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Study of the $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays with the ATLAS detector

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Abstract The decays $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ are studied with the ATLAS detector at the LHC using a dataset corresponding to integrated luminosities of 4.9 and 20.6 fb^{-1} of pp collisions collected at centre-of-mass energies $\sqrt{s} = 7$ TeV and 8 TeV, respectively. Signal candidates are identified through $J/\psi \to \mu^+\mu^-$ and $D_s^{(*)+} \to \phi\pi^+(\gamma/\pi^0)$ decays. With a two-dimensional likelihood fit involving the B_c^+ reconstructed invariant mass and an angle between the μ^+ and D_s^+ candidate momenta in the muon pair rest frame, the yields of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$, and the transverse polarisation fraction in $B_c^+ \to J/\psi D_s^{*+}$ decay are measured. The transverse polarisation fraction is determined to be $\Gamma_{\pm\pm}(B_c^+ \to J/\psi D_s^{*+})/\Gamma(B_c^+ \to J/\psi D_s^{*+}) = 0.38 \pm 0.23 \pm 0.07$, and the derived ratio of the branching fractions of the two modes is $\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}/\mathcal{B}_{B_c^+\to J/\psi D_s^+} = 2.8^{+1.2}_{-0.8} \pm 0.3$, where the first error is statistical and the second is systematic. Finally, a sample of $B_c^+ \to J/\psi\pi^+$ decays is used to derive the ratios of branching fractions $\mathcal{B}_{B_c^+\to J/\psi D_s^+}/\mathcal{B}_{B_c^+\to J/\psi\pi^+} = 3.8 \pm 1.1 \pm 0.4 \pm 0.2$ and $\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}/\mathcal{B}_{B_c^+\to J/\psi\pi^+} = 10.4 \pm 3.1 \pm 1.5 \pm 0.6$, where the third error corresponds to the uncertainty of the branching fraction of $D_s^+ \to \phi(K^+K^-)\pi^+$ decay. The available theoretical predictions are generally consistent with the measurement.

1 Introduction

The B_c^+ meson[1] is the only known weakly decaying particle consisting of two heavy quarks. The ground $\bar{b}c$ state was first observed by CDF [1] via its semileptonic decay $B_c^+ \to J/\psi\ell^+\nu_\ell$. An excited $\bar{b}c$ state has been observed recently by ATLAS [2] using the B_c^+ decay mode $B_c^+ \to J/\psi\pi^+$. The presence of two heavy quarks, each of which can decay weakly, affects theoretical calculations of the decay properties of the B_c^+ meson. In the case of $\bar{b} \to \bar{c}c\bar{s}$ processes, decays to charmonium and a D_s^+ or a D_s^{*+} meson are predicted to occur via colour-suppressed and colour-favoured spectator diagrams as well as via the weak annihilation diagram (see Fig. 1). The latter, in contrast to decays of other B mesons, is not Cabibbo-suppressed and can contribute significantly to the decay amplitudes. The decay properties are addressed in various theoretical calculations [3–9] and can also be compared to the analogous properties in the lighter B meson systems such as $B_d^0 \to D^{*-}D_s^{(*)+}$ or $B^+ \to \bar{D}^{*0}D_s^{(*)+}$. The decays $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$, which have been observed recently by the LHCb experiment [10], provide a means to test these theoretical predictions.

This paper presents a measurement of the branching fractions of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays, normalised to that of $B_c^+ \to J/\psi\pi^+$ decay, and polarisation in $B_c^+ \to J/\psi D_s^{*+}$ decay performed with the ATLAS detector [11]. The D_s^+ meson is reconstructed via the $D_s^+ \to \phi\pi^+$ decay with the ϕ meson decaying into a pair of charged kaons. The D_s^{*+} meson decays into a D_s^+ meson and a soft photon or π^0. Detecting such soft neutral particles is very challenging, thus no attempt to reconstruct them is made in the analysis. The J/ψ meson is reconstructed via its decay into a muon pair.

The measurement presented in this paper allows an independent verification of the results of Ref. [10] with comparable statistical and systematic uncertainties. The following ratios are measured: $\mathcal{R}_{D_s^+/\pi^+} = \mathcal{B}_{B_c^+\to J/\psi D_s^+}/\mathcal{B}_{B_c^+\to J/\psi\pi^+}$, $\mathcal{R}_{D_s^{*+}/\pi^+} = \mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}/\mathcal{B}_{B_c^+\to J/\psi\pi^+}$, and $\mathcal{R}_{D_s^{*+}/D_s^+} = \mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}/\mathcal{B}_{B_c^+\to J/\psi D_s^+}$, where $\mathcal{B}_{B_c^+\to X}$ denotes the branching fraction of the $B_c^+ \to X$ decay. The decay $B_c^+ \to J/\psi D_s^{*+}$ is a transition of a pseudoscalar meson into a pair of vector states and is thus described by the three helicity amplitudes, A_{++}, A_{--}, and A_{00}, where the subscripts correspond to the helicities of J/ψ and D_s^{*+} mesons. The contribution of the A_{++} and A_{--} amplitudes, referred to as the $A_{\pm\pm}$ component, corresponds to the J/ψ and D_s^{*+} transverse polarisation. The fraction of transverse polarisation,

[1] Charge conjugate states are implied throughout the paper unless otherwise stated.

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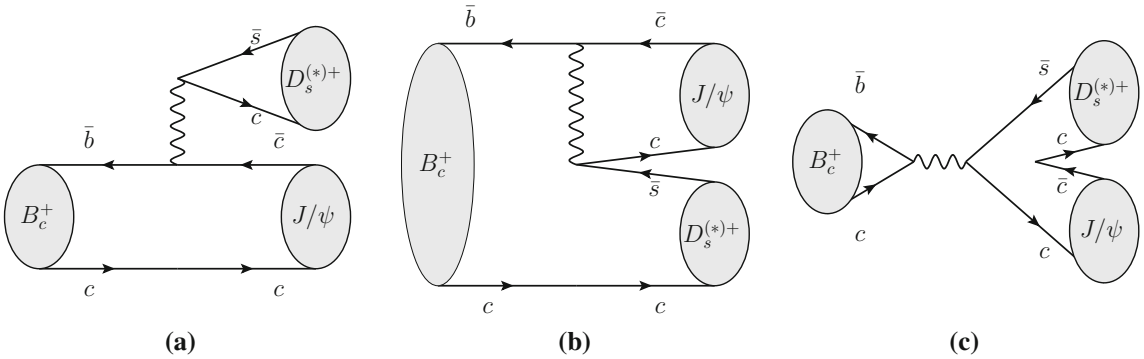


Fig. 1 Feynman diagrams for $B_c^+ \to J/\psi D_s^{(*)+}$ decays: **a** colour-favoured spectator, **b** colour-suppressed spectator, and **c** annihilation topology

$\Gamma_{\pm\pm}/\Gamma = \Gamma_{\pm\pm}(B_c^+ \to J/\psi D_s^{*+})/\Gamma(B_c^+ \to J/\psi D_s^{*+})$, is also measured. From a naive prediction by spin counting, one would expect this fraction to be 2/3, while calculations [8,9] predict values of 0.41–0.48.

This analysis is based on a combined sample of pp collision data collected by the ATLAS experiment at the LHC at centre-of-mass energies $\sqrt{s} = 7\,\text{TeV}$ and 8 TeV corresponding to integrated luminosities of 4.9 and 20.6 fb^{-1}, respectively.

2 The ATLAS detector, trigger selection and Monte Carlo samples

ATLAS is a general-purpose detector consisting of several subsystems including the inner detector (ID), calorimeters and the muon spectrometer (MS). Muon reconstruction makes use of both the ID and the MS. The ID comprises three types of detectors: a silicon pixel detector, a silicon microstrip semiconductor tracker (SCT) and a transition radiation tracker. The ID provides a pseudorapidity[2] coverage up to $|\eta| = 2.5$. Muons pass through the calorimeters and reach the MS if their transverse momentum, p_T, is above approximately 3 GeV.[3] Muon candidates are formed either from a stand-alone MS track matched to an ID track or, in case the MS stand-alone track is not reconstructed, from an ID track extrapolated to the MS and matched to track segments in the MS. Candidates of the latter type are referred to as segment-tagged muons while the former are called combined muons. Muon track parameters are taken from the ID measurement alone in this analysis, since the precision of the measured track parameters for muons in the p_T range of interest is dominated by the ID track reconstruction.

The ATLAS trigger system consists of a hardware-based Level-1 trigger and a two-stage high level trigger (HLT). At Level-1, the muon trigger uses dedicated MS chambers to search for patterns of hits satisfying different p_T thresholds. The region-of-interest around these hit patterns then serves as a seed for the HLT muon reconstruction, in which dedicated algorithms are used to incorporate information from both the MS and the ID, achieving a position and momentum resolution close to that provided by the offline muon reconstruction. Muons are efficiently triggered in the pseudorapidity range $|\eta| < 2.4$.

Triggers based on single-muon, dimuon, and three-muon signatures are used to select $J/\psi \to \mu^+\mu^-$ decays for the analysis. The third muon can be produced in the B_c^+ signal events in semileptonic decays of the two other heavy-flavour hadrons. The majority of events are collected by dimuon triggers requiring a vertex of two oppositely charged muons with an invariant mass between 2.5 and 4.3 GeV. During the data taking, the p_T threshold for muons in these triggers was either 4 or 6 GeV. Single-muon triggers additionally increase the acceptance for asymmetric J/ψ decays where one muon has $p_\text{T} < 4\,\text{GeV}$. Finally, three-muon triggers had a p_T threshold of 4 GeV, thus enhancing the acceptance during the periods of high luminosity when the p_T threshold for at least one muon in the dimuon triggers was 6 GeV.

Monte Carlo (MC) simulation is used for the event selection criteria optimisation and the calculation of the acceptance for the considered B_c^+ decay modes. The MC samples of the B_c^+ decays were generated with PYTHIA 6.4 [12] along with a dedicated extension for the B_c^+ production based on calculations from Refs. [13–16]. The decays of B_c^+ are then simulated with EVTGEN [17]. The generated events were passed through a full simulation of the detector using the ATLAS simulation framework [18] based on GEANT 4 [19,20] and processed with the same reconstruction algorithms as were used for the data.

[2] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

[3] Using a system of units with $c = 1$ is implied throughout the paper.

3 Reconstruction and event selection

The J/ψ candidates are reconstructed from pairs of oppositely charged muons. At least one of the two muons is required to be a combined muon. Each pair is fitted to a common vertex [21]. The quality of the vertex fit must satisfy $\chi^2/\text{ndf} < 15$, where the ndf stands for the number of degrees of freedom. The candidates in the invariant mass window $2800\,\text{MeV} < m(\mu^+\mu^-) < 3400\,\text{MeV}$ are retained.

For the $D_s^+ \to \phi(K^+K^-)\pi^+$ reconstruction, tracks of particles with opposite charges are assigned kaon mass hypotheses and combined in pairs to form ϕ candidates. An additional track is assigned a pion mass and combined with the ϕ candidate to form a D_s^+ candidate. To ensure good momentum resolution, all three tracks are required to have at least two hits in the silicon pixel detector and at least six hits in the SCT. Only three-track combinations successfully fitted to a common vertex with $\chi^2/\text{ndf} < 8$ are kept. The ϕ candidate invariant mass, $m(K^+K^-)$, and the D_s^+ candidate invariant mass, $m(K^+K^-\pi^+)$, are calculated using the track momenta refitted to the common vertex. Only candidates with $m(K^+K^-)$ within $\pm 7\,\text{MeV}$ around the ϕ mass, $m_\phi = 1019.461\,\text{MeV}$ [22], and with $1930\,\text{MeV} < m(K^+K^-\pi^+) < 2010\,\text{MeV}$ are retained.

The $B_c^+ \to J/\psi D_s^+$ candidates are built by combining the five tracks of the J/ψ and D_s^+ candidates. The J/ψ meson decays instantly at the same point as the B_c^+ does (secondary vertex) while the D_s^+ lives long enough to form a displaced tertiary vertex. Therefore the five-track combinations are refitted assuming this cascade topology [21]. The invariant mass of the muon pair is constrained to the J/ψ mass, $m_{J/\psi} = 3096.916\,\text{MeV}$ [22]. The three D_s^+ daughter tracks are constrained to a tertiary vertex and their invariant mass is fixed to the mass of D_s^+, $m_{D_s^+} = 1968.30\,\text{MeV}$ [22]. The combined momentum of the refitted D_s^+ decay tracks is constrained to point to the dimuon vertex. The quality of the cascade fit must satisfy $\chi^2/\text{ndf} < 3$.

The B_c^+ meson is reconstructed within the kinematic range $p_\text{T}(B_c^+) > 15\,\text{GeV}$ and $|\eta(B_c^+)| < 2.0$, where the detector acceptance is high and depends weakly on $p_\text{T}(B_c^+)$ and $\eta(B_c^+)$.

The refitted tracks of the D_s^+ daughter hadrons are required to have $|\eta| < 2.5$ and $p_\text{T} > 1\,\text{GeV}$, while the muons must have $|\eta| < 2.3$ and $p_\text{T} > 3\,\text{GeV}$. To further discriminate the sample of D_s^+ candidates from a large combinatorial background, the following requirements are applied:

- $\cos\theta^*(\pi) < 0.8$, where $\theta^*(\pi)$ is the angle between the pion momentum in the $K^+K^-\pi^+$ rest frame and the $K^+K^-\pi^+$ combined momentum in the laboratory frame;
- $|\cos^3\theta'(K)| > 0.15$, where $\theta'(K)$ is the angle between one of the kaons and the pion in the K^+K^- rest frame. The decay of the pseudoscalar D_s^+ meson to the ϕ (vector) plus π (pseudoscalar) final state results in an alignment of the spin of the ϕ meson perpendicularly to the direction of motion of the ϕ relative to D_s^+. Consequently, the distribution of $\cos\theta'(K)$ follows a $\cos^2\theta'(K)$ shape, implying a uniform distribution for $\cos^3\theta'(K)$. In contrast, the $\cos\theta'(K)$ distribution of the combinatorial background is uniform and its $\cos^3\theta'(K)$ distribution peaks at zero. The cut suppresses the background significantly while reducing the signal by 15 %.

The B_c^+ candidate is required to point back to a primary vertex such that $d_0^\text{PV}(B_c^+) < 0.1\,\text{mm}$ and $z_0^\text{PV}(B_c^+)\sin\theta(B_c^+) < 0.5\,\text{mm}$, where d_0^PV and z_0^PV are respectively the transverse and longitudinal impact parameters with respect to the primary vertex. All primary vertices in the event are considered. If there is more than one primary vertex satisfying these requirements (∼0.5 % events both in data and MC simulation), the one with the largest sum of squared transverse momenta of the tracks originating from it is chosen.

The transverse decay length[4] of the B_c^+ candidate is required to satisfy $L_{xy}(B_c^+) > 0.1\,\text{mm}$. The transverse decay length of the D_s^+ measured from the B_c^+ vertex must be $L_{xy}(D_s^+) > 0.15\,\text{mm}$. In order to remove fake candidates, both $L_{xy}(B_c^+)$ and $L_{xy}(D_s^+)$ are required not to exceed 10 mm.

Taking into account the characteristic hard fragmentation of b-quarks, a requirement $p_\text{T}(B_c^+)/\sum p_\text{T}(\text{trk}) > 0.1$ is applied, where the sum in the denominator is taken over all tracks originating from the primary vertex (tracks of the B_c^+ candidate are included in the sum if they are associated with the primary vertex). The requirement reduces a sizeable fraction of combinatorial background while having almost no effect on the signal.

The following angular selection requirements are introduced to further suppress the combinatorial background:

- $\cos\theta^*(D_s^+) > -0.8$, where $\theta^*(D_s^+)$ is the angle between the D_s^+ candidate momentum in the rest frame of the B_c^+ candidate, and the B_c^+ candidate line of flight in the laboratory frame. The distribution of $\cos\theta^*(D_s^+)$ is uniform for the decays of pseudoscalar B_c^+ meson before any kinematic selection while it tends to increase for negative values of $\cos\theta^*(D_s^+)$ for the background.
- $\cos\theta'(\pi) > -0.8$, where $\theta'(\pi)$ is the angle between the J/ψ candidate momentum and the pion momentum in the $K^+K^-\pi^+$ rest frame. Its distribution is nearly uniform for the signal processes but peaks towards -1 for the background.

[4] The transverse decay length of a particle is defined as the transverse distance between the production (primary) vertex and the particle decay (secondary) vertex projected along its transverse momentum.

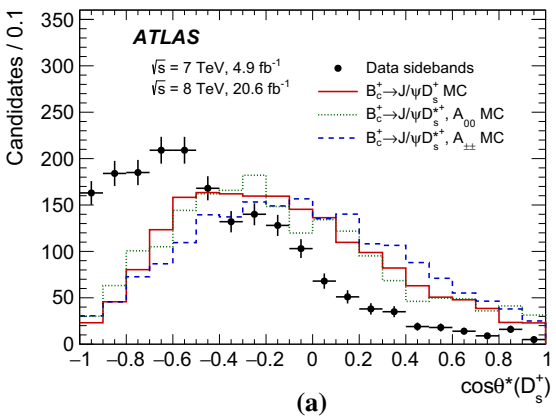


Fig. 2 Distributions of **a** $\cos\theta^*(D_s^+)$ and **b** $\cos\theta'(\pi)$, where $\theta^*(D_s^+)$ and $\theta'(\pi)$ are two angular variables defined in Sect. 3. The distributions are shown for data sidebands (*black dots*) and MC simulation of $B_c^+ \to J/\psi D_s^+$ signal (*red solid line*) and A_{00} (*green dotted line*) and $A_{\pm\pm}$ (*blue dashed line*) components of $B_c^+ \to J/\psi D_s^{*+}$ signal. The distributions are obtained after applying all selection criteria except the ones on the plotted variable. The MC distributions are normalised to data

Distributions of these two variables after applying all other selection requirements described in this section are shown in Fig. 2. They are shown for the simulated signal samples, as well as for sidebands of the mass spectrum in data, defined as the regions 5640 MeV $< m(J/\psi D_s^+) <$ 5900 MeV (left sideband) and 6360 MeV $< m(J/\psi D_s^+) <$ 6760 MeV (right sideband). A dip in the $\cos\theta'(\pi)$ distribution for the $B_c^+ \to J/\psi D_s^+$ signal is caused by rejection of $B_s^0 \to J/\psi\phi$ candidates discussed below.

Various possible contributions of partially reconstructed $B \to J/\psi X$ decays were studied. The only significant one was found from the $B_s^0 \to J/\psi\phi$ decay process. This contribution arises when the combination of the tracks from a true $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay with a fifth random track results in a fake $B_c^+ \to J/\psi(\mu^+\mu^-)D_s^+(K^+K^-\pi^+)$ candidate. For each reconstructed B_c^+ candidate, an additional vertex fit is performed. The two muon tracks and the two kaon tracks are fitted to a common vertex, where the kaon tracks are assumed to be from $\phi \to K^+K^-$ and the muon pair is constrained to have the nominal J/ψ mass. The mass of the B_s^0 candidate, $m(\mu^+\mu^-K^+K^-)$, is then calculated from the refitted track parameters. Candidates with 5340 MeV $< m(\mu^+\mu^-K^+K^-) <$ 5400 MeV are rejected. This requirement suppresses the bulk of the B_s^0 events while rejecting only ∼4 % of the signal.

After applying the selection requirements described above, 1547 $J/\psi D_s^+$ candidates are selected in the mass range 5640–6760 MeV.

4 $B_c^+ \to J/\psi D_s^{(*)+}$ candidate fit

The mass distribution of the selected $B_c^+ \to J/\psi D_s^{(*)+}$ candidates is shown in Fig. 3. The peak near the B_c^+ mass, $m_{B_c^+} = 6275.6$ MeV [22], is attributed to the signal of

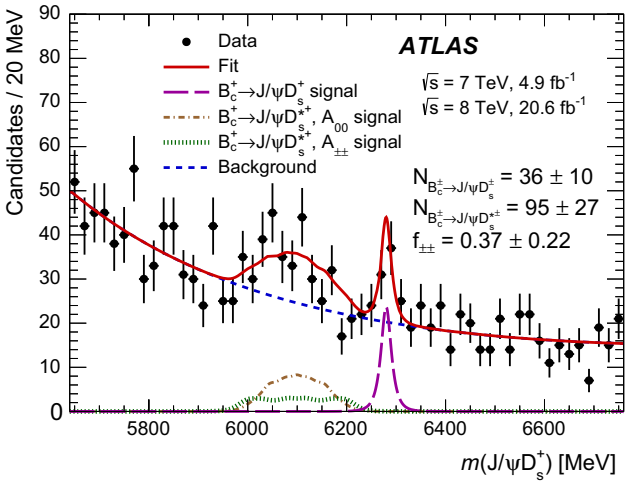
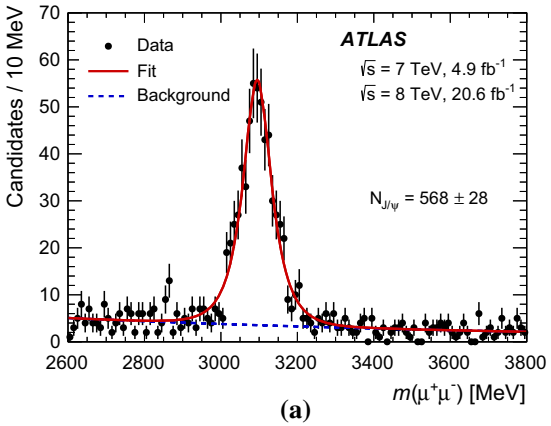


Fig. 3 The mass distribution for the selected $J/\psi D_s^+$ candidates. The *red solid line* represents the projection of the fit to the model described in the text. The contribution of the $B_c^+ \to J/\psi D_s^+$ decay is shown with the *magenta long-dashed line*; the *brown dash-dot* and *green dotted lines* show the $B_c^+ \to J/\psi D_s^{*+}$ A_{00} and $A_{\pm\pm}$ component contributions, respectively; the *blue dashed line* shows the background model. The uncertainties of the listed fit result values are statistical only

$B_c^+ \to J/\psi D_s^+$ decay while a wider structure between 5900 and 6200 MeV corresponds to $B_c^+ \to J/\psi D_s^{*+}$ with subsequent $D_s^{*+} \to D_s^+\gamma$ or $D_s^{*+} \to D_s^+\pi^0$ decays where the neutral particle is not reconstructed.

Mass distributions of the J/ψ and D_s^+ candidates corresponding to the $J/\psi D_s^+$ mass region of the observed $B_c^+ \to J/\psi D_s^{(*)+}$ signals are shown in Fig. 4. To obtain these plots, the B_c^+ candidates are built without the mass constraints in the cascade fit, with the mass of the candidate calculated as $m(J/\psi D_s^+) = m(\mu^+\mu^-K^+K^-\pi^+) - m(\mu^+\mu^-) + m_{J/\psi} - m(K^+K^-\pi^+) + m_{D_s^+}$, where $m_{J/\psi}$ and $m_{D_s^+}$ are the nominal masses of the respective par-



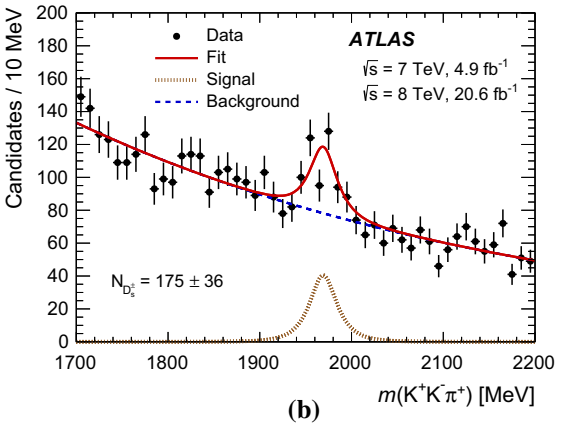


Fig. 4 Mass distribution of the **a** J/ψ and **b** D_s^+ candidates after the full $B_c^+ \to J/\psi D_s^{(*)+}$ selection (without mass constraints in the cascade fit) in the mass window of the B_c^+ candidate 5900 MeV $< m(J/\psi D_s^+) <$ 6400 MeV. The spectra are fitted with a sum of an exponential and a modified Gaussian function. The uncertainties of the shown J/ψ and D_s^+ yields are statistical only

ticles. The mass of the B_c^+ candidate is required to be 5900 MeV $< m(J/\psi D_s^+) <$ 6400 MeV while the mass windows for the corresponding intermediate resonances are widened to the plotting ranges. The J/ψ and D_s^+ mass distributions are fitted with a sum of an exponential function describing the background and a modified Gaussian function [23,24] describing the corresponding signal peak. The modified Gaussian function is defined as

$$\text{Gauss}^{\text{mod}} \sim \exp\left(-\frac{x^{1+\frac{1}{1+x/2}}}{2}\right), \tag{1}$$

where $x = |m_0 - m|/\sigma$ with the mean mass m_0 and width σ being free parameters. The fitted masses of J/ψ (3095.1 ± 2.4 MeV) and D_s (1969.0 ± 4.1 MeV) agree with their nominal masses, the widths are consistent with those in the simulated samples, and the signal yields are found to be $N_{J/\psi} = 568 \pm 28$ and $N_{D_s^\pm} = 175 \pm 36$.

The information about the helicity in $B_c^+ \to J/\psi D_s^{*+}$ decay is encoded both in the mass distribution of the $J/\psi D_s^+$ system and in the distribution of the helicity angle, $\theta'(\mu^+)$, which is defined in the rest frame of the muon pair as the angle between the μ^+ and the D_s^+ candidate momenta. Thus, a two-dimensional extended unbinned maximum-likelihood fit of the $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$ distributions is performed. The A_{++} and A_{--} helicity amplitude contributions are described by the same mass and angular shapes because of the parity symmetry of the J/ψ and D_s^{*+} decays. This is confirmed by the MC simulation. Thus these components are treated together as the $A_{\pm\pm}$ component, while the shape of the A_{00} component is different and is therefore treated separately. A simultaneous fit to the mass and angular distributions significantly improves the sensitivity to the contributions of the helicity amplitudes in $B_c^+ \to J/\psi D_s^{*+}$ decay with respect to a one-dimensional mass fit.

Four two-dimensional probability density functions (PDFs) are defined to describe the $B_c^+ \to J/\psi D_s^+$ signal, the $A_{\pm\pm}$ and A_{00} components of the $B_c^+ \to J/\psi D_s^{*+}$ signal, and the background. The signal PDFs are factorised into mass and angular components. The effect of correlations between their mass and angular shapes is found to be small and is accounted for as a systematic uncertainty.

The mass distribution of the $B_c^+ \to J/\psi D_s^+$ signal is described by a modified Gaussian function. For the $B_c^+ \to J/\psi D_s^{*+}$ signal components, the mass shape templates obtained from the simulation with the kernel estimation technique [25] are used. The branching fractions of $D_s^{*+} \to D_s^+\pi^0$ and $D_s^{*+} \to D_s^+\gamma$ decays for the simulation are set to the world average values [22]. The position of the templates along the mass axis is varied in the fit simultaneously with the position of the $B_c^+ \to J/\psi D_s^+$ signal peak. The background mass shape is described with a two-parameter exponential function, $\exp\left[a \cdot m(J/\psi D_s^+) + b \cdot m(J/\psi D_s^+)^2\right]$.

To describe the $|\cos\theta'(\mu^+)|$ shapes, templates from the kernel estimation are used. The templates for the signal angular PDFs are extracted from the simulated samples. Although their shapes are calculable analytically, using the templates allows the fit to account for detector effects. The background angular description is based on the $|\cos\theta'(\mu^+)|$ shape of the candidates in the sidebands of $J/\psi D_s^+$ mass spectra. Two templates are produced from the angular distributions of the candidates in the left and right mass sidebands as defined in Sect. 3. The angular PDF for the background is defined as a conditional PDF of $|\cos\theta'(\mu^+)|$ given the per-candidate $m(J/\psi D_s^+)$. For the candidates in the lower half of the left sideband (5640–5770 MeV), the template from the left sideband is used. Similarly, the template from the right sideband is used for the upper half of the right sideband (6560–6760 MeV). For the candidates in the middle part of the mass spectrum (5770–

Table 1 Parameters of the $B_c^+ \to J/\psi D_s^{(*)+}$ signals obtained with the unbinned extended maximum-likelihood fit. The width parameter of the modified Gaussian function is fixed to the MC value. Only statistical uncertainties are shown. No acceptance corrections are applied to the signal yields

Parameter	Value
$m_{B_c^+ \to J/\psi D_s^+}$ (MeV)	6279.9 ± 3.5
$N_{B_c^+ \to J/\psi D_s^+}$	36 ± 10
$N_{B_c^+ \to J/\psi D_s^{*+}}$	95 ± 27
$f_{\pm\pm}$	0.37 ± 0.22

6560 MeV), a linear interpolation between the two templates is used.

The fit has seven free parameters: the mass of the B_c^+ meson, $m_{B_c^+ \to J/\psi D_s^+}$; the relative contribution of the $A_{\pm\pm}$ component to the total $B_c^+ \to J/\psi D_s^{*+}$ decay rate in the selected sample, $f_{\pm\pm}$; the two parameters of the exponential background; the yields of the two signal modes, $N_{B_c^+ \to J/\psi D_s^+}$ and $N_{B_c^+ \to J/\psi D_s^{*+}}$, and the background yield. The width of the modified Gaussian function, $\sigma_{B_c^+ \to J/\psi D_s^+}$, is fixed to the value obtained from the fit to the simulated signal, $\sigma_{B_c^+ \to J/\psi D_s^+} = 9.95$ MeV. Leaving this parameter free in the data fit results in the value 7.9 ± 3.0 MeV, consistent with the simulation in the range of statistical uncertainty.

It was checked that the fit procedure provides unbiased values and correct statistical uncertainties for the extracted parameters using pseudo-experiments. The values of the relevant parameters obtained from the fit are given in Table 1. The fitted B_c^+ mass agrees with the world average value [22].

The mass and angular projections of the fit on the selected $J/\psi D_s^+$ candidate dataset are also shown in Figs. 3 and 5a, respectively. In order to illustrate the effect of the angular part of the fit in separating the helicity amplitudes, the $|\cos\theta'(\mu^+)|$ projection for the subset of candidates with the masses 5950 MeV $< m(J/\psi D_s^+) <$ 6250 MeV corresponding to the region of the observed $B_c^+ \to J/\psi D_s^{*+}$ signal is shown in Fig. 5b.

The statistical significance for the observed B_c^+ signal estimated from toy MC studies is 4.9 standard deviations.

5 $B_c^+ \to J/\psi\pi^+$ candidate reconstruction and fit

$B_c^+ \to J/\psi\pi^+$ candidates are reconstructed by fitting a common vertex of a pion candidate track and the two muons from a J/ψ candidate, selected as described in Sect. 3. For the pion candidate, tracks identified as muons are vetoed in order to suppress the substantial background from $B_c^+ \to J/\psi\mu^+\nu_\mu X$ decays. The invariant mass of the two muons in the vertex fit is constrained to the J/ψ nominal mass. The quality of the fit must satisfy $\chi^2/\text{ndf} < 3$. The following selection requirements applied to the $B_c^+ \to J/\psi\pi^+$ candidates are analogous to those for $B_c^+ \to J/\psi D_s^+$ candidates described in Sect. 3: the candidates must be within the kinematic range $p_T(B_c^+) > 15$ GeV, $|\eta(B_c^+)| < 2.0$; the refitted values of the transverse momenta and pseudorapidities of the muons are required to satisfy $p_T(\mu^\pm) > 3$ GeV, $|\eta(\mu^\pm)| < 2.3$; the same requirements on pointing to the primary vertex and the ratio $p_T(B_c^+)/\sum p_T(\text{trk})$ are applied. The refitted pion track kinematics must satisfy $p_T(\pi^+) > 5$ GeV and $|\eta(\pi^+)| < 2.5$. The transverse decay length

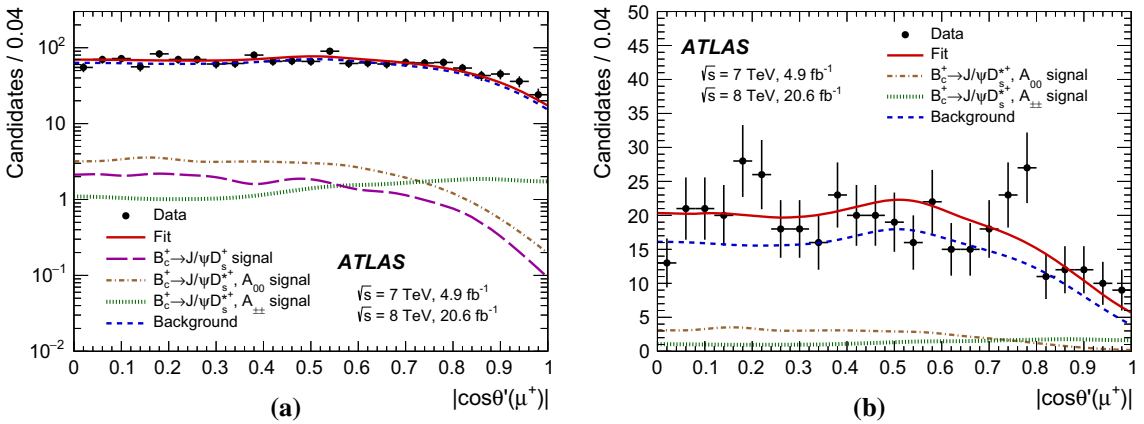


Fig. 5 The projection of the likelihood fit on the variable $|\cos\theta'(\mu^+)|$, where the helicity angle $\theta'(\mu^+)$ is the angle between the μ^+ and D_s^+ candidate momenta in the rest frame of the muon pair from J/ψ decay, for **a** the full selected $J/\psi D_s^+$ candidate dataset and **b** a subset of the candidates in a mass range 5950 MeV $< m(J/\psi D_s^+) <$ 6250 MeV corresponding to the observed signal of $B_c^+ \to J/\psi D_s^{*+}$ decay. The *red solid line* represents the full fit projection. The contribution of the $B_c^+ \to J/\psi D_s^+$ decay is shown with the *magenta long-dashed line* (it is not drawn in **b** because this contribution vanishes in that mass range); the *brown dash-dot* and *green dotted lines* show the $B_c^+ \to J/\psi D_s^{*+}$ A_{00} and $A_{\pm\pm}$ component contributions, respectively; the *blue dashed line* shows the background model

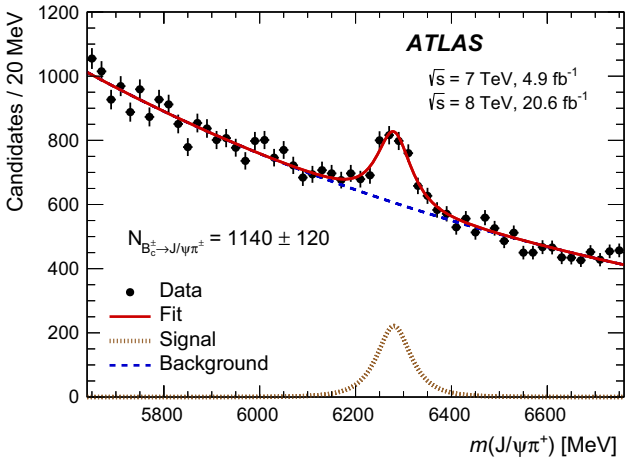


Fig. 6 The mass distribution for the selected $B_c^+ \to J/\psi\pi^+$ candidates. The *red solid line* represents the result of the fit to the model described in the text. The *brown dotted* and *blue dashed lines* show the signal and background component projections, respectively. The uncertainty of the shown signal yield is statistical only

is required to be $L_{xy}(B_c^+) > 0.2$ mm, and not to exceed 10 mm.

To further suppress combinatorial background, the following selection is applied:

- $\cos\theta^*(\pi) > -0.8$, where $\theta^*(\pi)$ is the angle between the pion momentum in the $\mu^+\mu^-\pi^+$ rest frame and the B_c^+ candidate line of flight in laboratory frame. This angular variable behaviour for the signal and the background is the same as that of $\cos\theta^*(D_s^+)$ used for $J/\psi D_s^+$ candidates selection.
- $|\cos\theta'(\mu^+)| < 0.8$, where $\theta'(\mu^+)$ is the angle between the μ^+ and π^+ momenta in the muon pair rest frame. The signal distribution follows a $\sin^2\theta'(\mu^+)$ shape, while the background is flat.

After applying the above-mentioned requirements, 38542 $J/\psi\pi^+$ candidates are selected in the mass range 5640–6760 MeV. Figure 6 shows the mass distribution of the selected candidates. An extended unbinned maximum-likelihood fit of the mass spectrum is performed to evaluate the $B_c^+ \to J/\psi\pi^+$ signal yield. The signal contribution is described with the modified Gaussian function while an exponential function is used for the background. The B_c^+ mass, $m_{B_c^+\to J/\psi\pi^+}$, the width of the modified Gaussian function, $\sigma_{B_c^+\to J/\psi\pi^+}$, the yields of the signal, $N_{B_c^+\to J/\psi\pi^+}$, and the background, and the slope of the exponential background are free parameters of the fit. The fit results are summarised in Table 2, and the fit projection is also shown in Fig. 6. The extracted B_c^+ mass value is consistent with the world average [22], and the signal peak width agrees with the simulation (37.4 MeV).

Table 2 Signal parameters of the $J/\psi\pi^+$ mass distribution obtained with the unbinned extended maximum-likelihood fit. Only statistical uncertainties are shown. No acceptance corrections are applied to the signal yields

Parameter	Value
$m_{B_c^+\to J/\psi\pi^+}$ (MeV)	6279.9 ± 3.9
$\sigma_{B_c^+\to J/\psi\pi^+}$ (MeV)	33.9 ± 4.2
$N_{B_c^+\to J/\psi\pi^+}$	1140 ± 120

6 Branching fractions and polarisation measurement

The ratios of the branching fractions $\mathcal{R}_{D_s^+/\pi^+}$ and $\mathcal{R}_{D_s^{*+}/\pi^+}$ are calculated as

$$\mathcal{R}_{D_s^{(*)+}/\pi^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{(*)+}}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}} = \frac{1}{\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}} \times \frac{\mathcal{A}_{B_c^+\to J/\psi\pi^+}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{(*)+}}} \times \frac{N_{B_c^+\to J/\psi D_s^{(*)+}}}{N_{B_c^+\to J/\psi\pi^+}}, \quad (2)$$

where $\mathcal{A}_{B_c^+\to X}$ and $N_{B_c^+\to X}$ are the total acceptance and the yield of the corresponding mode. For $\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}$, the CLEO measurement [26] of the partial $D_s^+ \to K^+K^-\pi^+$ branching fractions, with a kaon-pair mass within various intervals around the nominal ϕ meson mass, is used. An interpolation between the partial branching fractions, measured for ± 5 and ± 10 MeV intervals, using a relativistic Breit–Wigner shape of the resonance yields the value $(1.85 \pm 0.11)\%$ for the ± 7 MeV interval which is used in the analysis. The effect of admixture of other D_s^+ decay modes with $(K^+K^-\pi^+)$ final state which are not present in the MC simulation is studied separately and accounted for as a systematic uncertainty.

The acceptance for the $B_c^+ \to J/\psi D_s^{*+}$ decay mode is different for the $A_{\pm\pm}$ and A_{00} components, thus the full acceptance for the mode is

$$\mathcal{A}_{B_c^+\to J/\psi D_s^{*+}} = \left(\frac{f_{\pm\pm}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+},A_{\pm\pm}}} + \frac{1-f_{\pm\pm}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+},A_{00}}} \right)^{-1}, \quad (3)$$

where the subscripts indicate the helicity state and $f_{\pm\pm}$ is the value extracted from the fit (Table 1). The acceptances are determined from the simulation and shown in Table 3.

The ratio $\mathcal{R}_{D_s^{*+}/D_s^+}$ is calculated as

$$\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi D_s^+}} = \frac{N_{B_c^+\to J/\psi D_s^{*+}}}{N_{B_c^+\to J/\psi D_s^+}} \times \frac{\mathcal{A}_{B_c^+\to J/\psi D_s^+}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+}}}, \quad (4)$$

Table 3 The acceptance $\mathcal{A}_{B_c^+ \to X}$ for all decay modes studied. Only uncertainties due to MC statistics are shown

Mode	$\mathcal{A}_{B_c^+ \to X}$ (%)
$B_c^+ \to J/\psi\pi^+$	4.106 ± 0.056
$B_c^+ \to J/\psi D_s^+$	1.849 ± 0.034
$B_c^+ \to J/\psi D_s^{*+}$, A_{00}	1.829 ± 0.053
$B_c^+ \to J/\psi D_s^{*+}$, $A_{\pm\pm}$	1.712 ± 0.035

where the ratio of the yields $N_{B_c^+ \to J/\psi D_s^{*+}}/N_{B_c^+ \to J/\psi D_s^+}$ and its uncertainty is extracted from the fit as a parameter in order to account for correlations between the yields.

The fraction of the $A_{\pm\pm}$ component contribution in $B_c^+ \to J/\psi D_s^{*+}$ decay is calculated from the $f_{\pm\pm}$ value quoted in Table 1 by applying a correction to account for the different acceptances for the two component contributions:

$$\Gamma_{\pm\pm}/\Gamma = f_{\pm\pm} \times \frac{\mathcal{A}_{B_c^+ \to J/\psi D_s^{*+}}}{\mathcal{A}_{B_c^+ \to J/\psi D_s^{*+}, \mathcal{A}_{\pm\pm}}}. \quad (5)$$

7 Systematic uncertainties

The systematic uncertainties of the measured values are determined by varying the analysis procedure and repeating all calculations. Although some sources can have rather large effects on the individual decay rate measurements, they largely cancel in the ratios of the branching fractions due to correlation between the effects on the different decay modes. The following groups of systematic uncertainties are considered.

The first group of sources of systematic uncertainty relates to possible differences between the data and simulation affecting the acceptances for the decay modes. Thus, an effect of the B_c^+ production model is evaluated by varying the simulated p_{T} and $|\eta|$ spectra while preserving agreement with the data distributions obtained using the abundant $B_c^+ \to J/\psi\pi^+$ channel. These variations have very similar effects on the acceptances for the different decay modes, thus giving rather moderate estimates of the uncertainties, not exceeding 3 % in total, on the ratios of branching fractions. The effect of presence of other D_s^+ decay modes with $(K^+K^-\pi^+)$ final state on the calculated acceptances is studied with a separate MC simulation. Its conservative estimate yields 0.4 % which is assigned as $\mathcal{R}_{D_s^+/\pi^+}$ and $\mathcal{R}_{D_s^{*+}/\pi^+}$ uncertainties. An uncertainty on the tracking efficiency is dominated by the uncertainty of the detector material description in the MC simulation. Samples generated with distorted geometries and with increased material are used to estimate the effect on track reconstruction efficiencies. When propagated to the ratios of branching fractions, these estimates give 0.5 % uncertainty for $\mathcal{R}_{D_s^+/\pi^+}$ and $\mathcal{R}_{D_s^{*+}/\pi^+}$ due to the two extra tracks in $B_c^+ \to J/\psi D_s^{(*)+}$ modes. Limited knowledge of the B_c^+ and D_s^+ lifetimes leads to an additional systematic uncertainty. The simulated proper decay times are varied within one standard deviation from the world average values [22] resulting in uncertainties of ∼1 % assigned to $\mathcal{R}_{D_s^+/\pi^+}$ and $\mathcal{R}_{D_s^{*+}/\pi^+}$ due to the B_c^+ lifetime, and 0.3 % due to the D_s^+ lifetime. Removing the requirement on $p_{\mathrm{T}}(B_c^+)/\sum p_{\mathrm{T}}(\mathrm{trk})$ is found to produce no noticeable effect on the measured values.

The next group of uncertainties originates from the signal extraction procedure. These uncertainties are evaluated separately for $J/\psi D_s^+$ and $J/\psi\pi^+$ candidate fits. For the former, the following variations of the fit model are applied and the difference is treated as a systematic uncertainty:

- different background mass shape parametrisations (three-parameter exponential, second- and third-order polynomials), different fitted mass range (reduced by up to 40 MeV from each side independently);
- a double Gaussian or double-sided Crystal Ball function [27–29] for $B_c^+ \to J/\psi D_s^+$ signal description; variation of the modified Gaussian width within 10 % of the MC simulation value;
- variation of the smoothness of the $B_c^+ \to J/\psi D_s^{*+}$ signal mass templates, which is controlled by a parameter of the kernel estimation procedure [25];
- similar variation of the smoothness of the $B_c^+ \to J/\psi D_s^{(*)+}$ signal angular templates;
- variation of the smoothness of the sideband templates used for the background angular PDF construction; different ranges of the sidebands; different sideband interpolation procedure;
- modelling of the correlation between the mass and angular parts of the signal PDFs. This correlation takes place only at the detector level and manifests itself in degradation of the mass resolution for higher values of $|\cos\theta'(\mu^+)|$. A dedicated fit model accounting for this effect is used for the data fit. The impact on the result is found to be negligible compared to the total uncertainty.

The first two items give the dominant contributions to the uncertainties of the ratios of branching fractions while the transverse polarisation fraction measurement is mostly affected by the background angular modelling variations. For the normalisation channel fit model, the similar variations of the background and signal mass shape parametrisation are applied. The deviations produced by the variations of the fits reach values as high as 10–15 % thus making them the dominant sources of systematic uncertainty.

The branching fractions of D_s^{*+} [22] are varied in simulation within their uncertainties to estimate their effect on the measured quantities. Very small uncertainties are obtained

Table 4 Relative systematic uncertainties on the measured ratios of branching fractions $R_{D_s^+/\pi^+}$, $R_{D_s^{*+}/\pi^+}$, $R_{D_s^{*+}/D_s^+}$ and on the transverse polarisation fraction $\Gamma_{\pm\pm}/\Gamma$

Source	Uncertainty (%)			
	$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$
Simulated $p_{\mathrm{T}}(B_c^+)$ spectrum	0.4	0.9	0.5	0.4
Simulated $\lvert\eta(B_c^+)\rvert$ spectrum	1.9	2.4	0.6	0.2
Other D_s^+ decay modes contribution	0.4	0.4	–	–
Tracking efficiency	0.5	0.5	<0.1	<0.1
B_c^+ lifetime	1.2	1.3	<0.1	<0.1
D_s^+ lifetime	0.3	0.3	<0.1	<0.1
$B_c^+ \to J/\psi D_s^{(*)+}$ signal extraction	4.4	10.5	10.7	17.4
$B_c^+ \to J/\psi\pi^+$ signal extraction	8.5	8.5	–	–
D_s^{*+} branching fractions	<0.1	<0.1	<0.1	1.1
MC sample sizes	2.3	2.4	2.7	2.2
Total	10.1	14.0	11.0	17.6
$\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}$	5.9	5.9	–	–

for the $\mathcal{R}_{D_s^{*+}/\pi^+}$ and $\mathcal{R}_{D_s^{*+}/D_s^+}$, while for $\Gamma_{\pm\pm}/\Gamma$, the estimate is ∼1 %.

The statistical uncertainties on the acceptance values due to the MC sample sizes are also treated as a separate source of systematic uncertainty and estimated to be 2–3 %.

In order to check for a possible bias from using three-muon triggers, vetoing the D_s^+ meson daughter tracks identified as muons is tested and found not to affect the measurement.

Finally, since $\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}$ enters Eq. (2), its uncertainty, evaluated from Ref. [26] as 5.9 %, is propagated to the final values of the relative branching fractions.

The systematic uncertainties on the measured quantities are summarised in Table 4.

8 Results

The following ratios of the branching fractions are measured:

$$\mathcal{R}_{D_s^+/\pi^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^+}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}} = 3.8 \pm 1.1(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.2(\text{BF}), \quad (6)$$

$$\mathcal{R}_{D_s^{*+}/\pi^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}} = 10.4 \pm 3.1(\text{stat.}) \pm 1.5(\text{syst.}) \pm 0.6(\text{BF}), \quad (7)$$

$$\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi D_s^+}} = 2.8^{+1.2}_{-0.8}(\text{stat.}) \pm 0.3(\text{syst.}), \quad (8)$$

where the BF uncertainty corresponds to the knowledge of $\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}$. The relative contribution of the $A_{\pm\pm}$ component in $B_c^+ \to J/\psi D_s^{*+}$ decay is measured to be

$$\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23(\text{stat.}) \pm 0.07(\text{syst.}) \quad (9)$$

These results are compared with those of the LHCb measurement [10] and to the expectations from various theoretical calculations in Table 5 and Fig. 7. The measurement agrees with the LHCb result. All ratios are well described by the recent perturbative QCD predictions [8]. The expectations from models in Refs. [3,5,7] as well as the sum-rules prediction [4] for the ratio $\mathcal{R}_{D_s^{*+}/D_s^+}$ are consistent with the measurement. The QCD relativistic potential model predictions [3] are consistent with the measured $\mathcal{R}_{D_s^+/\pi^+}$ ratio while the expectations from the sum rules [4] and models in Refs. [5–7] are somewhat smaller than the measured value. The predictions in Refs. [3–5,7] are also generally smaller than the measured ratio $\mathcal{R}_{D_s^{*+}/\pi^+}$; however, the discrepancies do not exceed two standard deviations when taking into account only the experimental uncertainty.

The measured fraction of the $A_{\pm\pm}$ component agrees well with the prediction of the relativistic independent quark model [9] and perturbative QCD [8].

9 Conclusion

A study of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays has been performed. The ratios of the branching fractions $\mathcal{B}_{B_c^+\to J/\psi D_s^+}/\mathcal{B}_{B_c^+\to J/\psi\pi^+}$, $\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}/\mathcal{B}_{B_c^+\to J/\psi\pi^+}$, $\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}/\mathcal{B}_{B_c^+\to J/\psi D_s^+}$ and the transverse polarisation fraction of $B_c^+ \to J/\psi D_s^{*+}$ decay have been measured by the ATLAS experiment at the LHC using pp collision data corresponding to an integrated luminosity of 4.9 fb^{-1} at 7 TeV centre-of-mass energy and 20.6 fb^{-1} at 8 TeV. The polarisation is found to be well described by the available

Table 5 Comparison of the results of this measurement with those of LHCb [10] and theoretical predictions based on a QCD relativistic potential model [3], QCD sum rules [4], relativistic constituent quark model (RCQM) [5], BSW relativistic quark model (with fixed average transverse quark momentum $\omega = 0.40\,\text{GeV}$) [6], light-front quark model (LFQM) [7], perturbative QCD (pQCD) [8], and relativistic independent quark model (RIQM) [9]. The uncertainties of the theoretical predictions are shown if they are explicitly quoted in the corresponding papers. Statistical and systematic uncertainties added in quadrature are shown for the results of ATLAS and LHCb

$\mathcal{R}_{D_s^+/\pi^+}$	$\mathcal{R}_{D_s^{*+}/\pi^+}$	$\mathcal{R}_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$	Ref.
3.8 ± 1.2	10.4 ± 3.5	$2.8^{+1.2}_{-0.9}$	0.38 ± 0.24	ATLAS
2.90 ± 0.62	–	2.37 ± 0.57	0.52 ± 0.20	LHCb [10]
2.6	4.5	1.7	–	QCD potential model [3]
1.3	5.2	3.9	–	QCD sum rules [4]
2.0	5.7	2.9	–	RCQM [5]
2.2	–	–	–	BSW [6]
2.06 ± 0.86	–	3.01 ± 1.23	–	LFQM [7]
$3.45^{+0.49}_{-0.17}$	–	$2.54^{+0.07}_{-0.21}$	0.48 ± 0.04	pQCD [8]
–	–	–	0.410	RIQM [9]

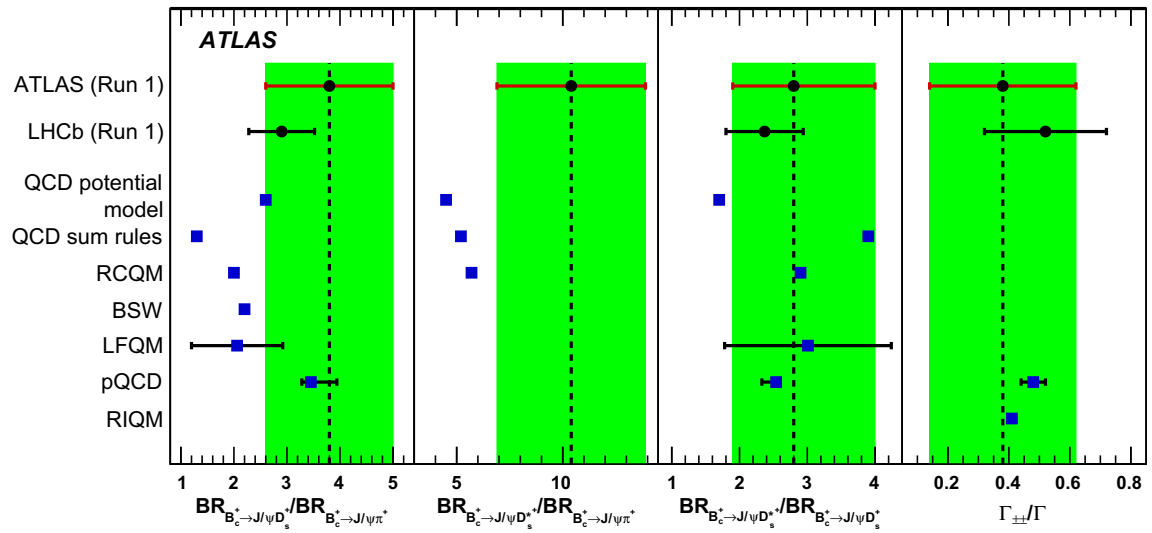


Fig. 7 Comparison of the results of this measurement with those of LHCb [10] and theoretical predictions based on a QCD relativistic potential model [3], QCD sum rules [4], relativistic constituent quark model (RCQM) [5], BSW relativistic quark model (with fixed average transverse quark momentum $\omega = 0.40\,\text{GeV}$) [6], light-front quark model (LFQM) [7], perturbative QCD (pQCD) [8], and relativistic independent quark model (RIQM) [9]. The uncertainties of the theoretical predictions are shown if they are explicitly quoted in the corresponding papers. Statistical and systematic uncertainties added in quadrature are quoted for the results of ATLAS and LHCb.

theoretical approaches. The measured ratios of the branching fraction are generally described by perturbative QCD, sum rules, and relativistic quark models. There is an indication of underestimation of the decay rates for the $B_c^+ \to J/\psi D_s^{(*)+}$ decays by some models, although the discrepancies do not exceed two standard deviations when taking into account only the experimental uncertainty. The measurement results agree with those published by the LHCb experiment.

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