Observation of the $B_c^+ \to J/\psi\pi^+\pi^0$ decay

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ABSTRACT: The first observation of the $B_c^+ \to J/\psi\pi^+\pi^0$ decay is reported with high significance using proton-proton collision data, corresponding to an integrated luminosity of $9\,\mathrm{fb}^{-1}$, collected with the LHCb detector at centre-of-mass energies of 7, 8, and 13 TeV. The ratio of its branching fraction relative to the $B_c^+ \to J/\psi\pi^+$ channel is measured to be

$$\frac{\mathcal{B}_{B_c^+ \to J/\psi\pi^+\pi^0}}{\mathcal{B}_{B_c^+ \to J/\psi\pi^+}} = 2.80 \pm 0.15 \pm 0.11 \pm 0.16 \,,$$

where the first uncertainty is statistical, the second systematic and the third related to imprecise knowledge of the branching fractions for $B^+ \to J/\psi K^{*+}$ and $B_c^+ \to J/\psi\pi^+$ decays, which are used to determine the π^0 detection efficiency. The $\pi^+\pi^0$ mass spectrum is found to be consistent with the dominance of an intermediate ρ^+ contribution in accordance with a model based on QCD factorisation.

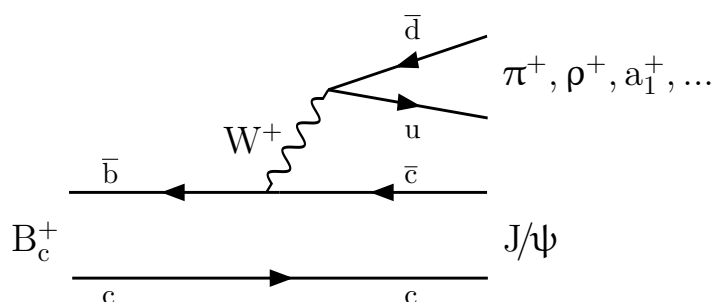KEYWORDS: B Physics, Hadron-Hadron Scattering, QCD, Spectroscopy

Contents

1 Introduction

The B_c^+ meson, consisting of two heavy quarks of different flavours, was discovered by the CDF collaboration [1, 2] at the Tevatron collider, and is the heaviest meson that can decay only through the weak interaction. The large b-quark production cross-section at the Large Hadron Collider (LHC) [3–8] enables the ATLAS, CMS and LHCb experiments to study in detail the production, decays and other properties of the B_c^+ meson [9–39].

The B_c^+ decay may proceed through the weak decay of either of its heavy constituents with the other quark playing the role of spectator, or by a $\overline{b}c$ annihilation into a virtual W^+ boson. The lifetime of the B_c^+ meson is about three times smaller [20, 23, 32] than that of the B^0 and B^+ mesons [40], confirming the important role played by the charm quark in B_c^+ meson decays. Its decay to charmonium and light hadrons proceeds via the spectator diagram as shown in figure 1, which is described by the quantum chromodynamics (QCD) factorisation approach [41, 42] using the form factors of the $B_c^+ \to [c\overline{c}]W^+$ transition [43–47] and the universal spectral function for the transition of the virtual W^+ boson into light hadrons [48–51]. This approach works remarkably well for all known decays of the B_c^+ meson into charmonia with an odd number of light hadrons in the final state [9–17].

The $B_c^+ \to J/\psi\pi^+\pi^0$ mode, which is the simplest decay into a charmonium state and an even number of light hadrons, has not yet been observed. Its final state is expected to be dominated by the $B_c^+ \to J/\psi\rho^+$ mode with a small admixture of $B_c^+ \to J/\psi\rho(1450)^+$ decays [52]. There are many predictions for the branching fraction ratio $\mathcal{R}$ of this decay relative to the $B_c^+ \to J/\psi\pi^+$ mode,

$$\mathcal{R} \equiv \frac{\mathcal{B}_{B_c^+\to J/\psi\pi^+\pi^0}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}}, \tag{1.1}$$

Figure 1. Diagram for the decays of the B_c^+ meson into the J/ψ meson and light hadrons.

which vary from 2.5 to 5.7 [46, 48, 53–69]. This decay is an important background source for the study of other decays of B_c^+ mesons [39] as well as rare decays of B^0 mesons [70].

This paper reports on the first observation of $B_c^+ \to J/\psi \pi^+ \pi^0$ decays[1] and the measurement of $\mathcal{R}$. A sample of the $B_c^+ \to J/\psi \pi^+$ mode is used for normalisation and a high-yield sample of $B^+ \to J/\psi \left(K^{*+} \to K^+ \pi^0 \right)$ decays is used to correct the detector resolution and any potential mass bias. The analysis is performed using proton-proton (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 [71, 72] 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 [73], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 T m, and three stations of silicon-strip detectors and straw drift tubes [74, 75] placed downstream of the magnet. The tracking system provides a measurement of the momentum p of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c. The minimum distance of a track to a primary pp collision vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T)$ μm, where p_T is the component of the momentum transverse to the beam in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov (RICH) detectors [76]. 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 [77].

The online event selection is performed by a trigger [78], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. 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

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[1]In this paper inclusion of charge-conjugate decays is implied.

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 samples of $B_c^+ \to J/\psi\pi^+\pi^0$, $B^+ \to J/\psi\,(K^{*+} \to K^+\pi^0)$ and $B_c^+ \to J/\psi\pi^+$ decays are used to model the signal mass shapes, optimise the selection requirements and compute the efficiencies needed to determine the branching fraction ratios. The PYTHIA [79] generator with a specific LHCb configuration [80] is used to simulate B^+ meson production from pp collisions. The BCVEGPY generator [81–84], which is interfaced to the PYTHIA parton shower and hadronisation model, is used to simulate B_c^+ meson production. The generator implements the complete lowest-order (α_s^4) perturbative QCD calculations of the dominant gluon-gluon fusion $gg \to B_c^+ + \overline{c} + b$ and $gg \to B_c^{*+} + \overline{c} + b$ processes, neglecting the contribution from the quark-pair annihilation $q\overline{q} \to B_c^+ + \overline{c} + b$ and $q\overline{q} \to B_c^{*+} + \overline{c} + b$ channels [85–89].

Decays of unstable particles are described by the EVTGEN package [90], in which final-state radiation is generated using PHOTOS [91]. The "BLL" model for $B_c^+ \to J/\psi\pi^+\pi^0$ decays [48–51, 92] assumes the factorisation into $B_c^+ \to J/\psi W^{*+}$ with a subsequent $W^{*+} \to \rho^+$ transition with a tiny fraction of $W^{*+} \to \rho(1450)^+$ in accordance with the model by Kühn and Santamaria [93] and the measurement of the hadronic structure of the $\tau^+ \to \pi^+\pi^0\overline{\nu}_\tau$ decay by the CLEO collaboration [94]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [95, 96] as described in ref. [97]. The transverse momentum and rapidity spectra of the B_c^+ mesons in simulated samples are adjusted to match those observed in a high-yield, low-background sample of reconstructed $B_c^+ \to J/\psi\pi^+$ decays. The detector response used for the identification of pions and kaons is sampled from $D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+$ and $K_S^0 \to \pi^+\pi^-$ calibration channels [76, 98]. To account for imperfections in the simulation of charged-particle reconstruction, the track-reconstruction efficiency determined from simulation is corrected using calibration samples of $J/\psi \to \mu^+\mu^-$ decays [99]. Samples of $B^+ \to J/\psi\,(K^{*+} \to K^+\,(\pi^0 \to \gamma\gamma))$ decays are used to correct the photon reconstruction efficiency in the simulation [100–104].

3 Event selection

The signal $B_c^+ \to J/\psi\pi^+\pi^0$ and control $B^+ \to J/\psi\,(K^{*+} \to K^+\pi^0)$ candidates are reconstructed using $J/\psi \to \mu^+\mu^-$ decays. The same dimuon final state of the J/ψ meson is used to reconstruct the normalisation $B_c^+ \to J/\psi\pi^+$ candidates. A loose preselection similar to that used in refs. [14, 39, 105] is applied, followed by a multivariate classifier to select a higher purity subset of candidates.

Muons, pions and kaons are identified by combining information from the RICH, calorimeter and muon detectors, and they are required to have transverse momenta larger than $500\,\mathrm{MeV}/c$. Pions and kaons are further required to have a momentum between 3.2 and $150\,\mathrm{GeV}/c$ to ensure good performance of the particle identification in the RICH detectors [76, 106]. To reduce the combinatorial background due to charged particles produced in pp interactions, only tracks that are inconsistent with originating from any PV are used. Photons are reconstructed from clusters in the electromagnetic calorimeter with transverse energy above $300\,\mathrm{MeV}$. The clusters must not be associated with reconstructed tracks [107, 108].

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
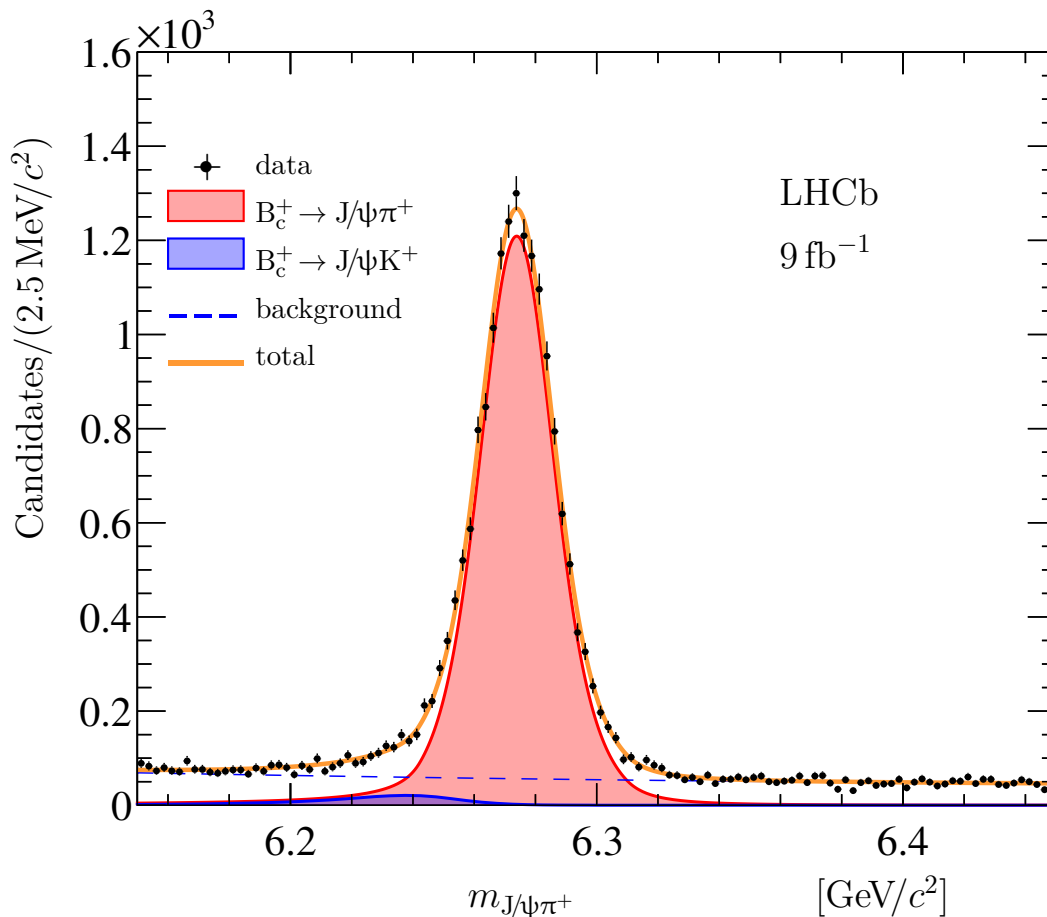
required to be within the range $3.0 < m_{\mu^+\mu^-} < 3.2\,\text{GeV}/c^2$. The position of the reconstructed dimuon vertex is required to be separated from any reconstructed PV. The π^0 candidates are reconstructed as diphoton pairs with mass within $30\,\text{MeV}/c^2$ of the known mass of the π^0 meson [40].

The selected $\text{J}/\psi\pi^+\pi^0$, $\text{J}/\psi\pi^+$ and $\text{J}/\psi\text{K}^+\pi^0$ combinations are used to form the B_c^+ and B^+ candidates. The $\pi^+\pi^0$ mass $m_{\pi^+\pi^0}$ is required to satisfy $620 < m_{\pi^+\pi^0} < 920\,\text{MeV}/c^2$ and the $\text{K}^+\pi^0$ mass must be within $50\,\text{MeV}/c^2$ of the known mass of the K^{*+} meson [40]. To improve the mass resolution for the B mesons, a kinematic fit [109] constrains the masses of the J/ψ and π^0 candidates to their known values [40] and requires the B candidates to originate from their associated PV.[2] The decay time t_B of the B_c^+ (B^+) candidates is required to satisfy $0.1 < t_\text{B} < 1.0\,\text{mm}/c$ ($0.2 < t_\text{B} < 2.0\,\text{mm}/c$) to suppress the large combinatorial background from tracks produced at the PV and from misreconstructed B candidates. The $\text{B}_\text{c}^+ \to \text{J}/\psi\pi^+\pi^0$ candidates with a $\text{J}/\psi\pi^+$ mass within $45\,\text{MeV}/c^2$ of the known mass of the B_c^+ meson are vetoed to avoid contamination from $\text{B}_\text{c}^+ \to \text{J}/\psi\pi^+$ decays with a random π^0 added. Similarly, candidates with the $\text{J}/\psi\pi^+$ mass between 5.180 and $5.305\,\text{GeV}/c^2$ are also vetoed to remove the background from $\text{B}^+ \to \text{J}/\psi\pi^+$ and $\text{B}^+ \to \text{J}/\psi\text{K}^+$ decays with a random π^0 added.

Further selection of the B_c^+ and B^+ candidates is based on a multivariate estimator known as a multi-layer perceptron (MLP) classifier. The MLP classifier is based on an artificial neural network algorithm [110, 111] configured with a cross-entropy cost estimator [112]. It reduces the combinatorial background to a low level while retaining a high signal efficiency. Three MLP classifiers are trained separately for the signal, normalisation and control candidates. The variables used in the classifiers include those related to the reconstruction quality, kinematics and decay time of the B_c^+ and B^+ candidates, kinematics of the final-state hadrons and photons, as well as a variable that characterises the identification of charged pions and kaons. The classifiers are trained using simulated signal samples, while the B_c^+ and B^+ candidates from data with mass outside the regions $6.00 < m_{\text{J}/\psi\pi^+\pi^0} < 6.50\,\text{GeV}/c^2$, $6.20 < m_{\text{J}/\psi\pi^+} < 6.34\,\text{GeV}/c^2$ and $5.10 < m_{\text{J}/\psi\text{K}^+\pi^0} < 5.50\,\text{GeV}/c^2$ are used to represent the background for the signal, normalisation and control modes, respectively. The k-fold cross-validation technique [113] with $k = 11$ is used to avoid introducing a bias in the MLP evaluation. The requirement on each of the MLP classifiers is chosen to maximise the figure-of-merit defined as $S/\sqrt{S + \kappa B}$, where S represents the expected signal yield, B is the background yield and κ is the fraction of the total background that affects the signal determination. The background yield B is calculated from fits to data, while $S = \varepsilon S_0$, where ε is the efficiency of the requirement on the response of the MLP classifier determined from simulation and S_0 is the signal yield obtained from the fit to the data with a loose requirement applied. The factor κ is determined from pseudoexperiments. The mass distributions for the selected $\text{B}_\text{c}^+ \to \text{J}/\psi\pi^+$, $\text{B}^+ \to \text{J}/\psi\text{K}^{*+}$ and $\text{B}_\text{c}^+ \to \text{J}/\psi\pi^+\pi^0$ candidates are shown in figures 2, 3 and 4, respectively.

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[2] Each B_c^+ or B^+ candidate is associated with the PV that yields the smallest χ^2_{IP}, which is defined as the difference in the vertex-fit χ^2 of a given PV reconstructed with and without the particle under consideration.
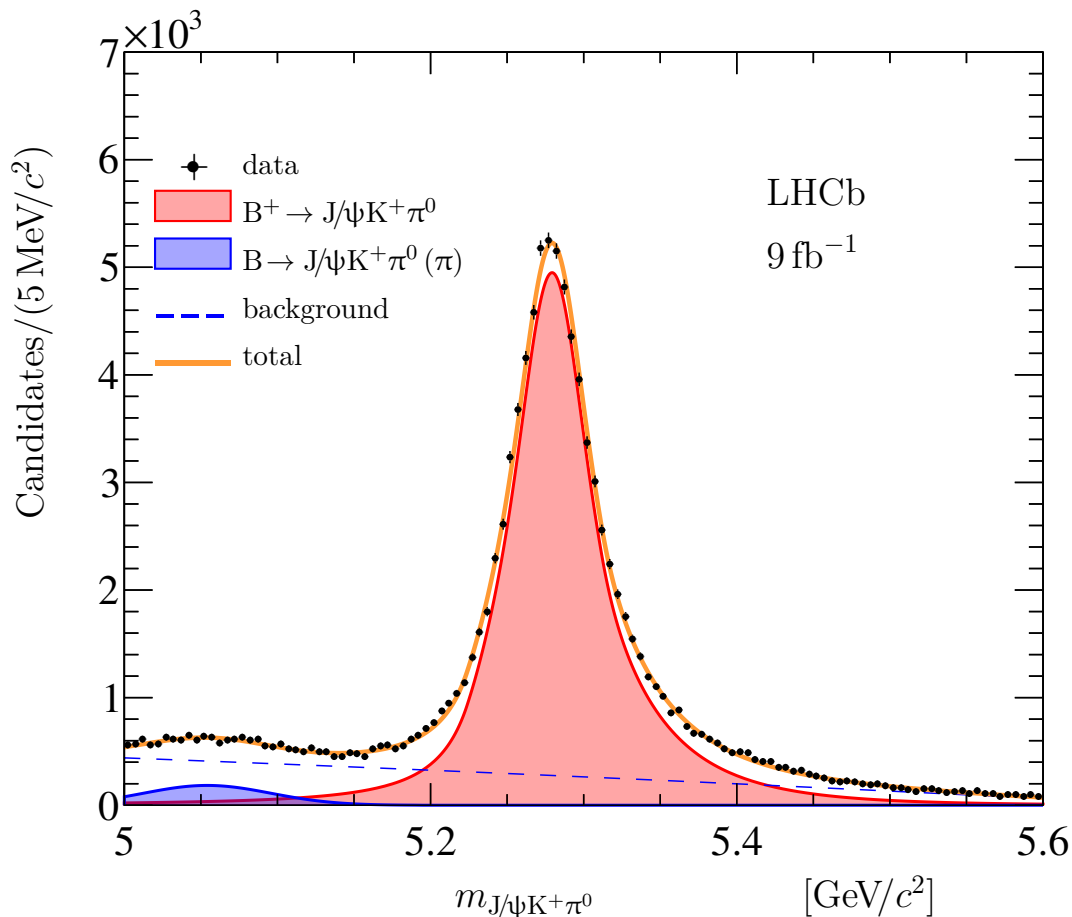
Figure 2. Mass distribution for selected $B_c^+ \to J/\psi\pi^+$ candidates with the result of the fit described in the text.

4 Determination of signal yields

The yields for the normalisation $B_c^+ \to J/\psi\pi^+$, control $B^+ \to J/\psi K^{*+}$ and signal $B_c^+ \to J/\psi\pi^+\pi^0$ decays are determined using extended unbinned maximum-likelihood fits to the $J/\psi\pi^+$, $J/\psi K^+\pi^0$ and $J/\psi\pi^+\pi^0$ mass spectra shown in figures 2, 3 and 4. Each signal component is parameterised as the sum of a modified Gaussian function with power law tails on both sides of the distribution [114, 115] and a standard Gaussian function with common location parameter.[3] The background components are parameterised by positive decreasing second-order polynomials for the fits to the $J/\psi\pi^+$ and $J/\psi K^+\pi^0$ mass spectra and with a positive convex decreasing fourth-order polynomial for the fit to the $J/\psi\pi^+\pi^0$ mass spectrum [116]. In addition, the fit model for the $J/\psi\pi^+$ mass spectrum includes a small component corresponding to the contribution from Cabibbo-suppressed $B_c^+ \to J/\psi K^+$ decays [11, 17] where the charged kaon is reconstructed as a pion. The shape of this component is taken from simulation. The fit model for the $J/\psi K^+\pi^0$ mass spectrum includes an additional component corresponding to contributions from $B^+ \to J/\psi K^+\pi^0\pi^0$ and $B^0 \to J/\psi K^+\pi^0\pi^-$ decays with missing π^0 or

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[3]The resulting signal shapes are parameterised as a location-scale family, $f(\frac{x-\mu}{\sigma})$, using the location parameter μ and the scale parameter σ, referred to as the resolution parameter hereafter.

Figure 3. Mass distribution for selected $B^+ \to J/\psi K^{*+}$ candidates with the result of the fit described in the text.
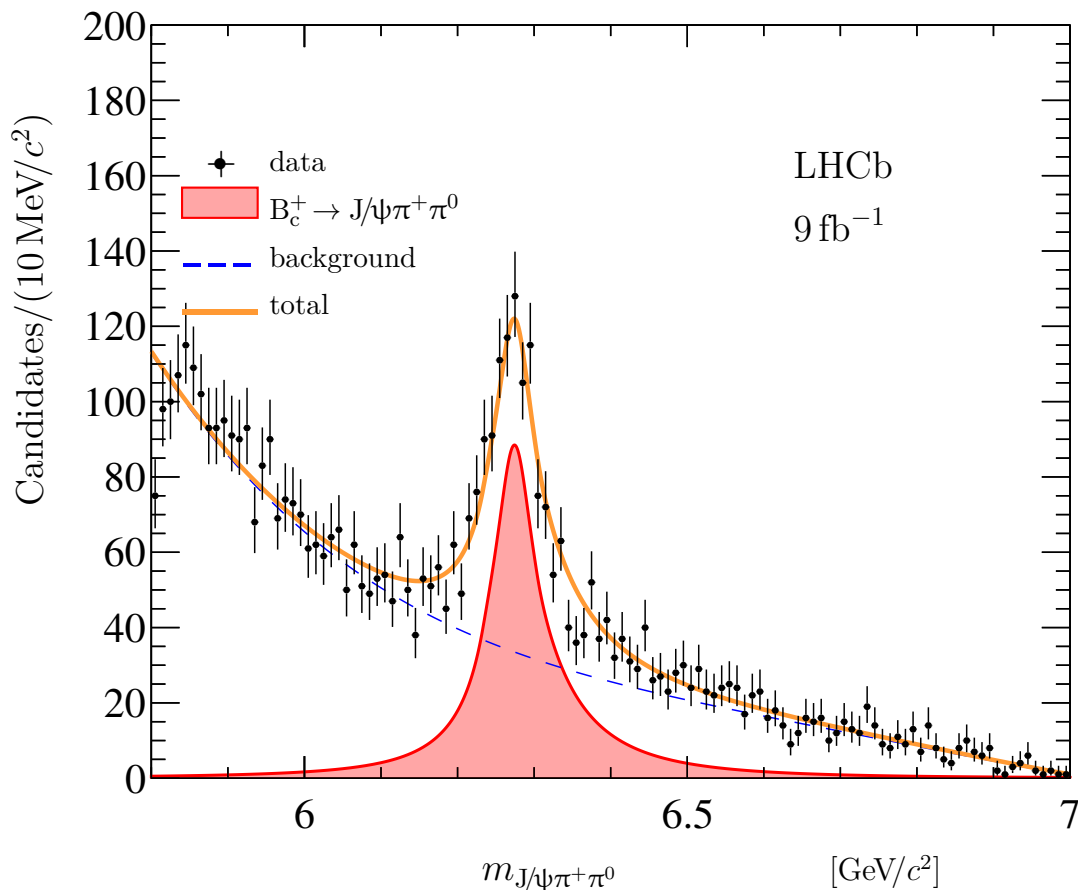
π^- particles. This component is parameterised using a Gaussian function. The signal shape parameters, except for the location parameters, are determined from simulation and their uncertainties are propagated to the fits using multivariate Gaussian constraints. For each fit, the location and resolution parameters are expressed as

$$\mu = \delta m_{\mathrm{B}} + m_{\mathrm{B}}, \tag{4.1a}$$

$$\sigma = s \times \sigma_{\mathrm{MC}}, \tag{4.1b}$$

where m_{B} is the known mass of the corresponding beauty meson [40], σ_{MC} is the resolution parameter obtained from simulation, the term δm_{B} corrects for a possible mass bias, and the scale factor s takes into account any difference in the mass resolution between simulation and data. The parameters δm_{B} and s are allowed to vary in the $J/\psi\pi^+$ and $J/\psi K^+\pi^0$ mass spectra fits, while the $J/\psi\pi^+\pi^0$ fit restricts them to the values obtained for the $B^+ \to J/\psi K^+\pi^0$ mode with their corresponding uncertainties propagated using Gaussian constraints.

The results of the fits are shown in figures 2, 3 and 4 with the parameters summarised in table 1. The statistical significance for the $B_c^+ \to J/\psi\pi^+\pi^0$ signal is estimated using Wilks' theorem [117] and is found to exceed 20 standard deviations. To validate the observed

Figure 4. Mass distribution for selected $B_c^+ \to J/\psi\pi^+\pi^0$ candidates with the result of the fit, described in the text.

Channel	$N\ [10^3]$	$\delta m_B\ [\mathrm{MeV}/c^2]$	s
$B_c^+ \to J/\psi\pi^+$	16.11 ± 0.15	-0.59 ± 0.35	1.10 ± 0.01
$B^+ \to J/\psi K^+\pi^0$	81.91 ± 0.52	-0.03 ± 0.20	1.11 ± 0.01
$B_c^+ \to J/\psi\pi^+\pi^0$	1.08 ± 0.06	-0.11 ± 0.49	1.11 ± 0.01

Table 1. Yields N, mass biases δm_B and resolution scale factors s from the fits to the $J/\psi\pi^+$, $J/\psi K^+\pi^0$ and $J/\psi\pi^+\pi^0$ mass spectra. The uncertainties for δm_B include those from the known masses of the B_c^+ and B^+ mesons. The mass bias and resolution scale parameters for the $B_c^+ \to J/\psi\pi^+\pi^0$ channel are constrained by those from the $B^+ \to J/\psi K^+\pi^0$ control channel.

$B_c^+ \to J/\psi\pi^+\pi^0$ signal, several cross-checks are performed. The data are split into data-taking periods with different polarity of the dipole magnet and into B_c^+ and B_c^- samples. Alternative multivariate estimators, such as decision trees with gradient boosting [118] and a projective likelihood estimator [119], are used. The results are found to be consistent among all samples and analysis techniques.

To validate the predictions of the BLL model, the $\pi^+\pi^0$ mass spectrum from $B_c^+ \to J/\psi\pi^+\pi^0$ decays is studied by extending the $\pi^+\pi^0$ mass interval to the region $m_{\pi^+\pi^0} < 1.6\,\mathrm{GeV}/c^2$. The

background-subtracted $\pi^+\pi^0$ mass spectrum is shown in figure 5, which uses the *sPlot* technique [120] based on the fit to the J/$\psi\pi^+\pi^0$ mass spectrum with the wider $\pi^+\pi^0$ mass interval. There is a clear peak corresponding to the decay $\rho^+ \to \pi^+\pi^0$, as expected by the BLL model. To quantify the possible deviations from the predictions, a fit to the $\pi^+\pi^0$ mass spectrum is performed using a function consisting of two components. The signal component corresponds to the coherent sum of the $B_c^+ \to J/\psi\rho^+$ and $B_c^+ \to J/\psi\rho(1450)^+$ contributions [93], with the shape obtained from the BLL model. The second component describes contributions differing from the BLL model, generically parameterised as

$$f(m_{\pi^+\pi^0}) \propto q^3(m_{\pi^+\pi^0})p(m_{\pi^+\pi^0})\mathcal{P}_1^+(m_{\pi^+\pi^0})\,, \tag{4.2}$$

where q is the pion momentum in the dipion rest-frame, p is the $\pi^+\pi^0$ momentum in the B_c^+ rest-frame [121], and $\mathcal{P}_1^+$ is a positive first-order polynomial function [116]. This parameterisation accounts for the phase-space terms and the suppression of the S-wave contribution. The unknown decay dynamics are absorbed by the polynomial function $\mathcal{P}_1^+$. The result of the fit to the background-subtracted $\pi^+\pi^0$ mass spectrum is superimposed in figure 5. The contribution of the second component vanishes in the fit, demonstrating good agreement between the observed $\pi^+\pi^0$ mass spectrum and the expectations from the BLL model [48–51, 92].

5 Branching fraction ratio computation

The ratio of branching fractions for the $B_c^+ \to J/\psi\pi^+\pi^0$ and $B_c^+ \to J/\psi\pi^+$ decays is calculated as

$$\mathcal{R} = \frac{N_{B_c^+\to J/\psi\pi^+\pi^0}}{N_{B_c^+\to J/\psi\pi^+}} \Big/ \frac{\varepsilon_{B_c^+\to J/\psi\pi^+\pi^0}}{\varepsilon_{B_c^+\to J/\psi\pi^+}}\,, \tag{5.1}$$

where the yields $N_{B_c^+\to J/\psi\pi^+\pi^0}$ and $N_{B_c^+\to J/\psi\pi^+}$ are taken from table 1, and ε denotes the corresponding efficiency, which is defined as the product of the detector acceptance and the reconstruction, selection and trigger efficiencies, where each subsequent efficiency is defined with respect to the previous one. Each of the partial efficiencies is calculated using the simulation samples described in section 2. The ratio of branching fractions is found to be

$$\mathcal{R} = 2.80 \pm 0.15\,,$$

where the uncertainty is statistical only.

6 Systematic uncertainties

Many sources of systematic uncertainties cancel in the ratio of branching fractions $\mathcal{R}$ due to the similarity between the signal and normalisation decay channels. The remaining contributions to the systematic uncertainty for $\mathcal{R}$ are summarised in table 2 and discussed below.

An important source of systematic uncertainty is the imperfect knowledge of the shapes of the signal and background components used in the fits. To estimate this effect, several alternative models are tested. The $B_c^+ \to J/\psi\pi^+\pi^0$ signal shape is parameterised as a sum of a Gaussian and three alternative functions:

Figure 5. Background-subtracted $\pi^+\pi^0$ mass distribution from the $B_c^+ \to J/\psi\pi^+\pi^0$ decays. The orange line shows the result of the two-component fit described in the text. The blue dashed line corresponds to the component parameterised by eq. (4.2), which vanishes in the fit.

1. a bifurcated generalised Student's t-distribution [122, 123];

2. a Johnson's $\mathcal{S}_U$-distribution [124, 125];

3. a generalised hyperbolic distribution [126, 127].

Similarly, the $B_c^+ \to J/\psi\pi^+$ signal component is modelled as the sum of a Gaussian function with three alternative shapes:

1. a bifurcated Student's t-distribution;

2. a generalised hyperbolic distribution;

3. a Pearson's type IV distribution [128].

Five alternative background functions are tested for the fit to the $J/\psi\pi^+\pi^0$ mass spectrum:

1. a positive decreasing convex third-order polynomial function [116];

2. a positive decreasing fourth-order polynomial function;

Source	Uncertainty [%]
Fit model	
Signal shapes	1.0
Background shapes	2.1
Efficiency determination	
B_c^+ kinematics	< 0.1
B_c^+ decay model	2.2
Track reconstruction efficiency	0.1
π^0 reconstruction efficiency	0.9
Hadron identification	0.6
Trigger efficiency	1.1
Data-simulation difference	2.0
Size of simulated samples	0.5
Total	4.1

Table 2. Relative systematic uncertainties for the ratio $\mathcal{R}$. The total systematic uncertainty is the quadratic sum of individual contributions. The systematic uncertainty of the π^0 reconstruction efficiency due to imprecise knowledge of the branching fraction of the $B^+ \to J/\psi K^{*+}$ and $B^+ \to J/\psi K^+$ decays is treated separately.

3. a product of an exponential function and a positive third-order polynomial function;

4. a sum of an exponential function and a positive third-order polynomial function;

5. a sum of a generalised Pareto distribution [129, 130] and a positive first-order polynomial function.

Lastly, for the background component of the $J/\psi\pi^+$ mass spectrum four alternative fit models are tested:

1. a positive decreasing third-order polynomial function;

2. a product of an exponential function and a positive first-order polynomial function;

3. a positive third-order polynomial function;

4. a positive fourth-order polynomial function.

For each alternative signal or background function, a large ensemble of pseudoexperiments is produced and fit with the baseline model. The absolute value of the mean over an ensemble for the relative difference between the fitted $B_c^+ \to J/\psi\pi^+\pi^0$ or $B_c^+ \to J/\psi\pi^+$ signal yields and their baseline results is calculated. Its maximal value is found to be 1.0% (2.1%) for the alternative signal (background) shapes and is taken as the systematic uncertainty related to the fit model. For each model test, the signal significance of the newly observed $B_c^+ \to J/\psi\pi^+\pi^0$ decay is estimated using Wilks' theorem [117] and is always found to exceed 20 standard deviations.

An uncertainty may originate from possible differences in the B_c^+ production kinematics between data and simulation. The transverse momentum and rapidity spectra of the B_c^+ mesons in the simulation are weighted to match those observed in a high-yield, low-background sample of $B_c^+ \to J/\psi\pi^+$ decays. The systematic uncertainty of the efficiency ratio caused by the finite size of this sample is estimated by varying the B_c^+-meson production kinematic spectra within their uncertainties in the weighting procedure. The induced variation for the ratio $\mathcal{R}$ is found to be smaller than 0.1%.

Simulated $B_c^+ \to J/\psi\pi^+\pi^0$ events are corrected for polarisation of the dipion system in the B_c^+ rest frame to reproduce the corresponding angular distribution observed in data. Variations of this correction within statistical uncertainties causes a relative variation of 2.2% for the efficiency for $B_c^+ \to J/\psi\pi^+\pi^0$ decays, which is taken as the systematic uncertainty related to the B_c^+ decay model.

There are residual differences in the reconstruction efficiency of charged-particle tracks that do not cancel completely in the ratio due to slightly different kinematic distributions of the final-state particles. The track-finding efficiencies obtained from simulated samples are corrected using calibration channels [99]. The uncertainties related to the efficiency correction factors are propagated to the ratios of the total efficiencies using pseudoexperiments and found to be 0.1% for the ratio $\mathcal{R}$.

The difference of the photon reconstruction efficiency between data and simulation is studied using large samples of $B^+ \to J/\psi(K^{*+} \to K^+(\pi^0 \to \gamma\gamma))$ and $B^+ \to J/\psi K^+$ decays [100–104]. The uncertainty for the photon efficiency corrections has three components: statistical, systematic and those related to the imprecise knowledge of the ratio of branching fractions for $B^+ \to J/\psi K^{*+}$ and $B^+ \to J/\psi K^+$ decays. The statistical and systematic uncertainties are propagated to the ratio of the total efficiencies using pseudoexperiments and the resulting 0.9% is taken as the systematic uncertainty related to the photon reconstruction. The uncertainty due to imprecise knowledge of external branching fractions of 5.9% [40] is treated separately.

The simulated detector response used for identification of pions is resampled from the control channels [76, 98]. The systematic uncertainty obtained through this procedure arises from the kernel shape used in the estimation of the probability density distributions. An alternative combined response is estimated using a modified kernel shape and the efficiency models are regenerated [131, 132]. The difference between the two efficiency ratios of 0.6% is taken as the systematic uncertainty related to hadron identification.

The systematic uncertainty related to the trigger efficiency has been previously studied by comparing the ratios of the trigger efficiencies in data and simulation using large samples of $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)K^+$ decays [133]. Based on this comparison, a conservative estimate of 1.1% for the relative difference between data and simulation is taken as the corresponding systematic uncertainty.

The imperfect data description by simulation due to remaining effects not described above is studied by varying the MLP selection criteria for the normalisation decay $B_c^+ \to J/\psi\pi^+$. The observed maximal difference between the efficiency estimated using data and simulation does not exceed 2.0%. This value is taken as the corresponding systematic uncertainty for the ratio $\mathcal{R}$. The last systematic uncertainty considered is due to the finite size of the simulated samples, which amounts to 0.5%. The total systematic uncertainty is calculated as the quadratic sum of the individual contributions.
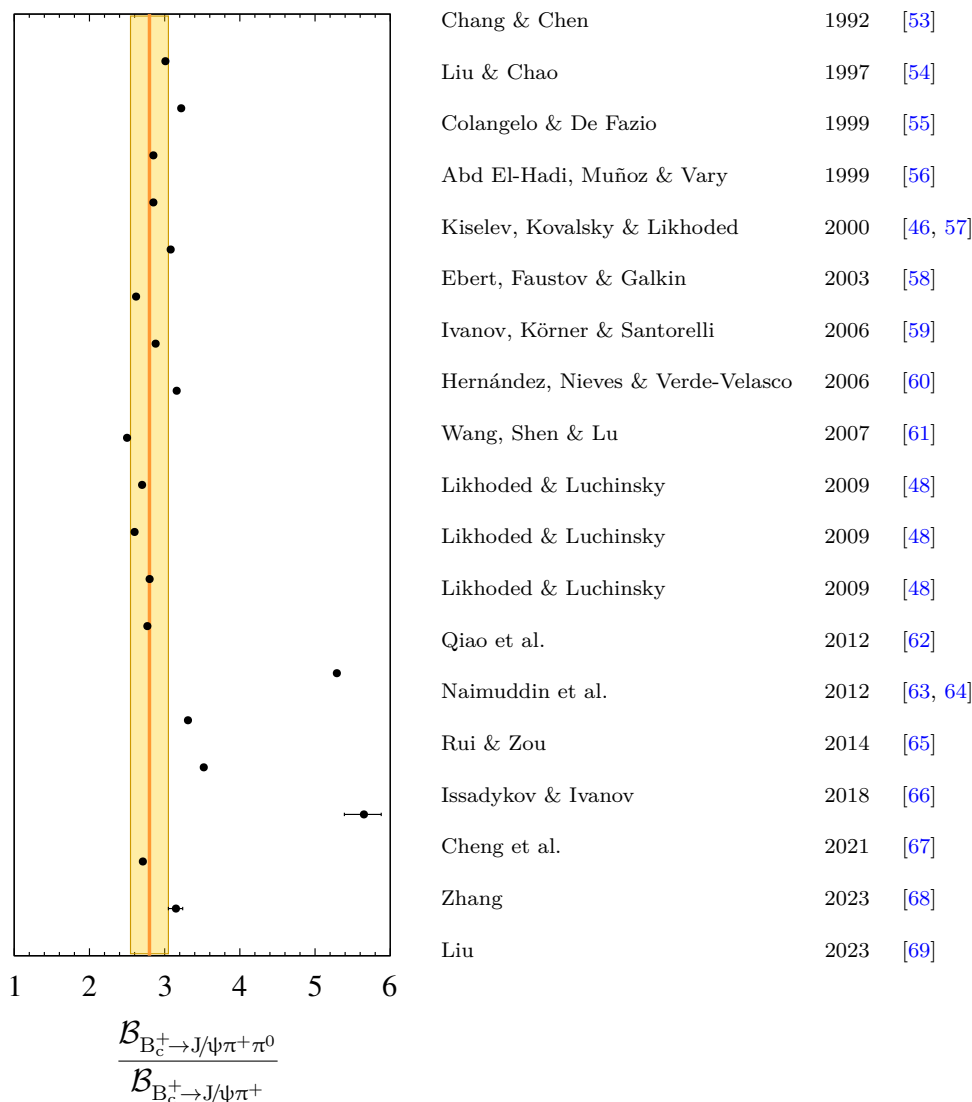
7 Results and discussion

The $B_c^+ \to J/\psi\pi^+\pi^0$ decay is observed with overwhelming significance using proton-proton collision data, corresponding to an integrated luminosity of $9\,\text{fb}^{-1}$, collected with the LHCb detector at centre-of-mass energies of 7, 8, and 13 TeV. The ratio of the $B_c^+ \to J/\psi\pi^+\pi^0$ branching fraction relative to the $B_c^+ \to J/\psi\pi^+$ channel is measured to be:

$$\mathcal{R} = \frac{\mathcal{B}_{B_c^+ \to J/\psi\pi^+\pi^0}}{\mathcal{B}_{B_c^+ \to J/\psi\pi^+}} = 2.80 \pm 0.15 \pm 0.11 \pm 0.16\,, \tag{7.1}$$

where the first uncertainty is statistical, the second systematic and the third due to uncertainties in the $B^+ \to J/\psi K^{*+}$ and $B^+ \to J/\psi K^+$ branching fractions. The comparison of the measured ratio with theory predictions [46, 48, 53–69] is shown in figure 6. While most of the theory predictions agree well with the measurement, calculations from refs. [65, 66] are only marginally consistent and results from refs. [63, 64, 67] are inconsistent with the measured value. The study of the $\pi^+\pi^0$ mass spectrum indicates that the $B_c^+ \to J/\psi\pi^+\pi^0$ decay is saturated by the $B_c^+ \to J/\psi\rho^+$ contribution, with a small admixture of the $B_c^+ \to J/\psi\rho(1450)^+$ decay, in accordance with theoretical expectations [48–52, 92].

Chang & Chen	1992	[53]
Liu & Chao	1997	[54]
Colangelo & De Fazio	1999	[55]
Abd El-Hadi, Muñoz & Vary	1999	[56]
Kiselev, Kovalsky & Likhoded	2000	[46, 57]
Ebert, Faustov & Galkin	2003	[58]
Ivanov, Körner & Santorelli	2006	[59]
Hernández, Nieves & Verde-Velasco	2006	[60]
Wang, Shen & Lu	2007	[61]
Likhoded & Luchinsky	2009	[48]
Likhoded & Luchinsky	2009	[48]
Likhoded & Luchinsky	2009	[48]
Qiao et al.	2012	[62]
Naimuddin et al.	2012	[63, 64]
Rui & Zou	2014	[65]
Issadykov & Ivanov	2018	[66]
Cheng et al.	2021	[67]
Zhang	2023	[68]
Liu	2023	[69]

$$\frac{\mathcal{B}_{B_c^+ \to J/\psi\pi^+\pi^0}}{\mathcal{B}_{B_c^+ \to J/\psi\pi^+}}$$

Figure 6. The measured ratio of the branching fractions of the $B_c^+ \to J/\psi\pi^+\pi^0$ and $B_c^+ \to J/\psi\pi^+$ decays in comparison with theory predictions. The colored band shows the measured ratio with corresponding uncertainties added in quadrature.

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