


Observation of $B_c^+ \rightarrow Dh^+h^-$ DecaysR. Aaij *et al.**
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Searches are presented for $B_c^+ \rightarrow Dh^+h^-$ decays, where D is a charmed meson and h^\pm is a charged pion or kaon, using pp collision data collected by the LHCb experiment corresponding to an integrated luminosity of 9 fb^{-1} . The decays $B_c^+ \rightarrow D^+K^+\pi^-$, $B_c^+ \rightarrow D^{*+}K^+\pi^-$, and $B_c^+ \rightarrow D_s^+K^+K^-$ are observed for the first time. Their branching fractions, expressed as ratios relative to that of the $B_c^+ \rightarrow B_s^0\pi^+$ decay, are determined to be $\mathcal{R}(B_c^+ \rightarrow D^+K^+\pi^-) = (1.96 \pm 0.23 \pm 0.08 \pm 0.10) \times 10^{-3}$, $\mathcal{R}(B_c^+ \rightarrow D^{*+}K^+\pi^-) = (3.67 \pm 0.55 \pm 0.24 \pm 0.20) \times 10^{-3}$, $\mathcal{R}(B_c^+ \rightarrow D_s^+K^+K^-) = (1.61 \pm 0.35 \pm 0.13 \pm 0.07) \times 10^{-3}$, where the first uncertainty is statistical, the second is systematic, and the third is due to the limited precision on the D -meson branching fractions. The decay channels proceed primarily through excited K^0 or D^0 resonances or ϕ mesons, and open a new avenue for studies of charge-parity violation in beauty mesons.

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Decays of B mesons provide a powerful probe for testing the standard model (SM) and exploring new physics. The B_c^+ meson, which is less extensively studied than B^0 , B^+ , and B_s^0 mesons, offers a unique opportunity to expand our understanding of B -meson properties and explore systems containing two heavy quarks. The B_c^+ meson decays exclusively via weak interactions, through three distinct processes. The decay through a b -quark transition contributes about 20% of the total width, the c -quark transition around 70%, and the remaining 10% is attributed to the $\bar{b}c \rightarrow W^+ \rightarrow \bar{q}q'$ weak annihilation amplitude [1].

Since the discovery of the B_c^+ meson [2,3], the study of its decays has prompted significant theoretical and experimental interest. The weak decay of the B_c^+ meson provides an ideal platform for investigating the nonperturbative realm of quantum chromodynamics (QCD) and CP -violating effects. Decays with an open-charm hadron in the final state, $B_c^+ \rightarrow DX$, are of particular interest because they include interfering amplitudes from $\bar{b}c$ annihilation [4] and $\bar{b} \rightarrow u\bar{u} \bar{s}(\bar{d})$ tree and electroweak loop (penguin) diagrams, which can give rise to observable CP -violating effects. Charge conjugate processes are implied throughout this Letter. Branching fractions (BFs) and CP asymmetries of two-body $B_c^+ \rightarrow D_s^{*+}P$ and $B_c^+ \rightarrow D_s^{*+}V$ decays, where $P(V)$ represents a pseudoscalar (vector) meson, have been calculated using the perturbative QCD approach [5,6]. However, experimental studies are quite limited due to

the relatively low production cross section of B_c^+ mesons in e^+e^- [7] and pp collisions [8] compared to that of b hadrons with lighter quarks. The first open-charm B_c^+ decay to be observed was $B_c^+ \rightarrow D^0K^+$, reported by the LHCb Collaboration [9]. This Letter has been extended in Ref. [10] to cover additional studies, including the first observation of the $B_c^+ \rightarrow D^+K^{*0}$ decay. The previous BF measurements favor a dominant annihilation contribution in the decay amplitude. These studies offer valuable insights into the contributions of different decay amplitudes in B_c^+ decays, enabling a better understanding of the SM [11,12]. Further experimental results are needed to understand how the different quark-level processes contribute in different decay channels.

This Letter describes searches for the decays $B_c^+ \rightarrow D^+K^+\pi^-$, $B_c^+ \rightarrow D^{*+}K^+\pi^-$, and $B_c^+ \rightarrow D_s^+K^+K^-$, which proceed via processes such as those depicted in Fig. 1. These three-body B_c^+ decays are expected to exhibit a rich dynamic structure with multiple intermediate resonances. Amplitude analyses of multibody decays, with their rich interference patterns and sensitivity to phases, provide unique insights into resonance properties, polarization fractions, and CP violation. The measurements described here are based on pp collision data collected by the LHCb experiment at center-of-mass energies of 7, 8, and 13 TeV, corresponding to a total integrated luminosity of about 9 fb^{-1} .

The LHCb detector [13–17] 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 that are particularly relevant to this analysis are: a silicon-strip vertex detector surrounding the pp interaction region that allows c and b hadrons to be identified from their characteristically long

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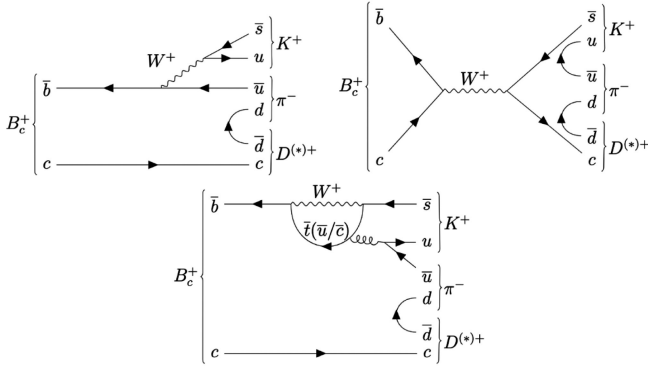


FIG. 1. Possible Feynman diagrams for the $B_c^+ \rightarrow D^{(*)+} K^+ \pi^-$ decay.

flight distance; a tracking system that provides a measurement of the momentum, p , of charged particles; and two ring-imaging Cherenkov (RICH) detectors that are able to discriminate between different species of charged hadrons. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter [18]. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [17]. The online event selection is performed by a trigger [19], which consists of a hardware stage [20], based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. Simulation samples are generated using BCVEGPy implemented in PYTHIA 8 [21–25] with a dedicated LHCb configuration [26]. These samples play an important role in optimizing the event selection and estimating the selection efficiencies of signal decays.

The D -meson candidates are reconstructed from their decays $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+$, and $D_s^+ \rightarrow K^+ K^- \pi^+$, which have relatively large BFs. These D -meson candidates are subsequently combined with charged pions and kaons to form B_c^+ candidates. The known $B_c^+ \rightarrow B_s^0 \pi^+$ decay, with $B_s^0 \rightarrow D_s^- (\rightarrow K^+ K^- \pi^+) \pi^+$, is used as a normalization channel, enabling measurements of the BF ratios

$$\begin{aligned} \mathcal{R}_{B_c^+ \rightarrow D h^+ h^-} &\equiv \frac{\mathcal{B}(B_c^+ \rightarrow D h^+ h^-)}{\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)} \\ &= \frac{N_{B_c^+ \rightarrow D h^+ h^-}}{N_{B_c^+ \rightarrow B_s^0 \pi^+}} \frac{\epsilon_{B_c^+ \rightarrow B_s^0 \pi^+}}{\epsilon_{B_c^+ \rightarrow D h^+ h^-}} \frac{\mathcal{B}(B_s^0)}{\mathcal{B}(D_{(s)}^{*+})}, \quad (1) \end{aligned}$$

where $N_{B_c^+ \rightarrow X}$ represents the yield of $B_c^+ \rightarrow X$ decays, $\epsilon_{B_c^+ \rightarrow X}$ represents their selection efficiency, $\mathcal{B}(D_{(s)}^{*+})$ represents the appropriate D -meson branching fraction for the signal channels, and $\mathcal{B}(B_s^0)$ represents the BF product $\mathcal{B}(B_s^0 \rightarrow D_s^- \pi^+) \mathcal{B}(D_s^- \rightarrow K^+ K^- \pi^-)$.

At the hardware-trigger level, events are required to have a hadron with transverse energy E_T in the calorimeters exceeding 3.5 GeV [18]. These trigger objects may originate directly from the B_c^+ decays of interest or from other particles in the event. The subsequent software trigger performs full event reconstruction and imposes stricter requirements: at least one charged particle must possess higher transverse momentum (p_T) than the hardware threshold and be significantly displaced from all reconstructed primary interaction vertices (PVs). Furthermore, the reconstructed events must have signal candidates forming a two-, three-, or four-track secondary vertex with a significant displacement from any PV [27,28]. For the offline event selection, momentum requirements are applied to reconstructed tracks to ensure that they fall within the kinematic ranges where the RICH detectors operate at full efficiency [29]. Additional requirements, including on particle identification (PID) quantities, track-fit quality, and the minimum impact parameter of a track relative to any PV, are applied to all final-state particles to ensure consistency with the signal decays. Masses of the reconstructed D candidates are required to be within ± 20 MeV/ c^2 (for D^+ and D_s^+ candidates) and ± 2 MeV/ c^2 (for D^{*+} candidates) of the known values [30]. A kinematic fit is performed to each candidate [31], with vertex constraints applied to both the B and D vertices, and with the D candidates' (D^+ , D^0 , and D_s^+) masses constrained to their known values [30]. This has the effect of significantly improving the D^{*+} mass resolution.

To further suppress background, a multivariate analysis based on a boosted decision tree (BDT) classifier [32] is implemented for each channel. The classifier is trained using a set of observables selected for their discriminating power between signal and background candidates. The input variables for the BDT training include calibrated PID quantities and topological observables, such as the impact-parameter significance, flight distance with respect to the PV, and the vertex-fit χ^2 , for different particles. For the training, simulated signal candidates are used as a proxy for the true signal while the background proxy sample uses data from the high- B_c^+ -mass sideband region [6450, 6750] MeV/ c^2 . To mitigate the effects of statistical fluctuations, the k-fold method [33] is applied to the samples during training. The requirement on the BDT output is chosen to maximize the figure of merit, $\epsilon_s/\sqrt{S+B}$, where ϵ_s is the signal efficiency estimated from simulation, S is the signal yield estimated based on the assumption $\mathcal{B}(B_c^+ \rightarrow D^+ K^+ \pi^-) = 2 \mathcal{B}(B_c^+ \rightarrow D^+ K^* (892)^0 (\rightarrow K^+ \pi^-))$, and B is the background yield in the signal region (defined as being within ± 40 MeV/ c^2 of the known B_c^+ mass) estimated from the sideband sample. The factor 2 in the assumption takes the other excited K^* states into consideration. The assumption $\mathcal{B}(B_c^+ \rightarrow D^{*+} K^+ \pi^-) = \mathcal{B}(B_c^+ \rightarrow D_s^+ K^+ K^-) = \mathcal{B}(B_c^+ \rightarrow D^+ K^+ \pi^-)$ is made when optimizing the BDT requirement

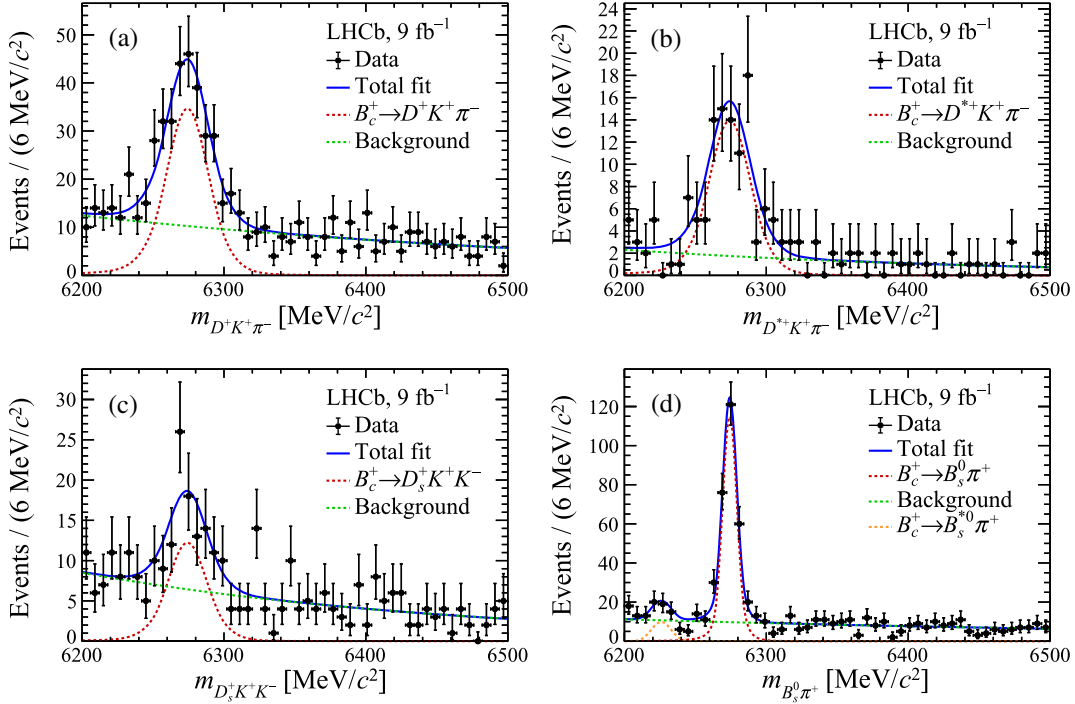


FIG. 2. Mass distributions for (a) $B_c^+ \rightarrow D^+ K^+ \pi^-$, (b) $B_c^+ \rightarrow D^{*+} K^+ \pi^-$, (c) $B_c^+ \rightarrow D_s^+ K^+ K^-$, and (d) $B_c^+ \rightarrow B_s^0 \pi^+$ candidates, after all selection criteria are imposed. The fit results are also shown.

for the other two signal decays. The resulting mass spectra for the $D^+ K^+ \pi^-$, $D^{*+} K^+ \pi^-$, $D_s^+ K^+ K^-$ and $B_s^0 \pi^+$ final states, after applying all selection criteria, are shown in Fig. 2.

A simultaneous unbinned maximum-likelihood fit is performed to all four mass spectra to determine the yield of each decay. To minimize the influence of partially reconstructed background in the signal channels, the mass fit range is chosen to be $[6200, 6500]$ MeV/c^2 . For all decays, the signal shape is described using the sum of a Gaussian function and a Crystal Ball function [34], modified to include power-law tails on both sides of the Gaussian core. The power-law tail parameters are fixed to values obtained from fits to the simulation. The four decay channels share a common B_c^+ peak position and width ratio for the two peaking functions, which are fixed to values obtained from simulation, allowing only one width to float. The main background contribution is combinatorial in nature, and is described by an exponential function. For the normalization channel $B_c^+ \rightarrow B_s^0 \pi^+$, the sample is contaminated by the decay $B_c^+ \rightarrow B_s^{*0} (\rightarrow B_s^0 \gamma) \pi^+$ where the photon is not reconstructed. This component is described by a shape obtained from the fast simulation package RapidSim [35]. The signal and background yields are left unconstrained during the fit. The fit projections are shown in Fig. 2.

The extracted signal yields are 230 ± 23 for the $B_c^+ \rightarrow D^+ K^+ \pi^-$ decay, 87 ± 12 for the $B_c^+ \rightarrow D^{*+} K^+ \pi^-$ decay, 68 ± 13 for the $B_c^+ \rightarrow D_s^+ K^+ K^-$ decay, and

267 ± 19 for the $B_c^+ \rightarrow B_s^0 \pi^+$ decay, where the uncertainties are statistical only. The signal significances are evaluated using Wilks's theorem [36], which is derived from the likelihood difference between the background-only and signal-plus-background hypotheses. The signal significance for all decay modes exceeds five standard deviations, after accounting for systematic uncertainties due to the choice of fit model.

The background-subtracted [37,38] two-body mass distributions of signal decays are shown in Fig. 3. A significant peak compatible with the $K^*(892)^0$ state and a smaller peak compatible with the $K^*(1430)^0$ state are seen in the $m_{K^+ \pi^-}$ mass spectrum for the $B_c^+ \rightarrow D^+ K^+ \pi^-$ decay. A peak compatible with the $K^*(892)^0$ state is also visible in the $m_{K^+ \pi^-}$ mass spectrum for the $B_c^+ \rightarrow D^{*+} K^+ \pi^-$ decay. A significant contribution in the low-mass $m_{K^+ K^-}$ region is observed in the $B_c^+ \rightarrow D_s^+ K^+ K^-$ decay, with part of it originating from the $\phi(1020)$ resonance. Additionally, a hint of the $f_2'(1525)$ state may also be present.

Measurements of the branching fractions require corrections for the efficiency to detect, reconstruct, and select the decays under study. For the three-body decays, the efficiency distribution across the phase space is nonuniform and is therefore calculated as a function of the two-dimensional mass combinations ($m_{D_{(s)}^{(*)+} K^+}$, $m_{D_{(s)}^{(*)+} h^-}$). The total efficiency is calculated as the product of several components, including the geometrical acceptance and reconstruction, trigger and selection efficiencies, all of

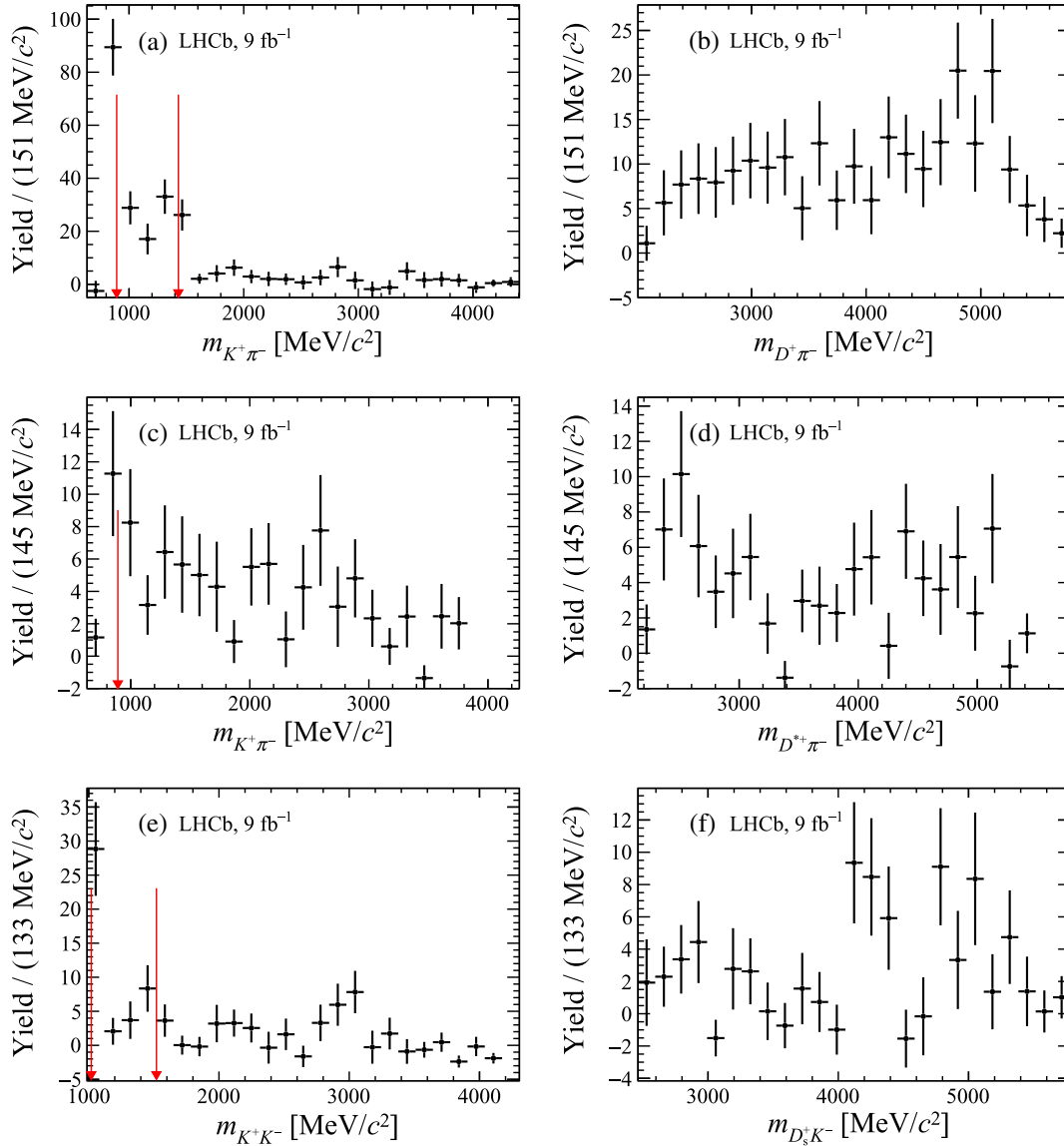


FIG. 3. Two-body mass distributions for (a),(b) $B_c^+ \rightarrow D^+ K^+ \pi^-$, (c),(d) $B_c^+ \rightarrow D^{*+} K^+ \pi^-$, and (e),(f) $B_c^+ \rightarrow D_s^+ K^+ K^-$ decays. The red arrows denote the positions of possible resonances in the $K^+ K^-$ or $K^+ \pi^-$ systems.

which are derived from simulation samples. To ensure good agreement between data and simulation, various corrections are applied to the simulated samples. The PID variables in the simulation are calibrated using data from $D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+) \pi^+$ decays [39]. The p_T distribution of B_c^+ mesons in the simulation sample are weighted to match those in the data sample, using the $B_c^+ \rightarrow J/\psi \pi^+$ decay, which has a large signal yield. Due to inaccuracies in the simulation of the hardware trigger, the trigger efficiency is corrected using the data-driven method of Ref. [19] to align the efficiency in the simulation with that in the data.

Many systematic effects cancel out in the BF ratio due to similar decay topology of signal and normalization channels. The remaining sources of systematic uncertainty in the BF ratio measurement are summarized in Table I. The

total systematic uncertainty is obtained by summing all contributions in quadrature. To account for the effect of the particular signal and background models used in the mass fit, alternative descriptions are used. These are a Cuijff function [40] for the signal peaks and a first-order Chebyshev polynomial function for the background. The resulting shift in the measurement with respect to the baseline result is assigned as a systematic uncertainty. The uncertainty due to the finite simulation sample size is included as a subdominant systematic uncertainty in the BF ratio measurement. The p_T weighting procedure, calibrated using $B_c^+ \rightarrow J/\psi \pi^+$ decays, is applied to the simulation samples. Due to the limited sample size of the calibration sample, this introduces a systematic uncertainty. To estimate its impact on the BF measurement, the uncertainty of

TABLE I. Absolute systematic uncertainties (in units of 10^{-3}) on the BF ratio measurements.

Sources	$\mathcal{R}_{B_c^+ \rightarrow D^+ K^+ \pi^-}$	$\mathcal{R}_{B_c^+ \rightarrow D^{*+} K^+ \pi^-}$	$\mathcal{R}_{B_c^+ \rightarrow D_s^+ K^+ K^-}$
Fit model	0.02	0.05	0.02
Simulation sample size	0.04	0.09	0.06
p_T weight	0.01	0.09	0.03
2D efficiency binning	0.06	0.18	0.08
Trigger correction	0.01	0.02	0.01
PID calibration	0.02	0.07	0.05
Total	0.08	0.24	0.13

the p_T weights are propagated to the BF measurement using pseudoexperiments.

The efficiency is determined as a function of ($m_{D(s)^+ K^+}$, $m_{D(s)^+ h^-}$). Variations in the binning scheme used for this evaluation lead to different results. To quantify the associated uncertainty, different binning schemes (10×10 , 15×15 , 20×20 , and 25×25) are applied when calculating the BF ratios, and the maximum variation is assigned as a systematic uncertainty. The systematic uncertainty from the hardware trigger correction is determined using the method of Ref. [19]. The PID variables from the simulated samples are corrected to match the large high-purity calibration samples [41]. The associated uncertainty is estimated by using alternative PID templates.

Taking all systematic uncertainties into account, the BF ratio between each signal decay and the normalization decay are determined by Eq. (1) to be

$$\begin{aligned} \mathcal{R}_{B_c^+ \rightarrow D^+ K^+ \pi^-} &= (1.96 \pm 0.23 \pm 0.08 \pm 0.10) \times 10^{-3}, \\ \mathcal{R}_{B_c^+ \rightarrow D^{*+} K^+ \pi^-} &= (3.67 \pm 0.55 \pm 0.24 \pm 0.20) \times 10^{-3}, \\ \mathcal{R}_{B_c^+ \rightarrow D_s^+ K^+ K^-} &= (1.61 \pm 0.35 \pm 0.13 \pm 0.07) \times 10^{-3}. \end{aligned}$$

where the first uncertainty is statistical, the second is systematic, and the third is due to the limited precision on the D -meson branching fractions [30].

To summarize, the decays $B_c^+ \rightarrow D^+ K^+ \pi^-$, $B_c^+ \rightarrow D^{*+} K^+ \pi^-$, and $B_c^+ \rightarrow D_s^+ K^+ K^-$ are observed for the first time, using a data sample corresponding to an integrated luminosity of 9 fb^{-1} collected by the LHCb experiment. Their branching fractions relative to the $B_c^+ \rightarrow B_s^0 \pi^+$ decay are measured. Following the recent upgrade of the LHCb detector [42], the experiment is now entering a new phase of data collection characterized by higher luminosity and enhanced trigger capabilities. This development opens the door to unprecedented investigations into hadronic B_c^+ decays. This Letter lays a crucial groundwork for future searches for local CP violation in B_c^+ decays, offering valuable insights into the underlying quark-level dynamics and contributing to our broader understanding of CP phenomena within the standard model.

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Data availability—Data associated to the plots in this publication are made available on the CERN Document Server in Ref. [43].

- [1] I. P. Gouz, V. V. Kiselev, A. K. Likhoded, V. I. Romanovsky, and O. P. Yushchenko, Prospects for the B_c studies at LHCb, *Phys. At. Nucl.* **67**, 1559 (2004).

- [2] F. Abe *et al.* (CDF Collaboration), Observation of the B_c meson in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. Lett.* **81**, 2432 (1998).
- [3] F. Abe *et al.* (CDF Collaboration), Observation of B_c mesons in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. D* **58**, 112004 (1998).
- [4] D.-S. Du and Z.-T. Wei, Space-like penguin effects in B_c decays, *Eur. Phys. J. C* **5**, 705 (1998).
- [5] Z. Rui, Z.-T. Zou, and C.-D. Lu, Two-body $B_c \rightarrow D_{(s)}^{(*)}P$, $D_{(s)}^{(*)}V$ decays in the perturbative QCD approach, *Phys. Rev. D* **86**, 074008 (2012).
- [6] Z.-T. Zou, Y. Li, and X. Liu, Study of $B_c \rightarrow DS$ decays in the perturbative QCD approach, *Phys. Rev. D* **97**, 053005 (2018).
- [7] X. Ai *et al.*, Flavor physics at the CEPC: A general perspective, *Chin. Phys.* **49**, 103003 (2025).
- [8] R. Aaij *et al.* (LHCb Collaboration), Measurement of the B_c^- production fraction and asymmetry in 7 and 13 TeV pp collisions, *Phys. Rev. D* **100**, 112006 (2019).
- [9] R. Aaij *et al.* (LHCb Collaboration), Observation of $B_c^+ \rightarrow D^0 K^+$ decays, *Phys. Rev. Lett.* **118**, 111803 (2017).
- [10] R. Aaij *et al.* (LHCb Collaboration), Study of $B_c^+ \rightarrow D^0 h^+$, $B_c^+ \rightarrow D_s^+ \phi$ and $B_c^+ \rightarrow D^+ K^{*0}$ decays, Report No. LHCb-PAPER-2024-035 [J. High Energy Phys. (to be published)].
- [11] H.-M. Choi and C.-R. Ji, Nonleptonic two-body decays of the B_c meson in the light-front quark model and the QCD factorization approach, *Phys. Rev. D* **80**, 114003 (2009).
- [12] R. Zhu, X.-L. Han, Y. Ma, and Z.-J. Xiao, Weak decays of B_c into two hadrons under flavor SU(3) symmetry, *Eur. Phys. J. C* **78**, 740 (2018).
- [13] A. A. Alves Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, *J. Instrum.* **3**, S08005 (2008).
- [14] LHCb Collaboration, LHCb detector performance, *Int. J. Mod. Phys. A* **30**, 1530022 (2015).
- [15] R. Aaij *et al.*, Performance of the LHCb vertex locator, *J. Instrum.* **9**, P09007 (2014).
- [16] R. Arink *et al.* (LHCb Outer Tracker Group), Performance of the LHCb outer tracker, *J. Instrum.* **9**, P01002 (2014).
- [17] A. A. Alves, Jr. *et al.*, Performance of the LHCb muon system, *J. Instrum.* **8**, P02022 (2013).
- [18] C. Abellán Beteta *et al.*, Calibration and performance of the LHCb calorimeters in Run 1 and 2 at the LHC, arXiv:2008.11556.
- [19] R. Aaij *et al.*, The LHCb trigger and its performance in 2011, *J. Instrum.* **8**, P04022 (2013).
- [20] R. Aaij *et al.*, A comprehensive real-time analysis model at the LHCb experiment, *J. Instrum.* **14**, P04006 (2019).
- [21] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008).
- [22] C.-H. Chang, C. Driouichi, P. Eerola, and X.-G. Wu, BCVEGPy: An event generator for hadronic production of the B_c meson, *Comput. Phys. Commun.* **159**, 192 (2004).
- [23] C.-H. Chang, J.-X. Wang, and X.-G. Wu, BCVEGPy2.0: A upgraded version of the generator BCVEGPy with the addition of hadroproduction of the P-wave B_c states, *Comput. Phys. Commun.* **174**, 241 (2006).
- [24] X.-Y. Wang and X.-G. Wu, A trick to improve the efficiency of generating unweighted B_c events from BCVEGPy, *Comput. Phys. Commun.* **183**, 442 (2012).
- [25] X.-G. Wu, BCVEGPy and GENXICC for the hadronic production of the doubly heavy mesons and baryons, *J. Phys. Conf. Ser.* **523**, 012042 (2014).
- [26] I. Belyaev *et al.* (LHCb Collaboration), Handling of the generation of primary events in Gauss, the LHCb simulation framework, *J. Phys. Conf. Ser.* **331**, 032047 (2011).
- [27] V. V. Gligorov and M. Williams, Efficient, reliable and fast high-level triggering using a bonsai boosted decision tree, *J. Instrum.* **8**, P02013 (2013).
- [28] T. Likhomanenko, P. Ilten, E. Khairullin, A. Rogozhnikov, A. Ustyuzhanin, and M. Williams, LHCb topological trigger reoptimization, *J. Phys. Conf. Ser.* **664**, 082025 (2015).
- [29] M. Adinolfi *et al.* (LHCb RICH Group), Performance of the LHCb RICH detector at the LHC, *Eur. Phys. J. C* **73**, 2431 (2013).
- [30] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [31] W. D. Hulsbergen, Decay chain fitting with a Kalman filter, *Nucl. Instrum. Methods Phys. Res., Sect. A* **552**, 566 (2005).
- [32] B. P. Roe, H.-J. Yang, J. Zhu, Y. Liu, I. Stancu, and G. McGregor, Boosted decision trees, an alternative to artificial neural networks, *Nucl. Instrum. Methods Phys. Res., Sect. A* **543**, 577 (2005).
- [33] A. Blum, A. Kalai, and J. Langford, Beating the hold-out: Bounds for k-fold and progressive cross-validation, in *Proceedings of the Twelfth Annual Conference on Computational Learning Theory, COLT '99* (Association for Computing Machinery, New York, NY, 1999), pp. 203–208, [10.1145/307400.307439](https://doi.org/10.1145/307400.307439).
- [34] T. Skwarnicki, A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances, Ph.D. thesis, Institute of Nuclear Physics, Krakow, 1986, <http://inspirehep.net/record/230779/>; Report No. DESY-F31-86-02.
- [35] G. A. Cowan, D. C. Craik, and M. D. Needham, RapidSim: An application for the fast simulation of heavy-quark hadron decays, *Comput. Phys. Commun.* **214**, 239 (2017).
- [36] S. S. Wilks, The large-sample distribution of the likelihood ratio for testing composite hypotheses, *Ann. Math. Stat.* **9**, 60 (1938).
- [37] M. Pivk and F. R. Le Diberder, sPlot: A statistical tool to unfold data distributions, *Nucl. Instrum. Methods Phys. Res., Sect. A* **555**, 356 (2005).
- [38] Y. Xie, sFit: A method for background subtraction in maximum likelihood fit, arXiv:0905.0724.
- [39] R. Aaij *et al.*, Selection and processing of calibration samples to measure the particle identification performance of the LHCb experiment in Run 2, *EPJ Tech. Instrum.* **6**, 1 (2019).
- [40] P. del Amo Sanchez *et al.* (BABAR Collaboration), Study of $B \rightarrow X\gamma$ decays and determination of $|V_{td}/V_{ts}|$, *Phys. Rev. D* **82**, 051101 (2010).
- [41] L. Anderlini *et al.*, The PIDCalib package, Report No. LHCb-PUB-2016-021, 2016, https://cds.cern.ch/record/2202412?ln=zh_CN.
- [42] R. Aaij *et al.* (LHCb Collaboration), The LHCb upgrade I, *J. Instrum.* **19**, P05065 (2024).
- [43] LHCb Collaboration (2025), <https://cds.cern.ch/record/2943182>.

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