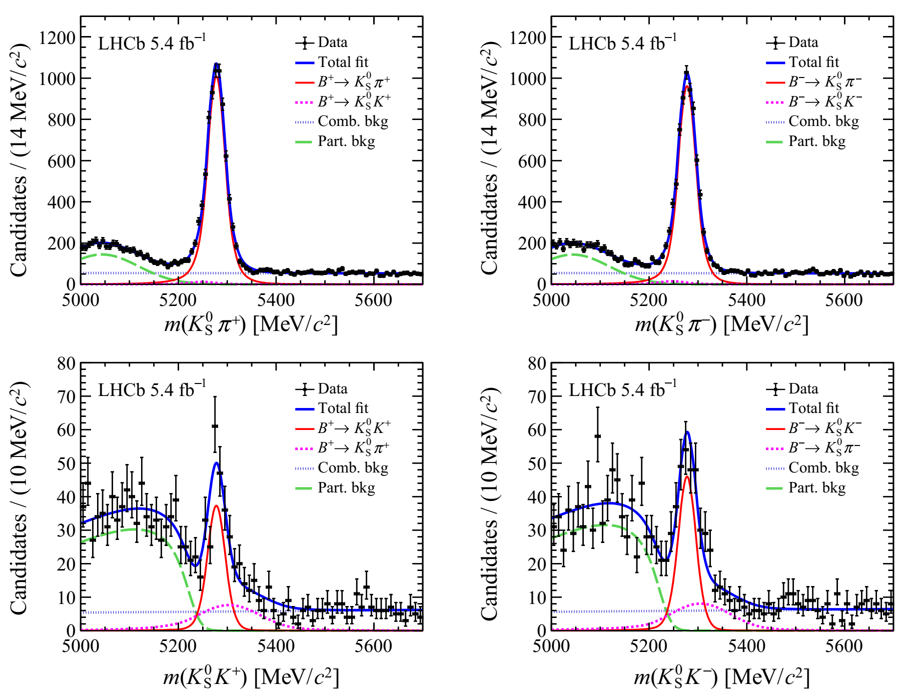

FIG. 1. Mass distributions of (top left) $K^0_S\pi^+$, (top right) $K^0_S\pi^-$, (bottom left) $K^0_S K^+$, and (bottom right) $K^0_S K^-$ pairs. For visualization, the data are presented with binned distributions using 100 bins for $K^0_S\pi^\pm$ and 70 bins for $K^0_S K^\pm$. The results of the simultaneous fit are also shown.

$N(B^\pm \to K^0_S\pi^\pm) = 14\,482 \pm 156$ and $N(B^\pm \to K^0_S K^\pm) = 393 \pm 28$, with corresponding raw charge asymmetries of $\mathcal{A}^{\rm raw}_{K^0_S\pi^+} = -0.030 \pm 0.009$ and $\mathcal{A}^{\rm raw}_{K^0_S K^+} = 0.109 \pm 0.062$.

The raw charge asymmetries for the $B^+ \to K^0_S\pi^+$ and $B^+ \to K^0_S K^+$ decays are corrected for detection and production asymmetries, $\mathcal{A}^{\rm det+prod}$, as well as for a small contribution from CP violation in the neutral kaon system, $\mathcal{A}^{K^0}$. The latter is assumed to be identical for both decay modes. At first order, the CP asymmetry for the $B^+ \to K^0_S K^+$ decay is

$$\mathcal{A}^{CP}(B^+ \to K^0_S K^+) \approx \mathcal{A}^{\rm raw}_{K^0_S K^+} - \mathcal{A}^{\rm det+prod}_{K^0_S K^+} - \mathcal{A}^{K^0}, \quad (2)$$

and similarly for $B^+ \to K^0_S\pi^+$, except for the opposite sign of $\mathcal{A}^{K^0}$, which is associated with the different flavor of K^0 in the two decays.

The detection and production asymmetries are determined using the $B^+ \to J/\psi K^+$ control channel selected in the same fiducial volume as the signal. The combined detection and production asymmetry for charged kaons and $B^\pm$ mesons is obtained by subtracting the known CP asymmetry [25] from the measured raw asymmetry of the control channel. This is evaluated in bins of K^+ momentum and combined through a weighted average using the $B^+ \to K^0_S K^+$ momentum spectrum, resulting in $\mathcal{A}^{\rm det+prod}_{K^0_S K^+} = (-1.02 \pm 0.32)\%$.

For the $B^+ \to K^0_S\pi^+$ decay, additional corrections are needed for the detection asymmetry difference between kaons and pions, and for CP violation in the neutral kaon system. The combined asymmetry is

$$\begin{aligned}\mathcal{A}^{\rm det+prod}_{K^0_S\pi^+} &= \mathcal{A}^{\rm det+prod}_{K^0_S K^+} - \mathcal{A}^{K^+\pi^-} \\ &= \mathcal{A}^{\rm det+prod}_{K^0_S K^+} - (\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0}) + \mathcal{A}^{K^0}, \quad (3)\end{aligned}$$

where the combined asymmetry $(\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0})$ has previously been measured as a function of the charged kaon momentum [33]. Potential effects from CP violation in the neutral kaon system, either through $K^0 - \bar{K}^0$ mixing [34] or K^0_L regeneration [35], are evaluated. The regeneration effect, where K^0_L interactions with detector material produce a K^0_S component, could contaminate the $B^+ \to K^0_S h^+$ sample with $B^+ \to K^0_L h^+$ decays. The resulting K^0 asymmetry is measured to be $\mathcal{A}^{K^0} = (-0.07 \pm 0.01)\%$ in both channels. The $K\pi$ asymmetry is determined to be $(\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0}) = (-0.64 \pm 0.01)\%$. The final detection and production asymmetry for charged pion is $\mathcal{A}^{\rm det+prod}_{K^0_S\pi^+} = (-0.31 \pm 0.32)\%$.

The ratio of branching fractions is computed as

$$\begin{aligned}\mathcal{R} \equiv \frac{\mathcal{B}(B^+ \to K^0_S K^+)}{\mathcal{B}(B^+ \to K^0_S\pi^+)} &= \frac{N(B^+ \to K^0_S K^+)}{N(B^+ \to K^0_S\pi^+)} \\ &\times \frac{\varepsilon(B^+ \to K^0_S\pi^+)}{\varepsilon(B^+ \to K^0_S K^+)}, \quad (4)\end{aligned}$$

where ε denotes the total efficiency, including acceptance, reconstruction, and selection effects. All efficiencies are derived from simulation after applying data-driven corrections.

The search for the $B_c^+ \to K^0_S K^+$ decay employs a BDTG trained on simulated $B_c^+ \to K^0_S K^+$ decays as signal and mass-sideband candidates as background. A working point is chosen to maximize the figure of merit $\varepsilon_{\rm BDTG}/(2.5 + \sqrt{N_{\rm B}})$ [36], where $\varepsilon_{\rm BDTG}$ is the signal efficiency of the BDTG requirement and $N_{\rm B}$ is the expected background yield in the B_c^+ signal mass region. The BDTG uses the same input variables as for the $B^+ \to K^0_S K^+$ mode. No significant signal is observed. An upper limit on the branching fraction ratio multiplied by the b-quark fragmentation probabilities, f_c and f_u corresponding to the hadronization fractions of a b quark into a B_c^+ and a B^+ meson respectively, $\mathcal{R}' \equiv (f_c/f_u) \cdot [\mathcal{B}(B_c^+ \to K^0_S K^+)/\mathcal{B}(B^+ \to K^0_S\pi^+)]$ is determined using the profile-likelihood method [37,38]. Systematic uncertainties are incorporated via a smeared likelihood-ratio function. The B_c^+ signal yield is obtained from a single Gaussian fit to data with the mean fixed to the known B_c^+ mass [25] and the width taken from simulation. The combinatorial background is assumed to be a first-order polynomial function. The mass distribution and the fit projection are shown in the End Matter.

The systematic uncertainties for the $\mathcal{A}^{CP}$ and $\mathcal{R}$ measurements are summarized in Table I. Systematic uncertainties from the fit model are evaluated by using alternative functions to describe the signal and background shapes, and by allowing B^+ and B^- peak positions to vary independently within the baseline model.

Systematic uncertainties associated with the PID corrections applied to the simulation account for effects from the PID efficiency binning scheme, calibration sample statistics, and PID response modeling. These uncertainties are combined in quadrature. The total systematic uncertainty from detector and production asymmetries is determined to be 0.32%, including a 0.30% contribution from the uncertainty on $\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$ [25]. Trigger asymmetries are incorporated in the overall production and detection corrections, which are estimated from $B^+ \to J/\psi K^+$ candidates, with only the associated uncertainties retained in this analysis using a data-driven approach.

Systematic uncertainties related to selection efficiencies are evaluated, including the limited size of the simulated samples. In addition, the stability of the measured observables is tested by varying the selection criteria. The

TABLE I. Systematic uncertainties on $\mathcal{A}^{CP}$ and $\mathcal{R}$ measurements. Absolute uncertainties are quoted for $\mathcal{A}^{CP}$, while relative uncertainties are given for $\mathcal{R}$.

	CP asymmetry (%)		
	$B^+ \to K_S^0\pi^+$	$B^+ \to K_S^0K^+$	$\mathcal{R}$ (%)
Fit model	0.15	1.29	1.92
PID weighting	0.01	0.01	0.35
$\mathcal{A}^{\mathrm{det+prod}}$	0.32	0.32	...
$\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0}$	...	0.01	...
$\mathcal{A}^{K^0}$	0.01	0.01	...
Trigger	0.70	0.74	0.23
Simulation sample size	...	...	0.87
BDTG selection	0.41	2.56	...
Mass veto selection	0.10	0.88	3.31
Tracking efficiency	...	...	0.01
K/π interaction	...	...	0.30
Total	0.89	3.11	3.96

systematic uncertainty associated with the BDTG selection is evaluated by repeating the full measurement while varying the BDTG requirement around the nominal working point. The resulting variation in the fitted is assigned as the systematic uncertainty. No uncertainty is assigned to the branching-fraction ratio, while uncertainties of 0.41% and 2.56% are obtained for the $K_S^0\pi^+$ and $K_S^0K^+$ modes, respectively; the larger value (2.56%) for is mainly driven by the smaller effective signal yield, making the result more sensitive to statistical fluctuations than to changes in the BDTG efficiency. For the $B^+ \to K_S^0\pi^+$ and $B^+ \to K_S^0K^+$ samples, an additional uncertainty is assigned by varying the mass veto on the $p\ \pi^-$ invariant mass from ± 6 to $\pm 10\ \mathrm{MeV}/c^2$ of the known Λ mass. Furthermore, for the $B^+ \to K_S^0K^+$ samples only, two mass vetoes are varied to evaluate the associated systematic uncertainties. The first is applied to the $K^+\ \pi^-$ invariant mass, where the veto window around the known D^0 mass is changed from ± 15 to $\pm 20\ \mathrm{MeV}/c^2$. The second is applied to the B^+ candidate mass, used to suppress background from misidentified $B^+ \to K_S^0\pi^+$ decays, where the baseline requirement of $\pm 45\ \mathrm{MeV}/c^2$ is varied to ± 40 and $\pm 50\ \mathrm{MeV}/c^2$. The systematic uncertainties from these variations on $\mathcal{A}^{CP}$ are 0.10% and 0.88% for the $K_S^0\pi^+$ and $K_S^0K^+$ modes, respectively, and 3.31% on the branching fraction ratio.

Tracking efficiency corrections are applied to simulated candidates as a function of p and η for each final-state particle, with the statistical uncertainty from the data calibration sample included. Additional systematic uncertainties arise from imperfect modeling of kaon and pion interactions with detector material in the simulation. The detection efficiency uncertainties from material interactions are estimated to be 1.1% for kaons and 1.4% for pions, determined by varying the detector material budget in the simulation by approximately $\pm 10\%$ [39]. These uncertainties are treated as fully correlated, resulting in a relative uncertainty of 0.3% for the ratio of pion to kaon efficiencies.

The *CP* asymmetries are determined to be

$$\mathcal{A}^{CP}(B^+ \to K_S^0\pi^+) = -0.028 \pm 0.009 \pm 0.009,$$
$$\mathcal{A}^{CP}(B^+ \to K_S^0K^+) = 0.118 \pm 0.062 \pm 0.031,$$

where the first uncertainty is statistical and the second systematic, representing about a factor-of-2 improvement in precision compared to the Run 1 results [11]. The combined statistical and systematic correlation between the asymmetries is estimated to be −0.10. The measured $\mathcal{A}^{CP}$ $(B^+ \to K_S^0\pi^+)$ value shows good consistency with previous results from *BABAR* [9], Belle [10], and LHCb in Run 1 [11], while exhibiting a 2.3σ difference with the most recent Belle II measurement [12]. The new LHCb result differs from theoretical predictions by 2.4σ from QCDF calculations [4,5] and by 2.1σ from the pQCD prediction [40]. Similarly, the measured $\mathcal{A}^{CP}$ $(B^+ \to K_S^0K^+)$ value shows differences of 2.5σ and 1.4σ with respect to QCDF and pQCD predictions, respectively. These indicate potential challenges in the theoretical description of hadronic effects in these decays.

The measured branching fraction ratio is

$$\frac{\mathcal{B}(B^+ \to K_S^0K^+)}{\mathcal{B}(B^+ \to K_S^0\pi^+)} = 0.055 \pm 0.004 \pm 0.002,$$

showing good agreement with both the previous LHCb measurement [11] and theoretical predictions [41].

The upper limit on the branching fraction ratio multiplied by the b-quark fragmentation probabilities between the $B_c^+ \to K_S^0K^+$ and $B^+ \to K_S^0\pi^+$ decay modes is determined at the 90% (95%) confidence level (CL) as

$$\frac{f_c}{f_u} \cdot \frac{\mathcal{B}(B_c^+ \to K_S^0K^+)}{\mathcal{B}(B^+ \to K_S^0\pi^+)} < 0.015(0.016)\ \text{at}\ 90\%(95\%)\ \text{CL}.$$

In summary, all measurements presented in this Letter are consistent with SM predictions, yet they provide the most precise experimental constraints to date on *CP* violation in these charmless hadronic B decays. The precision achieved for $\mathcal{A}^{CP}(B^+ \to K_S^0\pi^+)$ with a total uncertainty of 0.013, a reduction by a factor of 2 compared to the previous best measurement, establishes a new benchmark for a theoretically clean null-test channel in the $b \to s$ sector. Similarly, the measurement of $\mathcal{A}^{CP}$ $(B^+ \to K_S^0K^+)$ reaches a precision that begins to discriminate between leading theoretical approaches, providing unique insight into hadronic dynamics. No significant signal is observed for the decay $B_c^+ \to K_S^0K^+$, and the resulting upper limit can be used to constrain the poorly understood weak annihilation contributions in many hadronic b-meson decays. Collectively, these results not only set new standards for precision but also establish a foundational dataset for future global analyses aimed at resolving persistent puzzles in flavor physics. With the increased statistic from the upgraded LHCb [42] and Belle II experiments, future investigations will build upon this precision frontier, further enhancing the sensitivity to potential deviations from the SM.

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Data availability—The data that support the findings of this article are openly available [43].

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End Matter

Study of $B_c^+ \to K_S^0 K^+$ mass distribution—The mass distribution of $B_c^+ \to K_S^0 K^+$ candidates is shown in Fig. 2. The signal significance is determined to be 1.0 standard deviation. Systematic studies were performed by varying the BDTG selection requirement and fixing the mean value and mass resolution of B_c^+ signal to the known value and simulation predictions, respectively. The significance determination is found to be stable under these variations.

Comparison with previous results and theory—Figure 3 shows comparisons of the measured *CP* asymmetries and branching fraction ratio with previous experimental results and theoretical predictions.

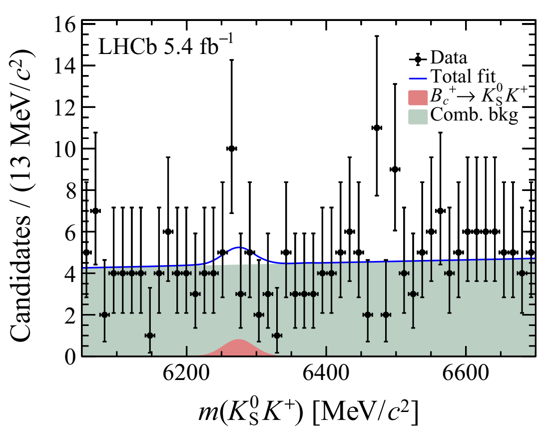

FIG. 2. Mass distribution of selected $B_c^+ \to K_S^0 K^+$ candidates. The data points with error bars are shown together with the result of the fit (solid curve).

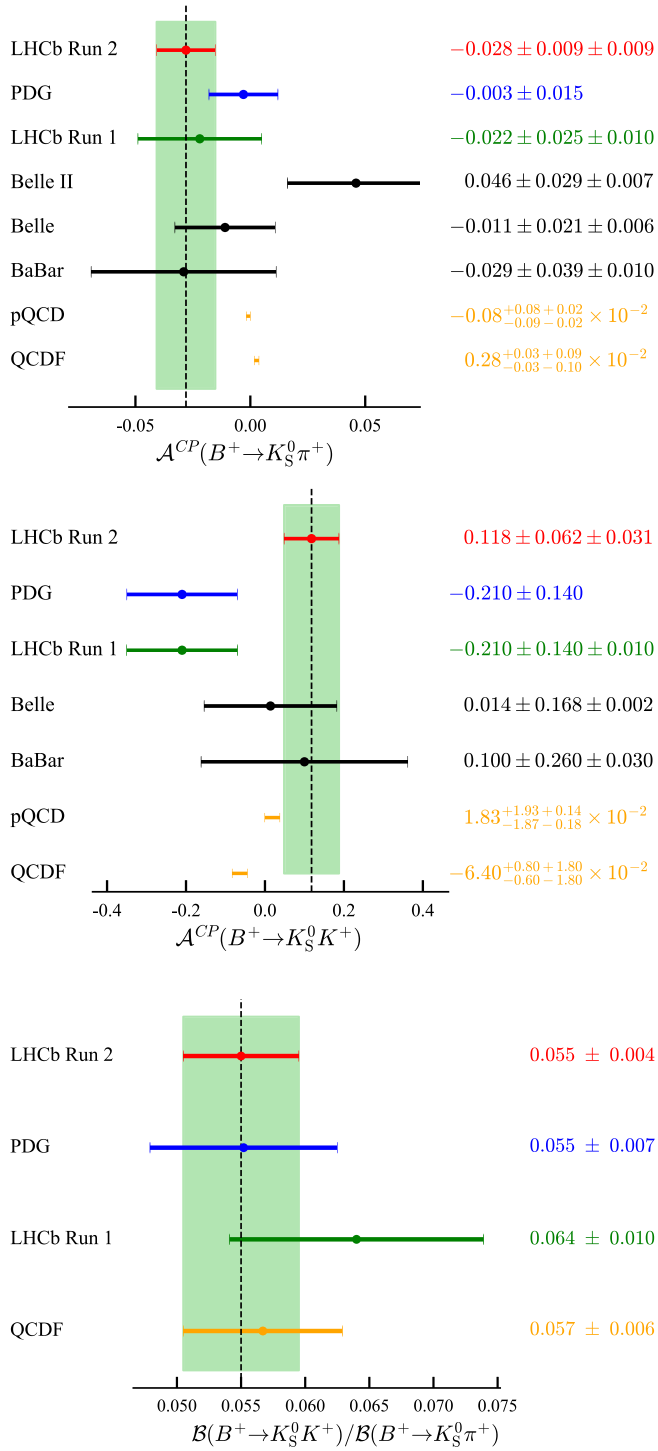

FIG. 3. Comparison of branching fraction ratios measured in this Letter with results from different experiments [9–12,25] and theoretical predictions [4,5,40,41].

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