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

The ATLAS Collaboration

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 fb$^{-1}$ and 20.6 fb$^{-1}$ of $pp$ collisions collected at centre-of-mass energies $\sqrt{s} = 7$ and 8 TeV, respectively. Signal candidates are identified through $J/\psi \to \mu^+ \mu^-$ and $D_s^+(\ast) \to \phi \pi$ decays. With a two-dimensional likelihood fit involving the $B_c^+$ reconstructed invariant mass and the $J/\psi$ helicity angle, 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 $\Gamma_{J/\psi D_s^{**}} / \Gamma_{J/\psi D_s^+} = 0.38 \pm 0.23^{+0.06}_{-0.07}$, and the derived ratio of the branching fractions of the two modes is $B(B_c^+ \to J/\psi D_s^+) / B(B_c^+ \to J/\psi D_s^{**}) = 2.7^{+1.1+0.4}_{-0.8-0.3}$, 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 $B(B_c^+ \to J/\psi D_s^+) / B(B_c^+ \to J/\psi \pi^+) = 3.8 \pm 1.1_{-0.6}^{+0.2} \pm 0.2$ and $B(B_c^+ \to J/\psi D_s^{**}) / B(B_c^+ \to J/\psi \pi^+) = 10.3 \pm 3.1_{-1.5}^{+0.3} \pm 0.6$, 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.

© 2015 CERN for the benefit of the ATLAS Collaboration.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-3.0 license.
1 Introduction

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

![Feynman diagrams for $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decays](image)

This paper presents a measurement of the branching fractions of $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decays normalised to that of $B_c^+ \rightarrow J/\psi \pi^+$ decay and polarisation in $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decay performed with the ATLAS detector [11]. The $D_s^{(*)+}$ meson is reconstructed via the $D_s^{(*)+} \rightarrow \phi \pi^+$ mode with the $\phi$ meson decaying into a pair of charged kaons. The $D_s^{(*)+}$ meson decays into a $D_s^+$ meson and a soft photon or $\pi^0$. Detecting such soft neutral particles is very challenging, thus no attempt to reconstruct them is made in the analysis. The $J/\psi$ meson is reconstructed via its decay into a muon pair. The following ratios are measured: $\mathcal{R}_{D_s^{(*)+} / D_s^+} = \frac{B_{D_s^+ \rightarrow J/\psi D_s^{(*)+}} / B_{D_s^+ \rightarrow J/\psi\pi^+}}{B_{D_s^+ \rightarrow J/\psi D_s^{(*)+}} / B_{D_s^+ \rightarrow J/\psi\pi^+}}$, $\mathcal{R}_{D_s^{(*)+} / D_s^+} = \frac{B_{D_s^+ \rightarrow J/\psi D_s^{(*)+}} / B_{D_s^+ \rightarrow J/\psi D_s^{(*)+}}}{B_{D_s^+ \rightarrow J/\psi D_s^{(*)+}} / B_{D_s^+ \rightarrow J/\psi\pi^+}}$, and $\mathcal{R}_{D_s^{(*)+} / D_s^+} = \frac{B_{D_s^+ \rightarrow J/\psi D_s^{(*)+}} / B_{D_s^+ \rightarrow J/\psi D_s^{(*)+}}}{B_{D_s^+ \rightarrow X}}$, where $B_{D_s^+ \rightarrow X}$ denotes the branching fraction of the $B_c^+ \rightarrow X$ decay. The decay $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ 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 $J/\psi$ and $D_s^{(*)+}$ mesons. The contribution of the $A_{+,+}$ amplitude, i.e. the fraction of transverse polarisation, $\Gamma_{A_{+,+}} / \Gamma = \frac{\Gamma(B_c^+ \rightarrow J/\psi D_s^{(*)+})/\Gamma(B_c^+ \rightarrow J/\psi D_s^{(*)0})}{\Gamma(B_c^+ \rightarrow J/\psi D_s^{(*)0})}$, is also measured.

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 $\sqrt{s} = 7$ and $8 \text{ TeV}$ corresponding to integrated luminosities of $4.9 \text{ fb}^{-1}$ and $20.6 \text{ fb}^{-1}$, respectively.

---

1 Charge conjugate states are implied throughout the paper unless otherwise stated.
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. 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 patterns of MS hits. Candidates of the latter type are referred to as segment-tagged muons while the former are called combined muons. Muon track parameters are taken in this analysis from the ID measurement alone, 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 the single-, di-, and three-muon signatures are used to select \(J/\psi \rightarrow \mu^+\mu^-\) for the analysis. The third muon can be produced in the \(B_s^+\) signal events in semileptonic decays of the two other heavy-flavoured hadrons. The majority of events are collected by dimuon triggers requiring a vertex of two oppositely charged muons with a mass between 2.5 and 4.3 GeV. During the data taking, the \(p_T\) threshold for muons in these triggers was 4 or 6 GeV. Single-muon triggers additionally increase the acceptance for asymmetric \(J/\psi\) decays where one muon has \(p_T < 4\) 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 \(p_T\) thresholds of the dimuon triggers were larger.

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

3 Reconstruction and event selection

The \(J/\psi\) 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

\(^2\) 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 \((r, \phi)\) are used in the transverse plane, \(\phi\) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \(\theta\) as \(\eta = -\ln\tan(\theta/2)\).
vertex fit must satisfy $\chi^2/n.d.f. < 15$, where the n.d.f. 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 $D_s^+ \rightarrow \phi(K^+K^-)\pi^+$ reconstruction, tracks of particles with opposite charges are assigned kaon mass hypotheses and combined in pairs to form $\phi$ candidates. An additional track is assigned a pion mass and combined with the $\phi$ candidate to form a $D_s^+$ candidate. To ensure good momentum resolution, all three tracks are required to have at least 2 pixel hits and at least 6 hits in the SCT. Only three-track combinations successfully fitted to a common vertex with $\chi^2/n.d.f. < 8$ are kept. The $\phi$ 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 $m(K^+K^-) < \pm 7 \text{ MeV}$ around the nominal $\phi$ mass, $m_{\phi} = 1019.461 \text{ MeV}$ [22], and with $1930 \text{ MeV} < m(K^+K^-\pi^+) < 2010 \text{ MeV}$ are retained.

The $B^+_c \rightarrow J/\psi D_s^+$ candidates are built by combining the five tracks of the $J/\psi$ and $D_s^+$ candidates. The $J/\psi$ 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. The invariant mass of the muon pair is constrained to the nominal $\phi$ mass, $m_{\phi} = 1019.461 \text{ MeV}$ [22]. The three $D_s^+$ daughter tracks are constrained to a tertiary vertex and their invariant mass is fixed to the nominal 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 $\chi^2/n.d.f. < 3$.

The $B_c^+$ meson is reconstructed within the kinematic range $p_T(B_c^+) > 15 \text{ GeV}$ and $|\eta(B_c^+)| < 2.0$, where the detector acceptance is high and depends weakly on $p_T(B_c^+)$ and $\eta(B_c^+)$. The refitted tracks of the $D_s^+$ daughter hadrons are required to have $|\eta| < 2.5$ and $p_T > 1 \text{ GeV}$, while the muons must have $|\eta| < 2.3$ and $p_T > 3 \text{ GeV}$. To further discriminate the sample of $D_s^+$ candidates from large combinatorial background, the following requirements are applied, following Ref. [23]:

- $\cos \theta^*(\pi) < 0.8$, 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 $\phi$ (vector) plus $\pi$ (pseudoscalar) final state results in an alignment of the spin of the $\phi$ meson perpendicularly to the direction of motion of the $\phi$ relative to $D_s^+$. Consequently, the distribution of $\cos \theta'(K)$ follows a $\cos^3 \theta'(K)$ shape, implying a flat distribution for $\cos^3 \theta'(K)$. In contrast, the $\cos \theta'(K)$ distribution of the combinatorial background is flat 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 $d_0^{PV}(B_c^+) < 0.1 \text{ mm}$ and $z_0^{PV}(B_c^+) \sin(\theta(B_c^+)) < 0.5 \text{ mm}$, 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 ($\sim 0.5\%$ events both in data and MC), the one with the largest sum of squared transverse momenta of the tracks originating from it is chosen.

The transverse decay length$^3$ 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

---

$^3$ 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.
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 $p_T(B^+_c)/\sum p_T(\text{trk}) > 0.1$ is applied, where the sum in the denominator is taken over all tracks originating from 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 flat for the decays of pseudo-scalar $B^+_c$ meson before any kinematic selection while it tends to negative values for the background.

- $\cos \theta'(\pi) > -0.8$, where $\theta'(\pi)$ is the angle between the $J/\psi$ candidate momentum and the pion momentum in the $K^+K^−\pi^+$ rest frame. Its distribution is nearly flat for the signal processes but peaks towards $-1$ for the background.

Various possible contributions of partially reconstructed $B \to J/\psi X$ decays have been studied. The only significant one has been found from the $B^+_c \to J/\psi \phi$ decay process. This contribution arises when the combination of the tracks from a true $B^{0}_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ 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 into one vertex, where the kaon tracks are assumed to be from $\phi \to K^+K^-$ and the muon pair is constrained to have the nominal $J/\psi$ mass. The mass of the $B^{0}_s$ 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 $B^{0}_s$ events while rejecting only $\sim 4\%$ of the signal.

After applying the selection requirements described above, 1547 $J/\psi D^+_s$ candidates are selected in the data sample.

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. 2. The peak near the nominal $B^+_c$ mass, $m_{B^+_c} = 6275.6$ MeV [22], is attributed to the signal of $B^+_c \to J/\psi D^+_s$ decay while a wider structure between 5900 MeV 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 $J/\psi$ 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. 3. To obtain these plots, the $B^+_c$ candidates have been 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 particles. The mass of the $B^+_c$ candidate is required to be $5900$ MeV $< m(J/\psi D^+_s) < 6400$ MeV. The $J/\psi$ and $D^+_s$ mass distributions are fitted with a sum of
an exponential function describing background and a modified Gaussian function [24] describing the corresponding signal peak. The modified Gaussian function is defined as

$$\text{Gauss}^{\text{mod}} \sim \exp \left[ -\frac{x^2}{2\sigma^2} \right],$$

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

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

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

The mass distribution of the $B_c^+ \rightarrow J/\psi D_s^+$ signal is described by a modified Gaussian function. For the $B_c^+ \rightarrow J/\psi D_s^{*+}$ signal components, the mass shape templates obtained from the simulation with the kernel...
Figure 3: Mass distribution of the $J/\psi$ (a) and $D_s^+$ (b) candidates after the full $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ selection (without mass constraints in the cascade fit) in the mass window of the $B_c^+$ candidate $5900 \text{ MeV} < m(J/\psi D_s^+) < 6400 \text{ MeV}$. The spectra are fitted with a sum of an exponential and a modified Gaussian function.

estimation technique [25] are used. The branching fractions of $D_s^{*+} \rightarrow D_s^+ \pi^0$ and $D_s^{*+} \rightarrow D_s^+ \gamma$ decays for the simulation are taken from Ref. [22]. The position of the templates along the mass axis is varied in the fit simultaneously with the position of the $B_c^+ \rightarrow J/\psi D_s^+$ 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. 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 ($5640–5900 \text{ MeV}$) and right ($6360–6760 \text{ MeV}$) sidebands. 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 ($5640–5770 \text{ MeV}$), 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 ($6560–6760 \text{ MeV}$). For the candidates in the middle part of the mass spectrum ($5770–6560 \text{ MeV}$), a linear interpolation between the two templates is used.

The fit has 7 free parameters: the mass of $B_c^+$ meson, $m_{B_c^+ \rightarrow J/\psi D_s^+}$; the relative contribution of the $A_{\pm \pm}$ amplitude to the total $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decay rate in the selected sample, $f_{\pm \pm}$; the two parameters of the exponential background; the yields of the two signal modes, $N_{B_c^+ \rightarrow J/\psi D_s^+}$ and $N_{B_c^+ \rightarrow J/\psi D_s^{(*)+}}$, and the background yield. The width of the modified Gaussian, $\sigma_{B_c^+ \rightarrow J/\psi D_s^+}$, is fixed to the value obtained from the fit to the simulated signal, $\sigma_{B_c^+ \rightarrow J/\psi D_s^+} = 9.96 \text{ MeV}$.

The fit procedure has been checked to provide 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. 2 and 4a, respectively. In order to illustrate the effect of the angular part of the fit on the helicity amplitudes separation, the $|\cos \theta'(\mu^+)|$ projection on a subset of the candidates with the masses $5950 \text{ MeV} < m(J/\psi D_s^+) < 6250 \text{ MeV}$ corresponding to the region of the observed $B_c^+ \rightarrow J/\psi D_s^+$ signal is shown in Fig. 4b.
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 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 |

Figure 4: The angular projection of the likelihood fit to the full selected \( J/\psi D_s^+ \) candidate dataset (a) and to a subset of the candidates in a mass range \( 5950 \text{ MeV} < m(J/\psi D_s^+) < 6250 \text{ MeV} \) (b) 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 \( B_c^+ \to J/\psi D_s^{(*)+} \), \( A_{s0} \) and \( A_{+\pm} \) amplitude contributions, respectively; the blue dashed line shows the background.

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 pion candidate track and the two muons from a \( J/\psi \) candidate to a common vertex, selected as described in Section 3. For the pion track, 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 \( J/\psi \) nominal mass. The quality of the fit must satisfy \( \chi^2/\text{n.d.f.} < 3 \). The refined values of the transverse momenta and pseudorapidities of the muon and pion tracks are required to be \( p_T(\mu^+) > 3 \text{ GeV} \), \( p_T(\pi^+) > 5 \text{ GeV} \), \( |\eta(\mu^+)| < 2.3 \), \( |\eta(\pi^+)| < 2.5 \), and the \( B_c^+ \) candidate is required to be in the kinematic range \( p_T(B_c^+) > 15 \text{ GeV} \), \( |\eta(B_c^+)| < 2.0 \).
The same requirements on pointing to the primary vertex and the ratio \( p_T(B^+_c)/\sum p_T(\text{trk}) \) as for \( B^+_c \to J/\psi D^{(*)+} \) modes are applied to \( B^+_c \to J/\psi \pi^+ \) candidates. The transverse decay length is required to be \( L_{xy}(B^+_c) > 0.2 \text{ mm} \), and not to exceed 10 mm.

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

- \( \cos \theta^*(\pi) > -0.8 \), where \( \cos \theta^*(\pi) \) is the angle between the pion momentum in \( \mu^+\mu^-\pi^+ \) 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 \( \mu^+ \) and \( \pi^+ \) momenta in the muon pair rest frame. The signal distributions follows a \( \sin^2 \theta'(\mu^+) \) shape, while the background is flat.

After applying the above-mentioned requirements, 31935 \( J/\psi \pi^+ \) candidates are selected in the data sample. Fig. 5 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 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, \( \sigma_{B^+_c \to J/\psi \pi^+} \), 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. 5. The extracted \( B^+_c \) mass value is consistent with the world average [22], and the signal peak width agrees with the simulation.

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 |

Figure 5: 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.
6 Branching fractions and polarisation measurement

The ratios of the branching fractions $R_{D_s^+/\pi^+}$ and $R_{D_s^+/\pi^+}$ are calculated as

$$R_{D_s^+/\pi^+} = \frac{\mathcal{B}_{B_s^+ \rightarrow J/\psi D_s^{(*)+}}}{\mathcal{B}_{B_s^+ \rightarrow J/\psi \pi^+}} = \frac{1}{\mathcal{B}_{D_s^{(*)+} \rightarrow J/\psi(K^+K^-)\pi^+}} \times \frac{\mathcal{A}_{B_s^+ \rightarrow J/\psi D_s^{(*)+}}}{\mathcal{A}_{B_s^+ \rightarrow J/\psi \pi^+}} \times \frac{N_{B_s^+ \rightarrow J/\psi D_s^{(*)+}}}{N_{B_s^+ \rightarrow J/\psi \pi^+}},$$

(2)

where $\mathcal{A}_{B_s^+ \rightarrow X}$ and $N_{B_s^+ \rightarrow X}$ are the total acceptances and the yields of the corresponding mode. For the $\mathcal{B}_{D_s^{(*)+} \rightarrow J/\psi(K^+K^-)\pi^+}$, the CLEO measurement [26] of the partial $D_s^+ \rightarrow K^+K^-\pi^+$ branching fractions, with a kaon pair mass within various intervals around the nominal $\phi$ meson mass, is used. An interpolation between the partial branching fractions, measured for $\pm 5$ MeV and $\pm 10$ MeV intervals, using a relativistic Breit-Wigner shape of the resonance yields the value $1.85 \pm 0.11\%$ for the $\pm 7$ MeV interval which is used in the analysis.

The acceptance for $B_s^+ \rightarrow J/\psi D_s^{(*)+}$ decay mode is different for $A_{\pm\mp}$ and $A_{00}$ amplitude contributions, thus the full acceptance of the mode is

$$\mathcal{A}_{B_s^+ \rightarrow J/\psi D_s^{(*)+}} = \left( \frac{f_{\pm\mp}}{\mathcal{A}_{B_s^+ \rightarrow J/\psi D_s^{(*)+}, A_{\pm\mp}}} + \frac{1 - f_{\pm\mp}}{\mathcal{A}_{B_s^+ \rightarrow J/\psi D_s^{(*)+}, A_{00}}} \right)^{-1},$$

(3)

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

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

| Mode                     | $\mathcal{A}_{B_s^+ \rightarrow X}$ [\%] |
|--------------------------|----------------------------------------|
| $B_s^+ \rightarrow J/\psi \pi^+$ | $4.110 \pm 0.056$ |
| $B_s^+ \rightarrow J/\psi D_s^+$  | $1.842 \pm 0.034$ |
| $B_s^+ \rightarrow J/\psi D_s^{(*)+}, A_{00}$ | $1.839 \pm 0.053$ |
| $B_s^+ \rightarrow J/\psi D_s^{(*)+}, A_{\pm\mp}$ | $1.720 \pm 0.035$ |

The ratio $R_{D_s^+/D_s^+}$ is calculated as

$$R_{D_s^+/D_s^+} = \frac{\mathcal{B}_{B_s^+ \rightarrow J/\psi D_s^{(*)+}}}{\mathcal{B}_{B_s^+ \rightarrow J/\psi D_s^+}} = \frac{N_{B_s^+ \rightarrow J/\psi D_s^{(*)+}}}{N_{B_s^+ \rightarrow J/\psi D_s^+}} \times \frac{\mathcal{A}_{B_s^+ \rightarrow J/\psi D_s^{(*)+}}}{\mathcal{A}_{B_s^+ \rightarrow J/\psi D_s^+}},$$

(4)

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

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

$$\Gamma_{\pm\mp}/\Gamma = f_{\pm\mp} \times \frac{\mathcal{A}_{B_s^+ \rightarrow J/\psi D_s^{(*)+}}}{\mathcal{A}_{B_s^+ \rightarrow J/\psi D_s^{(*)+}, A_{\pm\mp}}}.$$

(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 for 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 systematics sources relates to possible differences between the data and simulation affecting the acceptances for the decay modes. Thus, an effect of $B_c^+$ production model is evaluated by varying the simulated $p_T$ and $|\eta|$ spectra while preserving agreement with the data distributions obtained using the abundant $B_c^+ \rightarrow J/\psi \pi^+$ channel. These variations have very similar effect 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. An uncertainty on the tracking efficiency is dominated by the uncertainty of the detector material description in the MC simulation. Its conservative estimate based on Ref. [27] gives $\sim 5\%$ for $R_{D^*_s/\pi^+}$ due to the two extra tracks in $B_c^+ \rightarrow J/\psi D^{(*)+}_s$ modes. The limited knowledge of $B_c^+$ and $D^+_s$ lifetimes leads to an additional systematic uncertainty. The simulated proper decay times have been varied within one standard deviation from the world average values [22] resulting in uncertainties of $\sim 1\%$ assigned to the $R_{D^*_s/\pi^+}$ and $R_{D^{(*)+}_s/\pi^+}$ due to $B_c^+$ lifetime and 0.1–0.3% for all measured values due to $D^+_s$ lifetime. Removing the requirement on $p_T(B_c^+)/\sum p_T(\text{trk})$ has been found to produce no sizeable effect on the measured values.

The next group of uncertainties comes from the signals 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 have been applied and the difference is treated as a systematic uncertainty:

- different background mass shape parametrisations (3-parameter exponential, 2nd and 3rd order polynomials), different fitted mass range (reduced by up to 40 MeV from each side independently);
- a standard Gaussian with per-candidate errors for $B_c^+ \rightarrow J/\psi D^+_s$ signal description; variation of the modified Gaussian width within its uncertainty extracted from simulation or treating it as an additional free parameter;
- variation of smoothness of the $B_c^+ \rightarrow J/\psi D^{(*)+}_s$ signal mass templates which is controlled by a parameter of the kernel estimation procedure [25];
- similar variation of smoothness of the $B_c^+ \rightarrow J/\psi D^{(*)+}_s$ signal angular templates;
- variation of smoothness of the sideband templates used for the background angular PDF construction; different ranges of the sidebands; different sidebands interpolation procedure;
- modelling of the correlation between the mass and angular part 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 has been 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 shapes parametrisation have been applied. The deviations produced by the variations of the fits reach as much as 10–15% thus making them the dominant sources of systematics.
The simulated branching fractions of $D_s^{*+}$ [22] have been varied within their uncertainties to estimate their effect on the measured quantities. Very small uncertainties are obtained for the $\mathcal{R}_{D_s^{*+}/\pi^+}$ and $\mathcal{R}_{D_s^{*+}/D_s^+}$, while for $\Gamma_{\pm\pm}/\Gamma$, the estimate is $\sim 1\%$.

The statistical uncertainties on the acceptance values due to limited MC statistics are also treated as a separate source of systematic uncertainty and estimated to be $2\sim 3\%$.

In order to check for a possible effect of using three-muon triggers, vetoing the $D_s^+$ meson daughter tracks identified as muons has been tested and found not to affect the measurement.

Finally, since the $\mathcal{B}_{D_s^{*+}\rightarrow \phi(K^+K^-)\pi^+}$ enters Eqn. 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.

### Table 4: Relative systematic uncertainties for the measured values.

| Source                                      | $\mathcal{R}_{D_s^{*+}/\pi^+}$ | $\mathcal{R}_{D_s^{*+}/\pi^+}$ | $\mathcal{R}_{D_s^{*+}/D_s^+}$ | $\Gamma_{\pm\pm}/\Gamma$ |
|---------------------------------------------|---------------------------------|---------------------------------|-------------------------------|--------------------------|
| Simulated $p_T(B_c^+)$ spectrum             | +0.4                            | +0.9                            | +0.4                          | +0.4                     |
| Simulated $|p(B_c^+)|$ spectrum                  | +1.8                            | +2.4                            | +0.6                          | +0.2                     |
| Tracking efficiency                         | ±5.0                            | ±4.9                            | ±0.1                          | ±0.1                     |
| $B_c^+$ lifetime                            | ±1.1                            | ±1.2                            | ±0.0                          | ±0.0                     |
| $D_s^+$ lifetime                            | ±0.3                            | ±0.3                            | ±0.1                          | ±0.1                     |
| $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ signal extraction | +1.7                            | +3.9                            | +12.8                         | +15.2                    |
| $B_c^+ \rightarrow J/\psi \pi^+$ signal extraction | −13.5                          | −10.7                           | −10.1                         | −17.8                    |
| $D_s^{*+}$ branching fractions              | +1.5                            | +1.5                            | ±0.2                          | +0.8                     |
| $D_s^{*+}$ lifetime                         | −7.4                            | −7.4                            | −0.3                          | −1.1                     |
| MC statistics                               | ±2.3                            | ±2.4                            | ±2.7                          | ±2.2                     |

Total $\mathcal{B}_{D_s^{*+}\rightarrow \phi(K^+K^-)\pi^+}$ = $\pm 5.9\%$ = $\pm 5.9\%$ = $\pm 5.9\%$.

### 8 Results

A study of $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$ decays has been presented. The following ratios of the branching fractions are measured:

$$\mathcal{R}_{D_s^{*+}/\pi^+} = \frac{\mathcal{B}_{B_c^+\rightarrow J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\rightarrow J/\psi \pi^+}} = 3.8 \pm 1.1 \text{ (stat.)} ^{+0.2}_{-0.6} \text{ (syst.)} \pm 0.2 \text{ (BF)},$$

(6)

$$\mathcal{R}_{D_s^{*+}/\pi^+} = \frac{\mathcal{B}_{B_c^+\rightarrow J/\psi D_s^{(*)+}}}{\mathcal{B}_{B_c^+\rightarrow J/\psi \pi^+}} = 10.3 \pm 3.1 \text{ (stat.)} ^{+0.8}_{-1.5} \text{ (syst.)} \pm 0.6 \text{ (BF)},$$

(7)

$$\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}_{B_c^+\rightarrow J/\psi D_s^{(*)+}}}{\mathcal{B}_{B_c^+\rightarrow J/\psi D_s^+}} = 2.7^{+1.1}_{-0.8} \text{ (stat.)} ^{+0.4}_{-0.3} \text{ (syst.)},$$

(8)
where the BF uncertainty corresponds to the limited knowledge of $\mathcal{B}_{D_s^+} \to J/\psi (K^+ K^-) \pi^+$. The relative contribution of $A_{\pm \pm}$ amplitude in $B_c^+ \to J/\psi D_s^{*+}$ decay is measured to be

$$\Gamma_{\pm \pm} / \Gamma = 0.38 \pm 0.23 \text{ (stat.)}^{+0.06}_{-0.07} \text{ (syst.)} \quad (9)$$

These results are confronted to those of LHCb measurement [10] and to the expectations from various theoretical calculations in Table 5. The measurement agree with the LHCb result. All ratios are well described by the recent perturbative QCD predictions [8]. The expectations from models in Ref. [3, 5, 7] as well as the sum rules prediction [4] for the ratio $\mathcal{R}_{D_s^+/\pi^+}$ is 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 Ref. [5–7] are somewhat smaller than the measured value. The predictions in Ref. [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 taking into account only experimental uncertainty.

Table 5: Comparison of this measurement results with those of LHCb measurement [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 [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.

| $\mathcal{R}_{D_s^+/\pi^+}$ | $\mathcal{R}_{D_s^{*+}/\pi^+}$ | $\mathcal{R}_{D_s^{*+}/D_s^+}$ | $\Gamma_{\pm \pm} / \Gamma$ | Ref. |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|------|
| 3.8$^{+1.2}_{-1.3}$        | 10.3$^{+3.3}_{-3.5}$        | 2.7$^{+1.2}_{-0.9}$         | 0.38 $\pm$ 0.24             | ATLAS|
| $2.90 \pm 0.62$            | $2.37 \pm 0.57$            | $0.48 \pm 0.20$            | $LHCb$ [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$\pm$ 0.86             | 3.01$\pm$ 1.23             | $-$                         | $-$                         | LFQM [7] |
| 3.45$^{+0.49}_{-0.17}$     | $2.54^{+0.07}_{-0.21}$     | 0.48 $\pm$ 0.04            | pQCD [8]                    |
| $-$                         | $-$                         | $-$                         | 0.410                       | RIQM [9] |

The measured fraction of the $A_{\pm \pm}$ amplitude is consistent with a value of 2/3 from a naive estimation by spin-counting and agrees well with the prediction of the relativistic independent quark model [9] and perturbative QCD [8].

In summary, the ratios of the branching fractions $\mathcal{B}_{B_c^+ \to J/\psi D_s^+}/\mathcal{B}_{B_c^+ \to J/\psi \pi^+}$, $\mathcal{B}_{B_c^+ \to J/\psi D_s^{*+}}/\mathcal{B}_{B_c^+ \to J/\psi D_s^+}$, 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 theoretical approaches. The measured ratios of the branching fraction are generally well described by perturbative QCD, sum rules and relativistic quark models. However, there is an indication of underestimation of the decay rates for the $B_c^+ \to J/\psi D_s^{*+}$ decays by some models. The measurement results agree with those published by the LHCb experiment.
References

[1] CDF Collaboration, F. Abe et al., Phys. Rev. Lett. 81 (1998) 2432–2437, arXiv: hep-ex/9805034 [hep-ex].

[2] ATLAS Collaboration, Phys. Rev. Lett. 113 (2014) 212004, arXiv: 1407.1032 [hep-ex].

[3] P. Colangelo and F. De Fazio, Phys. Rev. D 61 (2000) 034012, arXiv: hep-ph/9909423 [hep-ph].

[4] V. Kiselev, 2002, arXiv: hep-ph/0211021 [hep-ph].

[5] M. Ivanov, J. Korner and P. Santorelli, Phys. Rev. D 73 (2006) 054024, arXiv: hep-ph/0602050 [hep-ph].

[6] R. Dhir and R. Verma, Phys. Rev. D 79 (2009) 034004, arXiv: 0810.4284 [hep-ph].

[7] H.-W. Ke, T. Liu and X.-Q. Li, Phys. Rev. D 89 (2014) 017501, arXiv: 1307.5925 [hep-ph].

[8] Z. Rui and Z.-T. Zou, Phys. Rev. D 90 (2014) 114030, arXiv: 1407.5550 [hep-ph].

[9] S. Kar et al., Phys. Rev. D 88 (2013) 094014.

[10] LHCb Collaboration, R. Aaij et al., Phys. Rev. D 87 (2013) 112012, arXiv: 1304.4530 [hep-ex].

[11] ATLAS Collaboration, JINST 3 (2008) S08003.

[12] T. Sjostrand, S. Mrenna and P. Skands, JHEP 0605 (2006) 026, arXiv: hep-ph/0603175 [hep-ph].

[13] A. Berezhnoy, A. Likhoded and O. Yushchenko, Phys. Atom. Nucl. 59 (1996) 709–713, arXiv: hep-ph/9504302 [hep-ph].

[14] A. Berezhnoy, V. Kiselev and A. Likhoded, Z. Phys. A 356 (1996) 79–87, arXiv: hep-ph/9602347 [hep-ph].

[15] A. Berezhnoy et al., Phys. Atom. Nucl. 60 (1997) 1729–1740, arXiv: hep-ph/9703341 [hep-ph].

[16] A. Berezhnoy, Phys. Atom. Nucl. 68 (2005) 1866–1872, arXiv: hep-ph/0407315 [hep-ph].

[17] D. Lange, Nucl. Instrum. Meth. A 462 (2001) 152–155.

[18] ATLAS Collaboration, Eur. Phys. J. C 70 (2010) 823–874, arXiv: 1005.4568 [physics.ins-det].

[19] GEANT4 Collaboration, S. Agostinelli et al., Nucl. Instrum. Meth. A 506 (2003) 250–303.

[20] J. Allison et al., IEEE Trans. Nucl. Sci. 53 (2006) 270.

[21] V. Kostyukhin, ATL-PHYS-2003-031, 2003, url: http://cds.cern.ch/record/685551.

[22] Particle Data Group, K. Olive et al., Chin. Phys. C 38 (2014) 090001.

[23] ATLAS Collaboration, ATLAS-CONF-2011-017, 2011, url: http://cds.cern.ch/record/1336746.

[24] ZEUS Collaboration, S. Chekanov et al., Eur. Phys. J. C 44 (2005) 13–25, arXiv: hep-ex/0505008 [hep-ex].

[25] K. Cranmer, Comput. Phys. Commun. 136 (2001) 198–207, arXiv: hep-ex/0011057 [hep-ex].
[26] CLEO Collaboration, J. Alexander et al., Phys. Rev. Lett. 100 (2008) 161804, arXiv: 0801.0680 [hep-ex].

[27] ATLAS Collaboration, New J. Phys. 13 (2011) 053033, arXiv: 1012.5104 [hep-ex].
Auxiliary material

Figure 6: Distributions of $\cos\theta^* (D_s^0)$ for the data sidebands (black dots) and MC simulation of $B_c^+ \rightarrow J/\psi D_s^+ ( \rightarrow J/\psi D_{s*}^+), A_{00}$ (green dotted line) and $A_{\pm \pm}$ (blue dashed line) signals. The angle $\theta^* (D_s^0)$ is an angle between the $D_s^0$ candidate momentum in the rest frame of the $B_c^+$ candidate, and the $B_c^+$ candidate line of flight in the laboratory frame. Data sidebands are defined as regions of $5640 \text{ MeV} < m(J/\psi D_s^+)<5900 \text{ MeV}$ and $6360 \text{ MeV} < m(J/\psi D_{s*}^+) < 6760 \text{ MeV}$. The distributions are obtained after applying all selection requirements except the one on $\cos\theta^* (D_s^0)$. The MC distributions are normalised to data.

Figure 7: Distributions of $\cos\theta' (\pi^+)$ for the data sidebands (black dots) and MC simulation of $B_c^+ \rightarrow J/\psi D_s^+ ( \rightarrow J/\psi D_{s*}^+), A_{00}$ (green dotted line) and $A_{\pm \pm}$ (blue dashed line) signals. The angle $\theta' (\pi^+)$ is an angle between the $J/\psi$ candidate momentum and the pion momentum in the $K^+K^-\pi^+$ rest frame. Data sidebands are defined as regions of $5640 \text{ MeV} < m(J/\psi D_s^+)<5900 \text{ MeV}$ and $6360 \text{ MeV} < m(J/\psi D_{s*}^+) < 6760 \text{ MeV}$. The distributions are obtained after applying all selection requirements except the one on $\cos\theta' (\pi^+)$. The MC distributions are normalised to data. The dip in the distribution for $B_c^0 \rightarrow J/\psi D_s^+$ signal is caused by rejection of the $B_c^0 \rightarrow J/\psi \phi$ candidates.
Figure 8: Comparison of the ATLAS measurement results 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 [6], light-front quark model (LFQM) [7], perturbative QCD (pQCD) [8], and relativistic independent quark model (RIQM) [9].