Study of $B_c^+ \to \chi_c \pi^+$ decays

The LHCb collaboration

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ABSTRACT: A study of $B_c^+ \to \chi_c \pi^+$ decays is reported using proton-proton collision data, collected with the LHCb detector at centre-of-mass energies of 7, 8, and 13 TeV, corresponding to an integrated luminosity of $9\,\mathrm{fb}^{-1}$. The decay $B_c^+ \to \chi_{c2}\pi^+$ is observed for the first time, with a significance exceeding seven standard deviations. The relative branching fraction with respect to the $B_c^+ \to J/\psi\pi^+$ decay is measured to be

$$\frac{\mathcal{B}_{B_c^+ \to \chi_{c2}\pi^+}}{\mathcal{B}_{B_c^+ \to J/\psi\pi^+}} = 0.37 \pm 0.06 \pm 0.02 \pm 0.01\,,$$

where the first uncertainty is statistical, the second is systematic, and the third is due to the knowledge of the $\chi_{c2} \to J/\psi\gamma$ branching fraction. No significant $B_c^+ \to \chi_{c1}\pi^+$ signal is observed and an upper limit for the relative branching fraction for the $B_c^+ \to \chi_{c1}\pi^+$ and $B_c^+ \to \chi_{c2}\pi^+$ decays of

$$\frac{\mathcal{B}_{B_c^+ \to \chi_{c1}\pi^+}}{\mathcal{B}_{B_c^+ \to \chi_{c2}\pi^+}} < 0.49$$

is set at the 90% confidence level.

Contents

1 Introduction

The B_c^+ meson, discovered in 1998 by the CDF collaboration [1, 2] at the Tevatron 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 [9–36]. 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 [37, 38], which relies on the form factors of the $B_c^+ \to [c\bar{c}]W^+$ transition [39–43], and on the universal spectral function for the virtual W^+ boson fragmenting into light hadrons [44–46].

The decays of beauty hadrons into final states with P-wave charmonium, such as χ_{c1} and χ_{c2} mesons, have been extensively studied by the ARGUS [47], CLEO [48, 49], BaBar [50–56], Belle [57–63], CDF [64] and LHCb [65–68] collaborations. In $B \to \chi_c K^{(*)}$ decays[1] a significant suppression of the tensor χ_{c2} state relative to the vector χ_{c1} state is observed in accordance with expectations from QCD factorisation [69]. In contrast, for decays of the beauty baryon Λ_b^0, the $\Lambda_b^0 \to \chi_{c1} pK^-$ and $\Lambda_b^0 \to \chi_{c2} pK^-$ decay widths are found to be approximately the same [66]. A similar trend is observed for the $\Lambda_b^0 \to \chi_{c1} p\pi^-$ and $\Lambda_b^0 \to \chi_{c2} p\pi^-$ decays [68]. For decays of the B_c^+ meson the inverted pattern is expected with a relative suppression of the decays with the χ_{c1} meson in the final state [70–78]. However, the experimental information on the decays of the B_c^+ meson into P-wave charmonium states is very limited. Currently no decays of the B_c^+ meson into the χ_{c1} and χ_{c2} states are observed, and there is only evidence

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[1]In this paper the symbol χ_c denotes the χ_{c1} and χ_{c2} states together and inclusion of charge-conjugate decays is implied.

for the $B_c^+ \to (\chi_{c0} \to K^+ K^-) \pi^+$ decay with the scalar χ_{c0} meson in the final state [23]. Additional measurements are required to test the theory predictions and, in particular, to clarify the role of QCD factorisation in B_c^+ meson decays.

This paper reports a study of $B_c^+ \to \chi_c \pi^+$ decays using the radiative decays $\chi_c \to J/\psi \gamma$. A sample of $B_c^+ \to J/\psi \pi^+$ decays is used for the normalisation and a high-yield sample of $B^+ \to \chi_{c1} K^+$ decays is used to calibrate the detector resolution and mass scale. The analysis is based on 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 [79, 80] 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 [81], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about $4\,\mathrm{Tm}$, and three stations of silicon-strip detectors and straw drift tubes [82, 83] 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 $200\,\mathrm{GeV}/c$. 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 [84, 85]. 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) [86, 87], 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) [88]. 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 [89].

The online event selection is performed by a trigger [90], 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 samples of $B_c^+ \to \chi_c \pi^+$, $B_c^+ \to J/\psi \pi^+$ and $B^+ \to \chi_c K^+$ 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 [91] generator with a specific LHCb configuration [92] is used to simulate pp collisions with B^+ meson production. For B_c^+ meson production the BCVEGPY generator [93–96] is used. It is based on the full perturbative QCD calculations at the lowest order α_s^4 via the dominant gluon-gluon fusion process $\mathrm{gg} \to B_c^+ (B_c^{*+}) + \bar{c} + b$ and neglecting contributions from the quark pair annihilation $q\bar{q} \to B_c^+ (B_c^{*+}) + \bar{c} + b$ channel [97–101]. The generator is interfaced with the PYTHIA parton

shower and hadronisation model. Decays of unstable particles are described by the EvtGen package [102], in which final-state radiation is generated using Photos [103].

The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [104, 105] as described in ref. [106]. 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 the $D^{*+} \to (D^0 \to K^- \pi^+)\, \pi^+$ and $K_S^0 \to \pi^+ \pi^-$ control channels [88, 107]. To account for imperfections in the simulation of charged particle reconstruction, the track reconstruction efficiency determined from simulation is corrected using $J/\psi \to \mu^+ \mu^-$ calibration samples [108]. Samples of $B^+ \to J/\psi\, (K^{*+} \to K^+ \pi^0)$ decays are used to correct the photon reconstruction efficiency in simulation [109–113].

3 Event selection

The signal $B_c^+ \to \chi_c \pi^+$ and control $B^+ \to \chi_c K^+$ candidates are reconstructed using $\chi_c \to J/\psi \gamma$ followed by $J/\psi \to \mu^+ \mu^-$ decays. The dimuon final state of the J/ψ meson is used to reconstruct $B_c^+ \to J/\psi \pi^+$ candidates that are used as a normalisation channel. A loose preselection is applied, followed by a multivariate classifier based on a decision tree with gradient boosting (BDTG) [114].

Muon, pion and kaon candidates are identified by combining information from the RICH, calorimeter and muon detectors. The candidates are required to have transverse momenta larger than 550 MeV/c and 200 MeV/c for muon and hadron candidates, respectively. Pions and kaons are required to have a momentum between 3.2 and 150 GeV/c to ensure good performance of particle identification in the RICH detectors [88, 115]. 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 $J/\psi \to \mu^+ \mu^-$ candidates. The reconstructed mass of the $\mu^+ \mu^-$ pair is required to be in the range $3.0 < m_{\mu^+ \mu^-} < 3.2$ GeV/c^2. The position of the reconstructed dimuon vertex is required to be inconsistent with that of any reconstructed PV.

The $\chi_c \to J/\psi \gamma$ candidates are formed by combining the selected J/ψ candidates with photon candidates that have been reconstructed using clusters in the electromagnetic calorimeter. Only clusters that are not matched to the trajectory of a track extrapolated from the tracking system [116, 117] are used. The transverse energy of photon candidates is required to exceed 400 MeV. The χ_c candidates are selected in the $J/\psi \gamma$ mass region between 3.4 and 3.7 GeV/c^2, which covers both the $\chi_{c1} \to J/\psi \gamma$ and $\chi_{c2} \to J/\psi \gamma$ decays.

The selected χ_c and J/ψ candidates are combined with charged tracks identified as pions or kaons to form $B_c^+ \to \chi_c \pi^+$, $B^+ \to \chi_c K^+$ and $B_c^+ \to J/\psi \pi^+$ candidates. A kinematic fit [118] that constrains the three-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 [119] and

the B candidate is constrained to originate from the associated PV.[2] 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 $100\,\mu\mathrm{m}/c$ and $150\,\mu\mathrm{m}/c$ for the B_c^+ and B^+ candidates, respectively, to reduce the background from particles originating directly from the PV. To suppress the cross-feed from $B^+ \to J/\psi \pi^+$ decays, the mass of the $J/\psi\pi^+$ system for the reconstructed $B_c^+ \to \chi_c \pi^+$ candidates is required to be outside of the mass range $5.22 < m_{J/\psi\pi^+} < 5.35\,\mathrm{GeV}/c^2$.

To further suppress combinatorial background for the $B_c^+ \to \chi_c \pi^+$, $B_c^+ \to J/\psi \pi^+$ and $B^+ \to \chi_c K^+$ decays, three separate BDTG classifiers are used, each trained on the corresponding simulated samples. As a proxy for the background, the B_c^+ candidates from data with a mass between 6.4 and $6.6\,\mathrm{GeV}/c^2$ are used for the B_c^+ classifiers and B^+ candidates with a mass between 5.35 and $5.50\,\mathrm{GeV}/c^2$ are used for the B^+ classifier. The k-fold cross-validation technique [120] with $k = 13$ is used to avoid introducing a bias in the BDTG evaluation. The BDTG classifiers are trained using variables related to the reconstruction quality, decay time of B candidates, kinematics of particles in the final state and variables related to hadron (pion for B_c^+ candidates and kaon for B^+ candidates) identification [88, 115]. The requirement on the BDTG output is chosen to maximise the Punzi figure-of-merit $\varepsilon/(\alpha/2 + \sqrt{B})$ [121] for $B_c^+ \to \chi_c \pi^+$ decays and $S/\sqrt{S+B}$ for $B_c^+ \to J/\psi \pi^+$ and $B^+ \to \chi_c K^+$ decays, where ε is the signal efficiency in simulation for $B_c^+ \to \chi_c \pi^+$ decays, $\alpha = 5$ is the desired signal significance in units of standard deviations, B is the expected background yield within a narrow mass window centred at the known mass of the b-hadron [119], and the signal yields S are estimated from simulated samples, normalised to the signal yields observed in data for a loose requirement on the BDTG output. After application of the BDTG requirement a small fraction of events, about 2.5% for the $B_c^+ \to \chi_c \pi^+$ and $B^+ \to \chi_c K^+$ candidates, and 0.5% for the $B_c^+ \to J/\psi \pi^+$ candidates in the signal region, contain multiple candidates. For each decay channel if two or more candidates are found in the same event, only one randomly chosen candidate is retained for further analysis.

To improve the B_c^+ and B^+ mass resolution, the mass of the B_c^+ and B^+ candidates is calculated using a kinematic fit [118], similar to the one described above, but with an additional constraint fixing the mass of the $J/\psi\gamma$ combination to the known χ_{c2} meson mass [119] for the $B_c^+ \to \chi_c \pi^+$ candidates, and to the known mass of the χ_{c1} meson [119] for the $B^+ \to \chi_c K^+$ candidates. The mass distributions for selected $B^+ \to \chi_c K^+$, $B_c^+ \to \chi_c \pi^+$ and $B_c^+ \to J/\psi \pi^+$ candidates are shown in figures 1, 2 and 3, respectively.

4 Signal yields

The yields for the $B^+ \to \chi_c K^+$, $B_c^+ \to \chi_c \pi^+$ and $B_c^+ \to J/\psi \pi^+$ decays are determined using extended unbinned maximum-likelihood fits. In this analysis, the detector resolution and a possible mass bias for the signal $B_c^+ \to \chi_c \pi^+$ channel are determined from the control channel $B^+ \to \chi_c K^+$, exploiting the similarity between the two final states.

The fit model for the $B^+ \to \chi_c K^+$ control channel consists of three components. The first component corresponds to the decay $B^+ \to \chi_{c1} K^+$, located close to the known mass of

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[2]Each B_c^+ or B^+ 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.
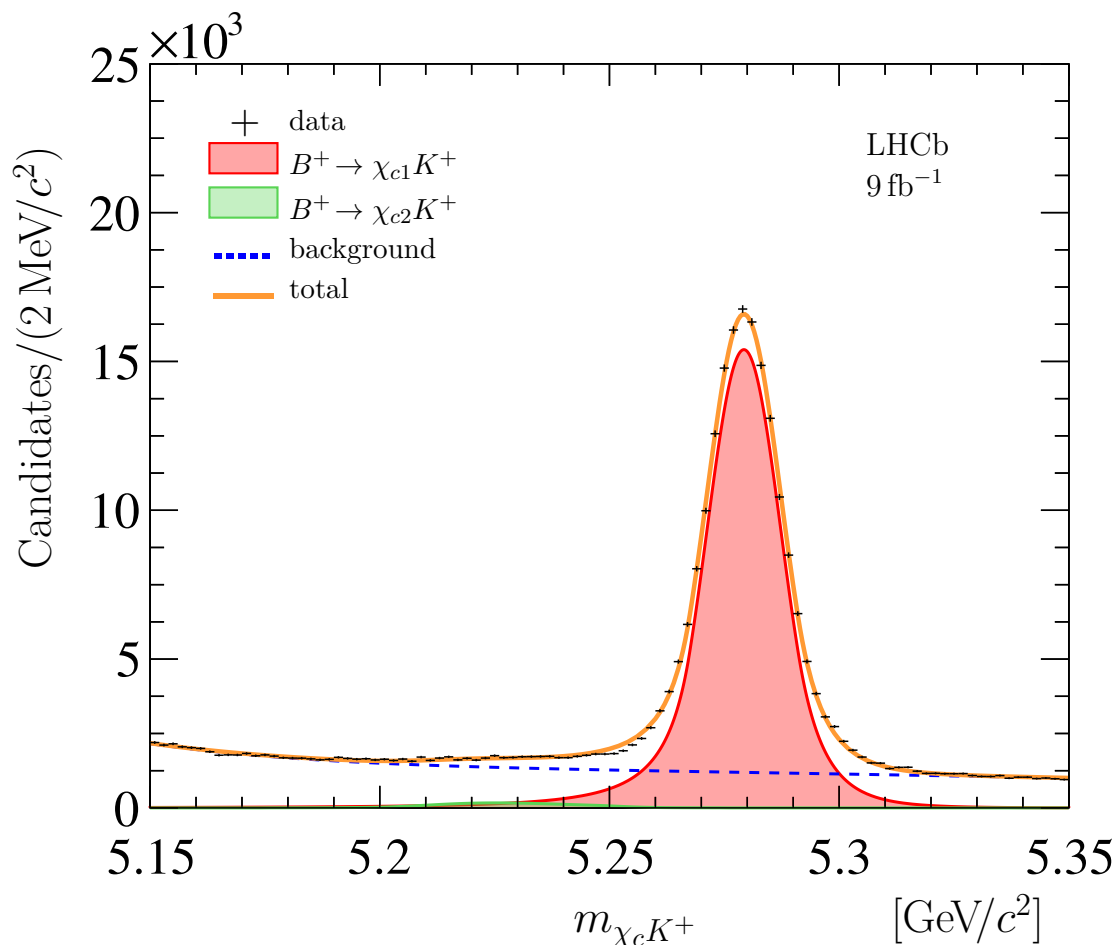
Figure 1. Mass distribution for selected $B^+ \to \chi_c K^+$ candidates with a χ_{c1} mass-constraint. The result of the fit, described in the text, is overlaid.

the B^+ meson, and is parameterised by a modified Gaussian function with power-law tails on both sides of the distribution [122, 123]. The second component corresponds to a small contribution from $B^+ \to \chi_{c2}K^+$ decays, and is parameterised by the sum of a Gaussian function and a modified Novosibirsk function [124]. Due to the mass difference between the χ_{c1} and χ_{c2} states [119, 125–127], the χ_{c1}-mass constraint used to evaluate the mass of the B^+ candidates shifts the position of this component toward lower masses. The third component corresponds to combinatorial background and is modelled by the product of an exponential function and a positive second-order polynomial function [128]. The shape parameters for the fit components describing the $B^+ \to \chi_{c1}K^+$ and $B^+ \to \chi_{c2}K^+$ decay contributions are taken from simulation and their uncertainties are propagated to the fit using a multivariate Gaussian constraint. The position and resolution parameters for the $B^+ \to \chi_{c1}K^+$ component are parameterised as

$$\mu_{B^+} = \delta m_{B^+} + m_{B^+}, \tag{4.1a}$$

$$\sigma_{B^+} = s_{B^+} \times \sigma_{B^+}^{\text{MC}}, \tag{4.1b}$$

where m_{B^+} is the known mass of the B^+ meson and $\sigma_{B^+}^{\text{MC}}$ is a resolution parameter obtained from simulation. The parameter δm_{B^+} accounts for a mass bias, while s_{B^+} describes potential
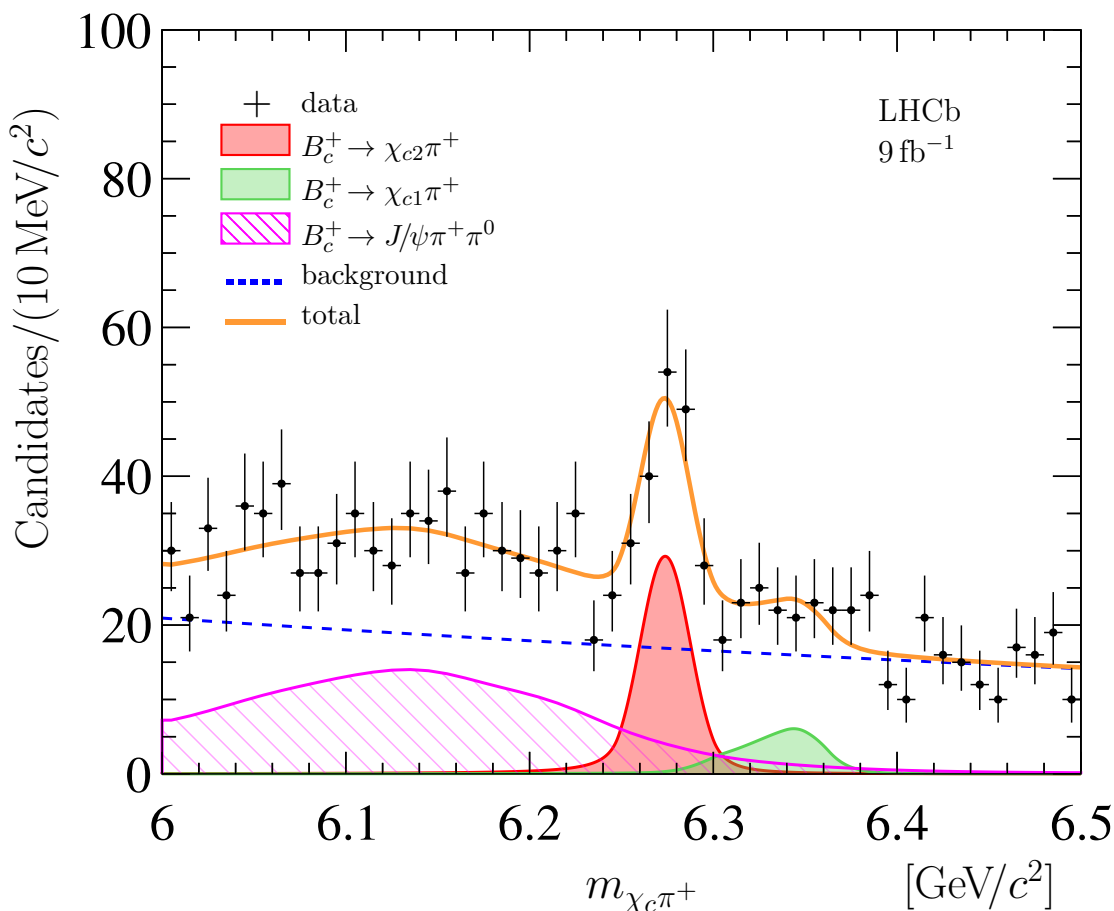
Figure 2. Mass distribution for selected $B_c^+ \to \chi_c \pi^+$ candidates with a χ_{c2} mass constraint. The result of the fit, described in the text, is overlaid.

differences between data and simulation for the resolution. The position parameters for the $B^+ \to \chi_{c1} K^+$ and $B^+ \to \chi_{c2} K^+$ components are allowed to vary in the fit, but their difference is constrained to the value obtained from simulation using a Gaussian constraint. The resulting fit is overlaid in figure 1, and the parameters of interest are listed in table 1. The yield of the $B^+ \to \chi_{c2} K^+$ decay is found to be much smaller than that of the $B^+ \to \chi_{c1} K^+$ decay as seen in previous measurements [55, 59, 65] and in accordance with expectations from QCD factorisation. The obtained mass bias parameter δm_{B^+} and resolution scale parameter s_{B^+} are used for the determination of the signal yield for the $B_c^+ \to \chi_c \pi^+$ channel.

The fit model for the $B_c^+ \to \chi_c \pi^+$ channel consists of four components. The first component corresponds to the $B_c^+ \to \chi_{c2} \pi^+$ decay and is parameterised by a modified Gaussian function. This component is located close to the known mass of the B_c^+ meson. The second smaller component corresponds to the $B_c^+ \to \chi_{c1} \pi^+$ decay and is parameterised by the sum of a modified Gaussian and a modified Novosibirsk function. Due to the mass difference between the χ_{c1} and χ_{c2} states, and the χ_{c2}-mass constraint used to evaluate the mass of the B_c^+ candidate, the position of this component is shifted towards higher masses. The third component corresponds to the partially reconstructed $B_c^+ \to J/\psi \pi^+ (\pi^0 \to \gamma\gamma)$ decay [129]

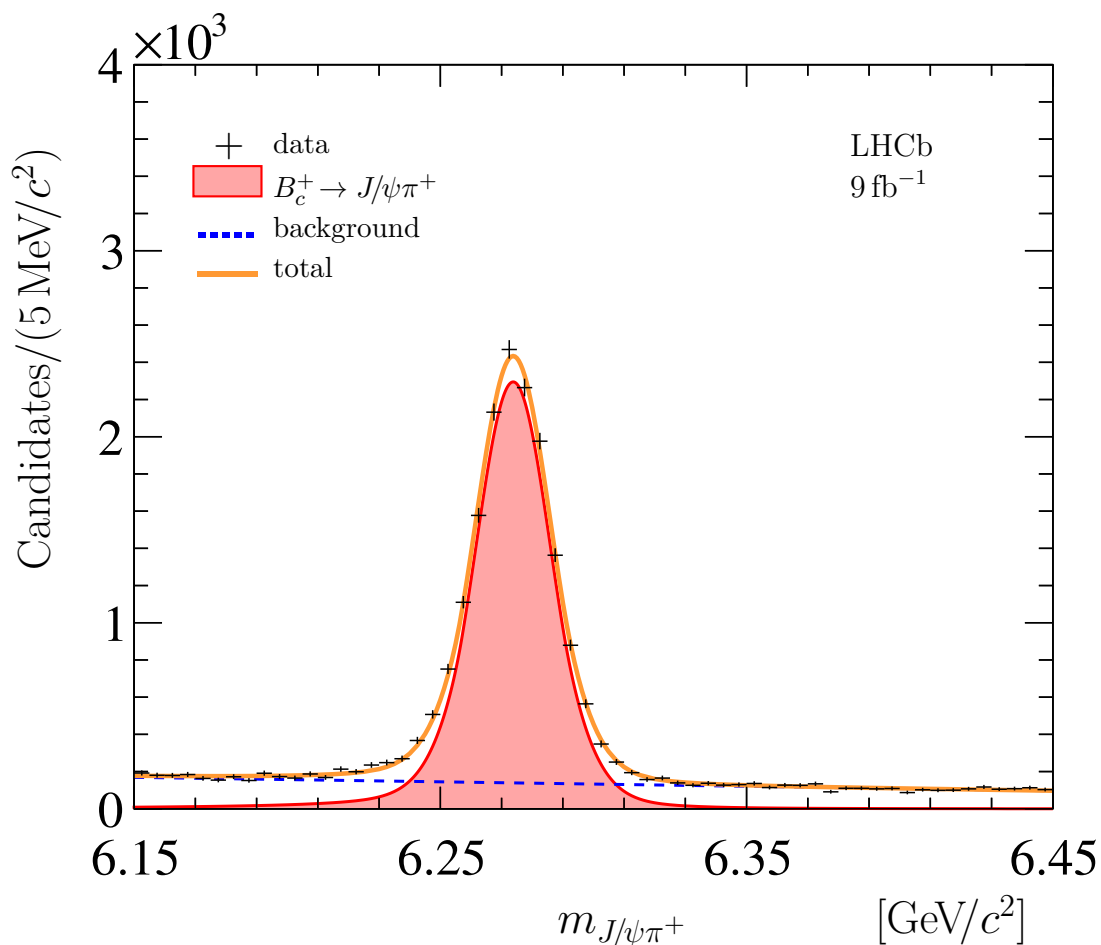**Figure 3.** Mass distributions for selected $B_c^+ \to J/\psi\pi^+$ candidates. The result of the fit, described in the text, is overlaid.

Parameter		Value
$N_{B^+ \to \chi_{c1}K^+}$	$[10^3]$	171.35 ± 0.61
$N_{B^+ \to \chi_{c2}K^+}$	$[10^3]$	3.28 ± 0.40
δm_{B^+}	$[\mathrm{MeV}/c^2]$	0.07 ± 0.12
s_{B^+}		1.102 ± 0.004

Table 1. Parameters of interest from the fit to the $\chi_c K^+$ mass spectrum: the yields of the $B^+ \to \chi_{c1}K^+$ and $B^+ \to \chi_{c2}K^+$ decays, the B^+ mass bias parameter δm_{B^+} and the resolution scale factor s_{B^+}.

where one photon is used in the misreconstructed $\chi_c \to J/\psi\gamma$ candidate and the other is not reconstructed. The shape of this component is obtained from the simulation. Finally, the combinatorial background is parameterised by an exponential function. Similar to the $B^+ \to \chi_c K^+$ case above, the shape parameters for the fit components describing the $B_c^+ \to \chi_{c1}\pi^+$ and $B_c^+ \to \chi_{c2}\pi^+$ contributions and the difference between the positions of the mass peaks of the $B_c^+ \to \chi_{c1}\pi^+$ and $B_c^+ \to \chi_{c2}\pi^+$ contributions are taken from simulation. Their uncertainties are propagated to the fit using a multivariate Gaussian constraint. Similar to eq. (4.1), the position and resolution parameters for the $B_c^+ \to \chi_{c2}\pi^+$ component

are parameterised as

$$\mu_{B_c^+} = \delta m_{B^+} + m_{B_c^+} \,, \tag{4.2a}$$

$$\sigma_{B_c^+} = s_{B^+} \times \sigma_{B_c^+}^{\mathrm{MC}} \,, \tag{4.2b}$$

where $m_{B_c^+}$ is the known mass of the B_c^+ meson [33] and $\sigma_{B_c^+}^{\mathrm{MC}}$ is a resolution parameter obtained from simulation. The values of δm_{B^+} and s_{B^+} are defined in eq. (4.1) and are taken from the fit to the $\chi_{c1}K^+$ mass spectrum above (see table 1). Their uncertainties, as well as the uncertainty for the $m_{B_c^+}$ value, are propagated to the fit using Gaussian constraints. The yield of the $B_c^+ \to \chi_{c1}\pi^+$ signal component, $N_{B_c^+ \to \chi_{c1}\pi^+}$, is parameterised as

$$N_{B_c^+ \to \chi_{c1}\pi^+} \equiv N_{B_c^+ \to \chi_{c2}\pi^+} \times \mathcal{R}_{\chi_{c2}}^{\chi_{c1}} \times \varepsilon_{\chi_{c2}}^{\chi_{c1}} \times \frac{\mathcal{B}_{\chi_{c1} \to J/\psi\gamma}}{\mathcal{B}_{\chi_{c2} \to J/\psi\gamma}} \,, \tag{4.3a}$$

where $N_{B_c^+ \to \chi_{c2}\pi^+}$ is the yield of the $B_c^+ \to \chi_{c2}\pi^+$ signal component, $\mathcal{R}_{\chi_{c2}}^{\chi_{c1}}$ is a free parameter in the fit corresponding to the ratio of branching fractions for the $B_c^+ \to \chi_{c1}\pi^+$ and $B_c^+ \to \chi_{c2}\pi^+$ decays

$$\mathcal{R}_{\chi_{c2}}^{\chi_{c1}} \equiv \frac{\mathcal{B}_{B_c^+ \to \chi_{c1}\pi^+}}{\mathcal{B}_{B_c^+ \to \chi_{c2}\pi^+}} \,, \tag{4.3b}$$

$\mathcal{B}_{\chi_c \to J/\psi\gamma}$ are the branching fractions for the $\chi_c \to J/\psi\gamma$ decays [119], and $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$ is the ratio of the total efficiencies for the $B_c^+ \to \chi_{c2}\pi^+$ and $B_c^+ \to \chi_{c1}\pi^+$ decays (see section 5)

$$\varepsilon_{\chi_{c2}}^{\chi_{c1}} \equiv \frac{\varepsilon_{B_c^+ \to \chi_{c1}\pi^+}}{\varepsilon_{B_c^+ \to \chi_{c2}\pi^+}} \,. \tag{4.3c}$$

The uncertainties for the $\mathcal{B}_{\chi_c \to J/\psi\gamma}$ and $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$ values including the systematic effects on the ratio of efficiencies, discussed in detail in section 6, are accounted for in the fit via Gaussian constraints. The result of the fit is overlaid in figure 2. The parameters of interest, namely the yield of the $B_c^+ \to \chi_{c2}\pi^+$ decays and the ratio of branching fractions $\mathcal{R}_{\chi_{c2}}^{\chi_{c1}}$, are found to be

$$N_{B_c^+ \to \chi_{c2}\pi^+} = 108 \pm 16 \,,$$
$$\mathcal{R}_{\chi_{c2}}^{\chi_{c1}} = 0.24 \, {}^{+\,0.13}_{-\,0.11} \,.$$

The significance for the $B_c^+ \to \chi_{c2}\pi^+$ signal is estimated using Wilks' theorem [130] and found to be 8.1 standard deviations, corresponding to the first observation of the $B_c^+ \to \chi_{c2}\pi^+$ decay. On the contrary, the $B_c^+ \to \chi_{c1}\pi^+$ signal is found to be insignificant, exhibiting a hierarchy of branching fractions opposite to that in the $B^+ \to \chi_c K^+$ case, but in qualitative agreement with the theory expectation for the suppression of the χ_{c1} state in $B_c^+ \to \chi_c\pi^+$ decays [70–78]. Using the $\mathrm{CL_s}$ technique [131], where the p-values are calculated based on the asymptotic properties of the profile likelihood ratio [132], an upper limit of

$$\mathcal{R}_{\chi_{c2}}^{\chi_{c1}} < 0.41 \tag{4.4}$$

is found at 90% confidence level.

The fit model for the normalisation $B_c^+ \to J/\psi\pi^+$ channel consists of two components. The first component corresponds to the $B_c^+ \to J/\psi\pi^+$ decay and is parameterised by the sum of

a modified Gaussian function and a Gaussian function with a common mean value. The second component describes the combinatorial background and is parameterised by a positive first-order polynomial function [128]. Similar to the $B^+ \to \chi_c K^+$ and $B_c^+ \to \chi_c \pi^+$ cases above, the shape parameters for the fit component describing the $B_c^+ \to J/\psi\pi^+$ contributions are taken from simulation and their uncertainties are propagated to the fit using a multivariate Gaussian constraint. The resolution parameter for the $B_c^+ \to J/\psi\pi^+$ component is parameterised as

$$\sigma_{B_c^+} = s_{B_c^+} \times \sigma_{B_c^+}^{\mathrm{MC}}, \tag{4.5}$$

where $\sigma_{\mathrm{MC}}^{B_c^+}$ is a resolution parameter obtained from simulation and the parameter s_{B^+} accounts for a possible difference between data and simulation for the resolution parameter. The resulting fit is overlaid in figure 3. The parameters of interest, namely the yield of the $B_c^+ \to J/\psi\pi^+$ signal and the resolution scale parameter s_{B^+}, are found to be

$$N_{B_c^+ \to J/\psi\pi^+} = (15.40 \pm 0.14) \times 10^3,$$
$$s_{B_c^+} = 1.106 \pm 0.011.$$

To validate the observed $B_c^+ \to \chi_{c2}\pi^+$ signal, several cross-checks are performed. The data are categorised according to the data-taking period, the polarity of the LHCb dipole magnet [133] and the charge of the B_c^+ candidates. Also, the χ_{c2} mass constraint, used for calculation of the mass of the B_c^+ candidates, is replaced by a χ_{c1} mass constraint. The results are found to be consistent among all samples and analysis techniques.

To confirm the $\chi_{c2} \to J/\psi\gamma$ signal within the observed $B_c^+ \to \chi_{c2}\pi^+$ signal, the background-subtracted $J/\psi\gamma$ mass spectrum is examined. For background subtraction, the sPlot technique [134] is used with the $\chi_c\pi^+$ mass as the discriminating variable. The background-subtracted $J/\psi\gamma$ spectrum is shown in figure 4 (left). The $\chi_{c1} \to J/\psi\gamma$ signal from the control sample of $B^+ \to \chi_{c1}K^+$ decays is used to examine the possible bias in the mass and mass resolution for the $J/\psi\gamma$ mass. The background-subtracted $J/\psi\gamma$ spectrum from the $B^+ \to \chi_{c1}K^+$ decays is presented in figure 4 (right). Unbinned extended fits are performed to the $J/\psi\gamma$ distributions with a model consisting of two components. The first component corresponds to the $\chi_c \to J/\psi\gamma$ signal and is parameterised with a modified Gaussian function for the χ_{c2} state and the sum of a modified Gaussian function and a Gaussian function with a common mean value for the χ_{c1} state. The second component describes the $B_c^+ \to J/\psi\gamma\pi^+$ and $B^+ \to J/\psi\gamma K^+$ decays without intermediate χ_{c2} and χ_{c1} mesons and is parameterised with a constant. Similar to the fits described above, the shape parameters for the χ_c components are taken from simulation and their uncertainties are propagated to the fits using a multivariate Gaussian constraint. Similar to eqs. (4.1) and (4.2) the position and resolution parameters for each χ_c component in the fits are parameterised as

$$\mu_{\chi_c} = \delta m_{\chi_{c1}} + m_{\chi_c}, \tag{4.6a}$$
$$\sigma_{\chi_c} = s_{\chi_{c1}} \times \sigma_{\chi_c}^{\mathrm{MC}}, \tag{4.6b}$$

where m_{χ_c} stands for the known mass of the corresponding χ_c state and $\sigma_{\mathrm{MC}}^{\chi_c}$ denotes the corresponding resolution parameter obtained from simulation. The mass bias parameter $\delta m_{\chi_{c1}}$ and resolution scale parameter $s_{\chi_{c1}}$, determined from the fit to the $J/\psi\gamma$ mass spectrum from
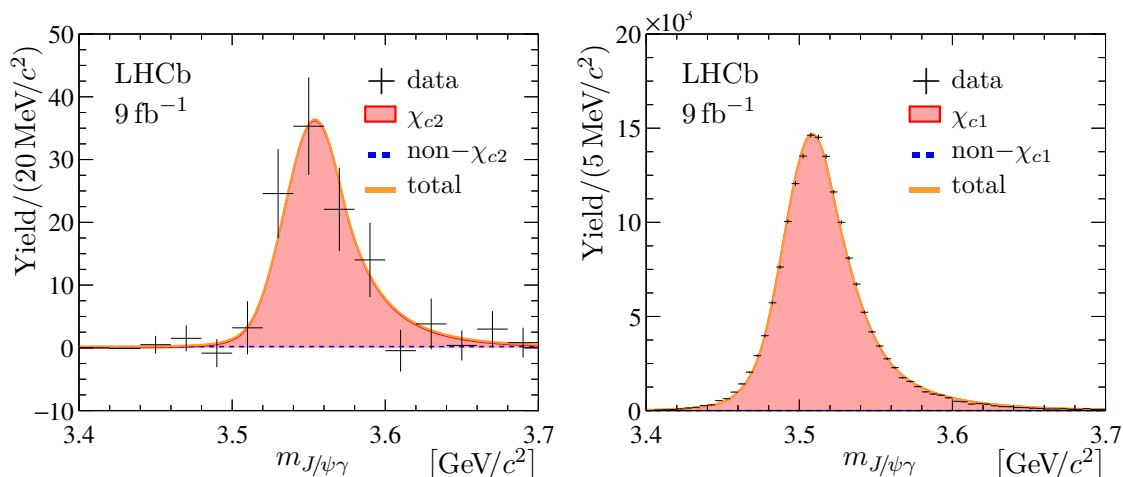
Figure 4. Background-subtracted $J/\psi\gamma$ mass distribution from (left) the $B_c^+ \to \chi_{c2}\pi^+$ decays and (right) $B^+ \to \chi_{c1}K^+$ decays. Projections of the fit, described in the text, are overlaid.

the control $B^+ \to \chi_{c1}K^+$ channel, are $\delta m_{\chi_{c1}} = -2.09 \pm 0.09\,\mathrm{MeV}/c^2$ and $s_{\chi_{c1}} = 1.027 \pm 0.004$. These values are used in the fit to the $J/\psi\gamma$ mass spectrum for the signal $B_c^+ \to \chi_{c2}\pi^+$ channel and their uncertainties are included using Gaussian constraints. The results of the fits to both $J/\psi\gamma$ mass spectra are overlaid in figure 4. For both $B^+ \to \chi_{c1}K^+$ and $B_c^+ \to \chi_{c2}\pi^+$ decays a good description of data is achieved without contributions from the non-χ_c components. This proves the observed $B_c^+ \to (J/\psi\gamma)\,\pi^+$ signal proceeds via the intermediate $\chi_{c2} \to J/\psi\gamma$ decay.

5 Efficiency and ratio of branching fractions

For each channel, the 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 simulation samples described in section 2. The ratio of efficiencies for the $B_c^+ \to \chi_{c1}\pi^+$ and $B_c^+ \to \chi_{c2}\pi^+$ channels, $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$, defined in eq. (4.3c), and the ratio of efficiencies for the $B_c^+ \to \chi_{c2}\pi^+$ and $B_c^+ \to J/\psi\pi^+$ channels, $\varepsilon_{J/\psi}^{\chi_{c2}}$, are found to be

$$\varepsilon_{\chi_{c2}}^{\chi_{c1}} = 0.763 \pm 0.003 \,, \tag{5.1a}$$

$$\varepsilon_{J/\psi}^{\chi_{c2}} = (9.84 \pm 0.03) \times 10^{-2} \,, \tag{5.1b}$$

where the uncertainties are due to the size of simulated samples.

The ratio of branching fractions for the $B_c^+ \to \chi_{c2}\pi^+$ and $B_c^+ \to J/\psi\pi^+$ decays is calculated as

$$\mathcal{R}_{J/\psi}^{\chi_{c2}} \equiv \frac{\mathcal{B}_{B_c^+ \to \chi_{c2}\pi^+}}{\mathcal{B}_{B_c^+ \to J/\psi\pi^+}} = \frac{N_{B_c^+ \to \chi_{c2}\pi^+}}{N_{B_c^+ \to J/\psi\pi^+}} \times \frac{1}{\varepsilon_{J/\psi}^{\chi_{c2}}} \times \frac{1}{\mathcal{B}_{\chi_{c2} \to J/\psi\gamma}} \,, \tag{5.2}$$

where the signal yields N are obtained in section 4, $\varepsilon_{J/\psi}^{\chi_{c2}}$ is the efficiency ratio from eq. (5.1b) and $\mathcal{B}_{\chi_{c2} \to J/\psi\gamma}$ is the known branching fraction of the $\chi_{c2} \to J/\psi\gamma$ decay [119]. The ratio of branching fractions is found to be

$$\mathcal{R}_{J/\psi}^{\chi_{c2}} = 0.37 \pm 0.06 \,,$$

where the uncertainty is statistical only. Systematic uncertainties are discussed in the following section.

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. The remaining contributions to the systematic uncertainty 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, several alternative shapes are tested. For the $B_c^+ \to \chi_{c2}\pi^+$ and $B_c^+ \to J/\psi\pi^+$ signal shapes two alternative models are tested:

- the sum of a generalised Student's t-distribution [135] and a Gaussian function;

- the sum of a modified Apollonios function [136] and a Gaussian function.

For the $B_c^+ \to \chi_{c1}\pi^+$ signal shape two alternative models are probed:

- the sum of a generalised Student's t-distribution and a modified Novosibirsk function [124];

- the sum of a modified Apollonios function and a modified Novosibirsk function.

For the background components, positive convex decreasing polynomial functions of the second and third-order are used as alternative background shapes for the fit to the $\chi_c\pi^+$ mass spectrum. For the fit to the $J/\psi\pi^+$ mass spectrum the product of an exponential function and a positive first-order polynomial function as well as a positive second-order polynomial function are tested. The systematic uncertainty related to the fit model is estimated using pseudoexperiments produced with the baseline fit model and fit with sets of the alternative models. The maximal deviations in the ratios of the signal yields for the $B_c^+ \to \chi_{c2}\pi^+$ and $B_c^+ \to J/\psi\pi^+$ decays with respect to the baseline models do not exceed 0.3% for the alternative signal models and 0.7% for the alternative background models. These values are taken as systematic uncertainties for the ratio $\mathcal{R}_{J/\psi}^{\chi_{c2}}$.

In the analysis, multiple candidates are randomly excluded. To estimate the systematic effect due to the exclusion procedure the analysis is repeated 300 times with different sets of candidates randomly removed. The variation of the relative signal yield between $B_c^+ \to \chi_{c2}\pi^+$ and $B_c^+ \to J/\psi\pi^+$ channels is found to be 2.0% and this value is assigned as the corresponding systematic uncertainty.

An important systematic uncertainty arises from differences between data and simulation. The transverse momentum and rapidity spectra of the B_c^+ mesons in the simulated samples are adjusted to match those observed in a high-yield, low-background sample of $B_c^+ \to J/\psi\pi^+$ decays. The finite size of this sample causes uncertainty in the obtained production spectra of the B_c^+ mesons. The associated systematic uncertainty in the efficiency ratios is estimated using the variation of the B_c^+ kinematic spectra within their uncertainties. The induced variations for the ratio $\mathcal{R}_{J/\psi}^{\chi_{c2}}$ and for the efficiency ratio $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$ are found to be 0.3% and 0.1%, respectively. These values are taken as corresponding systematic uncertainties.

Source	$\mathcal{R}_{J/\psi}^{\chi_{c2}}$	$\varepsilon_{\chi_{c2}}^{\chi_{c1}}$
Fit model		
Signal shape	0.3	—
Background shape	0.7	—
Multiple candidates exclusion	2.0	—
B_c^+ production spectra	0.3	0.1
Track reconstruction	< 0.1	< 0.1
Photon reconstruction	3.0	—
Pion identification	0.5	0.6
Trigger efficiency	1.1	1.1
Data-simulation difference	2.1	—
Size of simulated sample	0.3	0.4
Total	4.4	1.3

Table 2. Relative systematic uncertainties (in %) for the ratio of branching fractions $\mathcal{R}_{J/\psi}^{\chi_{c2}}$ and the ratio of efficiencies for the $B_c^+ \to \chi_{c1}\pi^+$ and $B_c^+ \to \chi_{c2}\pi^+$ decays. The total uncertainty is the quadratic sum of individual contributions.

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 cancel completely in the efficiency ratios. The track-finding efficiency obtained from simulated samples is corrected using calibration channels [108]. The uncertainties related to the efficiency correction factors are propagated to the ratios of the total efficiencies using pseudoexperiments and found to be smaller than 0.1% both for the ratio $\mathcal{R}_{J/\psi}^{\chi_{c2}}$ and for the efficiency ratio $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$. Differences in the photon reconstruction efficiencies between data and simulation are studied using a large sample of $B^+ \to J/\psi \left(K^{*+} \to K^+ \pi^0 \right)$ decays [111–113]. The uncertainty due to the finite size of the sample is propagated to the ratio of the total efficiencies using pseudoexperiments and is found to be less than 0.1%. The additional uncertainty due to the imprecise knowledge of the ratio of branching fractions for the $B^+ \to J/\psi K^{*+}$ and $B^+ \to J/\psi K^+$ decays [119] is 3.0%. The squared sum of these uncertainties is taken as a systematic uncertainty for the ratio $\mathcal{R}_{J/\psi}^{\chi_{c2}}$ related to the photon reconstruction. The corresponding systematic uncertainty for the efficiency ratio $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$ is found to be negligible.

The modelling of the pion identification in the simulation is improved by sampling the corresponding distributions in the $D^{*+} \to \left(D^0 \to K^- \pi^+ \right) \pi^+$ and $K_S^0 \to \pi^+ \pi^-$ control channels [88, 107]. The systematic uncertainty obtained through this procedure arises 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 changed shape and the efficiency models are regenerated [137, 138]. The difference between the two estimates for the efficiency ratios is taken as the systematic uncertainty related to pion identification and is found to be 0.5% and 0.6% for the ratio $\mathcal{R}_{J/\psi}^{\chi_{c2}}$ and for the efficiency ratio $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$, respectively.

Large samples of $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S) K^+$ decays [139] 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 [139].

Discrepancies in reconstructed quantities between the simulated samples and data, due to effects other than those described above, are studied by varying the BDTG selection criteria for the normalisation decay $B_c^+ \to J/\psi\pi^+$ over its full range and repeating the fit. The observed maximal difference between the efficiency estimated using data and simulation does not exceed 2.1%. This value is taken as a corresponding systematic uncertainty for the ratio $\mathcal{R}_{J/\psi}^{\chi_{c2}}$. The corresponding systematic uncertainty for the efficiency ratio $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$ is considered to be negligible due to the very similar kinematics of the corresponding decay channels.

The systematic uncertainty due to the finite size of the simulated samples, used to calculate the efficiency ratios from eqs. (5.1), is found to be 0.3% and 0.4% for the ratio $\mathcal{R}_{J/\psi}^{\chi_{c2}}$ and for the efficiency ratio $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$, respectively. The total systematic uncertainty is estimated as the sum in quadrature of the individual contributions.

For each choice of an alternative fit model and for each pseudoexperiment with random removal of multiple candidates, the statistical significance for the $B_c^+ \to \chi_{c2}\pi^+$ decay is recalculated using Wilks' theorem [130]. The smallest significance of 7.6 standard deviations is taken as the overall significance of the signal, including systematic uncertainties.

The systematic uncertainty for the efficiency ratio $\varepsilon_{\chi_{c2}}^{\chi_{c1}}$, discussed above, is included in the fit model via a Gaussian constraint. Therefore the upper limit for the $\mathcal{R}_{\chi_{c2}}^{\chi_{c1}}$ ratio from eq. (4.4) already accounts for the corresponding systematic uncertainty. The remaining uncertainties are related to the fit model and the exclusion of multiple candidates. To account for these, the upper limit is recalculated for each fit with the alternative models and for each pseudoexperiment with random removal of multiple candidates and the maximal obtained value of

$$\mathcal{R}_{\chi_{c2}}^{\chi_{c1}} < 0.49 \text{ at } 90\% \text{ CL}$$

is conservatively taken as the upper limit including systematic uncertainties.

7   Results and conclusions

The decay modes $B_c^+ \to \chi_c \pi^+$ are studied 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 $13\,\mathrm{TeV}$. The first observation of the decay $B_c^+ \to \chi_{c2}\pi^+$, with a significance of 7.6 standard deviations, is reported. Using the $B_c^+ \to J/\psi\pi^+$ decay as a normalisation channel, and the known value of the branching fraction for the $\chi_{c2} \to J/\psi\gamma$ decay of $(19.0 \pm 0.5)\%$ [119], the ratio of the branching fractions is measured to be

$$\frac{\mathcal{B}_{B_c^+ \to \chi_{c2}\pi^+}}{\mathcal{B}_{B_c^+ \to J/\psi\pi^+}} = 0.37 \pm 0.06 \pm 0.02 \pm 0.01 \,,$$

where the first uncertainty is statistical, the second is systematic and the third is due to knowledge of the $\chi_{c2} \to J/\psi\gamma$ branching fraction [119]. The measured value is compatible with predictions from refs. [72] and [73].
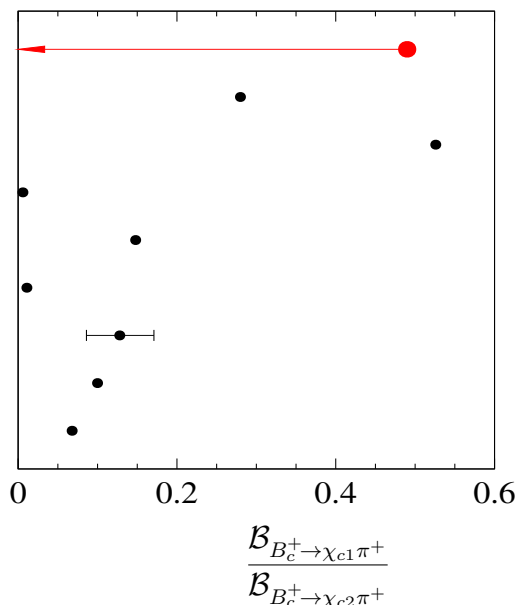
Figure 5. Comparison of upper limit on the branching fraction ratio between $B_c^+ \to \chi_{c1}\pi^+$ and $B_c^+ \to \chi_{c2}\pi^+$ decays set in this analysis with theoretical predictions.

No significant $B_c^+ \to \chi_{c1}\pi^+$ signal is observed and the upper limit on the relative branching fraction between the $B_c^+ \to \chi_{c1}\pi^+$ and $B_c^+ \to \chi_{c2}\pi^+$ decays is found to be

$$\frac{\mathcal{B}_{B_c^+ \to \chi_{c1}\pi^+}}{\mathcal{B}_{B_c^+ \to \chi_{c2}\pi^+}} < 0.49 \text{ at } 90\% \, \text{CL} \, .$$

The comparison of this upper limit with theoretical predictions, reported in refs. [70–77] is shown in figure 5. The upper limit obtained is in agreement with all but one prediction and disfavours the calculation from the relativistic quark model [71].

Acknowledgments

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