Observation of the decay $B\_c \to J/\psi K^+K^-\pi^+$

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Observation of the decay $B_c^+ \to J/\psi K^+K^-\pi^+$

The LHCb collaboration[†]

Abstract

The decay $B_c^+ \to J/\psi K^+K^-\pi^+$ is observed for the first time, using proton-proton collisions collected with the LHCb detector corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$. A signal yield of 78 ± 14 decays is reported with a significance of 6.2 standard deviations. The ratio of the branching fraction of $B_c^+ \to J/\psi K^+K^-\pi^+$ decays to that of $B_c^+ \to J/\psi\pi^+$ decays is measured to be $0.53 \pm 0.10 \pm 0.05$, where the first uncertainty is statistical and the second is systematic.

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1 Introduction

The B_c^+ meson is of special interest, as it is the only meson consisting of two heavy quarks of different flavours. It is the heaviest meson that decays through weak interactions, with either the c or $\bar{\mathrm{b}}$ quark decaying or through their weak annihilation [1, 2]. Although the B_c^+ meson was discovered in 1998 by the CDF collaboration [3], relatively few decay channels were observed [4] prior to LHCb measurements [5–9].

In the factorisation approximation [10], the $\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+$ decay[1] is characterised by the form factors of the $\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\mathrm{W}^+$ transition and the spectral functions for the subsequent hadronisation of the virtual W^+ boson into light hadrons [2]. A measurement of the branching fractions of exclusive B_c^+ meson decays into final states consisting of charmonium and light hadrons allows the validity of the factorisation theorem to be tested. Similar studies of factorisation have been performed on $\mathrm{B} \to \mathrm{D}^{(*)}\mathrm{K}^-\mathrm{K}^{*0}$ decays [11]. The predictions for the ratio of branching fractions $\mathcal{B}\left(\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+\right)/\mathcal{B}\left(\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\pi^+\right)$ are 0.49 and 0.47 [12], using form factor contributions from Refs. [13] and [14], respectively.

In this article, the first observation of the decay $\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+$ and a measurement of $\mathcal{B}(\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+)/\mathcal{B}(\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\pi^+)$ are reported. The analysis is based on proton-proton (pp) collision data, corresponding to an integrated luminosity of $1\,\mathrm{fb}^{-1}$ at a centre-of-mass energy of 7 TeV and $2\,\mathrm{fb}^{-1}$ at 8 TeV, collected with the LHCb detector.

2 Detector and software

The LHCb detector [15] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system provides a momentum measurement with relative uncertainty that varies from 0.4% at $5\,\mathrm{GeV}/c$ to 0.6% at $100\,\mathrm{GeV}/c$, and impact parameter resolution of $20\,\mu\mathrm{m}$ for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors [16]. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [17]. The trigger [18] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

This analysis uses events collected by triggers that select the $\mu^+\mu^-$ pair from the J/ψ meson decay with high efficiency. At the hardware stage either one or two muon candidates are required. In the case of single muon triggers, the transverse momentum, p_{T}, of the candidate is required to be greater than $1.5\,\mathrm{GeV}/c$. For dimuon candidates, the product of the p_{T} of muon candidates is required to satisfy $\sqrt{p_{\mathrm{T}1}p_{\mathrm{T}2}} > 1.3\,\mathrm{GeV}/c$. At the subsequent software trigger stage, two muons with invariant mass in the interval

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[1] The inclusion of charge conjugate modes is implicit throughout this paper.

$2.97 < m_{\mu^+\mu^-} < 3.21\,\mathrm{GeV}/c^2$, and consistent with originating from a common vertex, are required.

Simulated pp collisions are generated using PYTHIA 6.4 [19] with the configuration described in Ref. [20]. Final-state QED radiative corrections are included using the PHOTOS package [21]. The B_c^+ mesons are produced by a dedicated generator, BCVEGPY [22]. The decays of all hadrons are performed by EVTGEN [23], and a specific model is implemented to generate the decays of $\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+$, assuming factorisation [12]. The model has different $\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi$ form factors implemented, calculated using QCD sum rules [13] or using a relativistic quark model [14]. These model predictions are very similar and those based on the latter are used in the simulation. The coupling of $\mathrm{K}^+\mathrm{K}^-\pi^+$ to the virtual W^+ is taken from τ decays [24], following Refs. [2,25,26], and modelled through the intermediate $\mathrm{a}_1^+ \to \overline{\mathrm{K}}^{*0}\mathrm{K}^+(\overline{\mathrm{K}}^{*0} \to \mathrm{K}^-\pi^+)$ decay chain. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [27] as described in Ref. [28].

3 Candidate selection

The signal $\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+$ and normalisation $\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\,\pi^+$ decays are reconstructed using the $\mathrm{J}/\psi \to \mu^+\mu^-$ channel. Common selection criteria are used in both channels with additional requirements to identify kaon candidates in the signal channel.

Muons are selected by requiring that the difference in logarithms of the muon hypothesis likelihood with respect to the pion hypothesis likelihood, $\Delta \ln \mathcal{L}_{\mu/\pi}$ [17,29], is greater than zero. To select kaons (pions) the corresponding difference in the logarithms of likelihoods of the kaon and pion hypotheses [16] is required to satisfy $\Delta \ln \mathcal{L}_{\mathrm{K}/\pi} > 2\ \ (< 0)$.

To ensure that they do not originate from a pp interaction vertex (PV), hadrons must have $\chi^2_{\mathrm{IP}} > 4$, where χ^2_{IP} is defined as the difference in χ^2 of a given PV reconstructed with and without the considered hadron. When more than one PV is reconstructed, that with the smallest value of χ^2_{IP} is chosen.

Oppositely-charged muons that have a transverse momentum greater than $0.55\,\mathrm{GeV}/c$ and that originate from a common vertex are paired to form J/ψ candidates. The quality of the vertex is ensured by requiring that the χ^2 of the vertex fit (χ^2_{vtx}) is less than 20. The vertex is required to be well-separated from the reconstructed PV by selecting candidates with decay length significance greater than 3. The invariant mass of the J/ψ candidate is required to be between 3.020 and $3.135\,\mathrm{GeV}/c^2$.

The selected J/ψ candidates are then combined with a π^+ meson candidate or a $\mathrm{K}^+\mathrm{K}^-\pi^+$ combination to form B_c^+ candidates. The quality of the common vertex is ensured by requiring $\chi^2_{\mathrm{vtx}} < 35\,(16)$ for the signal (normalisation) channel, and that the χ^2 values for the distance of closest approach for the $\mathrm{K}^+\mathrm{K}^-$, $\mathrm{K}^-\pi^+$ and $\mathrm{K}^+\pi^+$ combinations are less than 9. To suppress the combinatorial background, the kaons (pions) are required to have $p_\mathrm{T} > 0.8\,(0.5)\,\mathrm{GeV}/c$. To improve the invariant mass resolution a kinematic fit [30] is performed. The invariant mass of the J/ψ candidate is constrained to the known value of J/ψ mass [31], the decay products of the B_c^+ candidate are required to originate from a common vertex, and the momentum vector of the B_c^+ candidate is required to point to the PV. When more than one PV is reconstructed, that with the smallest value of χ^2_{IP} is chosen. The χ^2 per degree of freedom for this fit is required to be less than 5. This requirement also reduces the potential contamination from decay chains with intermediate long-lived particles, namely $\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\mathrm{D}_s^+$, $\mathrm{B}_c^+ \to \mathrm{B}_s^0\pi^+$ and $\mathrm{B}_c^+ \to \mathrm{B}^+\mathrm{K}^-\pi^+$, followed by $\mathrm{D}_s^+ \to \mathrm{K}^+\mathrm{K}^-\pi^+$, $\mathrm{B}_s^0 \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-$ and $\mathrm{B}^+ \to \mathrm{J}/\psi\,\mathrm{K}^+$, respectively. To reduce contributions from the known $\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\mathrm{D}_s^+$ [7] and $\mathrm{B}_c^+ \to \mathrm{B}_s^0\pi^+$ decays [8] to a negligible level, the invariant masses of the $\mathrm{K}^+\mathrm{K}^-\pi^+$ and $\mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-$ systems are required to differ from the known D_s^+ and B_s^0 masses [31, 32] by more than 18 and 51 MeV/c^2, respectively, corresponding to $\pm 3\sigma$, where σ is the mass resolution of the intermediate state. The decay time of the B_c^+ candidate (ct) is required to be between 150 μm and 1 mm. The upper limit corresponds to approximately 7 lifetimes of the B_c^+ meson.

4 Signal and normalisation yields

The invariant mass distribution of the selected $\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+$ candidates is shown in Fig. 1(a). To estimate the signal yield, N_{S}, an extended unbinned maximum likelihood fit to the mass distribution is performed. The B_c^+ signal is modelled by a Gaussian distribution and the background by an exponential function. The values of the signal parameters obtained from the fit are summarised in Table 1 and the result is shown in Fig. 1(a). The statistical significance of the observed signal yield is calculated as $\sqrt{2\Delta\ln\mathcal{L}}$, where $\Delta\ln\mathcal{L}$ is the change in the logarithm of the likelihood function when the signal component is excluded from the fit, relative to the default fit, and is found to be 6.3 standard deviations.

The invariant mass distribution of the selected $\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\pi^+$ candidates is shown in Fig. 1(b). To estimate the signal yield, an extended unbinned maximum likelihood fit to the mass distribution is performed, where the B_c^+ signal is modelled by a Gaussian distribution and the background by an exponential function. The fit gives a yield of 2099 ± 59 events.

For $\mathrm{B}_c^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+$ candidates, the resonant structures in the $\mathrm{K}^-\pi^+$, $\mathrm{K}^+\mathrm{K}^-$, $\mathrm{K}^+\mathrm{K}^-\pi^+$, $\mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-$, $\mathrm{J}/\psi\,\mathrm{K}^-\pi^+$ and $\mathrm{J}/\psi\,\mathrm{K}^+$ systems are studied and the possible contributions from the decays $\mathrm{B}_c^+ \to \mathrm{B}^0\mathrm{K}^+$ and $\mathrm{B}_c^+ \to \mathrm{B}^+\mathrm{K}^-\pi^+$, followed by subsequent decays $\mathrm{B}^0 \to \mathrm{J}/\psi\,\mathrm{K}^-\pi^+$ and $\mathrm{B}^+ \to \mathrm{J}/\psi\,\mathrm{K}^+$ are investigated. The *sPlot* technique [33] is used to

Table 1: Parameters of the signal function of the fit to the $\mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+$ mass distribution. Uncertainties are statistical only.

Parameter	Value
$m_{\mathrm{B}_c^+}$ [MeV/c^2]	6274.8 ± 1.7
$\sigma_{\mathrm{B}_c^+}$ [MeV/c^2]	8.8 ± 1.5
N_{S}	78 ± 14

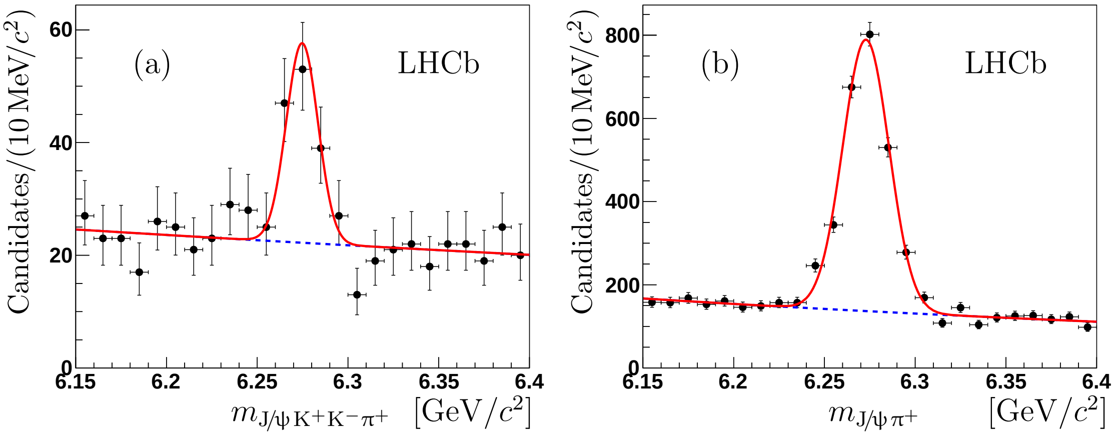

Figure 1: Mass distribution for selected (a) $B_c^+ \to J/\psi K^+K^-\pi^+$ and (b) $B_c^+ \to J/\psi \pi^+$ candidates. The result of the fit described in the text is superimposed (solid line) together with the background component (dashed line).

subtract the estimated background contribution from the corresponding mass distributions. The results are shown in Fig. 2.

The binned $K^-\pi^+$ invariant mass distribution, presented in Fig. 2(a), is fitted with the sum of two components, one representing the $\overline{K}^{*0}$ resonance and a non-resonant component modelled with the LASS parametrisation [34]. The resonant component is described by a relativistic P-wave Breit-Wigner function. The form factor for the $(1^-) \to (0^-)\,(0^-)$ decay is taken from lowest order perturbation theory [35], while the peak position and the natural width are fixed to their known values [31]. The resulting resonant yield is 44 ± 10 decays, where the uncertainty is statistical only.

Figures 2(b)–(f) show the invariant mass distributions for the K^+K^-, $K^+K^-\pi^+$, $J/\psi K^+K^-$, $J/\psi K^-\pi^+$ and $J/\psi K^+$ final states. In contrast to Fig. 2(a), no narrow structures are visible. The predictions from the model of Ref. [12] are also presented in Fig. 2, and are found to give an acceptable description of the data.

5 Efficiency and systematic uncertainties

As the ratio of branching fractions is measured, many potential sources of systematic uncertainty cancel in the ratio of efficiencies for the normalisation and signal decays. The overall efficiency for both decays is the product of the geometrical acceptance of the detector, reconstruction, selection and trigger efficiencies. These are estimated using simulation and the ratio of the efficiencies is found to be

$$\frac{\varepsilon(B_c^+ \to J/\psi \pi^+)}{\varepsilon(B_c^+ \to J/\psi K^+K^-\pi^+)} = 14.3 \pm 0.4,$$

where the uncertaintty is statistical only. Systematic uncertainties that do not cancel in this ratio are discussed below and summarised in Table 2.

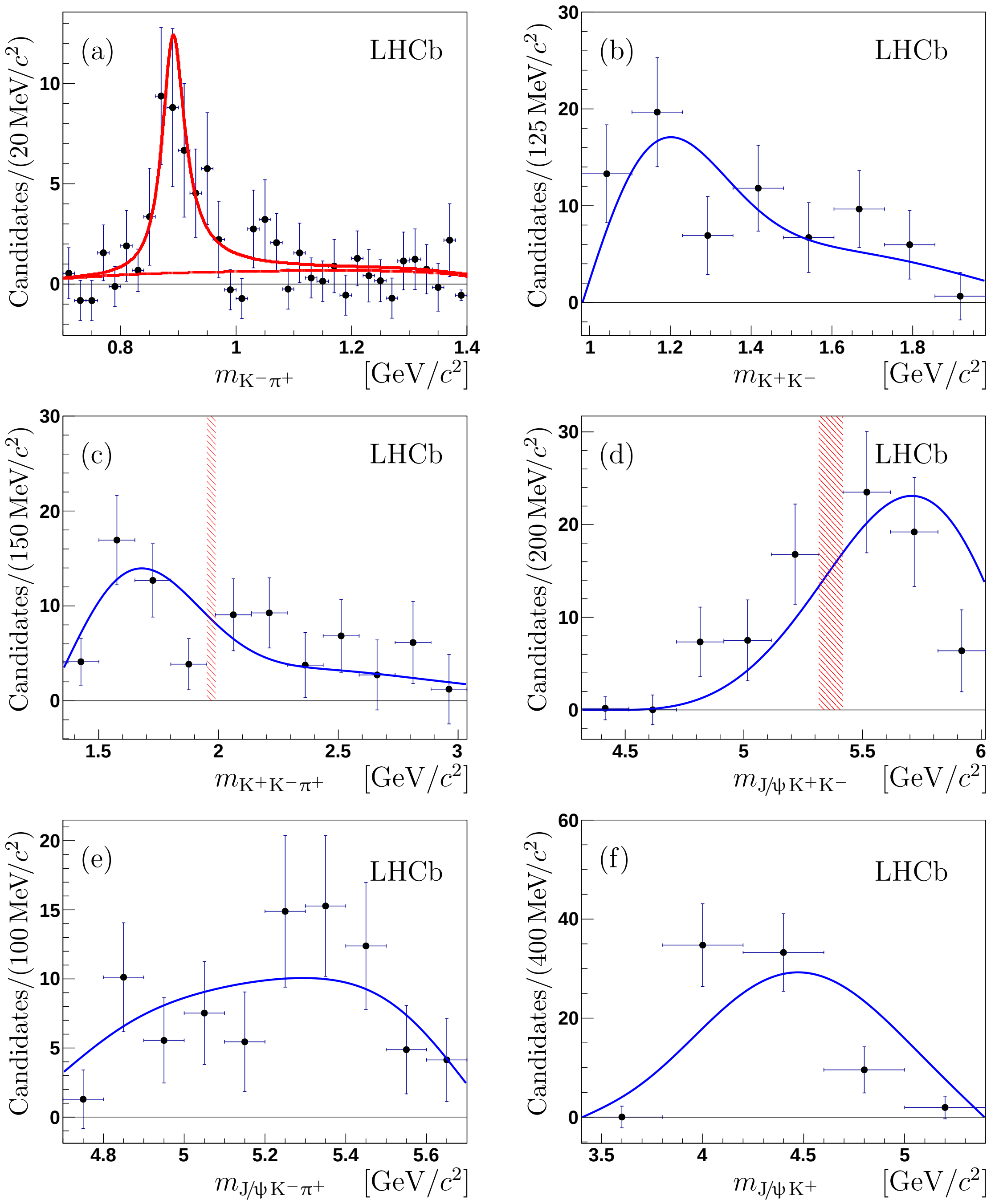

Figure 2: Background-subtracted invariant mass distributions for (a) $K^-\pi^+$, (b) K^+K^-, (c) $K^+K^-\pi^+$, (d) $J/\psi K^+K^-$, (e) $J/\psi K^-\pi^+$ and (f) $J/\psi K^+$ in $B_c^+ \to J/\psi K^+K^-\pi^+$ decay. The (red) full line in the $K^-\pi^+$ mass distribution (a) is composed of a resonant $\overline{K}^{*0}$ contribution and a non-resonant component indicated by the dashed line. The (blue) full line in (b)–(f) shows the predictions of the model [12] used in the simulation. The regions ± 18 MeV/c^2 around the D_s^+ mass and ± 51 MeV/c^2 around the B_s^0 mass are excluded from the analysis and are indicated by the shaded areas on (c) and (d), respectively.

The main uncertainty arises from the imperfect knowledge of the shape of the signal and background components used to model the $\mathrm{B_c^+}$ mass distributions. It is estimated using an alternative model to describe the $\mathrm{B_c^+} \to \mathrm{J}/\psi\,\mathrm{K^+K^-}\pi^+$ and $\mathrm{B_c^+} \to \mathrm{J}/\psi\,\pi^+$ mass distributions consisting of a Crystal Ball function [36] for the signal and a linear function for the background. The changes in the yields relative to the default fits are used to determine a 5.0 % uncertainty on the number of signal candidates in both channels, and is dominated by the large background level in signal decay.

Other systematic uncertainties arise from differences between data and simulation in the track reconstruction efficiency for charged particles. The largest of these arises from the knowledge of the hadronic interaction probability in the detector, which has an uncertainty of 2.0 % per track [37]. Further uncertainties related to the recontruction of charged kaons contribute 0.6 % per kaon [7,38]. The differences in the kinematic properties of the charged pion in the signal and normalisation channels are also considered as a source of systematic uncertainty. The total uncertainty assigned to track reconstruction and selection is 4.2 %.

The systematic uncertainty associated with kaon identification is studied using a kinematically similar sample of reconstructed $\mathrm{B^+} \to \mathrm{J}/\psi\ (\mathrm{K^+K^-})_{\phi}\,\mathrm{K^+}$ decays [7]. An uncertainty of 3.0 % is assigned.

A source of systematic uncertainty arises from the potential disagreement between data and simulation in the efficiencies of the selection criteria. To study this effect, the criteria are varied to values that correspond to a 20 % change in the signal yields. The variation of the relative difference between data and simulation on the number of selected signal candidates reaches 1.6 %, which is assigned as a systematic uncertainty from this source, and includes effects related to pion identification criteria.

The dependence of the $\mathrm{B_c^+} \to \mathrm{J}/\psi\,\mathrm{K^+K^-}\pi^+$ decay reconstruction and selection efficiency on the decay model implemented in the simulation is estimated from a comparison of the $\mathrm{K^+K^-}\pi^+$ invariant mass distributions in data and simulation, which has the greatest dependence on the decay model. This combined efficiency is recomputed after reweighting the $\mathrm{K^+K^-}\pi^+$ mass distribution to that observed in data. The relative difference of 2.5 % observed is taken as the systematic uncertainty due to the decay model.

Other systematic uncertainties are related to the widths of the $\mathrm{K^+K^-}\pi^+$ and $\mathrm{J}/\psi\,\mathrm{K^+K^-}$ mass regions vetoed in the analysis to reject contributions from $\mathrm{B_c^+} \to \mathrm{J}/\psi\,\mathrm{D_s^+}$ and $\mathrm{B_c^+} \to \mathrm{B_s^0}\pi^+$ decays. These are estimated by varying the widths of the vetoed regions and recomputing the $\mathrm{B_c^+} \to \mathrm{J}/\psi\,\mathrm{K^+K^-}\pi^+$ signal yields, taking into account the changes in efficiency. A systematic uncertainty of 1.0 % is assigned.

The efficiency of the requirement on the $\mathrm{B_c^+}$ decay time depends on the value of the $\mathrm{B_c^+}$ lifetime used in the simulation. The decay time distributions for simulated events are reweighted after changing the $\mathrm{B_c^+}$ lifetime by one standard deviation around the known value [31], as well as using the lifetime value recently measured by the CDF collaboration [39], and the efficiencies are recomputed. The observed 2.5 % variation in the ratio of efficiencies is used as the systematic uncertainty.

The agreement of the absolute trigger efficiency between data and simulation has been validated to a precision of 4 % using the technique described in Refs. [18,37,40] with a large sample of $\mathrm{B^+} \to \mathrm{J}/\psi\ (\mathrm{K^+K^-})_{\phi}\,\mathrm{K^+}$ events [7]. A further cancellation of uncertainties in

Table 2: Relative systematic uncertainties for the ratio of branching fractions of $\mathrm{B_c^+} \to \mathrm{J/\psi\, K^+K^-\pi^+}$ and $\mathrm{B_c^+} \to \mathrm{J/\psi\, \pi^+}$. The total uncertainty is the quadratic sum of the individual components.

Source	Uncertainty [%]
Fit model	5.0
Track reconstruction and selection	4.2
Kaon identification	3.0
Data and simulation disagreement	1.6
Decay model dependence	2.5
Vetoed mass intervals	1.0
$\mathrm{B_c^+}$ lifetime	2.5
Trigger	1.1
Stability of data taking conditions	2.5
Geometrical acceptance	0.4
Total	8.7

the ratio of branching fractions has been tested with the high statistics decay modes $\mathrm{B^+} \to \mathrm{J/\psi\, K^+}$ and $\mathrm{B^+} \to \mathrm{\psi(2S) K^+}$ [41], resulting in a systematic uncertainty of 1.1 %.

Potential uncertainties related to the stability of the data taking conditions are tested by studying the ratio of the yields of $\mathrm{B^+} \to \mathrm{J/\psi\, K^+\pi^+\pi^-}$ and $\mathrm{B^+} \to \mathrm{J/\psi\, K^+}$ decays for different data taking periods. According to this study an additional systematic uncertainty of 2.5 % is assigned [7]. The final source of systematic uncertainty considered originates from the dependence of the geometrical acceptance on both the beam crossing angle and the position of the luminous region. The observed difference in the efficiency ratios is taken as an estimate of the systematic uncertainty and is 0.4 %. The correlation between this uncertainty and the previous one is neglected.

6 Results and summary

The decay $\mathrm{B_c^+} \to \mathrm{J/\psi\, K^+K^-\pi^+}$ is observed for the first time, and a signal yield of 78 ± 14 is reported. This analysis uses a data sample corresponding to an integrated luminosity of $1\,\mathrm{fb^{-1}}$ at a centre-of-mass energy of 7 TeV and $2\,\mathrm{fb^{-1}}$ at 8 TeV. The significance, taking into account the systematic uncertainties due to the fit function, peak position and mass resolution in the default fit, is estimated to be 6.2 standard deviations.

Using the $\mathrm{B_c^+} \to \mathrm{J/\psi\, \pi^+}$ mode as a normalisation channel, the ratio of branching fractions is calculated as

$$\frac{\mathcal{B}\,(\mathrm{B_c^+} \to \mathrm{J/\psi\, K^+K^-\pi^+})}{\mathcal{B}\,(\mathrm{B_c^+} \to \mathrm{J/\psi\, \pi^+})} = \frac{N\,(\mathrm{B_c^+} \to \mathrm{J/\psi\, K^+K^-\pi^+})}{N\,(\mathrm{B_c^+} \to \mathrm{J/\psi\, \pi^+})} \times \frac{\varepsilon(\mathrm{B_c^+} \to \mathrm{J/\psi\, \pi^+})}{\varepsilon(\mathrm{B_c^+} \to \mathrm{J/\psi\, K^+K^-\pi^+})},$$

where N is the number of reconstructed decays obtained from the fit described in Sect. 4.

The ratio of branching fractions is measured to be

$$\frac{\mathcal{B}\,(\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+)}{\mathcal{B}\,(\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\,\pi^+)} = 0.53 \pm 0.10 \pm 0.05,$$

where the first uncertainty is statistical and the second systematic. The largest contribution to the $\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\,\mathrm{K}^+\mathrm{K}^-\pi^+$ decay is found to be from $\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\,\overline{\mathrm{K}}^{*0}\mathrm{K}^+$ decays. The theoretical predictions for the branching fraction ratio of 0.49 and 0.47 [12], using form factors from Refs. [13] and [14], respectively, are found to be in good agreement with this measurement.

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