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

ATLAS Collaboration

CERN, 1211 Geneva 23, Switzerland

Received: 27 July 2015 / Accepted: 19 October 2015 © CERN for the benefit of the ATLAS collaboration 2015. This article is published with open access at Springerlink.com

Abstract The decays $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$ 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 $J/\psi \rightarrow \mu^+\mu^-$ and $D_s^{(*)+} \rightarrow \phi\pi^+$ ($\rho/\pi^0$) decays. With a two-dimensional likelihood fit involving the reconstructed invariant mass and an angle between the $\mu^+$ and $D_s^{(*)+}$ candidate momenta in the muon pair rest frame, the yields of $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$, and the transverse polarisation fraction in $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decay are measured. The transverse polarisation fraction is determined to be $\Gamma_{\pm\pm}(B_c^+ \rightarrow J/\psi D_s^{(*)+})/\Gamma(B_c^+ \rightarrow J/\psi D_s^{(*)+}) = 0.38 \pm 0.23 \pm 0.07$, and the derived ratio of the branching fractions of the two modes is $B_{B_c^+ \rightarrow J/\psi D_s^+}/B_{B_c^+ \rightarrow J/\psi D_s^{*+}} = 2.8^{+1.2}_{-0.8} \pm 0.3$, where the first error is statistical and the second is systematic. Finally, a sample of $B_c^+ \rightarrow J/\psi \pi^+$ decays is used to derive the ratios of branching fractions $B_{B_c^+ \rightarrow J/\psi D_s^+}/B_{B_c^+ \rightarrow J/\psi \pi^+} = 3.8 \pm 1.1 \pm 0.4 \pm 0.2$ and $B_{B_c^+ \rightarrow J/\psi D_s^{*+}}/B_{B_c^+ \rightarrow J/\psi \pi^+} = 10.4 \pm 3.1 \pm 1.5 \pm 0.6$, where the third error corresponds to the uncertainty of the branching fraction of $D_s^{(*)+} \rightarrow \phi(K^+K^-)\pi^+$ decay. The available theoretical predictions are generally consistent with the measurement.

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 observed recently 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 $\bar{b} \rightarrow \bar{c}\bar{c}s$ 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 $B_0 \rightarrow D^{(*)+}D^{(*)0}$ or $B_0 \rightarrow \bar{D}^{(*)0}D^{(*)+}$. The decays $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$, 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 $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$ 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 $D_s^{*+} \rightarrow \phi\pi^+$ decay 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 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: $R_{D_s^{*+} / \pi^+} = B_{B_c^+ \rightarrow J/\psi D_s^+} / B_{B_c^+ \rightarrow J/\psi \pi^+}$, $R_{D_s^{*+} / \pi^+} = B_{B_c^+ \rightarrow J/\psi D_s^{*+}} / B_{B_c^+ \rightarrow J/\psi \pi^+}$, and $R_{D_s^{*+} / D_s^{+}} = B_{B_c^+ \rightarrow J/\psi D_s^{*+}} / B_{B_c^+ \rightarrow J/\psi D_s^+}$, where $B_{B_c^+ \rightarrow X}$ denotes the branching fraction of the $B_c^+$ 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 $A_{++}$ and $A_{--}$ amplitudes, referred to as the $A_{\pm\pm}$ component, corresponds to the $J/\psi$ and $D_s^{(*)+}$ transverse polarisation. The fraction of transverse polarisation
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 \(J/\psi \rightarrow \mu^+\mu^-\) 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 \(J/\psi\) 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 \(p_T\) 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 \((r, \phi)\) 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 \(\eta = -\ln(\tan(\theta/2))\).

\(^3\) Using a system of units with \(c = 1\) is implied throughout the paper.

---

Fig. 1 Feynman diagrams for \(B_c^+ \rightarrow J/\psi D_s^{(*)}\) decays: a) colour-favoured spectator, b) colour-suppressed spectator, and c) annihilation topology.
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 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 \( D_\psi^+ \rightarrow \phi(K^+K^-)\pi^+ \) 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 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 \( \phi \) 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 \( m(K^+K^-) \) within \( \pm 7 \text{MeV} \) around the \( \phi \) 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 three-track combinations are refitted assuming this cascade topology [21]. The invariant mass of the muon pair is constrained to the \( J/\psi \) 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 \( p_T(B_c^+) > 15 \text{GeV} \) 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 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 \( \phi \) (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 \( \cos^2 \theta^*(K) \) 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 \( d_0^{PV}(B_c^+) < 0.1 \text{mm} \) 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 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 \( p_T(B_c^+)/\sum p_T(\text{trk}) > 0.1 \) is applied, where the sum in the denominator is taken over all tracks originating from the primary vertex (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 \( J/\psi \) 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.
The mass distribution of the selected well as for sidebands of the mass spectrum in data, defined Fig. 2. They are shown for the simulated signal samples, as calculated from the refitted track parameters. Candidates with mass of the muon pair is constrained to have the nominal candidate. For each reconstructed \( B_c \) was found from the decay is shown with the red line. The contribution of the \( B_c \) decay is shown with the magenta long-dashed line; the brown dash-dotted and green dotted lines show the \( B_c \) decay to \( J/\psi D_s^{(*)-} \), \( A_00 \) and \( A_{0\pm} \) component contributions, respectively; the blue dashed line shows the background model. The uncertainties of the listed fit result values are statistical only.

\[ B^+ \rightarrow J/\psi D_s^{(*)+} \] decay while a wider structure between 5900 and 6200 MeV corresponds to \( B^+_c \rightarrow J/\psi D_s^{(*)+} \) with subsequent \( D_s^{(*)} \rightarrow D_s^{(*)-} \gamma \) or \( D_s^{(*)} \rightarrow D_s^{(*)-} \pi^0 \) 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 \( B^+_c \rightarrow J/\psi D_s^{(*)+} \) 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 \( m(B_c^+ D_s^{(*)}) = m(B_c^+) + m(D_s^{(*)}) - m(J/\psi) - m(K^- K^+ \pi^0) \), where \( m(B_c^+) \) and \( m(D_s^{(*)}) \) are the nominal masses of the respective par-
Fig. 4 Mass distribution of the a $J/\psi$ and b $D_s^+$ 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 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 $J/\psi$ and $D_s^+$ yields are statistical only.

Four two-dimensional probability density functions (PDFs) are defined to describe the $B^+_c \rightarrow J/\psi D_s^{(*)+}$ signal, the $A_{\pm\pm}$ and $A_{00}$ components of the $B^+_c \rightarrow J/\psi D_s^{(*)+}$ signal, and the background. The signal PDFs are factorised into mass and angular components. The effect of correlations between their mass and angular shapes is 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 estimation technique [25] are used. The branching fractions of $D_s^{(*)+} \rightarrow D_s^0 \pi^0$ and $D_s^{(*)+} \rightarrow D_s^+ \gamma$ 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 $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ signal peak. The background mass shape is described with a two-parameter exponential function, $\exp \left[ a \cdot m(J/\psi D_s^{(*)+}) + b \right]$.

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 $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{B_c^+ \rightarrow J/\psi D_s^+}$ (MeV)</td>
<td>6279.9 ± 3.5</td>
</tr>
<tr>
<td>$N_{B_c^+ \rightarrow J/\psi D_s^+}$</td>
<td>36 ± 10</td>
</tr>
<tr>
<td>$N_{B_c^+ \rightarrow J/\psi D_s^{(*)+}}$</td>
<td>95 ± 27</td>
</tr>
<tr>
<td>$f_{\pm \pm}$</td>
<td>0.37 ± 0.22</td>
</tr>
</tbody>
</table>

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

The fit has seven free parameters: the mass of the $B_c^+$ meson, $m_{B_c^+ \rightarrow J/\psi D_s^+}$, the relative contribution of the $A_{\pm \pm}$ component 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 function, $\sigma_{B_c^+ \rightarrow J/\psi D_s^{(*)+}}$, is fixed to the value obtained from the fit to the simulated signal, $\sigma_{B_c^+ \rightarrow J/\psi D_s^+}$ = 9.95 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 $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ 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 $B_c^+$ → $J/\psi \pi^+$ candidate reconstruction and fit

$B_c^+ \rightarrow J/\psi \pi^+$ candidates are reconstructed by fitting a common vertex of a pion candidate track and the two muons from a $J/\psi$ 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 $B_c^+ \rightarrow J/\psi \mu^+ \nu \chi$ 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 $\chi^2/ndf < 3$. The following selection requirements applied to the $B_c^+ \rightarrow J/\psi \pi^+$ candidates are analogous to those for $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ 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 $p_T(\mu^+) > 3$ GeV, $|\eta(\mu^+)| < 2.3$; 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 $\mu^+$ and $D_s^+$ candidate momenta in the rest frame of the muon pair from $J/\psi$ 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 $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decay. The red solid line represents the full fit projection. The contribution of the $B_c^+ \rightarrow J/\psi D_s^+$ 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 $B_c^+ \rightarrow J/\psi D_s^{(*)+} A_{00}$ and $A_{\pm \pm}$ component contributions, respectively; the blue dashed line shows the background model](image)
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 $\mu^{+}$ and $\pi^{+}$ 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).

![Fig. 6](image_url)
Table 3: The acceptance $A_{B^+_c \rightarrow X}$ for all decay modes studied. Only uncertainties due to MC statistics are shown.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$A_{B^+_c \rightarrow X}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+_c \rightarrow J/\psi \pi^+$</td>
<td>4.106 ± 0.056</td>
</tr>
<tr>
<td>$B^+_c \rightarrow J/\psi D^+_s$</td>
<td>1.849 ± 0.034</td>
</tr>
<tr>
<td>$B^+_c \rightarrow J/\psi D^+<em>s, A</em>{00}$</td>
<td>1.829 ± 0.053</td>
</tr>
<tr>
<td>$B^+_c \rightarrow J/\psi D^+<em>s, A</em>{\pm\pm}$</td>
<td>1.712 ± 0.035</td>
</tr>
</tbody>
</table>

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

The effect of presence of other contributions dominating the uncertainty of the detector material description.

The following groups of systematic uncertainties are considered:

- 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 $B^+_c \rightarrow J/\psi D^+_s$ signal description; variation of the modified Gaussian width within 10 % of the MC simulation value;
- variation of the smoothness of the $B^+_c \rightarrow J/\psi D^+_s$ signal mass templates, which is controlled by a parameter of the kernel estimation procedure [25];
- similar variation of the smoothness of the $B^+_c \rightarrow J/\psi D^+_s$ 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 $|\cos 0^\prime (\mu^0)|$. 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 same 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...
for the $R_{D_s^{+}/\pi^+}$ and $R_{D_s^{*+}/D_s^+}$, while for $\Gamma_{\pm\pm}/\Gamma$, the estimate is $\sim 1\%$.

The statistical uncertainties on the acceptance values due to 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 $B_{D_s^-\to\phi(K^+K^-)\pi^+}$ 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:

$$R_{D_s^{+}/\pi^+} = \frac{B_{D_s^{+}\to J/\psi D_s^+}}{B_{D_s^{+}\to J/\psi\pi^+}} = 3.8 \pm 1.1\text{(stat.)} \pm 0.4\text{(syst.)} \pm 0.2\text{(BF)},$$

$$R_{D_s^{*+}/\pi^+} = \frac{B_{D_s^{*+}\to J/\psi D_s^+}}{B_{D_s^{*+}\to J/\psi\pi^+}} = 10.4 \pm 3.1\text{(stat.)} \pm 1.5\text{(syst.)} \pm 0.6\text{(BF)},$$

$$R_{D_s^{*+}/D_s^+} = \frac{B_{D_s^{*+}\to J/\psi D_s^+}}{B_{D_s^{*+}\to J/\psi\pi^+}} = 2.8^{+1.2}_{-0.8}\text{(stat.)} \pm 0.3\text{(syst.)},$$

where the BF uncertainty corresponds to the knowledge of $B_{D_s^{+}\to\phi(K^+K^-)\pi^+}$. The relative contribution of the $A_{\pm\pm}$ component in $B_{c}^{+} \to J/\psi D_s^{*+}$ decay is measured to be $\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23\text{(stat.)} \pm 0.07\text{(syst.)}$ (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 $R_{D_s^{*+}/D_s^+}$ are consistent with the measurement. The QCD relativistic potential model predictions [3] are consistent with the measured $R_{D_s^{*+}/\pi^+}$ 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. [3–7] are also generally smaller than the measured ratio $R_{D_s^{*+}/\pi^+}$; 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 $B_{B_s^+\to J/\psi D_s^+}/B_{B_s^{*+}\to J/\psi\pi^+}$, $B_{B_s^+\to J/\psi D_s^{*+}}/B_{B_s^{*+}\to J/\psi\pi^+}$, $B_{B_s^+\to J/\psi D_s^{*+}}/B_{B_s^{*+}\to J/\psi D_s^+}$, 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.

<table>
<thead>
<tr>
<th>$\Gamma_{+}\Gamma$</th>
<th>$\Gamma_{+}\Gamma$</th>
<th>$\Gamma_{+}\Gamma$</th>
<th>$\Gamma_{+}\Gamma$</th>
<th>$\Gamma_{+}\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{D_{s}^{+}/\pi^{+}}$</td>
<td>$\tau_{D_{s}^{+}/\pi^{+}}$</td>
<td>$\tau_{D_{s}^{+}/\pi^{+}}$</td>
<td>$\tau_{D_{s}^{+}/\pi^{+}}$</td>
<td>$\tau_{D_{s}^{+}/\pi^{+}}$</td>
</tr>
<tr>
<td>3.8 ± 1.2</td>
<td>10.4 ± 3.5</td>
<td>2.8 ± 1.2</td>
<td>0.38 ± 0.24</td>
<td>ATLAS</td>
</tr>
<tr>
<td>2.90 ± 0.62</td>
<td>–</td>
<td>2.37 ± 0.57</td>
<td>0.52 ± 0.20</td>
<td>LHCb [10]</td>
</tr>
<tr>
<td>2.6</td>
<td>4.5</td>
<td>1.7</td>
<td>–</td>
<td>QCD potential model [3]</td>
</tr>
<tr>
<td>1.3</td>
<td>5.2</td>
<td>2.9</td>
<td>–</td>
<td>QCD sum rules [4]</td>
</tr>
<tr>
<td>2.0</td>
<td>5.7</td>
<td>2.9</td>
<td>–</td>
<td>RCQM [5]</td>
</tr>
<tr>
<td>2.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>BSW [6]</td>
</tr>
<tr>
<td>2.06 ± 0.86</td>
<td>–</td>
<td>3.01 ± 1.23</td>
<td>–</td>
<td>LFQM [7]</td>
</tr>
<tr>
<td>3.45 ± 0.49</td>
<td>–</td>
<td>2.54 ± 0.07</td>
<td>0.48 ± 0.04</td>
<td>pQCD [8]</td>
</tr>
<tr>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.410</td>
<td>RIQM [9]</td>
</tr>
</tbody>
</table>

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 shown 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 $B_{s}^{+} \rightarrow J/\psi D_{s}^{*}(+)^{(*)}$ 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.

Acknowledgments We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; STFC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DLR and DSM, Germany; INFN, Italy; INFN, India; MOST and NSRF, Korea; MES of Russia and NRC KI, Russian Federation; JINR; MSHE, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Wallis, Switzerland; NASU, Ukraine; STFC, United Kingdom; DOE and NSF, United States; and all the other funding agencies and private foundations for the support of research programs.

Springer
Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP³.

References


29. T. Skwarnicki, A study of the radiative cascade transitions between the $\Upsilon$ and $\Upsilon'$ resonances, PhD thesis, Institute of Nuclear Physics, Krakow, DESY-F31-86-02 (1986). http://inspirehep.net/recor...
National Institute of Physics and Nuclear Engineering, Bucharest, Romania; Physics Department, National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj Napoca, Romania; University Politehnica Bucharest, Bucharest, Romania; West University in Timisoara, Timisoara, Romania

Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, UK

Department of Physics, Carleton University, Ottawa, ON, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago, IL, USA

Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile; Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China; Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui, China; Department of Physics, Nanjing University, Nanjing, Jiangsu, China; School of Physics, Shandong University, Shandong, China; Shanghai Key Laboratory for Particle Physics and Cosmology, Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China; Physics Department, Tsinghua University, Beijing 100084, China

Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

Nevis Laboratory, Columbia University, Irvington, NY, USA

Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy; Dipartimento di Fisica, Università della Calabria, Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland; Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland

Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland

Physics Department, Southern Methodist University, Dallas, TX, USA

Physics Department, University of Texas at Dallas, Richardson, TX, USA

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia; High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

INFN Sezione di Genova, Genoa, Italy; Dipartimento di Fisica, Università di Genova, Genoa, Italy

E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia; High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK

INFN Laboratori Nazionali di Frascati, Frascati, Italy

Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

Section de Physique, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova, Genoa, Italy; Dipartimento di Fisica, Università di Genova, Genoa, Italy

E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia; High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, UK

II Physikalisches Institut, Georg-August-Universität, Gottingen, Germany

Department of Physics, Hampton University, Hampton, VA, USA

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, USA

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

Department of Applied Physics, The Chinese University of Hong Kong, Shatin, NT, Hong Kong; Department of Physics, The University of Hong Kong, Hong Kong, Hong Kong; Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

Department of Physics, Indiana University, Bloomington, IN, USA

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

University of Iowa, Iowa City, IA, USA
153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
158 Department of Physics, University of Toronto, Toronto, ON, Canada
159 (a) TRIUMF, Vancouver, BC, Canada; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
160 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
161 Department of Physics and Astronomy, Tufts University, Medford, MA, USA
162 Centro de Investigaciones, Universidad Antonio Narino, Bogotá, Colombia
163 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA
164 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy; (b) ICTP, Trieste, Italy; (c) Dipartimento di Chimica Fisica e Ambiente, Università di Udine, Udine, Italy
165 Department of Physics, University of Illinois, Urbana, IL, USA
166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
168 Department of Physics, University of British Columbia, Vancouver, BC, Canada
169 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
170 Department of Physics, University of Warwick, Coventry, UK
171 Waseda University, Tokyo, Japan
172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
173 Department of Physics, University of Wisconsin, Madison, WI, USA
174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
175 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
176 Department of Physics, Yale University, New Haven, CT, USA
177 Yerevan Physics Institute, Yerevan, Armenia
178 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

a Also at Department of Physics, King’s College London, London, UK
b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
c Also at Novosibirsk State University, Novosibirsk, Russia
d Also at TRIUMF, Vancouver, BC, Canada
e Also at Department of Physics, California State University, Fresno, CA, USA
f Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
g Also at Departamento de Física e Astronomía, Facultade de Ciencias, Universidade do Porto, Porto, Portugal
h Also at Tomsk State University, Tomsk, Russia
i Also at CPPM, Aix-Marseille Université and CNRS-IN2P3, Marseille, France
j Also at Universita di Napoli Parthenope, Naples, Italy
k Also at Institute of Particle Physics (IPP), Waterloo, Canada
l Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK
m Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
n Also at Louisiana Tech University, Ruston, LA, USA
o Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
p Also at Department of Physics, National Tsing Hua University, Taiwan
q Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA
r Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
s Also at CERN, Geneva, Switzerland
t Also at Georgian Technical University (GTU), Tbilisi, Georgia
u Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
v Also at Manhattan College, New York, NY, USA
Also at Hellenic Open University, Patras, Greece
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at School of Physics, Shandong University, Shandong, China
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
Also at Section de Physique, Université de Genève, Geneva, Switzerland
Also at International School for Advanced Studies (SISSA), Trieste, Italy
Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
Also at National Research Nuclear University MEPhI, Moscow, Russia
Also at Department of Physics, Stanford University, Stanford, CA, USA
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

* Deceased