

Search for the $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ decay



The LHCb collaboration

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ABSTRACT: A search for the decay $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ is reported using proton-proton collision data collected with the LHCb detector between 2011 and 2018 at centre-of-mass energies of 7, 8, and 13 TeV, corresponding to an integrated luminosity of 9 fb^{-1} . No significant signal is observed. Using the decay $B_c^+ \rightarrow \psi(2S)\pi^+$ as a normalisation channel, an upper limit for the ratio of branching fractions

$$\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)} = \frac{\mathcal{B}_{B_c^+ \rightarrow \chi_{c1}(3872)\pi^+}}{\mathcal{B}_{B_c^+ \rightarrow \psi(2S)\pi^+}} \times \frac{\mathcal{B}_{\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-}}{\mathcal{B}_{\psi(2S) \rightarrow J/\psi\pi^+\pi^-}} < 0.05 \text{ (0.06)},$$

is set at the 90 (95)% confidence level.

KEYWORDS: B Physics, Branching fraction, Hadron-Hadron Scattering, QCD

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1 Introduction

The B_c^+ mesons are of interest because they contain two different heavy-flavour quarks, charm and beauty. The ground state possesses a diverse array of weak decay modes, due to the fact that either of the heavy quarks can decay while the other acts as a spectator quark. Additionally, two valence quarks may annihilate via a virtual W boson. Studies of B_c^+ decay channels and measurements of their branching fractions contribute to improve the understanding of models describing strong interactions and test various effective models. Experiments at the Large Hadron Collider (LHC) have opened a new era for B_c^+ meson investigations. The large b -quark production cross-section at the LHC enables the ATLAS, CMS and LHCb experiments to study the production, decays and other properties of the B_c^+ meson [1–29].

Over the past decade, numerous B_c^+ -meson decays involving conventional charmonium states (such as the J/ψ , $\psi(2S)$ or $\chi_{c1}(1P)$ mesons) were observed [30]. Decays of beauty hadrons have proven to be a convenient and fruitful tool for the search and study of charmonium-like states. These states exhibit properties that suggest the presence of a $c\bar{c}$ component in their quark content, yet they cannot be associated with any conventional charmonium resonance [31–42]. The first such state, the $\chi_{c1}(3872)$,¹ was observed by the Belle collaboration in the $J/\psi\pi^+\pi^-$ mass spectrum from $B^+ \rightarrow J/\psi\pi^+\pi^-K^+$ decays [43]. For over twenty years since its discovery, the properties of this state have been intensively investigated in e^+e^- collisions by the BaBar [44–51], Belle [52–59], and BESIII [60–65] collaborations. Additionally, studies have been conducted in proton-antiproton collisions by the CDF [66–69] and D0 [70] collaborations, as well as in proton-proton (pp) collisions by the ATLAS [71], CMS [72, 73] and LHCb [74–88] collaborations. The LHCb collaboration has also explored proton-nucleus collisions [89], and the CMS collaboration has studied lead-lead collisions [90]. However, this state has yet to be observed in exclusive B_c^+ -meson decays. The study of B_c^+ -meson decays

¹ $X(3872)$ in the original paper.

into the $\chi_{c1}(3872)$ particle can be useful to clarify the nature of this enigmatic state. Within the compact-tetraquark interpretation of the $\chi_{c1}(3872)$ state [91], a significant enhancement of the branching fraction for the $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ mode is expected, which is anticipated to be similar to the $B_c^+ \rightarrow J/\psi\pi^+$ channel [92].

In 2017, the ATLAS collaboration measured the production cross-sections of the $\chi_{c1}(3872)$ state in pp collisions at $\sqrt{s} = 8$ TeV [71], where the short-lived contribution of the nonprompt production was assumed to arise from the decays of B_c^+ mesons. Subsequently, they reported the fraction of the $\chi_{c1}(3872)$, produced from B_c^+ decays, integrated over the transverse momentum and rapidity range ($p_T > 10$ GeV/c, $|y| < 0.75$), to be

$$\frac{\sigma_{pp \rightarrow B_c^+ X} \times \mathcal{B}_{B_c^+ \rightarrow \chi_{c1}(3872)X}}{\sigma_{pp \rightarrow b\bar{b}X} \times \mathcal{B}_{b \rightarrow \chi_{c1}(3872)X}} = (25 \pm 13 \pm 2 \pm 5) \%,$$

where the first uncertainty is statistical, the second one systematic and the last one due to the unknown polarisation of the $\chi_{c1}(3872)$ state in B_c^+ -meson decays. Since the production cross-section of B_c^+ -mesons is much smaller than the inclusive beauty production cross-section [9], this result can be interpreted as a significant enhancement of $\chi_{c1}(3872)$ production in B_c^+ meson decays.

This paper reports a search for the $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ decay² using 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. The decay mode $B_c^+ \rightarrow \psi(2S)\pi^+$ is used as a normalisation channel and the result reported as a ratio of branching fractions,

$$\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)} \equiv \frac{\mathcal{B}_{B_c^+ \rightarrow \chi_{c1}(3872)\pi^+}}{\mathcal{B}_{B_c^+ \rightarrow \psi(2S)\pi^+}} \times \frac{\mathcal{B}_{\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-}}{\mathcal{B}_{\psi(2S) \rightarrow J/\psi\pi^+\pi^-}}. \quad (1.1)$$

A high-yield sample of $B_c^+ \rightarrow J/\psi\pi^+\pi^+\pi^-$ decays [1, 25, 26], without intermediate either $\chi_{c1}(3872)$ or $\psi(2S)$ states, is used as a control mode to calibrate detector resolution effects. Samples of $B^+ \rightarrow \chi_{c1}(3872)K^+$ and $B^+ \rightarrow \psi(2S)K^+$ decays are used to parameterise the $\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-$ and $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ signals and to study systematic uncertainties.

2 Detector and simulation

The LHCb detector [93, 94] 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 [95], 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 [96, 97] 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 $J/\psi \rightarrow \mu^+\mu^-$ and $B^+ \rightarrow J/\psi K^+$ decays collected concurrently with the data sample used for this analysis [98, 99]. The relative accuracy of this

²Inclusion of charge-conjugate states is implied throughout the paper.

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) [100, 101], the impact parameter, is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$, 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) [102]. 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 [103].

The online event selection is performed by a trigger [104], 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 common vertex that is significantly displaced from any PV, and the mass of the $\mu^+\mu^-$ pair is required to exceed $2.7 \text{ GeV}/c^2$.

Simulated events are used to model the signal mass shapes, optimise the selection requirements and compute the efficiencies required for determination of the branching fraction ratio $\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)}$. The PYTHIA [105] generator with a specific LHCb configuration [106] is used to simulate pp collisions with B^+ meson production. For B_c^+ meson production, the BCVEGPy generator [107–110] is used. It is based on the full perturbative-QCD calculations at lowest order α_s^4 via the dominant gluon-gluon fusion processes $gg \rightarrow B_c^+ (B_c^{*+}) + \bar{c} + b$ and neglecting contributions from the quark-pair annihilation channels $q\bar{q} \rightarrow B_c^+ (B_c^{*+}) + \bar{c} + b$ [111–115]. The generator is interfaced with the PYTHIA parton shower and hadronisation model. Decays of unstable particles are described by the EVTGEN package [116], in which final-state radiation is generated using PHOTOS [117]. The $\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-$ decay is modelled as an S -wave decay via the intermediate $J/\psi \rho^0$ state [75, 77], while the $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ decay follows the model described in refs. [118–120]. Both decay models are further corrected using large samples of $B^+ \rightarrow \chi_{c1}(3872)K^+$ and $B^+ \rightarrow \psi(2S)K^+$ decays [81, 84]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [121, 122] as described in ref. [123]. 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 $B_c^+ \rightarrow J/\psi \pi^+$ decays. The detector response used for the identification of pions is sampled from the $D^{*+} \rightarrow (D^0 \rightarrow K^- \pi^+) \pi^+$ and $K_S^0 \rightarrow \pi^+ \pi^-$ control channels [102, 124]. To account for imperfections in the simulation of charged-particle reconstruction, the track reconstruction efficiency determined from simulation is corrected using $J/\psi \rightarrow \mu^+ \mu^-$ calibration samples [125].

3 Event selection

The $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ and $B_c^+ \rightarrow \psi(2S)\pi^+$ candidates are reconstructed using the $X_{c\bar{c}} \rightarrow J/\psi \pi^+ \pi^-$ decay mode.³ As $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-$ decays share

³The symbol $X_{c\bar{c}}$ denotes the $\chi_{c1}(3872)$ and $\psi(2S)$ states collectively.

the same final state, the same preselection is applied to all three modes. For all cases, the J/ψ candidates are reconstructed via their dimuon decays.

Muon and pion candidates are identified by combining information from the RICH, calorimeter and muon systems, and are required to have transverse momenta larger than 550 MeV/c and 200 MeV/c for muon and pion candidates, respectively. Pions are required to have a momentum between 3.2 and 150 GeV/c to ensure good performance of particle identification in the RICH detectors [102, 126]. To reduce combinatorial backgrounds from particles produced in pp interactions, only tracks that are inconsistent with originating from any PV are used.

Pairs of oppositely charged muons consistent with originating from a common vertex are combined to form $J/\psi \rightarrow \mu^+\mu^-$ candidates. The reconstructed mass of the $\mu^+\mu^-$ pair is required to be in the range $3.0 < m_{\mu^+\mu^-} < 3.2 \text{ GeV}/c^2$. The position of the reconstructed dimuon vertex is required to be separated from any reconstructed PV.

The selected J/ψ candidates are combined with a pair of oppositely charged pions to form $X_{c\bar{c}}$ candidates. The $J/\psi \pi^+\pi^-$ mass comprising $\psi(2S)$ candidates is required to be in the $3.66 < m_{J/\psi \pi^+\pi^-} < 3.71 \text{ GeV}/c^2$ region, while for the $\chi_{c1}(3872)$ candidates the $3.85 < m_{J/\psi \pi^+\pi^-} < 3.90 \text{ GeV}/c^2$ region is used. The selected $X_{c\bar{c}}$ candidates are combined with charged tracks identified as pions to form $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ candidates. To construct the $B_c^+ \rightarrow J/\psi \pi^+\pi^+\pi^-$ control sample, the selected J/ψ candidates are combined with three charged tracks identified as pions. The $J/\psi \pi^+\pi^+\pi^-$ combinations already selected as $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ candidates are not included as $B_c^+ \rightarrow J/\psi \pi^+\pi^+\pi^-$ candidates.

A kinematic fit [127] that constrains the five-track combination to form a common vertex is performed, in which the mass of the $\mu^+\mu^-$ combination is set equal to the known J/ψ mass [30], and the B_c^+ candidate is constrained to originate from the associated PV. Each B_c^+ candidate is associated with the PV that yields the smallest χ_{IP}^2 , where χ_{IP}^2 is defined as the difference in the vertex-fit χ^2 of a given PV reconstructed with and without the particle under consideration. A good fit quality is required to further suppress combinatorial background. The measured decay time of the selected candidate is required to be greater than $75 \mu\text{m}/c$, to reduce the background from particles originating directly from the PV.

To further reduce the combinatorial background for the $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+\pi^+\pi^-$ decays, a multivariate classifier is used based on a decision tree with gradient boosting (BDTG) [128]. The classifier is trained on a mixture of simulated samples from $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ and $B_c^+ \rightarrow \psi(2S)\pi^+$ decays to represent the signal. As a proxy for the background, B_c^+ candidates from data with a mass between 6.35 and 6.60 GeV/c² are used, excluding the regions of $m_{J/\psi \pi^+\pi^-}$ populated by $\chi_{c1}(3872) \rightarrow J/\psi \pi^+\pi^-$ and $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ decays. The k -fold cross-validation technique [129] with $k = 13$ is taken to avoid introducing a bias in the BDTG evaluation. The classifier is trained using variables related to the reconstruction quality, decay time of B_c^+ candidates, kinematics of particles in the final state and variables related to pion identification [102, 126]. The requirement on the BDTG output is chosen to maximise the Punzi figure-of-merit $\varepsilon/(\alpha/2 + \sqrt{B})$ [130], where ε is the signal efficiency in simulation for $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ decay, $\alpha = 5$ represents the desired signal significance in units of standard deviations, and B is the expected background yield within a narrow mass region centred at the known B_c^+ and $\chi_{c1}(3872)$ masses [30].

The mass distributions for selected $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-$ candidates are shown in figure 1. To improve the resolution on the $J/\psi \pi^+ \pi^-$ mass for the $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ candidates and to eliminate a small correlation between $m_{(J/\psi \pi^+ \pi^-) \pi^+}$ and $m_{J/\psi \pi^+ \pi^-}$ [41, 81], the $m_{J/\psi \pi^+ \pi^-}$ variable is computed by constraining the mass of the B_c^+ candidates to its known mass [30]. For better visibility, the $(J/\psi \pi^+ \pi^-) \pi^+$ mass spectra for the $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ candidates are shown for candidates within the narrow mass regions around the known masses of the $\psi(2S)$ and $\chi_{c1}(3872)$ mesons, $3.680 < m_{J/\psi \pi^+ \pi^-} < 3.692 \text{ GeV}/c^2$ and $3.864 < m_{J/\psi \pi^+ \pi^-} < 3.879 \text{ GeV}/c^2$, respectively. The $J/\psi \pi^+ \pi^-$ mass spectra are shown for candidates within the narrow mass region around the known mass of the B_c^+ meson $6.24 < m_{(J/\psi \pi^+ \pi^-) \pi^+} < 6.31 \text{ GeV}/c^2$.

4 Signal yields and efficiencies

The yields for the $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-$ decays are determined using a simultaneous extended unbinned maximum-likelihood fit to the two-dimensional distributions of $m_{(J/\psi \pi^+ \pi^-) \pi^+}$ vs. $m_{J/\psi \pi^+ \pi^-}$ for the $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ candidates, and the one-dimensional mass distribution of selected $B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-$ control candidates.

The two-dimensional fit functions for the $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ channels are defined as a sum of four components:

1. Signal $B_c^+ \rightarrow (X_{c\bar{c}} \rightarrow J/\psi \pi^+ \pi^-) \pi^+$ decays parameterised as a product of B_c^+ and $X_{c\bar{c}}$ signal shapes, each of which are modelled by the sum of a Gaussian function with a modified Gaussian function with power-law-replaced tails on both sides of the distribution [131, 132];
2. Contributions from nonresonant decays $B_c^+ \rightarrow (J/\psi \pi^+ \pi^-)_{\text{NR}} \pi^+$ without proceeding through a narrow intermediate $X_{c\bar{c}}$ state, parameterised as a product of the B_c^+ signal shape with a three-body phase-space function [133] and a linear function in the $J/\psi \pi^+ \pi^-$ mass;
3. Random combinations of $X_{c\bar{c}}$ and π^+ candidates, parameterised as a product of the $X_{c\bar{c}}$ signal shape with a linear function in the $(J/\psi \pi^+ \pi^-) \pi^+$ mass;
4. Combinatorial background consisting of random $(J/\psi \pi^+ \pi^-) \pi^+$ combinations, described by a two-dimensional nonfactorisable positive second-order polynomial function.

For the $B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-$ channel, the one-dimensional fit function consists of two components:

1. Signal $B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-$ decays, parameterised by the modified Gaussian function previously described;
2. Combinatorial background, modelled by a first-order polynomial function.

The shape parameters for the fit components describing $B_c^+ \rightarrow X_{c\bar{c}} \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-$ decays are taken from simulation and their uncertainties propagated to the fit through multivariate Gaussian constraints. The B_c^+ signal peak position

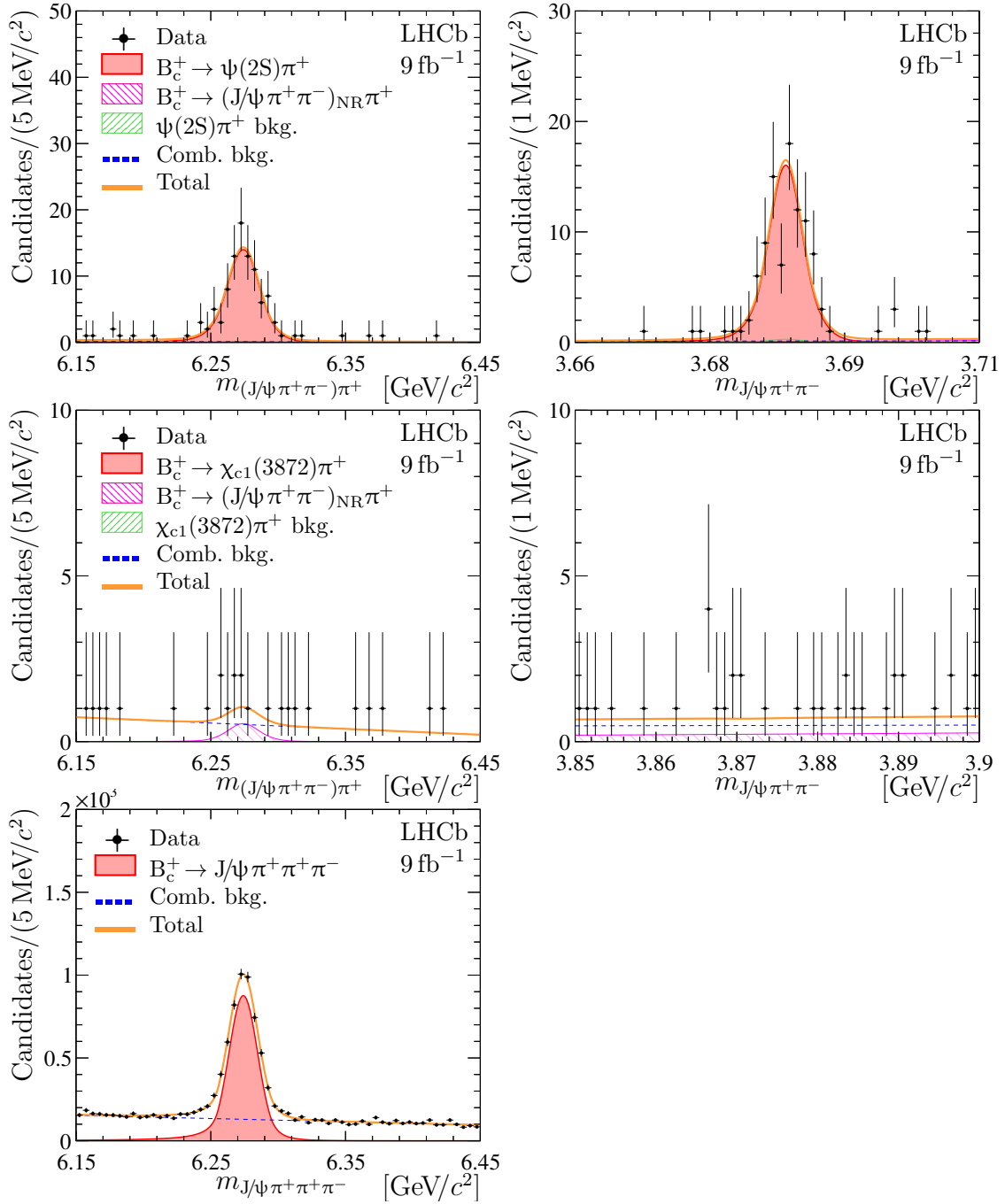


Figure 1. Distributions and fit projections of the (left) $J/\psi \pi^+ \pi^+ \pi^-$ and (right) $J/\psi \pi^+ \pi^-$ masses for selected (top) $B_c^+ \rightarrow \psi(2S)\pi^+$, (middle) $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ and (bottom) $B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-$ candidates. For $B_c^+ \rightarrow X_{c\bar{c}}\pi^+$ decays, the $(J/\psi \pi^+ \pi^-)\pi^+$ and $J/\psi \pi^+ \pi^-$ mass spectra are shown for candidates within narrow regions around the known $X_{c\bar{c}}$ and B_c^+ masses, respectively, as described in the text.

parameter is shared between all decays and allowed to vary in the fit. The mass resolution parameters $\sigma_{B_c^+}$ for the B_c^+ components are parameterised as

$$\sigma_{B_c^+} = f_{B_c^+} \times \sigma_{B_c^+}^{\text{sim}}, \quad (4.1)$$

where $\sigma_{B_c^+}^{\text{sim}}$ are mass resolution parameters obtained from simulation. The parameter $f_{B_c^+}$ accounts for a possible difference between data and simulation. Furthermore, the parameter $f_{B_c^+}$ is shared and free to vary in the fit to data. The position and mass resolution parameters for the $X_{c\bar{c}}$ components, $m_{\chi_{c1}(3872)}$, $m_{\psi(2S)}$, $\sigma_{\chi_{c1}(3872)}$, and $\sigma_{\psi(2S)}$, are parameterised as

$$m_{\chi_{c1}(3872)} = \delta m_{X_{c\bar{c}}} + m_{\psi(2S)}, \quad (4.2a)$$

$$\sigma_{\chi_{c1}(3872)} = f_{X_{c\bar{c}}} \times \sigma_{\chi_{c1}(3872)}^{\text{sim}}, \quad (4.2b)$$

$$\sigma_{\psi(2S)} = f_{X_{c\bar{c}}} \times \sigma_{\psi(2S)}^{\text{sim}}, \quad (4.2c)$$

where the position of the $\psi(2S)$ signal peak, $m_{\psi(2S)}$, is allowed to vary in the fit, while $\sigma_{\chi_{c1}(3872)}^{\text{sim}}$ and $\sigma_{\psi(2S)}^{\text{sim}}$ are mass resolution parameters obtained from simulation. The parameter $\delta m_{X_{c\bar{c}}}$ corresponds to the mass difference between the $\chi_{c1}(3872)$ and $\psi(2S)$ mesons, while $f_{X_{c\bar{c}}}$ describes potential differences between data and simulation in terms of resolution. Both parameters are determined in ref. [81] and their uncertainties propagated to the fit via Gaussian constraints.

The yield of the $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ signal component, $N_{B_c^+ \rightarrow \chi_{c1}(3872)\pi^+}$, is parameterised as

$$N_{B_c^+ \rightarrow \chi_{c1}(3872)\pi^+} \equiv N_{B_c^+ \rightarrow \psi(2S)\pi^+} \times \mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)} \times \epsilon_{\psi(2S)}^{\chi_{c1}(3872)}, \quad (4.3)$$

where $N_{B_c^+ \rightarrow \psi(2S)\pi^+}$ is the yield of the $B_c^+ \rightarrow \psi(2S)\pi^+$ signal component, $\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)}$ is a free parameter in the fit corresponding to the ratio of branching fractions for $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ and $B_c^+ \rightarrow \psi(2S)\pi^+$ decays as defined in eq. (1.1), and $\epsilon_{\psi(2S)}^{\chi_{c1}(3872)}$ is the ratio of the total efficiencies for $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ and $B_c^+ \rightarrow \psi(2S)\pi^+$ decays,

$$\epsilon_{\psi(2S)}^{\chi_{c1}(3872)} \equiv \frac{\epsilon_{B_c^+ \rightarrow \chi_{c1}(3872)\pi^+}}{\epsilon_{B_c^+ \rightarrow \psi(2S)\pi^+}}. \quad (4.4)$$

For each channel, the total efficiency is defined as the product of the detector acceptance, reconstruction, selection and trigger efficiencies, where each subsequent efficiency is defined with respect to the previous one. Each of the efficiencies is calculated using the calibrated simulation samples described in section 2. The ratio of the efficiencies for the $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ and $B_c^+ \rightarrow \psi(2S)\pi^+$ channels, $\epsilon_{\psi(2S)}^{\chi_{c1}(3872)}$, defined in eq. (4.4), is found to be

$$\epsilon_{\psi(2S)}^{\chi_{c1}(3872)} = 1.673 \pm 0.003,$$

where the uncertainty is due to size of the simulated samples. A smaller energy release in the $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ decay causes a larger fraction of charged pions to escape reconstruction and selection, that is a primary reason for the smaller efficiency for the $B_c^+ \rightarrow \psi(2S)\pi^+$ channel [41, 79, 81, 86]. The uncertainties for the $\epsilon_{\psi(2S)}^{\chi_{c1}(3872)}$ value, including systematic effects, discussed in detail in section 5, is accounted for in the fit via a Gaussian constraint.

Parameter	Value
$N_{B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^-}$	5049 ± 91
$N_{B_c^+ \rightarrow \psi(2S) \pi^+}$	96 ± 11
$\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)} \quad [\%]$	$-0.1^{+2.5}_{-2.1}$
$m_{B_c^+} \quad [\text{MeV}/c^2]$	6274.15 ± 0.21
$m_{\psi(2S)} \quad [\text{MeV}/c^2]$	3686.05 ± 0.27
$\delta m_{X_{c\bar{c}}} \quad [\text{MeV}/c^2]$	185.54 ± 0.06
$f_{B_c^+}$	1.118 ± 0.021
$f_{X_{c\bar{c}}}$	1.048 ± 0.004

Table 1. Parameters of interest obtained from the simultaneous unbinned extended maximum-likelihood fit. In addition to statistical sources, the uncertainties also account for a systematic component due to the inclusion of $\varepsilon_{\psi(2S)}^{\chi_{c1}(3872)}$ in the fit.

The result of the fit is shown in figure 1, and the parameters of interest summarised in table 1. The B_c^+ peak position parameter $m_{B_c^+}$ is in good agreement with the known mass of the B_c^+ meson [30], and the resolution scale factor $f_{B_c^+}$ is in good agreement with the value obtained in ref. [25]. The $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ signal is observed to be consistent with zero.

5 Systematic uncertainties

The decay channels under investigation share similar kinematics and topologies, leading to the cancellation of many sources of systematic uncertainties in the branching-fraction ratio. The remaining contributions to the systematic uncertainty are discussed below. There are two categories of systematic uncertainties. The first category consists of uncertainties that affect the ratio of total efficiencies $\varepsilon_{\psi(2S)}^{\chi_{c1}(3872)}$ from eq. (4.4), mostly related to the difference between data and simulation. Those are summarised in table 2. The second category consists of uncertainties related to the choice of the fit model.

To address the differences between data and simulation, the transverse momentum and rapidity spectra of B_c^+ mesons in the simulated samples are adjusted to match those observed in a high-yield low-background sample of $B_c^+ \rightarrow J/\psi \pi^+$ decays [28]. The finite size of this sample introduces uncertainty in the resulting production spectra of the B_c^+ mesons. The associated systematic uncertainty in the efficiency ratio is estimated using the variation of the B_c^+ kinematic spectra within their uncertainties, for which the induced relative variation on the efficiency ratio $\varepsilon_{\psi(2S)}^{\chi_{c1}(3872)}$ is found to be much smaller than 0.1%.

Due to the slightly different kinematic distributions of the final-state particles, there are residual differences in the reconstruction efficiency of charged-particle tracks that do not completely cancel out in the efficiency ratio. The track-finding efficiency obtained from simulated samples is corrected using calibration channels [125]. Uncertainties related to such efficiency correction factors are then propagated to the ratio of total efficiencies using pseudoexperiments and found to be 0.2%.

Pion identification in the simulation is modelled by sampling the corresponding distributions in the $D^{*+} \rightarrow (D^0 \rightarrow K^- \pi^+) \pi^+$ and $K_S^0 \rightarrow \pi^+ \pi^-$ control channels [102, 124]. The systematic uncertainty obtained through this procedure originates from the kernel shape used in the estimation of the probability-density distributions. An alternative response is estimated using a different kernel estimation with a modified shape, and the efficiency models recomputed [134, 135]. The difference between the two estimates for the efficiency ratio is taken as the systematic uncertainty related to pion identification and is found to be 0.1%.

Large samples of $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow \psi(2S)K^+$ decays [136] are used to estimate the systematic uncertainty related to the trigger efficiency. A conservative estimate of 1.1% for the relative difference between data and simulation is taken as the corresponding systematic uncertainty [136].

Discrepancies in reconstructed quantities between the simulated samples and data, arising from factors other than those previously described, are studied by varying the BDTG selection criteria for the control $B^+ \rightarrow \chi_{c1}(3872)K^+$ and $B^+ \rightarrow \psi(2S)K^+$ decays [81] over the entire range. The observed maximal difference between the efficiency estimated using data and simulation does not exceed 0.8%, which is taken as a corresponding systematic uncertainty.

Model corrections for $\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-$ and $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ decays are obtained from the control $B^+ \rightarrow \chi_{c1}(3872)K^+$ and $B^+ \rightarrow \psi(2S)K^+$ decay modes [81] using the algorithm described in ref. [137]. The systematic uncertainty associated with the correction is estimated as the largest deviation of the efficiency ratio $\varepsilon_{\psi(2S)}^{\chi_{c1}(3872)}$ value from the baseline and found to be 1.5%, which is assigned as systematic uncertainty associated with the $X_{c\bar{c}}$ decay model.

The systematic uncertainty due to the finite size of the simulated samples, used to calculate the efficiency ratio from eq. (4.4), is found to be 0.2%. The systematic uncertainties for the efficiency ratio $\varepsilon_{\psi(2S)}^{\chi_{c1}(3872)}$ are summarised in table 2, where their total is estimated as the sum in quadrature of the individual contributions and accounted for in the fit via a Gaussian constraint.

Using the CL_s technique [138], where the p -values are computed based on the asymptotic properties of the profile likelihood ratio [139], an upper limit of $\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)} < 0.04$ (0.05) is set at the 90 (95)% confidence level (CL), accounting for the systematic effects relating to the efficiency ratio. The remaining uncertainty is related to the imperfect understanding of the shapes of the signal and background components used in the fits. To estimate this, several alternative signal shapes are tested, in particular, the sum of a generalised Student's t -distribution [140] with a Gaussian function, and the sum of a modified Apollonios function [141] with a Gaussian function. For the background components, the product of an exponential function with a positive first-order polynomial function, as well as a positive second-order polynomial function, are tested as alternative background shapes for the fit to the $X_{c\bar{c}}\pi^+$ and $J/\psi \pi^+ \pi^-$ mass spectra. For each alternative model, the upper limit on the $\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)}$ ratio is recalculated where the maximal obtained value

$$\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)} < 0.05 \text{ (0.06) at 90 (95)\% CL,}$$

is conservatively taken as the upper limit including systematic uncertainties.

Source	$\sigma \left(\epsilon_{\psi(2S)}^{\chi_{c1}(3872)} \right) [\%]$
B_c^+ production spectra	< 0.1
Track reconstruction	0.2
Pion identification	0.1
Trigger efficiency	1.1
Data-simulation difference	0.8
$\chi_{c1}(3872)$ and $\psi(2S)$ decay models	1.5
Size of simulated samples	0.2
Sum in quadrature	2.0

Table 2. Relative systematic uncertainties (in %) for the efficiency ratio of the $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ and $B_c^+ \rightarrow \psi(2S)\pi^+$ decays. The total uncertainty is calculated as the quadratic sum of individual contributions.

6 Conclusions

A search for the $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ decay is performed using 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. No $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ signal is observed. Using $B_c^+ \rightarrow \psi(2S)\pi^+$ decays as a normalisation channel, an upper limit on the relative branching fraction between $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ and $B_c^+ \rightarrow \psi(2S)\pi^+$ decays is set to be

$$\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)} = \frac{\mathcal{B}_{B_c^+ \rightarrow \chi_{c1}(3872)\pi^+}}{\mathcal{B}_{B_c^+ \rightarrow \psi(2S)\pi^+}} \times \frac{\mathcal{B}_{\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-}}{\mathcal{B}_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}} < 0.05 \text{ (0.06) at } 90 \text{ (95)\% CL}.$$

A comparison of this upper limit with similar measurements in other beauty-hadron decays, as reported in refs. [30, 41, 79, 81, 86], is shown in figure 2. No large enhancement for $\chi_{c1}(3872)$ production in B_c^+ decays is observed, which supports neither the conclusions drawn by the ATLAS collaboration [71], nor expectations from the compact-tetraquark interpretation of the $\chi_{c1}(3872)$ state [92].

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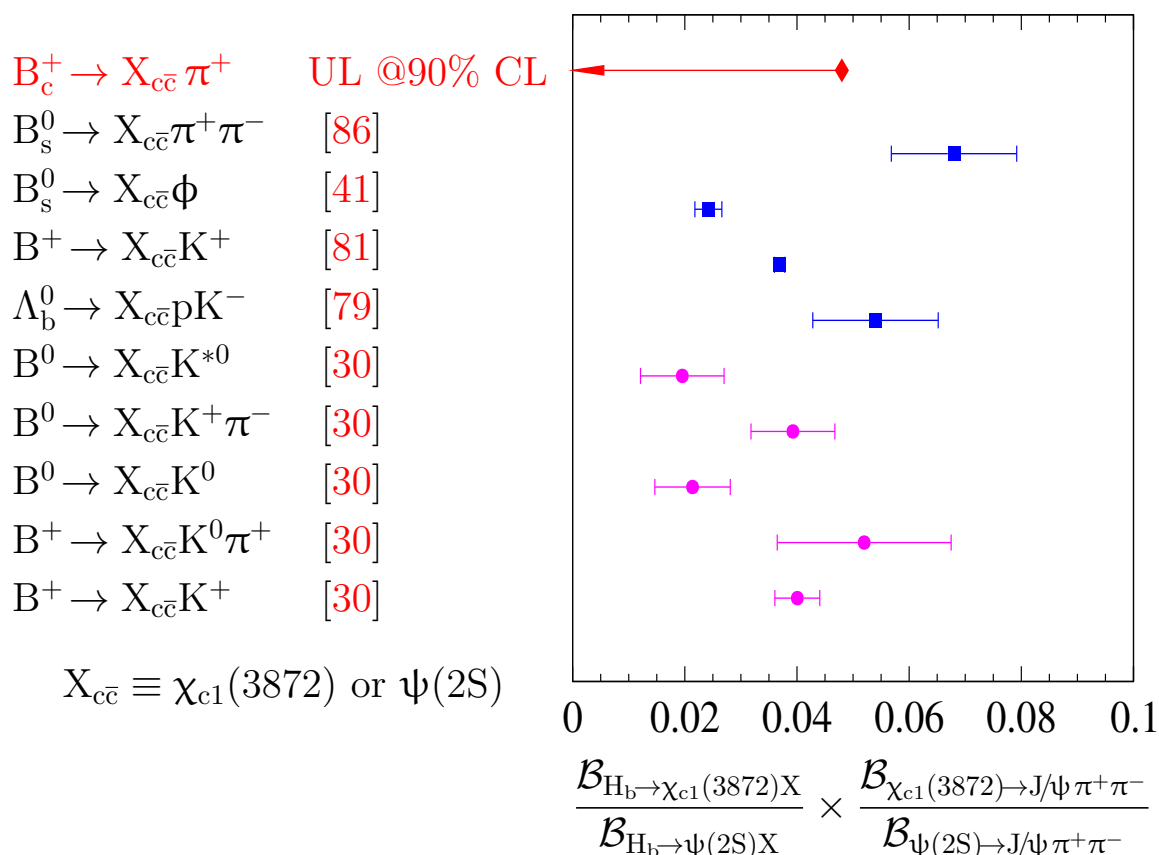


Figure 2. Comparison of the upper limit on the branching fraction ratio between $B_c^+ \rightarrow \chi_{c1}(3872)\pi^+$ and $B_c^+ \rightarrow \psi(2S)\pi^+$ decays set in this analysis, shown in red, with measurements of the ratios of branching fractions for $H_b \rightarrow \chi_{c1}(3872)X$ and $H_b \rightarrow \psi(2S)X$ decays of various beauty hadrons performed by the LHCb collaboration (blue squares) and Belle, BaBar and CDF collaborations (magenta circles).

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