Published for SISSA by Springer

Received: *August 19, 2022*
Revised: *October 14, 2022*
Accepted: *November 8, 2022*
Published: *July 26, 2023*

Study of B_c^+ meson decays to charmonia plus multihadron final states

The LHCb collaboration

E-mail: Ivan.Belyaev@cern.ch

Abstract: Four decay modes of the B_c^+ meson into a J/ψ meson and multiple charged kaons or pions are studied using proton-proton collision data, collected with the LHCb detector at centre-of-mass energies of 7, 8, and 13 TeV and corresponding to an integrated luminosity of $9\,\text{fb}^{-1}$. The decay $B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$ is observed for the first time, and evidence for the $B_c^+ \to J/\psi 4\pi^+3\pi^-$ decay is found. The decay $B_c^+ \to J/\psi 3\pi^+2\pi^-$ is observed and the previous observation of the $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$ decay is confirmed using the $\psi(2S) \to J/\psi\pi^+\pi^-$ decay mode. Ratios of the branching fractions of these four B_c^+ decay channels are measured.

Keywords: B Physics, Hadron-Hadron Scattering, QCD, Spectroscopy

ArXiv ePrint: 2208.08660

https://doi.org/10.1007/JHEP07(2023)198

Contents

---

1 Introduction

The B_c^+ meson, discovered in 1998 by the CDF collaboration [1, 2] at the Tevatron $p\overline{p}$ collider, is the only known meson that contains two different heavy-flavour quarks, charm and beauty. The high b-quark production cross-section at the Large Hadron Collider (LHC) [3–8] enables the LHCb, ATLAS and CMS experiments to study in detail the production, decays and other properties of the B_c^+ meson [9–35]. The B_c^+ meson has a rich set of decay modes since either of the heavy quarks can decay while the other behaves as a spectator quark, or both quarks can annihilate via a virtual W^+ boson.

Decays of the B_c^+ meson to charmonium and light hadrons can be described using the quantum chromodynamics (QCD) factorisation approach [36, 37], which relies on the form factors of the $B_c^+ \to J/\psi W^+$ transition [38–42] and on the universal spectral function for the virtual W^+ boson fragmenting into light hadrons [43–45]. The spectral function can be calculated or, alternatively, determined using the multihadron decays of the τ lepton or e^+e^- annihilation to light hadrons. The phenomenological model proposed by Berezhnoy, Likhoded and Luchinsky (BLL model) [43–49], based on this approach, describes well the measured branching fractions for the $B_c^+ \to J/\psi \pi^+\pi^+\pi^-$, $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$, $B_c^+ \to J/\psi K^+\pi^+\pi^-$, $B_c^+ \to J/\psi K^+K^-\pi^+$, and $B_c^+ \to J/\psi K^+K^+K^-$ decays [10, 14, 35] as well as the major characteristics of their light-hadron systems and resonance structure. Additional measurements of the branching fractions of various B_c^+ decays into the final states consisting of charmonium and multiple light hadrons would allow for more precise tests of the factorisation hypothesis.

Special interest in the decays of the B_c^+ meson to a J/ψ meson and multiple light hadrons arises for the case where both the number of light hadrons and the energy released in the decay are large. In such a scenario, one expects that the statistical, or quasi-classical, approach [50, 51] could be applied to describe the multibody system of the light hadrons recoiling against the J/ψ meson. The properties of such systems of light hadrons could be comparable to those from models used for the description of correlations in multihadron production, in particular in heavy-ion collisions [52]. Experimentally, evidence for 32 ± 8 decays of B_c^+ mesons into a J/ψ meson and five charged pions, $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$, was obtained by the LHCb collaboration [15]. This study was done using data collected in proton-proton (pp) collisions at centre-of-mass energies of 7 and 8 TeV, corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$. The measured branching fraction, relative to the $B_c^+ \to J/\psi \pi^+$ decay mode, and characteristics of the multipion system, are consistent with expectations from the BLL model [46].

This paper reports a study of the B_c^+ meson decaying into final states with charmonium and five light hadrons,[1] namely $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$, $B_c^+ \to J/\psi K^+ K^- \pi^+ \pi^+ \pi^-$, $B_c^+ \to (\psi(2S) \to J/\psi \pi^+ \pi^-)\, \pi^+ \pi^+ \pi^-$, and the final state with seven charged pions, $B_c^+ \to J/\psi 4\pi^+ 3\pi^-$. The analysis is based on pp collision data, corresponding to an integrated luminosity of 9 fb^{-1}, collected with the LHCb detector at centre-of-mass energies of 7, 8, and 13 TeV.

2 Detector and simulation

The LHCb detector [53, 54] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region [55], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes [56, 57] placed downstream of the magnet. The tracking system provides a measurement of the momentum of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c. The momentum scale is calibrated using samples of $J/\psi \to \mu^+\mu^-$ and $B^+ \to J/\psi K^+$ decays collected concurrently with the data sample used for this analysis [58, 59]. The relative accuracy of this procedure is estimated to be 3×10^{-4} using samples of other fully reconstructed b hadrons, Υ and K_S^0 mesons. The minimum distance between a track and a primary pp-collision vertex (PV) [60, 61], the impact parameter, is measured with a resolution of $(15 + 29/p_T)\,\mu\mathrm{m}$, 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 (RICH) [62]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [63].

---

[1] Inclusion of charge-conjugate decays is implied throughout the paper.

The online event selection is performed by a trigger [64], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which performs a full event reconstruction. The hardware trigger selects muon candidates with high transverse momentum or dimuon candidates with a high value of the product of the transverse momenta of the two muons. In the software trigger, two oppositely-charged muons are required to form a good-quality vertex that is significantly displaced from any PV, and the mass of the $\mu^+\mu^-$ pair is required to exceed $2.7\,\mathrm{GeV}/c^2$.

Simulated events are used to model the signal mass shapes and to compute the efficiencies needed to determine the branching fraction ratios. In the simulation, pp collisions are generated using PYTHIA [65] with a specific LHCb configuration [66]. Decays of unstable particles are described by the EVTGEN package [67], in which final-state radiation is generated using PHOTOS [68]. The decay channels in this study are simulated using the BLL model [49, 69]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [70, 71] as described in ref. [72]. To account for imperfections in the simulation of charged-particle reconstruction, the track-reconstruction efficiency determined from simulation is corrected using calibration samples [73].

3 Event selection

The $B_c^+ \to J/\psi\, n h^\pm$ candidates, where $n = 5, 7$ represents the number of light hadrons in the final state and $h^\pm$ stands for a charged kaon or pion, are reconstructed using the $J/\psi \to \mu^+\mu^-$ decay mode. The selection criteria largely follow those described in refs. [14, 15, 35, 74]. The selection starts from reconstructed charged tracks of good quality and muon, pion and kaon candidates are identified by combining information from the RICH, calorimeter and muon detectors [75]. The muon candidates are required to have a transverse momentum larger than $550\,\mathrm{MeV}/c$. Pairs of oppositely charged muons consistent with originating from a common vertex are combined to form $J/\psi \to \mu^+\mu^-$ candidates. The reconstructed mass of the $\mu^+\mu^-$ pair is required to be in the range $3.0 < m_{\mu^+\mu^-} < 3.2\,\mathrm{GeV}/c^2$, which approximately corresponds to a $\pm 7\sigma$ region around the known J/ψ meson mass [76], where σ is the $\mu^+\mu^-$ mass resolution.

To form the B_c^+ candidates, the selected J/ψ candidates are combined with charged tracks identified as kaons or pions, requiring a well reconstructed vertex. Kaons and pions are required to have a momentum between 3.2 and $150\,\mathrm{GeV}/c$, to ensure a good performance of the particle identification [62, 75]. To reduce the combinatorial background, only tracks that are inconsistent with originating from any reconstructed PV in the event are considered, and the scalar sum of the transverse momenta of the light-hadron candidates is required to be larger than a minimum value. Each B_c^+ candidate is associated with the PV that yields the smallest χ^2_{IP}, where χ^2_{IP} is defined as the difference in the vertex-fit χ^2 of a given PV reconstructed with and without the particle under consideration. To improve the mass resolution for the B_c^+ candidates, a kinematic fit is performed [77]. This fit constrains the mass of the $\mu^+\mu^-$ pair to the known mass of the J/ψ meson [76] and constrains the B_c^+ candidate to originate from its associated PV. A requirement on the quality of this fit is applied to further suppress combinatorial background. Such a requirement also reduces contributions from the B_c^+ decays proceeding through intermediate D^+, D_s^+, B^+ or B^0 mesons. The proper decay time of the B_c^+ candidate, calculated with respect to the associated PV, is required to be lager than a minimum value, which suppresses random combinations of J/ψ candidates and charged tracks, which include tracks originating from the PV. The mass of selected B_c^+ candidates is required to be between 6.15 and 6.45 GeV/c^2.

For the selected $B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$ candidates, an excess of events is seen in the $J/\psi K^\pm\pi^\pm\pi^\mp$ mass spectra at the known mass of the B^+ meson [76]. Similarly, for the selected $B_c^+ \to J/\psi 3\pi^+2\pi^-$ candidates a slight excess of events is seen in the $\pi^+\pi^+\pi^-$ mass spectrum close to the known mass of the D^+ meson [76]. Such B_c^+ candidates are excluded from further analysis. No excess of candidates is observed in the $\pi^+\pi^+\pi^-$ mass distribution near the mass of the D_s^+ meson. For the $B_c^+ \to J/\psi 3\pi^+2\pi^-$ and $B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$ decays, the contributions from the $B_c^+ \to (\psi(2S) \to J/\psi \pi^+\pi^-)\, h^+h^+h^-$ decays are removed by rejecting candidates with any $J/\psi\pi^+\pi^-$ combination having mass within the range $3.68 < m_{J/\psi\pi^+\pi^-} < 3.69\,\text{GeV}/c^2$. The $B_c^+ \to J/\psi 3\pi^+2\pi^-$ candidates with at least one $J/\psi\pi^+\pi^-$ mass within the $3.67 < m_{J/\psi\pi^+\pi^-} < 3.70\,\text{GeV}/c^2$ range are considered as $B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\,\pi^+\pi^+\pi^-$ candidates in the subsequent analysis.

For each decay channel, when two or more B_c^+ candidates are found in the same event, only one randomly chosen candidate is retained for further analysis. The mass distributions for selected $B_c^+ \to J/\psi 3\pi^+2\pi^-$, $B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$, and $B_c^+ \to J/\psi 4\pi^+3\pi^-$ candidates are shown in figure 1. Figure 2 shows the mass distributions for selected $B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+\pi^+\pi^-$ candidates and for $J/\psi\pi^+\pi^-$ combinations for these candidates.

4 Signal yields

The yields for the $B_c^+ \to J/\psi n h^\pm$ decays are determined using an extended unbinned maximum-likelihood fit. The fit is performed simultaneously to the three mass distributions of selected $B_c^+ \to J/\psi 3\pi^+2\pi^-$, $B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$ and $B_c^+ \to J/\psi 4\pi^+3\pi^-$ candidates; and to the two-dimensional distribution of the $J/\psi 3\pi^+2\pi^-$ mass, $m_{J/\psi 3\pi^+2\pi^-}$, versus the $J/\psi\pi^+\pi^-$ mass, $m_{J/\psi\pi^+\pi^-}$, for the $B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+\pi^+\pi^-$ candidates. Following refs. [78, 79], to improve the resolution on the $J/\psi\pi^+\pi^-$ mass for the $B_c^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)\pi^+\pi^+\pi^-$ candidates and to eliminate a small correlation between the $m_{J/\psi 3\pi^+2\pi^-}$ and $m_{J/\psi\pi^+\pi^-}$ variables, the $m_{J/\psi\pi^+\pi^-}$ variable is computed [77] by constraining the mass of the B_c^+ candidate to its known value [33].

For each B_c^+ mass distribution, the one-dimensional fit function consists of two components:

1. signal $B_c^+ \to J/\psi n h^\pm$ decays, parameterised by a modified Gaussian function with power-law tails on both sides of the distribution [80, 81]. The tail parameters are fixed to the values obtained from simulation;

2. random $J/\psi n h^\pm$ combinations, modelled by a first-order polynomial function.

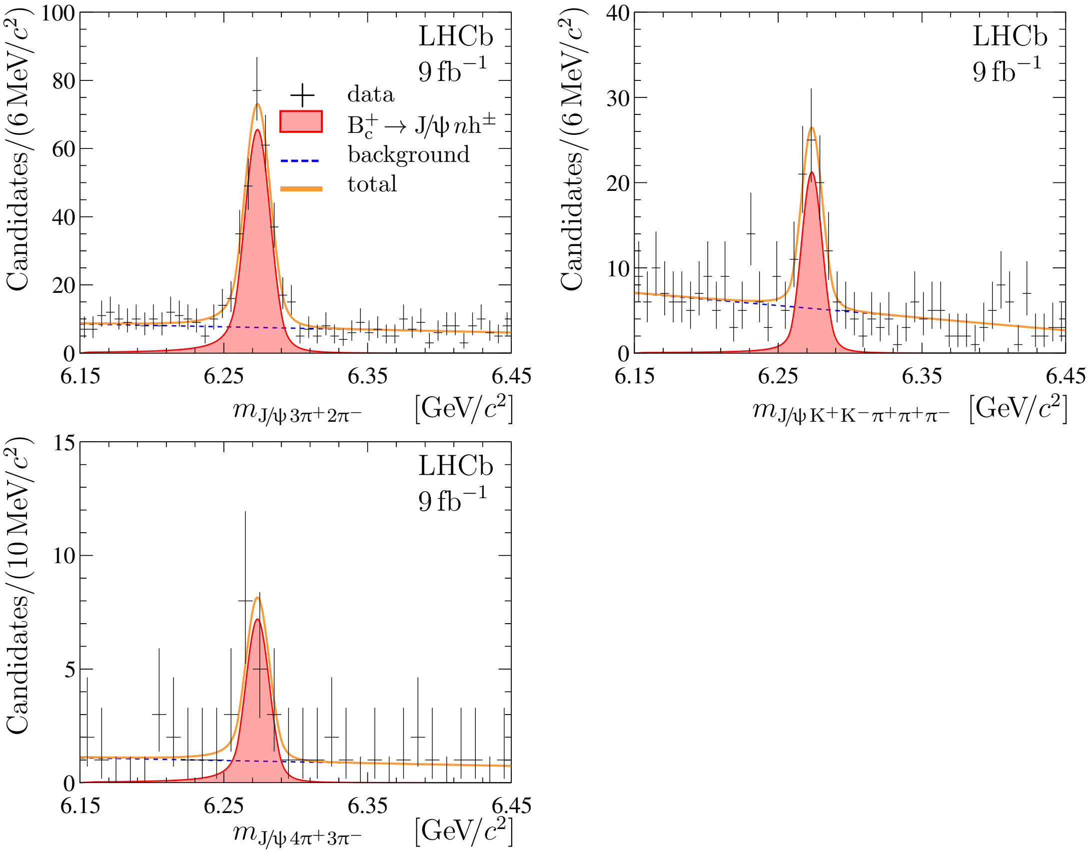

Figure 1. Mass distributions for selected (top left) $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$, (top right) $B_c^+ \to J/\psi\, K^+ K^- \pi^+ \pi^+ \pi^-$ and (bottom) $B_c^+ \to J/\psi\, 4\pi^+ 3\pi^-$ candidates. Projections of the fit, described in the text, are overlaid.

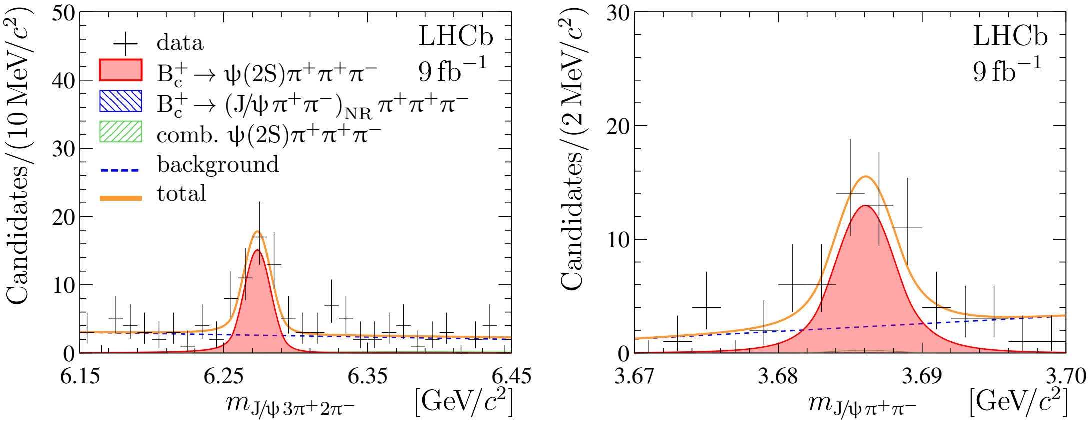

Figure 2. (Left) Distribution of the $J/\psi\, 3\pi^+ 2\pi^-$ mass for selected $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$ candidates with the $J/\psi\, \pi^+\pi^-$ mass between 3.679 and 3.692 GeV/c^2. (Right) Distribution of the $J/\psi\, \pi^+\pi^-$ mass for selected $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$ candidates with the $J/\psi\, 3\pi^+ 2\pi^-$ mass between 6.245 and 6.301 GeV/c^2. Projections of the fit, described in the text, are overlaid.

Decay	Yield	$\mathcal{S}$ [σ]
$B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$	268 ± 20	21.0
$B_c^+ \to J/\psi\, K^+ K^- \pi^+ \pi^+ \pi^-$	69 ± 11	9.1
$B_c^+ \to J/\psi\, 4\pi^+ 3\pi^-$	16 ± 5	4.9
$B_c^+ \to (\psi(2S) \to J/\psi\, \pi^+\pi^-)\pi^+\pi^+\pi^-$	40 ± 8	6.4

Table 1. Signal yields obtained from the simultaneous unbinned extended maximum-likelihood fit. The uncertainties are statistical only. The last column shows the statistical significance estimated using Wilks' theorem, in units of standard deviations.

The two-dimensional fit function for the $B_c^+ \to (\psi(2S) \to J/\psi\, \pi^+\pi^-)\pi^+\pi^+\pi^-$ channel is defined as the sum of four components:

1. signal $B_c^+ \to (\psi(2S) \to J/\psi\, \pi^+\pi^-)\pi^+\pi^+\pi^-$ decays, parameterised as the product of B_c^+ and $\psi(2S)$ signal functions each modelled by a modified Gaussian function with power-law tails on both sides of the distribution [80, 81]. The tail parameters are fixed to the values obtained from simulation;
2. contributions from non-resonant $B_c^+ \to (J/\psi\, \pi^+\pi^-)_{\mathrm{NR}}\, \pi^+\pi^+\pi^-$ decays, not proceeding through the intermediate $\psi(2S)$ state, but falling into the $3.67 < m_{J/\psi\pi^+\pi^-} < 3.70\,\mathrm{GeV}/c^2$ region, parameterised as the product of the B_c^+ signal function and a phase-space function describing a three-body out of the six-body final state [82], modified by a positive linear function of the $J/\psi\, \pi^+\pi^-$ mass;
3. random combinations for $\psi(2S)$ and $\pi^+\pi^+\pi^-$ candidates, parameterised as the product of the $\psi(2S)$ signal function and a positive linear function of the mass of the $J/\psi\, 3\pi^+ 2\pi^-$ system;
4. random $J/\psi\, 3\pi^+ 2\pi^-$ combinations, described by a two-dimensional positive-definite second-order polynomial function.

For all B_c^+ signal functions, the peak-position parameter is shared by all decays and allowed to vary in the fit. The ratio of the mass resolutions of the B_c^+ decays in data and simulation, $s_{B_c^+}$, is shared by all decay modes and is allowed to vary in the fit, to account for a discrepancy in the mass resolution between data and simulation [78, 79, 83]. The ratio of the mass resolution of the $\psi(2S) \to J/\psi\, \pi^+\pi^-$ decays in data and simulation, $s_{\psi(2S)} = 1.048 \pm 0.004$, and the peak-position parameter for the $\psi(2S)$ signal component are Gaussian constrained to the values obtained from a previous LHCb study [78]. The projections of the fit are overlaid in figure 1 for $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$, $B_c^+ \to J/\psi\, K^+ K^- \pi^+ \pi^+ \pi^-$, and $B_c^+ \to J/\psi\, 4\pi^+ 3\pi^-$ candidates and in figure 2 for the $B_c^+ \to (\psi(2S) \to J/\psi\, \pi^+\pi^-)\pi^+\pi^+\pi^-$ candidates. The signal yields obtained from the fit are listed in table 1, along with the statistical significance estimated using Wilks' theorem [84]. The resolution correction factors are found to be $s_{B_c^+} = 1.00 \pm 0.06$

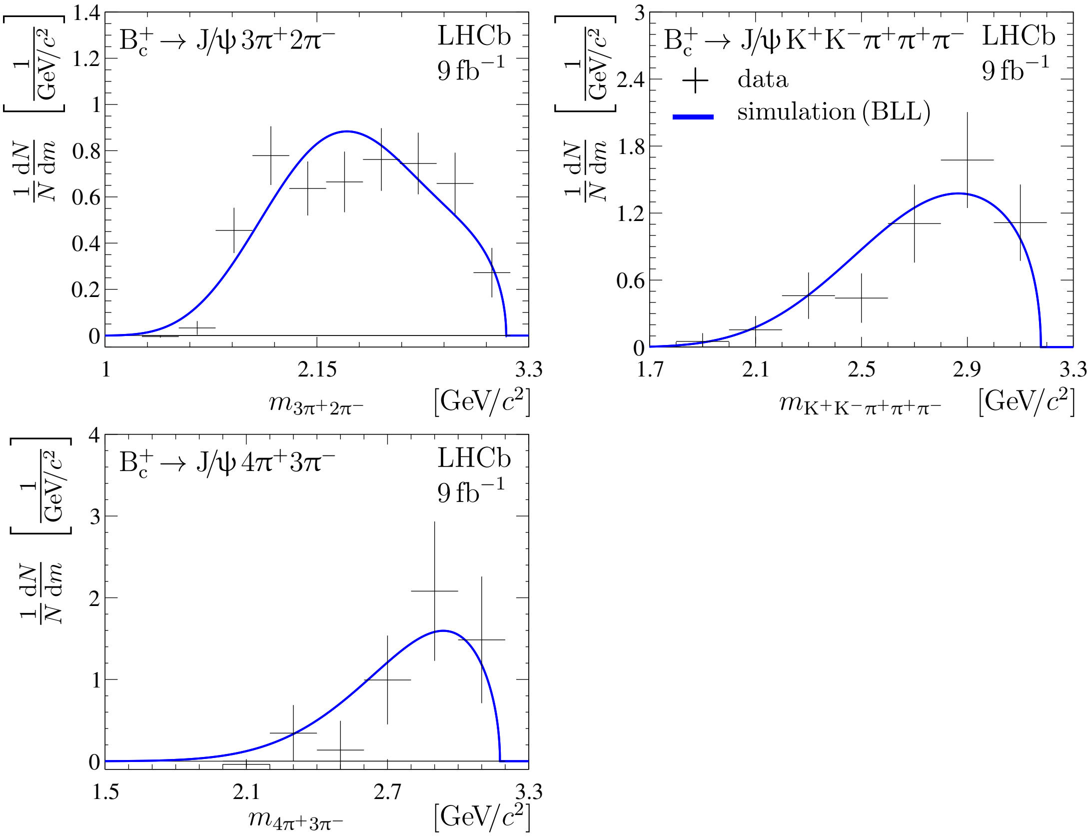

Figure 3. Mass spectra for the light-hadron system for the (top left) $B_c^+ \to J/\psi\, 3\pi^+2\pi^-$, (top right) $B_c^+ \to J/\psi\, K^+K^-\pi^+\pi^+\pi^-$ and (bottom) $B_c^+ \to J/\psi\, 4\pi^+3\pi^-$ decays. Expectations from the BLL model are overlaid.

and $s_{\psi(2S)} = 1.048 \pm 0.004$. For all previously unobserved modes, the significance is confirmed by simulating a large number of pseudoexperiments according to the background distribution observed in data.

The background-subtracted mass spectra for the light-hadron system for the observed decays of the B_c^+ mesons are obtained using the *sPlot* technique [85], based on the results of the fit described above. The distributions are shown in figures 3 and 4 (right) together with the expectations from the BLL model. For all cases, good agreement with the BLL model is observed. No $D_s^+ \to 3\pi^+2\pi^-$, $D_s^+ \to 4\pi^+3\pi^-$ or $D_s^+ \to \pi^+\pi^+\pi^-$ signals are observed in the studied spectra.

The background-subtracted $\pi^+\pi^+\pi^-$ mass distribution from the $B_c^+ \to J/\psi\, 3\pi^+2\pi^-$ decays is shown in figure 4 (left). The observed spectrum is in good agreement with the expectations from the BLL model. The background-subtracted $\pi^+\pi^-$ mass spectra from the $B_c^+ \to J/\psi\, 3\pi^+2\pi^-$ and $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$ decays are shown in figure 5. Figures 4 and 5 contain all possible $\pi^+\pi^+\pi^-$ and $\pi^+\pi^-$ combinations from a single B_c^+ candidate. The fits to the $\pi^+\pi^-$ mass distributions are performed using a function that contains two terms: a component corresponding to decays via the intermediate $\rho^0 \to \pi^+\pi^-$ resonance and a smooth function describing the $\pi^+\pi^-$ mass spectrum without a $\rho^0 \to \pi^+\pi^-$ signal, la-

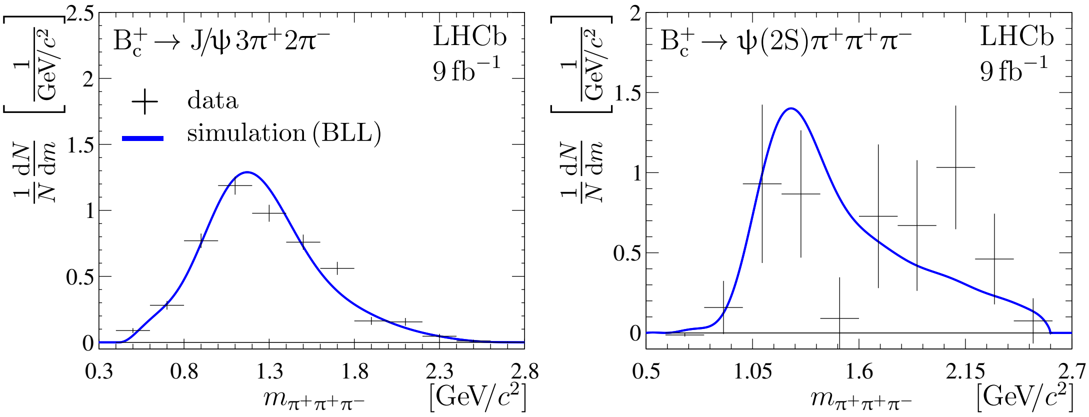

Figure 4. Mass spectra for the $\pi^+\pi^+\pi^-$ combinations from the (left) $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$ (6 entries per B_c^+ candidate) and (right) $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$ decays. The expectations from the BLL model are overlaid.

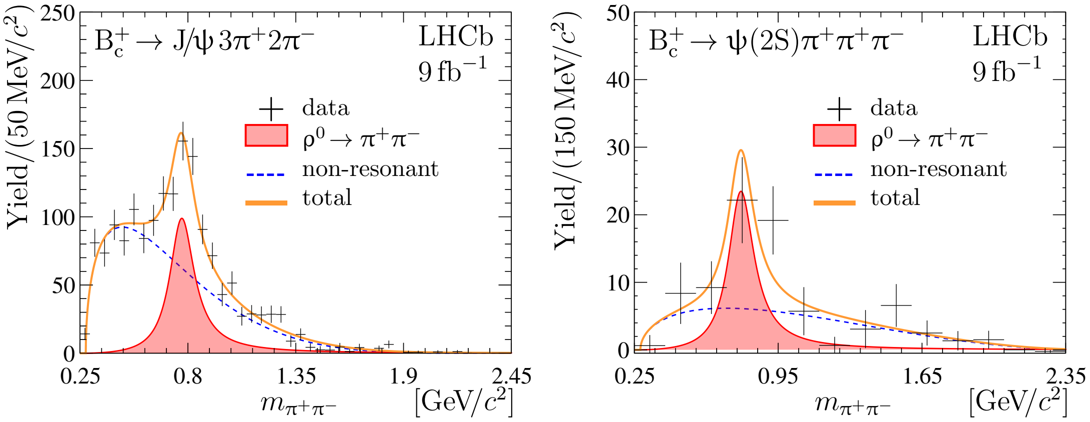

Figure 5. Background-subtracted $\pi^+\pi^-$ mass distributions from (left) $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$ (6 entries per B_c^+ candidate) and (right) $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$ (2 entries per B_c^+ candidate) decays. The results of the fits described in the text are overlaid.

belled as "non-resonant" in figure 5. The resonance component is parameterised with a relativistic P-wave Breit–Wigner function with a Blatt–Weisskopf form factor with a meson radius of 3.5 GeV^{-1} [86]. The non-resonant component is parameterised with the product of the phase-space function describing a two-body combination from a six-body combination in the $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$ case and a two-body combination from a four-body combination in the $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$ case [82], and a positive first-order polynomial function that accounts for the unknown decay dynamics. The results of the fits, overlaid in figure 5, are consistent with a large fraction of the decays proceeding via an intermediate $\rho^0 \to \pi^+\pi^-$ resonance, as expected within the BLL model. Making a more quantitative statement would require a more complicated treatment of the multihadron system, which is beyond the scope of this paper.

The background-subtracted $K^+\pi^-$ and $K^-\pi^+$ mass spectra and the low-mass part of the K^+K^- mass spectrum from the $B_c^+ \to J/\psi\, K^+K^-\pi^+\pi^+\pi^-$ decays are shown in fig-

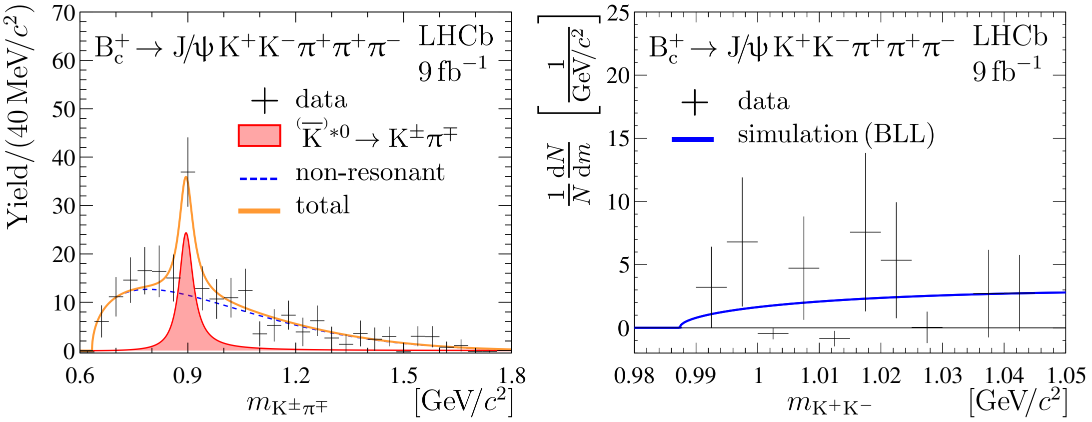

Figure 6. Background-subtracted (left) $K^\pm\pi^\mp$ (3 entries per B_c^+ candidate) mass and (right) low-mass part of the K^+K^- mass distribution from the $B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-$ decays. The results of the fit described in the text are overlaid on the left plot, while expectations from the BLL model are overlaid on the right plot.

ure 6. A fit to the $K^\pm\pi^\mp$ mass spectrum is performed using a two-component function, similar to the function described above, and consisting of a component corresponding to decays via the intermediate K^{*0} or $\overline{K}{}^{*0}$ resonance and a smooth function describing decays without a K^{*0} or $\overline{K}{}^{*0}$ resonance. The resonance component is parameterised with a relativistic P-wave Breit–Wigner function. Fit results are overlaid in figure 6 (left) and indicate a presence of decays via intermediate K^{*0} and $\overline{K}{}^{*0}$ mesons. The K^+K^- mass spectrum, shown in figure 6 (right), exhibits no sign of the ϕ resonance, in agreement both with the expected suppression of the ϕ meson production due to the Okubo–Zweig–Iizuka rule [87–91] and with expectations from the BLL model. A similar suppression has been observed for the $B_c^+ \to J/\psi K^+K^-\pi^+$ decays [14, 35].

5 Ratios of branching fractions

Three ratios of branching fractions are reported in this paper,

$$\mathcal{R}^{J/\psi K^+K^-\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi K^+K^-\pi^+\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+2\pi^-)}, \tag{5.1a}$$

$$\mathcal{R}^{J/\psi 4\pi^+3\pi^-}_{J/\psi 3\pi^+2\pi^-} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi 4\pi^+3\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+2\pi^-)}, \tag{5.1b}$$

$$\mathcal{R}^{\psi(2S)\pi^+\pi^+\pi^-}_{J/\psi 3\pi^+2\pi^-} \equiv \frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-) \times \mathcal{B}(\psi(2S) \to J/\psi \pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+2\pi^-)}. \tag{5.1c}$$

Each ratio of branching fractions for the decays of B_c^+ mesons into the final states X and Y is calculated as

$$\mathcal{R}^{\mathrm{X}}_{\mathrm{Y}} = \frac{N_{\mathrm{X}}}{N_{\mathrm{Y}}} \times \frac{\varepsilon_{\mathrm{Y}}}{\varepsilon_{\mathrm{X}}}, \tag{5.2}$$

where N is the signal yield reported in table 1 and ε denotes the corresponding efficiency. The efficiency is defined as the product of geometric acceptance and of reconstruction, selection, hadron-identification and trigger efficiencies. All of these contributions, except that of the hadron-identification efficiency, are determined using simulated samples, corrected as described in section 2. The hadron-identification efficiency is calculated separately for each hadron track [62], determined from large calibration samples of $D^{*+}\to(D^0\to K^-\pi^+)\,\pi^+$, $K^0_{\mathrm{S}}\to\pi^+\pi^-$ and $D^+_s\to(\phi\to K^+K^-)\,\pi^+$ decays [92]. The measured ratios of branching fractions are

$$
\begin{aligned}
\mathcal{R}^{J/\psi\,K^+K^-\pi^+\pi^+\pi^-}_{J/\psi\,3\pi^+2\pi^-} &= (33.7\pm5.7)\times10^{-2}\,,\\
\mathcal{R}^{J/\psi\,4\pi^+3\pi^-}_{J/\psi\,3\pi^+2\pi^-} &= (28.5\pm8.7)\times10^{-2}\,,\\
\mathcal{R}^{\psi(2\mathrm{S})\pi^+\pi^+\pi^-}_{J/\psi\,3\pi^+2\pi^-} &= (17.6\pm3.6)\times10^{-2}\,,
\end{aligned}
$$

where uncertainties are statistical only and correlation coefficients are listed in table 3.

6 Systematic uncertainties

The decay channels under study have similar kinematics and topologies, therefore, many sources of systematic uncertainty cancel in the branching fraction ratios, $\mathcal{R}^X_Y$. The remaining contributions to the systematic uncertainty are summarised in table 2 and are discussed below.

An important source of systematic uncertainty on the ratios is the imperfect knowledge of the shapes of signal and background components used in the fits. To estimate this uncertainty, several alternative models are tested. For the B_c^+ and $\psi(2\mathrm{S})$ signal shapes, a generalized Student's t-distribution [93, 94] and a modified Apollonios function [95] are employed as an alternative model. For the background components, the degree of the polynomials used in the fits is increased by one. Also, the product of an exponential function and a first-order polynomial function is considered as an alternative background shape. The systematic uncertainty related to the fit model is estimated with large ensembles of pseudoexperiments. For each alternative model an ensemble of pseudoexperiments is generated and each pseudoexperiment is fitted with the baseline model. The maximal deviations in the ratios of the mean values of signal yields over the ensemble with respect to the baseline model do not exceed 2.5% for the variations of the signal model and 1.0% for the variations of background model, and are taken as systematic uncertainties. The sample of $B_c^+\to J/\psi\,3\pi^+2\pi^-$ decays is used to assess the systematic uncertainty due to the procedure of multiple candidate exclusion, if two or more B_c^+ candidates are found from the same pp collision. A large set of pseudoexperiments is performed with a random rejection of multiple candidates. The variation of the signal yield for the $B_c^+\to J/\psi\,3\pi^+2\pi^-$ channel between the pseudoexperiments is found to be of 1.3% and this value is assigned as the corresponding systematic uncertainty.

To assess the systematic uncertainty related to the B_c^+ decay model used in the simulation [49, 69], the reconstructed mass distributions of the light-hadron systems in simulation are adjusted to reproduce the distributions observed in data. The uncertainty associated with the low yield of the target data distributions is accounted for by varying them within their uncertainties. The changes in the ratios $\mathcal{R}^X_Y$ do not exceed 5.1% and are taken as systematic uncertainties related to the B_c^+ decay model.

Source	Uncertainty [%]
Fit model	
Signal shape	0.1 – 2.5
Background shape	0.4 – 1.0
Multiple candidates exclusion	1.3
B_c^+ decay model	2.2 – 5.1
Efficiency corrections	0.1 – 1.1
Hadron interactions	0.0 – 2.8
Trigger efficiency	1.1
Data-simulation difference	2.3
Size of simulated sample	1.5 – 2.4
Total	4.4 – 7.1

Table 2. Ranges of relative systematic uncertainties for the various ratios of branching fractions, $\mathcal{R}_Y^X$. The total systematic uncertainty is the quadratic sum of individual contributions.

An additional uncertainty arises from the difference between data and simulation in the reconstruction efficiency of charged-particle tracks. The track-finding efficiencies obtained from simulation are corrected using data calibration samples [73]. The uncertainties related to the correction factors, together with the uncertainty in the hadron-identification efficiency due to the finite size of the calibration samples [62, 92], are propagated to the ratio of total efficiencies using pseudoexperiments. The obtained systematic uncertainty for the $\mathcal{R}_Y^X$ ratios does not exceed 1.1%. The hadronic interaction length of the detector is known with 10% uncertainty [96]. It corresponds to an additional uncertainty for the track-finding efficiency of 1.1% (1.4%) per charged kaon (pion) track [73, 96, 97]. This uncertainty is assumed to be totally correlated and partly cancels for the ratios. The systematic uncertainty of 1.1% related to the trigger efficiency is estimated by comparing the ratios of trigger efficiencies in data and simulation using large samples of $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)K^+$ decays [98]. Another source of uncertainty is a potential disagreement between data and simulation in the estimation of efficiencies, due to possible effects not explicitly considered above. This is studied by varying the selection criteria of the high yield $B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$ data sample in ranges that lead up to a ±20% change in the measured signal yields. The resulting difference between the efficiencies estimated using data and simulation does not exceed 2.3%, which is taken as a systematic uncertainty for the ratios $\mathcal{R}_Y^X$. The last systematic uncertainty considered is due to the finite size of the simulated samples, and it varies between 1.5% and 2.4%. The total systematic uncertainty is estimated as the quadratic sum of individual contributions. For each choice of the alternative fit model the statistical significance for the channels under study is recalculated from data using Wilks' theorem [84]. The smallest significances found are 9.0, 5.2 and 4.7 standard deviations for the $B_c^+ \to J/\psi\, K^+ K^- \pi^+ \pi^+ \pi^-$, $B_c^+ \to (\psi(2S) \to J/\psi\, \pi^+ \pi^-)\, \pi^+ \pi^+ \pi^-$ and $B_c^+ \to J/\psi\, 4\pi^+ 3\pi^-$ decays, respectively. These values are taken as the significance including systematic uncertainty.

7 Summary

Several $B_c^+ \to J/\psi\, nh^\pm$ decays are studied using proton-proton collision data, corresponding to an integrated luminosity of 9 fb^{-1}, collected with the LHCb detector at centre-of-mass energies of 7, 8, and 13 TeV. The first observation of the decay $B_c^+ \to J/\psi\, K^+K^-\pi^+\pi^+\pi^-$ is reported. The decays $B_c^+ \to J/\psi\, 3\pi^+2\pi^-$ and $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$, with $\psi(2S) \to J/\psi\, \pi^+\pi^-$, are confirmed and the first evidence for the $B_c^+ \to J/\psi\, 4\pi^+3\pi^-$ decay is obtained with a significance of 4.7 standard deviations.

Three ratios of branching fractions, defined in eqs. (5.1), are measured as

$$\begin{aligned}
\mathcal{R}^{J/\psi\, K^+K^-\pi^+\pi^+\pi^-}_{J/\psi\, 3\pi^+2\pi^-} &= (33.7 \pm 5.7 \pm 1.6) \times 10^{-2}\,, \\
\mathcal{R}^{J/\psi\, 4\pi^+3\pi^-}_{J/\psi\, 3\pi^+2\pi^-} &= (28.5 \pm 8.7 \pm 2.0) \times 10^{-2}\,, \\
\mathcal{R}^{\psi(2S)\pi^+\pi^+\pi^-}_{J/\psi\, 3\pi^+2\pi^-} &= (17.6 \pm 3.6 \pm 0.8) \times 10^{-2}\,,
\end{aligned}$$

where the first uncertainty is statistical and the second systematic. Correlation coefficients for statistical and systematic uncertainties for the measured ratios of branching fractions are given in appendix A. The mass spectra for the light-hadron system, as well as the mass spectra for the intermediate combinations of light hadrons agree with the phenomenological model by Berezhnoy, Likhoded and Luchinsky based on QCD factorisation [43–49]. The ratio $\mathcal{R}^{J/\psi\, K^+K^-\pi^+\pi^+\pi^-}_{J/\psi\, 3\pi^+2\pi^-}$ is found to be higher than the analogous ratio of the branching fractions of the $B_c^+ \to J/\psi\, K^+K^-\pi^+$ to $B_c^+ \to J/\psi\, \pi^+\pi^+\pi^-$ decays, which was measured to be equal to $(18.5 \pm 1.3 \pm 0.6) \times 10^{-2}$ [35].

The majority of branching fractions for the B_c^+ mesons are known relative to the $B_c^+ \to J/\psi\, \pi^+$ mode. All measurements presented here can be related to the reference $B_c^+ \to J/\psi\, \pi^+$ decay mode through the $B_c^+ \to \left(\psi(2S) \to J/\psi\, \pi^+\pi^-\right) \pi^+\pi^+\pi^-$ decay mode. The most precise determination can be achieved using a combination of the measurements of the ratio of branching fractions for the $B_c^+ \to \psi(2S)\pi^+\pi^+\pi^-$ and $B_c^+ \to \psi(2S)\pi^+$ decays in ref. [35], and the ratios of the branching fractions for the $B_c^+ \to \psi(2S)\pi^+$, $B_c^+ \to J/\psi\, \pi^+\pi^+\pi^-$ and $B_c^+ \to J/\psi\, \pi^+$ decays from refs. [9, 19, 20].

A Correlation matrices

The correlation coefficients for the statistical and systematic uncertainties of the measured ratios, $\mathcal{R}^X_Y$, are shown in table 3.

	$\mathcal{R}^{J/\psi\, 4\pi^+3\pi^-}_{J/\psi\, 3\pi^+2\pi^-}$		$\mathcal{R}^{\psi(2S)\pi^+\pi^+\pi^-}_{J/\psi\, 3\pi^+2\pi^-}$	
	(stat)	(syst)	(stat)	(syst)
$\mathcal{R}^{J/\psi\, K^+K^-\pi^+\pi^+\pi^-}_{J/\psi\, 3\pi^+2\pi^-}$	+10	+19	+15	+33
$\mathcal{R}^{J/\psi\, 4\pi^+3\pi^-}_{J/\psi\, 3\pi^+2\pi^-}$			+8	+20

Table 3. Off-diagonal correlation coefficients (in percent) for statistical and systematic uncertainties of the measured ratios $\mathcal{R}^X_Y$.

Acknowledgments

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), Polish WLCG (Poland) and NERSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and ARDC (Australia); Minciencias (Colombia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); GVA, XuntaGal, GENCAT and Prog. Atracción Talento, CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

References

[1] CDF collaboration, *Observation of the B_c meson in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV*, Phys. Rev. Lett. **81** (1998) 2432 [hep-ex/9805034] [INSPIRE].

[2] CDF collaboration, *Observation of B_c mesons in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV*, Phys. Rev. D **58** (1998) 112004 [hep-ex/9804014] [INSPIRE].

[3] LHCb collaboration, *Measurement of $\sigma(pp \to b\bar{b}X)$ at $\sqrt{s} = 7$ TeV in the forward region*, Phys. Lett. B **694** (2010) 209 [arXiv:1009.2731] [INSPIRE].

[4] LHCb collaboration, *Measurement of J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C **71** (2011) 1645 [arXiv:1103.0423] [INSPIRE].

[5] LHCb collaboration, *Measurement of the $B^{\pm}$ production cross-section in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP **04** (2012) 093 [arXiv:1202.4812] [INSPIRE].

[6] LHCb collaboration, *Measurement of B meson production cross-sections in proton-proton collisions at $\sqrt{s} = 7$ TeV*, JHEP **08** (2013) 117 [arXiv:1306.3663] [INSPIRE].

[7] LHCb collaboration, *Production of J/ψ and Υ mesons in pp collisions at $\sqrt{s} = 8$ TeV*, JHEP **06** (2013) 064 [arXiv:1304.6977] [INSPIRE].

[8] LHCb collaboration, *Measurement of forward J/ψ production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **10** (2015) 172 [*Erratum ibid.* **05** (2017) 063] [`arXiv:1509.00771`] [INSPIRE].

[9] LHCb collaboration, *First observation of the decay $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$*, *Phys. Rev. Lett.* **108** (2012) 251802 [`arXiv:1204.0079`] [INSPIRE].

[10] LHCb collaboration, *Observation of the decay $B_c^+ \to \psi(2S)\pi^+$*, *Phys. Rev. D* **87** (2013) 071103 [`arXiv:1303.1737`] [INSPIRE].

[11] LHCb collaboration, *Observation of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays*, *Phys. Rev. D* **87** (2013) 112012 [*Addendum ibid.* **89** (2014) 019901] [`arXiv:1304.4530`] [INSPIRE].

[12] LHCb collaboration, *First observation of the decay $B_c^+ \to J/\psi K^+$*, *JHEP* **09** (2013) 075 [`arXiv:1306.6723`] [INSPIRE].

[13] LHCb collaboration, *Observation of the decay $B_c^+ \to B_s^0\pi^+$*, *Phys. Rev. Lett.* **111** (2013) 181801 [`arXiv:1308.4544`] [INSPIRE].

[14] LHCb collaboration, *Observation of the decay $B_c \to J/\psi K^+K^-\pi^+$*, *JHEP* **11** (2013) 094 [`arXiv:1309.0587`] [INSPIRE].

[15] LHCb collaboration, *Evidence for the decay $B_c^+ \to J/\psi 3\pi^+2\pi^-$*, *JHEP* **05** (2014) 148 [`arXiv:1404.0287`] [INSPIRE].

[16] LHCb collaboration, *First observation of a baryonic B_c^+ decay*, *Phys. Rev. Lett.* **113** (2014) 152003 [`arXiv:1408.0971`] [INSPIRE].

[17] LHCb collaboration, *Measurement of B_c^+ production in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Phys. Rev. Lett.* **114** (2015) 132001 [`arXiv:1411.2943`] [INSPIRE].

[18] LHCb collaboration, *Measurement of the lifetime of the B_c^+ meson using the $B_c^+ \to J/\psi\pi^+$ decay mode*, *Phys. Lett. B* **742** (2015) 29 [`arXiv:1411.6899`] [INSPIRE].

[19] CMS collaboration, *Measurement of the ratio of the production cross sections times branching fractions of $B_c^\pm \to J/\psi\pi^\pm$ and $B^\pm \to J/\psi K^\pm$ and $\mathcal{B}(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp)$ $/\mathcal{B}(B_c^\pm \to J/\psi\pi^\pm)$ in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **01** (2015) 063 [`arXiv:1410.5729`] [INSPIRE].

[20] LHCb collaboration, *Measurement of the branching fraction ratio $\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)$ $/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$*, *Phys. Rev. D* **92** (2015) 072007 [`arXiv:1507.03516`] [INSPIRE].

[21] ATLAS collaboration, *Study of the $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays with the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 4 [`arXiv:1507.07099`] [INSPIRE].

[22] LHCb collaboration, *Search for B_c^+ decays to the $p\bar{p}\pi^+$ final state*, *Phys. Lett. B* **759** (2016) 313 [`arXiv:1603.07037`] [INSPIRE].

[23] LHCb collaboration, *Study of B_c^+ decays to the $K^+K^-\pi^+$ final state and evidence for the decay $B_c^+ \to \chi_{c0}\pi^+$*, *Phys. Rev. D* **94** (2016) 091102 [`arXiv:1607.06134`] [INSPIRE].

[24] LHCb collaboration, *Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \to J/\psi K^+)$ $/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$*, *JHEP* **09** (2016) 153 [`arXiv:1607.06823`] [INSPIRE].

[25] LHCb collaboration, *Observation of $B_c^+ \to J/\psi D^{(*)}K^{(*)}$ decays*, *Phys. Rev. D* **95** (2017) 032005 [`arXiv:1612.07421`] [INSPIRE].

[26] LHCb collaboration, *Observation of $B_c^+ \to D^0K^+$ decays*, *Phys. Rev. Lett.* **118** (2017) 111803 [`arXiv:1701.01856`] [INSPIRE].

JHEP07(2023)198

[27] LHCb collaboration, *Measurement of the ratio of branching fractions* $\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)$ $/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$, *Phys. Rev. Lett.* **120** (2018) 121801 [`arXiv:1711.05623`] [INSPIRE].

[28] LHCb collaboration, *Search for* B_c^+ *decays to two charm mesons*, *Nucl. Phys. B* **930** (2018) 563 [`arXiv:1712.04702`] [INSPIRE].

[29] CMS collaboration, *Measurement of b hadron lifetimes in pp collisions at* $\sqrt{s} = 8$ *TeV*, *Eur. Phys. J. C* **78** (2018) 457 [*Erratum ibid.* **78** (2018) 561] [`arXiv:1710.08949`] [INSPIRE].

[30] CMS collaboration, *Observation of two excited* B_c^+ *states and measurement of the* $B_c^+(2S)$ *mass in pp collisions at* $\sqrt{s} = 13$ *TeV*, *Phys. Rev. Lett.* **122** (2019) 132001 [`arXiv:1902.00571`] [INSPIRE].

[31] LHCb collaboration, *Observation of an excited* B_c^+ *state*, *Phys. Rev. Lett.* **122** (2019) 232001 [`arXiv:1904.00081`] [INSPIRE].

[32] LHCb collaboration, *Measurement of the* B_c^- *meson production fraction and asymmetry in* 7 *and* 13 *TeV pp collisions*, *Phys. Rev. D* **100** (2019) 112006 [`arXiv:1910.13404`] [INSPIRE].

[33] LHCb collaboration, *Precision measurement of the* B_c^+ *meson mass*, *JHEP* **07** (2020) 123 [`arXiv:2004.08163`] [INSPIRE].

[34] LHCb collaboration, *Updated search for* B_c^+ *decays to two charm mesons*, *JHEP* **12** (2021) 117 [`arXiv:2109.00488`] [INSPIRE].

[35] LHCb collaboration, *Study of* B_c^+ *decays to charmonia and three light hadrons*, *JHEP* **01** (2022) 065 [`arXiv:2111.03001`] [INSPIRE].

[36] M. Bauer, B. Stech and M. Wirbel, *Exclusive Nonleptonic Decays of* D, D_s, *and* B *Mesons*, *Z. Phys. C* **34** (1987) 103 [INSPIRE].

[37] M. Wirbel, *Description of Weak Decays of* D *and* B *Mesons*, *Prog. Part. Nucl. Phys.* **21** (1988) 33 [INSPIRE].

[38] S.S. Gershtein, V.V. Kiselev, A.K. Likhoded and A.V. Tkabladze, *Physics of* B_c *mesons*, *Phys. Usp.* **38** (1995) 1 [`hep-ph/9504319`] [INSPIRE].

[39] S.S. Gershtein et al., *Theoretical status of the* B_c *meson*, in the proceedings of the *4th International Workshop on Progress in Heavy Quark Physics*, (1997) [`hep-ph/9803433`] [INSPIRE].

[40] V.V. Kiselev, A.K. Likhoded and A.I. Onishchenko, *Semileptonic* B_c *meson decays in sum rules of QCD and NRQCD*, *Nucl. Phys. B* **569** (2000) 473 [`hep-ph/9905359`] [INSPIRE].

[41] V.V. Kiselev, A.E. Kovalsky and A.K. Likhoded, B_c *decays and lifetime in QCD sum rules*, *Nucl. Phys. B* **585** (2000) 353 [`hep-ph/0002127`] [INSPIRE].

[42] D. Ebert, R.N. Faustov and V.O. Galkin, *Properties of heavy quarkonia and* B_c *mesons in the relativistic quark model*, *Phys. Rev. D* **67** (2003) 014027 [`hep-ph/0210381`] [INSPIRE].

[43] A.K. Likhoded and A.V. Luchinsky, *Light hadron production in* $B_c \to J/\psi + X$ *decays*, *Phys. Rev. D* **81** (2010) 014015 [`arXiv:0910.3089`] [INSPIRE].

[44] A.K. Likhoded and A.V. Luchinsky, *Production of a pion system in exclusive* $B_c \to V(P) + n\pi$ *decays*, *Phys. Atom. Nucl.* **76** (2013) 787 [INSPIRE].

[45] A. Berezhnoy, A. Likhoded and A. Luchinsky, $B_c \to J/\psi(B_s, B_s^*) + n\pi$ *decays*, *PoS* **QFTHEP2011** (2013) 076 [`arXiv:1111.5952`] [INSPIRE].

[46] A.V. Luchinsky, *Production of charged π-mesons in exclusive $B_c \to V(P) + n\pi$ decays*, *Phys. Rev. D* **86** (2012) 074024 [`arXiv:1208.1398`] [INSPIRE].

[47] A.V. Luchinsky, *Production of K mesons in exclusive B_c decays*, `arXiv:1307.0953` [INSPIRE].

[48] A.V. Luchinsky, *Excited ρ mesons in $B_c \to \psi^{(\prime)} K K_S$ decays*, *Phys. Rev. D* **99** (2019) 036019 [`arXiv:1812.09783`] [INSPIRE].

[49] A.V. Luchinsky, *Multiple charged meson production in exclusive Bc decays: $K + 4\pi$, $KK + 3\pi$, 7π cases*, *Phys. Lett. B* **832** (2022) 137269 [`arXiv:2204.01136`] [INSPIRE].

[50] G. Wataghin, *Thermal equilibrium between elementary particles*, *Phys. Rev.* **63** (1943) 137.

[51] K. Richter et al., *New state of binding of anti-protons in atoms*, *Phys. Rev. Lett.* **66** (1991) 149 [INSPIRE].

[52] M. Gyulassy, S.K. Kauffmann and L.W. Wilson, *Pion interferometry of nuclear collisions. 1. Theory*, *Phys. Rev. C* **20** (1979) 2267 [INSPIRE].

[53] LHCb collaboration, *The LHCb detector at the LHC*, 2008 *JINST* **3** S08005 [INSPIRE].

[54] LHCb collaboration, *LHCb detector performance*, *Int. J. Mod. Phys. A* **30** (2015) 1530022 [`arXiv:1412.6352`] [INSPIRE].

[55] R. Aaij et al., *Performance of the LHCb vertex locator*, 2014 *JINST* **9** P09007 [`arXiv:1405.7808`] [INSPIRE].

[56] R. Arink et al., *Performance of the LHCb Outer Tracker*, 2014 *JINST* **9** P01002 [`arXiv:1311.3893`] [INSPIRE].

[57] P. d'Argent et al., *Improved performance of the LHCb Outer Tracker in LHC Run 2*, 2017 *JINST* **12** P11016 [`arXiv:1708.00819`] [INSPIRE].

[58] LHCb collaboration, *Measurement of the Λ_b^0, Ξ_b^- and Ω_b^- baryon masses*, *Phys. Rev. Lett.* **110** (2013) 182001 [`arXiv:1302.1072`] [INSPIRE].

[59] LHCb collaboration, *Precision measurement of D meson mass differences*, *JHEP* **06** (2013) 065 [`arXiv:1304.6865`] [INSPIRE].

[60] E. E. Bowen, *Vertexing and tracking software at LHCb*, *PoS* **Vertex2014** (2014) 038 [INSPIRE].

[61] A. Dziurda, *Studies of time-dependent CP violation in charm decays of B_s^0 mesons*, Ph.D. thesis, Institute of Nuclear Physics, Kwakow, Poland (2015).

[62] M. Adinolfi et al., *Performance of the LHCb RICH detector at the LHC*, *Eur. Phys. J. C* **73** (2013) 2431 [`arXiv:1211.6759`] [INSPIRE].

[63] A.A. Alves Jr. et al., *Performance of the LHCb muon system*, 2013 *JINST* **8** P02022 [`arXiv:1211.1346`] [INSPIRE].

[64] R. Aaij et al., *The LHCb Trigger and its Performance in 2011*, 2013 *JINST* **8** P04022 [`arXiv:1211.3055`] [INSPIRE].

[65] T. Sjostrand, S. Mrenna and P.Z. Skands, *A Brief Introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [`arXiv:0710.3820`] [INSPIRE].

[66] I. Belyaev et al., *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, *J. Phys. Conf. Ser.* **331** (2011) 032047 [INSPIRE].

[67] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152 [INSPIRE].

[68] N. Davidson, T. Przedzinski and Z. Was, *PHOTOS interface in C++: technical and physics documentation*, *Comput. Phys. Commun.* **199** (2016) 86 [`arXiv:1011.0937`] [INSPIRE].

[69] A.V. Berezhnoy, A.K. Likhoded and A.V. Luchinsky, *BC_NPI module for the analysis of $B_c \to J/\psi + n\pi$ and $B_c \to B_s + n\pi$ decays within the EvtGen package*, `arXiv:1104.0808` [INSPIRE].

[70] J. Allison et al., *Geant4 developments and applications*, *IEEE Trans. Nucl. Sci.* **53** (2006) 270 [INSPIRE].

[71] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].

[72] M. Clemencic et al., *The LHCb simulation application, Gauss: design, evolution and experience*, *J. Phys. Conf. Ser.* **331** (2011) 032023 [INSPIRE].

[73] LHCb collaboration, *Measurement of the track reconstruction efficiency at LHCb*, 2015 *JINST* **10** P02007 [`arXiv:1408.1251`] [INSPIRE].

[74] LHCb collaboration, *Observation of $B^+ \to J/\psi 3\pi^+ 2\pi^-$ and $B^+ \to \psi(2S)\pi^+\pi^+\pi^-$ decays*, *Eur. Phys. J. C* **77** (2017) 72 [`arXiv:1610.01383`] [INSPIRE].

[75] A. Powell et al., *Particle identification at LHCb*, *PoS* **ICHEP2010** (2010) 020 [INSPIRE].

[76] PARTICLE DATA GROUP collaboration, *Review of particle physics*, *PTEP* **2020** (2020) 083C01 [INSPIRE].

[77] W.D. Hulsbergen, *Decay chain fitting with a Kalman filter*, *Nucl. Instrum. Meth. A* **552** (2005) 566 [`physics/0503191`] [INSPIRE].

[78] LHCb collaboration, *Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J\psi\pi^+\pi^-)\,K^+$ decays*, *JHEP* **08** (2020) 123 [`arXiv:2005.13422`] [INSPIRE].

[79] LHCb collaboration, *Study of $B_s^0 \to J\psi\pi^+\pi^-K^+K^-$ decays*, *JHEP* **02** (2021) 024 [*Erratum ibid.* **04** (2021) 170] [`arXiv:2011.01867`] [INSPIRE].

[80] LHCb collaboration, *Observation of J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Lett. B* **707** (2012) 52 [`arXiv:1109.0963`] [INSPIRE].

[81] T. Skwarnicki, *A study of the radiative CASCADE transitions between the Υ' and Υ resonances*, Ph.D. thesis, Krakow, INP, Poland (1986) [INSPIRE].

[82] E. Byckling and K. Kajantie, *Particle kinematics*, John Wiley & Sons Inc., New York (1973).

[83] LHCb collaboration, *Study of the lineshape of the $\chi_{c1}(3872)$ state*, *Phys. Rev. D* **102** (2020) 092005 [`arXiv:2005.13419`] [INSPIRE].

[84] S.S. Wilks, *The large-sample distribution of the likelihood ratio for testing composite hypotheses*, *Annals Math. Statist.* **9** (1938) 60 [INSPIRE].

[85] M. Pivk and F.R. Le Diberder, *SPlot: a statistical tool to unfold data distributions*, *Nucl. Instrum. Meth. A* **555** (2005) 356 [`physics/0402083`] [INSPIRE].

[86] J.M. Blatt and V.F. Weisskopf, *Theoretical nuclear physics*, Springer, New York (1952) [`DOI:10.1007/978-1-4612-9959-2`] [INSPIRE].

[87] S. Okubo, *ϕ meson and unitary symmetry model*, *Phys. Lett.* **5** (1963) 165 [INSPIRE].

[88] G. Zweig, *An SU_3 model for strong interaction symmetry and its breaking; Version 2*, CERN-TH-412 (1964) [`DOI:10.17181/CERN-TH-412`].

[89] J. Iizuka, *Systematics and phenomenology of meson family*, *Prog. Theor. Phys. Suppl.* **37** (1966) 21 [INSPIRE].

[90] C.P. Singh and C. Singh, *Phenomenology for Okubo-Zweig-Iizuka rule breaking*, *Phys. Lett. B* **68** (1977) 350 [INSPIRE].

[91] C.A. Singh, *Violation of the Okubo-Zweig-Iizuka rule in the decay mode* $B(1235) \to \phi(1020) + \pi$, *Pramana* **9** (1978) 629 [INSPIRE].

[92] 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** (2019) 1 [`arXiv:1803.00824`] [INSPIRE].

[93] W.S. Gosset, *The Probable Error of a Mean*, *Biometrika* **6** (1908) 1.

[94] S. Jackman, *Bayesian analysis for the social sciences*, John Wiley & Sons, Inc., Hoboken, New Jersey, USA (2009).

[95] D. Martínez Santos and F. Dupertuis, *Mass distributions marginalized over per-event errors*, *Nucl. Instrum. Meth. A* **764** (2014) 150 [`arXiv:1312.5000`] [INSPIRE].

[96] LHCb collaboration, *Prompt K_s^0 production in pp collisions at $\sqrt{s} = 0.9$ TeV*, *Phys. Lett. B* **693** (2010) 69 [`arXiv:1008.3105`] [INSPIRE].

[97] LHCb collaboration, *Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **03** (2016) 159 [*Erratum ibid.* **09** (2016) 013] [`arXiv:1510.01707`] [INSPIRE].

[98] LHCb collaboration, *Measurement of relative branching fractions of B decays to $\psi(2S)$ and J/ψ mesons*, *Eur. Phys. J. C* **72** (2012) 2118 [`arXiv:1205.0918`] [INSPIRE].

The LHCb collaboration

R. Aaij[32], A.S.W. Abdelmotteleb[50], C. Abellan Beteta[44], F. Abudinén[50], T. Ackernley[54], B. Adeva[40], M. Adinolfi[48], P. Adlarson[77], H. Afsharnia[9], C. Agapopoulou[13], C.A. Aidala[78], S. Aiola[25], Z. Ajaltouni[9], S. Akar[59], K. Akiba[32], J. Albrecht[15], F. Alessio[42], M. Alexander[53], A. Alfonso Albero[39], Z. Aliouche[56], P. Alvarez Cartelle[49], R. Amalric[13], S. Amato[2], J.L. Amey[48], Y. Amhis[11,42], L. An[42], L. Anderlini[22], M. Andersson[44], A. Andreianov[38], M. Andreotti[21], D. Andreou[62], D. Ao[6], F. Archilli[17], A. Artamonov[38], M. Artuso[62], E. Aslanides[10], M. Atzeni[44], B. Audurier[12], S. Bachmann[17], M. Bachmayer[43], J.J. Back[50], A. Bailly-reyre[13], P. Baladron Rodriguez[40], V. Balagura[12], W. Baldini[21], J. Baptista de Souza Leite[1], M. Barbetti[22,j], R.J. Barlow[56], S. Barsuk[11], W. Barter[55], M. Bartolini[49], F. Baryshnikov[38], J.M. Basels[14], G. Bassi[29,q], B. Batsukh[4], A. Battig[15], A. Bay[43], A. Beck[50], M. Becker[15], F. Bedeschi[29], I.B. Bediaga[1], A. Beiter[62], V. Belavin[38], S. Belin[40], V. Bellee[44], K. Belous[38], I. Belov[38], I. Belyaev[38], G. Benane[10], G. Bencivenni[23], E. Ben-Haim[13], A. Berezhnoy[38], R. Bernet[44], S. Bernet Andres[76], D. Berninghoff[17], H.C. Bernstein[62], C. Bertella[56], A. Bertolin[28], C. Betancourt[44], F. Betti[42], Ia. Bezshyiko[44], S. Bhasin[48], J. Bhom[35], L. Bian[68], M.S. Bieker[15], N.V. Biesuz[21], S. Bifani[47], P. Billoir[13], A. Biolchini[32], M. Birch[55], F.C.R. Bishop[49], A. Bitadze[56], A. Bizzeti, M.P. Blago[49], T. Blake[50], F. Blanc[43], J.E. Blank[15], S. Blusk[62], D. Bobulska[53], J.A. Boelhauve[15], O. Boente Garcia[12], T. Boettcher[59], A. Boldyrev[38], C.S. Bolognani[74], R. Bolzonella[21,i], N. Bondar[38,42], F. Borgato[28], S. Borghi[56], M. Borsato[17], J.T. Borsuk[35], S.A. Bouchiba[43], T.J.V. Bowcock[54], A. Boyer[42], C. Bozzi[21], M.J. Bradley[55], S. Braun[60], A. Brea Rodriguez[40], J. Brodzicka[35], A. Brossa Gonzalo[40], J. Brown[54], D. Brundu[27], A. Buonaura[44], L. Buonincontri[28], A.T. Burke[56], C. Burr[42], A. Bursche[66], A. Butkevich[38], J.S. Butter[32], J. Buytaert[42], W. Byczynski[42], S. Cadeddu[27], H. Cai[68], R. Calabrese[21,i], L. Calefice[15], S. Cali[23], R. Calladine[47], M. Calvi[26,m], M. Calvo Gomez[76], P. Campana[23], D.H. Campora Perez[74], A.F. Campoverde Quezada[6], S. Capelli[26,m], L. Capriotti[20], A. Carbone[20,g], G. Carboni[31], R. Cardinale[24,k], A. Cardini[27], P. Carniti[26,m], L. Carus[14], A. Casais Vidal[40], R. Caspary[17], G. Casse[54], M. Cattaneo[42], G. Cavallero[42], V. Cavallini[21,i], S. Celani[43], J. Cerasoli[10], D. Cervenkov[57], A.J. Chadwick[54], M.G. Chapman[48], M. Charles[13], Ph. Charpentier[42], C.A. Chavez Barajas[54], M. Chefdeville[8], C. Chen[3], S. Chen[4], A. Chernov[35], S. Chernyshenko[46], V. Chobanova[40], S. Cholak[43], M. Chrzaszcz[35], A. Chubykin[38], V. Chulikov[38], P. Ciambrone[23], M.F. Cicala[50], X. Cid Vidal[40], G. Ciezarek[42], G. Ciullo[i,21], P.E.L. Clarke[52], M. Clemencic[42], H.V. Cliff[49], J. Closier[42], J.L. Cobbledick[56], V. Coco[42], J.A.B. Coelho[11], J. Cogan[10], E. Cogneras[9], L. Cojocariu[37], P. Collins[42], T. Colombo[42], L. Congedo[19], A. Contu[27], N. Cooke[47], I. Corredoira [40], G. Corti[42], B. Couturier[42], D.C. Craik[44], M. Cruz Torres[1,e], R. Currie[52], C.L. Da Silva[61], S. Dadabaev[38], L. Dai[65], X. Dai[5], E. Dall'Occo[15], J. Dalseno[40], C. D'Ambrosio[42], J. Daniel[9], A. Danilina[38], P. d'Argent[15], J.E. Davies[56], A. Davis[56], O. De Aguiar Francisco[56], J. de Boer[42], K. De Bruyn[73],

S. De Capua[56], M. De Cian[43], U. De Freitas Carneiro Da Graca[1], E. De Lucia[23],
J.M. De Miranda[1], L. De Paula[2], M. De Serio[19,f], D. De Simone[44], P. De Simone[23],
F. De Vellis[15], J.A. de Vries[74], C.T. Dean[61], F. Debernardis[19,f], D. Decamp[8],
V. Dedu[10], L. Del Buono[13], B. Delaney[58], H.-P. Dembinski[15], V. Denysenko[44],
O. Deschamps[9], F. Dettori[27,h], B. Dey[71], A. Di Cicco[23], P. Di Nezza[23],
I. Diachkov[38], S. Didenko[38], L. Dieste Maronas[40], S. Ding[62], V. Dobishuk[46],
A. Dolmatov[38], C. Dong[3], A.M. Donohoe[18], F. Dordei[27], A.C. dos Reis[1], L. Douglas[53],
A.G. Downes[8], P. Duda[75], M.W. Dudek[35], L. Dufour[42], V. Duk[72], P. Durante[42], M.
M. Duras[75], J.M. Durham[61], D. Dutta[56], A. Dziurda[35], A. Dzyuba[38], S. Easo[51],
U. Egede[63], A. Egorychev[38], V. Egorychev[38], S. Eidelman[38,†], C. Eirea Orro[40],
S. Eisenhardt[52], E. Ejopu[56], S. Ek-In[43], L. Eklund[77], S. Ely[62], A. Ene[37],
E. Epple[59], S. Escher[14], J. Eschle[44], S. Esen[44], T. Evans[56], F. Fabiano[27,h],
L.N. Falcao[1], Y. Fan[6], B. Fang[68], L. Fantini[72,p], M. Faria[43], S. Farry[54],
D. Fazzini[26,m], L.F Felkowski[75], M. Feo[42], M. Fernandez Gomez[40], A.D. Fernez[60],
F. Ferrari[20], L. Ferreira Lopes[43], F. Ferreira Rodrigues[2], S. Ferreres Sole[32],
M. Ferrillo[44], M. Ferro-Luzzi[42], S. Filippov[38], R.A. Fini[19], M. Fiorini[21,i], M. Firlej[34],
K.M. Fischer[57], D.S. Fitzgerald[78], C. Fitzpatrick[56], T. Fiutowski[34], F. Fleuret[12],
M. Fontana[13], F. Fontanelli[24,k], R. Forty[42], D. Foulds-Holt[49], V. Franco Lima[54],
M. Franco Sevilla[60], M. Frank[42], E. Franzoso[21,i], G. Frau[17], C. Frei[42], D.A. Friday[53],
J. Fu[6], Q. Fuehring[15], T. Fulghesu[13], E. Gabriel[32], G. Galati[19,f], M.D. Galati[32],
A. Gallas Torreira[40], D. Galli[20,g], S. Gambetta[52,42], Y. Gan[3], M. Gandelman[2],
P. Gandini[25], Y. Gao[7], Y. Gao[5], M. Garau[27,h], L.M. Garcia Martin[50],
P. Garcia Moreno[39], J. García Pardiñas[26,m], B. Garcia Plana[40], F.A. Garcia Rosales[12],
L. Garrido[39], C. Gaspar[42], R.E. Geertsema[32], D. Gerick[17], L.L. Gerken[15],
E. Gersabeck[56], M. Gersabeck[56], T. Gershon[50], L. Giambastiani[28], V. Gibson[49],
H.K. Giemza[36], A.L. Gilman[57], M. Giovannetti[23,t], A. Gioventù[40],
P. Gironella Gironell[39], C. Giugliano[21,i], M.A. Giza[35], K. Gizdov[52],
E.L. Gkougkousis[42], V.V. Gligorov[13,42], C. Göbel[64], E. Golobardes[76], D. Golubkov[38],
A. Golutvin[55,38], A. Gomes[1,a], S. Gomez Fernandez[39], F. Goncalves Abrantes[57],
M. Goncerz[35], G. Gong[3], I.V. Gorelov[38], C. Gotti[26], J.P. Grabowski[70],
T. Grammatico[13], L.A. Granado Cardoso[42], E. Graugés[39], E. Graverini[43], G. Graziani,
A. T. Grecu[37], L.M. Greeven[32], N.A. Grieser[4], L. Grillo[53], S. Gromov[38],
B.R. Gruberg Cazon[57], C. Gu[3], M. Guarise[21,i], M. Guittiere[11], P. A. Günther[17],
E. Gushchin[38], A. Guth[14], Y. Guz[38], T. Gys[42], T. Hadavizadeh[63], G. Haefeli[43],
C. Haen[42], J. Haimberger[42], S.C. Haines[49], T. Halewood-leagas[54], M.M. Halvorsen[42],
P.M. Hamilton[60], J. Hammerich[54], Q. Han[7], X. Han[17], E.B. Hansen[56],
S. Hansmann-Menzemer[17], L. Hao[6], N. Harnew[57], T. Harrison[54], C. Hasse[42],
M. Hatch[42], J. He[6,c], K. Heijhoff[32], C. Henderson[59], R.D.L. Henderson[63,50],
A.M. Hennequin[58], K. Hennessy[54], L. Henry[42], J. Herd[55], J. Heuel[14], A. Hicheur[2],
D. Hill[43], M. Hilton[56], S.E. Hollitt[15], J. Horswill[56], R. Hou[7], Y. Hou[8], J. Hu[17],
J. Hu[66], W. Hu[5], X. Hu[3], W. Huang[6], X. Huang[68], W. Hulsbergen[32], R.J. Hunter[50],
M. Hushchyn[38], D. Hutchcroft[54], P. Ibis[15], M. Idzik[34], D. Ilin[38], P. Ilten[59],
A. Inglessi[38], A. Iniukhin[38], A. Ishteev[38], K. Ivshin[38], R. Jacobsson[42], H. Jage[14],

S.J. Jaimes Elles[41], S. Jakobsen[42], E. Jans[32], B.K. Jashal[41], A. Jawahery[60],
V. Jevtic[15], E. Jiang[60], X. Jiang[4,6], Y. Jiang[6], M. John[57], D. Johnson[58],
C.R. Jones[49], T.P. Jones[50], B. Jost[42], N. Jurik[42], I. Juszczak[35], S. Kandybei[45],
Y. Kang[3], M. Karacson[42], D. Karpenkov[38], M. Karpov[38], J.W. Kautz[59], F. Keizer[42],
D.M. Keller[62], M. Kenzie[50], T. Ketel[32], B. Khanji[15], A. Kharisova[38],
S. Kholodenko[38], G. Khreich[11], T. Kirn[14], V.S. Kirsebom[43], O. Kitouni[58],
S. Klaver[33], N. Kleijne[29,q], K. Klimaszewski[36], M.R. Kmiec[36], S. Koliiev[46],
A. Kondybayeva[38], A. Konoplyannikov[38], P. Kopciewicz[34], R. Kopecna[17],
P. Koppenburg[32], M. Korolev[38], I. Kostiuk[32,46], O. Kot[46], S. Kotriakhova,
A. Kozachuk[38], P. Kravchenko[38], L. Kravchuk[38], R.D. Krawczyk[42], M. Kreps[50],
S. Kretzschmar[14], P. Krokovny[38], W. Krupa[34], W. Krzemien[36], J. Kubat[17], S. Kubis[75],
W. Kucewicz[35,34], M. Kucharczyk[35], V. Kudryavtsev[38], G.J. Kunde[61], A. Kupsc[77],
D. Lacarrere[42], G. Lafferty[56], A. Lai[27], A. Lampis[27,h], D. Lancierini[44],
C. Landesa Gomez[40], J.J. Lane[56], R. Lane[48], G. Lanfranchi[23], C. Langenbruch[14],
J. Langer[15], O. Lantwin[38], T. Latham[50], F. Lazzari[29,u], M. Lazzaroni[25,l],
R. Le Gac[10], S.H. Lee[78], R. Lefèvre[9], A. Leflat[38], S. Legotin[38], P. Lenisa[i,21],
O. Leroy[10], T. Lesiak[35], B. Leverington[17], A. Li[3], H. Li[66], K. Li[7], P. Li[17],
P.-R. Li[67], S. Li[7], T. Li[4], T. Li[66], Y. Li[4], Z. Li[62], X. Liang[62], C. Lin[6],
T. Lin[51], R. Lindner[42], V. Lisovskyi[15], R. Litvinov[27,h], G. Liu[66], H. Liu[6], Q. Liu[6],
S. Liu[4,6], A. Lobo Salvia[39], A. Loi[27], R. Lollini[72], J. Lomba Castro[40], I. Longstaff[53],
J.H. Lopes[2], A. Lopez Huertas[39], S. López Soliño[40], G.H. Lovell[49], Y. Lu[4,b],
C. Lucarelli[22,j], D. Lucchesi[28,o], S. Luchuk[38], M. Lucio Martinez[74],
V. Lukashenko[32,46], Y. Luo[3], A. Lupato[56], E. Luppi[21,i], A. Lusiani[29,q], K. Lynch[18],
X.-R. Lyu[6], L. Ma[4], R. Ma[6], S. Maccolini[20], F. Machefert[11], F. Maciuc[37],
I. Mackay[57], V. Macko[43], P. Mackowiak[15], L.R. Madhan Mohan[48], A. Maevskiy[38],
D. Maisuzenko[38], M.W. Majewski[34], J.J. Malczewski[35], S. Malde[57], B. Malecki[35,42],
A. Malinin[38], T. Maltsev[38], G. Manca[27,h], G. Mancinelli[10], C. Mancuso[11,25,l],
D. Manuzzi[20], C.A. Manzari[44], D. Marangotto[25,l], J.F. Marchand[8], U. Marconi[20],
S. Mariani[22,j], C. Marin Benito[39], J. Marks[17], A.M. Marshall[48], P.J. Marshall[54],
G. Martelli[72,p], G. Martellotti[30], L. Martinazzoli[42,m], M. Martinelli[26,m],
D. Martinez Santos[40], F. Martinez Vidal[41], A. Massafferri[1], M. Materok[14], R. Matev[42],
A. Mathad[44], V. Matiunin[38], C. Matteuzzi[26], K.R. Mattioli[12], A. Mauri[32],
E. Maurice[12], J. Mauricio[39], M. Mazurek[42], M. McCann[55], L. Mcconnell[18],
T.H. McGrath[56], N.T. McHugh[53], A. McNab[56], R. McNulty[18], J.V. Mead[54],
B. Meadows[59], G. Meier[15], D. Melnychuk[36], S. Meloni[26,m], M. Merk[32,74],
A. Merli[25,l], L. Meyer Garcia[2], D. Miao[4,6], M. Mikhasenko[70,d], D.A. Milanes[69],
E. Millard[50], M. Milovanovic[42], M.-N. Minard[8,†], A. Minotti[26,m], T. Miralles[9],
S.E. Mitchell[52], B. Mitreska[56], D.S. Mitzel[15], A. Mödden[15], R.A. Mohammed[57],
R.D. Moise[14], S. Mokhnenko[38], T. Mombächer[40], M. Monk[50,63], I.A. Monroy[69],
S. Monteil[9], M. Morandin[28], G. Morello[23], M.J. Morello[29,q], J. Moron[34],
A.B. Morris[70], A.G. Morris[50], R. Mountain[62], H. Mu[3], E. Muhammad[50],
F. Muheim[52], M. Mulder[73], K. Müller[44], C.H. Murphy[57], D. Murray[56], R. Murta[55],
P. Muzzetto[27,h], P. Naik[48], T. Nakada[43], R. Nandakumar[51], T. Nanut[42], I. Nasteva[2],

M. Needham[52], N. Neri[25,l], S. Neubert[70], N. Neufeld[42], P. Neustroev[38], R. Newcombe[55], J. Nicolini[15,11], E.M. Niel[43], S. Nieswand[14], N. Nikitin[38], N.S. Nolte[58], C. Normand[8,h,27], J. Novoa Fernandez[40], C. Nunez[78], A. Oblakowska-Mucha[34], V. Obraztsov[38], T. Oeser[14], D.P. O'Hanlon[48], S. Okamura[21,i], R. Oldeman[27,h], F. Oliva[52], C.J.G. Onderwater[73], R.H. O'Neil[52], J.M. Otalora Goicochea[2], T. Ovsiannikova[38], P. Owen[44], A. Oyanguren[41], O. Ozcelik[52], K.O. Padeken[70], B. Pagare[50], P.R. Pais[42], T. Pajero[57], A. Palano[19], M. Palutan[23], Y. Pan[56], G. Panshin[38], L. Paolucci[50], A. Papanestis[51], M. Pappagallo[19,f], L.L. Pappalardo[21,i], C. Pappenheimer[59], W. Parker[60], C. Parkes[56], B. Passalacqua[21,i], G. Passaleva[22], A. Pastore[19], M. Patel[55], C. Patrignani[20,g], C.J. Pawley[74], A. Pearce[42], A. Pellegrino[32], M. Pepe Altarelli[42], S. Perazzini[20], D. Pereima[38], A. Pereiro Castro[40], P. Perret[9], M. Petric[53], K. Petridis[48], A. Petrolini[24,k], A. Petrov[38], S. Petrucci[52], M. Petruzzo[25], H. Pham[62], A. Philippov[38], R. Piandani[6], L. Pica[29,q], M. Piccini[72], B. Pietrzyk[8], G. Pietrzyk[11], M. Pili[57], D. Pinci[30], F. Pisani[42], M. Pizzichemi[26,m,42], V. Placinta[37], J. Plews[47], M. Plo Casasus[40], F. Polci[13,42], M. Poli Lener[23], M. Poliakova[62], A. Poluektov[10], N. Polukhina[38], I. Polyakov[42], E. Polycarpo[2], S. Ponce[42], D. Popov[6,42], S. Popov[38], S. Poslavskii[38], K. Prasanth[35], L. Promberger[17], C. Prouve[40], V. Pugatch[46], V. Puill[11], G. Punzi[29,r], H.R. Qi[3], W. Qian[6], N. Qin[3], S. Qu[3], R. Quagliani[43], N.V. Raab[18], R.I. Rabadan Trejo[6], B. Rachwal[34], J.H. Rademacker[48], R. Rajagopalan[62], M. Rama[29], M. Ramos Pernas[50], M.S. Rangel[2], F. Ratnikov[38], G. Raven[33,42], M. Rebollo De Miguel[41], F. Redi[42], J. Reich[48], F. Reiss[56], C. Remon Alepuz[41], Z. Ren[3], P.K. Resmi[10], R. Ribatti[29,q], A.M. Ricci[27], S. Ricciardi[51], K. Richardson[58], M. Richardson-Slipper[52], K. Rinnert[54], P. Robbe[11], G. Robertson[52], A.B. Rodrigues[43], E. Rodrigues[54], E. Rodriguez Fernandez[40], J.A. Rodriguez Lopez[69], E. Rodriguez Rodriguez[40], D.L. Rolf[42], A. Rollings[57], P. Roloff[42], V. Romanovskiy[38], M. Romero Lamas[40], A. Romero Vidal[40], J.D. Roth[78,†], M. Rotondo[23], M.S. Rudolph[62], T. Ruf[42], R.A. Ruiz Fernandez[40], J. Ruiz Vidal[41], A. Ryzhikov[38], J. Ryzka[34], J.J. Saborido Silva[40], N. Sagidova[38], N. Sahoo[47], B. Saitta[27,h], M. Salomoni[42], C. Sanchez Gras[32], I. Sanderswood[41], R. Santacesaria[30], C. Santamarina Rios[40], M. Santimaria[23], E. Santovetti[31,t], D. Saranin[38], G. Sarpis[14], M. Sarpis[70], A. Sarti[30], C. Satriano[30,s], A. Satta[31], M. Saur[15], D. Savrina[38], H. Sazak[9], L.G. Scantlebury Smead[57], A. Scarabotto[13], S. Schael[14], S. Scherl[54], M. Schiller[53], H. Schindler[42], M. Schmelling[16], B. Schmidt[42], S. Schmitt[14], O. Schneider[43], A. Schopper[42], M. Schubiger[32], S. Schulte[43], M.H. Schune[11], R. Schwemmer[42], B. Sciascia[23,42], A. Sciuccati[42], S. Sellam[40], A. Semennikov[38], M. Senghi Soares[33], A. Sergi[24,k], N. Serra[44], L. Sestini[28], A. Seuthe[15], Y. Shang[5], D.M. Shangase[78], M. Shapkin[38], I. Shchemerov[38], L. Shchutska[43], T. Shears[54], L. Shekhtman[38], Z. Shen[5], S. Sheng[4,6], V. Shevchenko[38], B. Shi[6], E.B. Shields[26,m], Y. Shimizu[11], E. Shmanin[38], R. Shorkin[38], J.D. Shupperd[62], B.G. Siddi[21,i], R. Silva Coutinho[62], G. Simi[28], S. Simone[19,f], M. Singla[63], N. Skidmore[56], R. Skuza[17], T. Skwarnicki[62], M.W. Slater[47], J.C. Smallwood[57], J.G. Smeaton[49], E. Smith[44], K. Smith[61], M. Smith[55], A. Snoch[32], L. Soares Lavra[9], M.D. Sokoloff[59], F.J.P. Soler[53],

A. Solomin[38,48], A. Solovev[38], I. Solovyev[38], R. Song[63], F.L. Souza De Almeida[2], B. Souza De Paula[2], B. Spaan[15,†], E. Spadaro Norella[25,l], E. Spedicato[20], E. Spiridenkov[38], P. Spradlin[53], V. Sriskaran[42], F. Stagni[42], M. Stahl[42], S. Stahl[42], S. Stanislaus[57], E.N. Stein[42], O. Steinkamp[44], O. Stenyakin[38], H. Stevens[15], S. Stone[62,†], D. Strekalina[38], F. Suljik[57], J. Sun[27], L. Sun[68], Y. Sun[60], P. Svihra[56], P.N. Swallow[47], K. Swientek[34], A. Szabelski[36], T. Szumlak[34], M. Szymanski[42], Y. Tan[3], S. Taneja[56], A.R. Tanner[48], M.D. Tat[57], A. Terentev[38], F. Teubert[42], E. Thomas[42], D.J.D. Thompson[47], K.A. Thomson[54], H. Tilquin[55], V. Tisserand[9], S. T'Jampens[8], M. Tobin[4], L. Tomassetti[21,i], G. Tonani[25,l], X. Tong[5], D. Torres Machado[1], D.Y. Tou[3], S.M. Trilov[48], C. Trippl[43], G. Tuci[6], A. Tully[43], N. Tuning[32], A. Ukleja[36], D.J. Unverzagt[17], A. Usachov[32], A. Ustyuzhanin[38], U. Uwer[17], A. Vagner[38], V. Vagnoni[20], A. Valassi[42], G. Valenti[20], N. Valls Canudas[76], M. van Beuzekom[32], M. Van Dijk[43], H. Van Hecke[61], E. van Herwijnen[55], C.B. Van Hulse[40,w], M. van Veghel[73], R. Vazquez Gomez[39], P. Vazquez Regueiro[40], C. Vázquez Sierra[42], S. Vecchi[21], J.J. Velthuis[48], M. Veltri[22,v], A. Venkateswaran[43], M. Veronesi[32], M. Vesterinen[50], D. Vieira[59], M. Vieites Diaz[43], X. Vilasis-Cardona[76], E. Vilella Figueras[54], A. Villa[20], P. Vincent[13], F.C. Volle[11], D. vom Bruch[10], A. Vorobyev[38], V. Vorobyev[38], N. Voropaev[38], K. Vos[74], C. Vrahas[52], R. Waldi[17], J. Walsh[29], G. Wan[5], C. Wang[17], G. Wang[7], J. Wang[5], J. Wang[4], J. Wang[3], J. Wang[68], M. Wang[5], R. Wang[48], X. Wang[66], Y. Wang[7], Z. Wang[44], Z. Wang[3], Z. Wang[6], J.A. Ward[50,63], N.K. Watson[47], D. Websdale[55], Y. Wei[5], C. Weisser[58], B.D.C. Westhenry[48], D.J. White[56], M. Whitehead[53], A.R. Wiederhold[50], D. Wiedner[15], G. Wilkinson[57], M.K. Wilkinson[59], I. Williams[49], M. Williams[58], M.R.J. Williams[52], R. Williams[49], F.F. Wilson[51], W. Wislicki[36], M. Witek[35], L. Witola[17], C.P. Wong[61], G. Wormser[11], S.A. Wotton[49], H. Wu[62], J. Wu[7], K. Wyllie[42], Z. Xiang[6], D. Xiao[7], Y. Xie[7], A. Xu[5], J. Xu[6], L. Xu[3], L. Xu[3], M. Xu[50], Q. Xu[6], Z. Xu[9], Z. Xu[6], D. Yang[3], S. Yang[6], X. Yang[5], Y. Yang[6], Z. Yang[5], Z. Yang[60], L.E. Yeomans[54], V. Yeroshenko[11], H. Yeung[56], H. Yin[7], J. Yu[65], X. Yuan[62], E. Zaffaroni[43], M. Zavertyaev[16], M. Zdybal[35], O. Zenaiev[42], M. Zeng[3], C. Zhang[5], D. Zhang[7], L. Zhang[3], S. Zhang[65], S. Zhang[5], Y. Zhang[5], Y. Zhang[57], A. Zharkova[38], A. Zhelezov[17], Y. Zheng[6], T. Zhou[5], X. Zhou[6], Y. Zhou[6], V. Zhovkovska[11], X. Zhu[3], X. Zhu[7], Z. Zhu[6], V. Zhukov[14,38], Q. Zou[4,6], S. Zucchelli[20,g], D. Zuliani[28], G. Zunica[56]

[1] *Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*
[2] *Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*
[3] *Center for High Energy Physics, Tsinghua University, Beijing, China*
[4] *Institute Of High Energy Physics (IHEP), Beijing, China*
[5] *School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[6] *University of Chinese Academy of Sciences, Beijing, China*
[7] *Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*
[8] *Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*
[9] *Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[10] *Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*

[11] Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
[12] Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
[13] LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
[14] I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
[15] Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
[16] Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
[17] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[18] School of Physics, University College Dublin, Dublin, Ireland
[19] INFN Sezione di Bari, Bari, Italy
[20] INFN Sezione di Bologna, Bologna, Italy
[21] INFN Sezione di Ferrara, Ferrara, Italy
[22] INFN Sezione di Firenze, Firenze, Italy
[23] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[24] INFN Sezione di Genova, Genova, Italy
[25] INFN Sezione di Milano, Milano, Italy
[26] INFN Sezione di Milano-Bicocca, Milano, Italy
[27] INFN Sezione di Cagliari, Monserrato, Italy
[28] Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy
[29] INFN Sezione di Pisa, Pisa, Italy
[30] INFN Sezione di Roma La Sapienza, Roma, Italy
[31] INFN Sezione di Roma Tor Vergata, Roma, Italy
[32] Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands
[33] Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands
[34] AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
[35] Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
[36] National Center for Nuclear Research (NCBJ), Warsaw, Poland
[37] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
[38] Affiliated with an institute covered by a cooperation agreement with CERN
[39] ICCUB, Universitat de Barcelona, Barcelona, Spain
[40] Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
[41] Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
[42] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[43] Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[44] Physik-Institut, Universität Zürich, Zürich, Switzerland
[45] NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
[46] Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
[47] University of Birmingham, Birmingham, United Kingdom
[48] H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
[49] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[50] Department of Physics, University of Warwick, Coventry, United Kingdom
[51] STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
[52] School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[53] School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[55] Imperial College London, London, United Kingdom
[56] Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[57] Department of Physics, University of Oxford, Oxford, United Kingdom
[58] Massachusetts Institute of Technology, Cambridge, MA, United States

JHEP07(2023)198

[59] *University of Cincinnati, Cincinnati, OH, United States*
[60] *University of Maryland, College Park, MD, United States*
[61] *Los Alamos National Laboratory (LANL), Los Alamos, NM, United States*
[62] *Syracuse University, Syracuse, NY, United States*
[63] *School of Physics and Astronomy, Monash University, Melbourne, Australia, associated to* [50]
[64] *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to* [2]
[65] *Physics and Micro Electronic College, Hunan University, Changsha City, China, associated to* [7]
[66] *Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China, associated to* [3]
[67] *Lanzhou University, Lanzhou, China, associated to* [4]
[68] *School of Physics and Technology, Wuhan University, Wuhan, China, associated to* [3]
[69] *Departamento de Fisica , Universidad Nacional de Colombia, Bogota, Colombia, associated to* [13]
[70] *Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany, associated to* [17]
[71] *Eotvos Lorand University, Budapest, Hungary, associated to* [42]
[72] *INFN Sezione di Perugia, Perugia, Italy, associated to* [21]
[73] *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to* [32]
[74] *Universiteit Maastricht, Maastricht, Netherlands, associated to* [32]
[75] *Tadeusz Kosciuszko Cracow University of Technology, Cracow, Poland, associated to* [35]
[76] *DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain, associated to* [39]
[77] *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, associated to* [53]
[78] *University of Michigan, Ann Arbor, MI, United States, associated to* [62]

[a] *Universidade de Brasília, Brasília, Brazil*
[b] *Central South U., Changsha, China*
[c] *Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China*
[d] *Excellence Cluster ORIGINS, Munich, Germany*
[e] *Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras*
[f] *Università di Bari, Bari, Italy*
[g] *Università di Bologna, Bologna, Italy*
[h] *Università di Cagliari, Cagliari, Italy*
[i] *Università di Ferrara, Ferrara, Italy*
[j] *Università di Firenze, Firenze, Italy*
[k] *Università di Genova, Genova, Italy*
[l] *Università degli Studi di Milano, Milano, Italy*
[m] *Università di Milano Bicocca, Milano, Italy*
[n] *Università di Modena e Reggio Emilia, Modena, Italy*
[o] *Università di Padova, Padova, Italy*
[p] *Università di Perugia, Perugia, Italy*
[q] *Scuola Normale Superiore, Pisa, Italy*
[r] *Università di Pisa, Pisa, Italy*
[s] *Università della Basilicata, Potenza, Italy*
[t] *Università di Roma Tor Vergata, Roma, Italy*
[u] *Università di Siena, Siena, Italy*
[v] *Università di Urbino, Urbino, Italy*
[w] *Universidad de Alcalá, Alcalá de Henares, Spain*
† *Deceased*