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Studies of the properties and decays of the B_c^+ meson at LHCb

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The results of searches for the decays $B_c^+ \to J/\psi K^+$ and $B_c^+ \to B_s^0 \pi^+$ are presented. The analysis is based on a data sample of pp collisions collected with the LHCb detector. The $B_c^+ \to J/\psi K^+$ analysis uses a data set corresponding to an integrated luminosity of 1 fb^{-1} taken at a center-of-mass energy of 7 TeV, whereas the $B_c^+ \to B_s^0 \pi^+$ analysis in addition uses the data set recorded in 2012, corresponding to 2 fb^{-1} taken at 8 TeV.
The decay $B_c^+ \to J/\psi K^+$ is observed with $5.0\,\sigma$ significance, and the decay $B_c^+ \to B_s^0 \pi^+$ is observed with significance in excess of five standard deviations, independently in two different B_s^0 decay channels. The decay $B_c^+ \to B_s^0 \pi^+$ is the first observation of a B meson decaying to another B meson via the weak interaction.

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PoS(EPS-HEP 2013)379

1. Introduction

The B_c^+ meson is the ground state of the $\bar{b}c$ system. As such it is the only doubly heavy meson system that decays weakly. Previous measurements of B_c^+ meson decays are those where the constituent b quark decays weakly to a c quark, with a charmonium in the final state, in combination with a Cabibbo favoured hadronic system of D_s^- mesons or pions, or semileptonically with a muon [1–9]. The existing measurements are summarized in Tab. 1. As there is little known on the production of B_c^+ mesons [10], the branching fraction measurements focus on the determination of relative event yields of two decays, and to achieve the highest experimental accuracy.

This paper will focus on the first measurement of the Cabibbo suppressed decay $B_c^+ \to J/\psi K^+$ [11], and on the first measurement of a decay of a B_c^+ meson to any other B meson, $B_c^+ \to B_s^0\pi^+$ [12], with the bottom quark acting as a spectator. Both decays predominantly occur through so-called "tree" diagrams, as illustrated in Fig. 1.

A wide range of predictions for the B_c^+ branching fractions exist, based on *e.g.* QCD sum rules [13, 14], or quark-potential models (see Refs. [15–19] and references therein). Study of the decays $B_c^+ \to J/\psi K^+$ and $B_c^+ \to B_s^0\pi^+$ allows these models to be tested, and experimental clarification is needed to shed light on the present theoretical status. Unlike most other, lighter, B decays, the higher order corrections in the expansion of Heavy Quark Effective Theory within the framework of quantum chromodynamics (QCD) are relatively large. The expansion is described in powers of m_c/m_b rather than $\Lambda_{\rm QCD}/m_b$, due to the presence of two heavy quark constituents, where $\Lambda_{\rm QCD}$ is the QCD scale, and m_c (m_b) the charm (bottom) quark mass. In addition, the study of a variety of B decays into different final states will allow tests of factorization [21]. A selection of theoretical predictions is given in Tab. 2.

In addition, knowledge of the production of B_s^0 mesons from B_c^+ decays is useful for time-dependent analyses of B_s^0 decays, to understand any associated decay-time bias due to the incorrect estimate of the B_s^0 decay time, or to take advantage of flavor tagging capabilities using the accompanying pion. This provides valuable information for the source of B_s^0 mesons at the LHC.

Table 1: Summary of measurements on the B_c^+ system.

Quantity	Measurement	Coll.	Ref.
$\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to J/\psi \ell^+ \nu)/\mathcal{B}(B^+ \to J/\psi K^+)$	$0.132^{+0.061}_{-0.052}$	CDF	[1,2]
$m(B_c^+ \to J/\psi\pi^+)$	6275.6 ± 3.8 MeV	CDF	[3]
$m(B_c^+ \to J/\psi\pi^+)$	6300 ± 15 MeV	D0	[4]
$\tau(B_c^+ \to J/\psi\pi^+)$	0.452 ± 0.055 ps	CDF	[5]
$\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to J/\psi\pi^+)/\mathcal{B}(B^+ \to J/\psi K^+)$	0.68 ± 0.12	LHCb	[6]
$m(B_c^+ \to J/\psi\pi^+)$	6273.7 ± 2.1 MeV	LHCb	[6]
$\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^-\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$	2.14 ± 0.45	LHCb	[7]
$\mathcal{B}(B_c^+ \to \psi(2S)\pi^+/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$	0.250 ± 0.070	LHCb	[8]
$\mathcal{B}(B_c^+ \to J/\psi D_s^-/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$	0.290 ± 0.062	LHCb	[9]
$\mathcal{B}(B_c^+ \to J/\psi D_s^{*-}/\mathcal{B}(B_c^+ \to J/\psi D_s^-)$	2.37 ± 0.57	LHCb	[9]
$m(B_c^+ \to J/\psi D_s^-)$	6276.28 ± 1.48 MeV	LHCb	[9]
$\mathcal{B}(B_c^+ \to J/\psi K^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$	0.069 ± 0.020	LHCb	[11], these proc.
$\mathcal{B}(B_c^+ \to B_s^0\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$	88 ± 21	LHCb	[12], these proc.

PoS(EPS-HEP 2013)379

Table 2: Selection of theoretical predictions of B_c^+ branching fractions (%). The ratio of branching fractions in the last two rows are calculated from the individual branching fractions. The semileptonic branching fractions are given to compare the predictions that are not affected by non-factorizable effects.

	Naimuddin et al. [15]	Ivanov et al. [16]	Ebert et al. [17, 18]	Kiselev et al. [13, 14]	Colangelo et al. [19]	Qiao et al. [20]
$\mathcal{B}(B_c^+ \to B_s^0\pi^+)$	12.01	3.9	2.52	16.4	4.0	-
$\mathcal{B}(B_c^+ \to B_s^*\pi^+)$	8.61	2.1	1.61	6.5	4.5	-
$\mathcal{B}(B_c^+ \to B_s^0 e^+\nu)$	-	1.10	0.84	4.03	0.8	-
$\mathcal{B}(B_c^+ \to J/\psi\pi^+)$	0.034	0.17	0.061	0.13	0.13	0.291
$\mathcal{B}(B_c^+ \to J/\psi K^+)$	0.003	0.013	0.005	0.011	0.0068	0.022
$\mathcal{B}(B_c^+ \to J/\psi e^+\nu)$	-	2.07	1.23	1.9	1.5	-
$\mathcal{B}(B_c^+ \to J/\psi K^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$	0.088	0.077	0.082	0.085	0.052	0.076
$\mathcal{B}(B_c^+ \to B_s^0\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$	353	23	41	126	31	-

The data collected with the LHCb detector [22] from pp collisions at $\sqrt{s} = 7\,\text{TeV}$ and $8\,\text{TeV}$, correspond to integrated luminosities of 1 fb^{-1} and 2 fb^{-1}, respectively. The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. The combined tracking system provides momentum measurement with relative uncertainty that varies from 0.4 % at $5\,\text{GeV}/c$ to 0.6 % at $100\,\text{GeV}/c$, and impact parameter resolution of $20\,\mu\text{m}$ for tracks with high transverse momentum, p_{T}. The B_s^0 candidates with muons in the final state are required to pass the hardware trigger, which selects dimuons with the product of transverse momenta, $\sqrt{p_{\text{T}1}p_{\text{T}2}} > 1.3\,\text{GeV}/c$, whereas the B_s^0 candidates with only hadrons in the final state are selected by requiring a hadron in the calorimeter with $E_{\text{T}} > 3.6\,\text{GeV}/c$.

2. Observation of the decay $B_c^+ \to J/\psi K^+$

The decay $B_c^+ \to J/\psi K^+$ is Cabibbo suppressed with respect to $B_c^+ \to J/\psi\pi^+$, and the predicted ratio of branching fractions is dominated by the ratio of the relevant CKM elements, together with the ratio of decay constants,

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi K^+)} \approx \left|\frac{V_{us}f_{K^+}}{V_{ud}f_{\pi^+}}\right|^2 = 0.077, \tag{2.1}$$

using $|V_{ud(s)}| = 0.97425\,(0.2252)$ and $f_{\pi^+(K^+)} = 130.41\,(156.1)$ MeV [23].

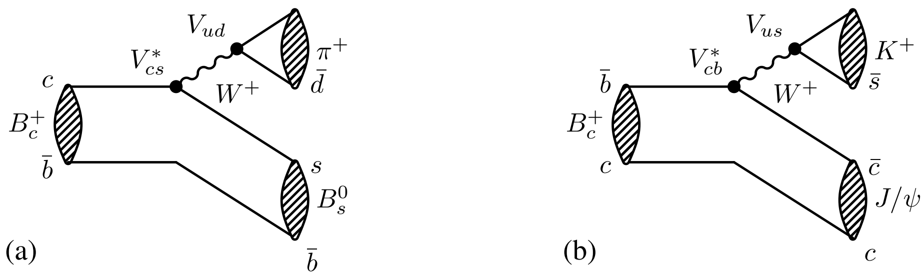

Figure 1: Leading-order Feynman diagram of the decays (a) $B_c^+ \to B_s^0\pi^+$ and (b) $B_c^+ \to J/\psi K^+$.

Special care needs to be taken in the particle identification of the bachelor particle to distinguish the $B_c^+ \to J/\psi K^+$ candidates from the more abundant $B_c^+ \to J/\psi \pi^+$ events. Both decays are selected using a multivariate analysis to suppress the combinatorial background. The difference in likelihood values for the kaon and pion hypotheses, $DLL_{K\pi}$, as provided by the two ring-imaging Cherenkov detectors, is used to discriminate between the two decays [24]. The B_c^+ candidates are split in four bins of $DLL_{K\pi}$ (< -5, $[-5;0]$, $[0;5]$, > 5), and with an unbinned maximum likelihood fit to the $J/\psi K^+$ invariant mass the yield of $B_c^+ \to J/\psi \pi^+$ and $B_c^+ \to J/\psi K^+$ candidates is determined, see Fig. 2b. The $B_c^+ \to J/\psi K^+$ signal is described by a double Crystal Ball function [25], whereas the $B_c^+ \to J/\psi \pi^+$ shape is shifted to higher masses due to the use of the kaon mass hypothesis. The observed $B_c^+ \to J/\psi K^+$ signal yield is 46 ± 12. The ratio of the total efficiencies, computed over the full $DLL_{K\pi}$ range, is $\varepsilon(B_c^+ \to J/\psi K^+)/\varepsilon(B_c^+ \to J/\psi \pi^+) = 1.029 \pm 0.007$, which results in

$$\frac{\mathscr{B}(B_c^+ \to J/\psi K^+)}{\mathscr{B}(B_c^+ \to J/\psi \pi^+)} = 0.069 \pm 0.019\,(\mathrm{stat}) \pm 0.005\,(\mathrm{sys})\,,$$

where the first uncertainty is statistical and the second is systematic, that is dominated by the uncertainty on the relative selection efficiency from the multivariate discriminant (5.7%).

3. Observation of the decay $B_c^+ \to B_s^0 \pi^+$

The decay $B_c^+ \to B_s^0 \pi^+$ is analyzed in the two decay modes $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to J/\psi \phi$, with the subsequent decays $D_s^- \to K^+ K^- \pi^-$, $J/\psi \to \mu^+ \mu^-$ and $\phi \to K^+ K^-$. The event selection and fits to the B_s^0 invariant mass distributions follow previous LHCb analyses based on these B_s^0 decay modes [26, 27]. The two channels are analysed independently and the final results are combined. The strategy is to normalize the final number of $B_c^+ \to B_s^0 \pi^+$ decays to the number of B_s^0 decays, which gives a result for the $B_c^+ \to B_s^0 \pi^+$ branching fraction multiplied by the ratio of B_c^+ and B_s^0 production rates, $(\sigma(B_c^+)/\sigma(B_s^0)) \times \mathscr{B}(B_c^+ \to B_s^0 \pi^+)$. Since the ratio of production rates, $\sigma(B_c^+)/\sigma(B_s^0)$, may depend on the kinematics of the produced B meson, the result is quoted for B mesons produced in the pseudorapidity range $2 < \eta(B) < 5$.

An unbinned maximum likelihood fit to the invariant mass distribution of $B_s^0 \to J/\psi \phi$ and $B_s^0 \to D_s^- \pi^+$ decays yields $103\,760 \pm 380$ and $73\,700 \pm 500$ candidates, respectively. The signal

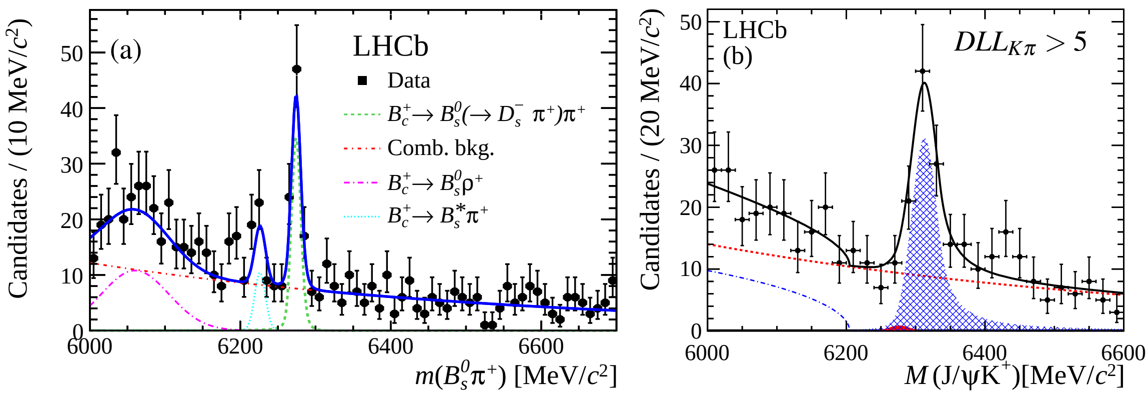

Figure 2: Mass distributions of the (a) $B_c^+ \to B_s^0(\to D_s^- \pi^+)\pi^+$ and (b) $B_c^+ \to J/\psi K^+$ candidates.

shapes are taken as double Crystal Ball functions with common peak value and with tails to either side of the peak, to account for final state radiation and detector resolution effects. The combinatorial backgrounds are modeled with exponential distributions. The lower mass sideband in the $B_s^0 \to D_s^- \pi^+$ final state is contaminated by partially reconstructed B decays such as $B_s^0 \to D_s^{*-}\pi^+$ and $B_s^0 \to D_s^- \rho^+$ decays, where the soft photon or neutral pion is not reconstructed, and by decays where one of the final state particles is misidentified as a kaon.

Subsequently, the B_s^0 candidates are combined with a charged pion to form a B_c^+ candidate. A multivariate analysis efficiently rejects the large background, predominantly originating from combining B_s^0 decays with a random pion from the primary vertex. The fit to the mass distribution of $B_c^+ \to B_s^0(\to J/\psi\,\phi)\pi^+$ and $B_c^+ \to B_s^0(\to D_s^-\pi^+)\pi^+$ decays yields statistical signal significances of $6.1\,\sigma$ and $7.7\,\sigma$, with 35 ± 8 and 64 ± 10 signal decays, respectively. The mass distribution of $B_c^+ \to B_s^0(\to D_s^-\pi^+)\pi^+$ candidates is shown in Fig. 2a. The total relative detection efficiency of $B_c^+ \to B_s^0\pi^+$ decays with respect to B_s^0 decays is estimated to be 15.2 % for the $B_s^0 \to J/\psi\,\phi$ decay and 33.9 % for the $B_s^0 \to D_s^-\pi^+$ final state.

The uncertainty due to the uncertainty on the B_c^+ lifetime is quantified by varying the lifetime in simulation, and reavluating the selection efficiency. The uncertainty is correlated between the two measurements, and is accounted for in the combined result of the ratio of production rates multiplied with the branching fraction

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathscr{B}(B_c^+ \to B_s^0\pi^+) = \left(2.37 \pm 0.31\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst})\,^{+0.17}_{-0.13}\,(\tau_{B_c^+})\right) \times 10^{-3},$$

where the first uncertainty is statistical, the second is systematic and the third is due to the uncertainty on the B_c^+ lifetime.

4. Conclusions

The results presented in this paper can be compared to the predictions shown in Tab. 2. The ratio $\mathscr{B}(B_c^+ \to J/\psi K^+)/\mathscr{B}(B_c^+ \to J/\psi\pi^+) = 0.069 \pm 0.020$ is in agreement with the expectations from factorisation, where the ratio is dominated by the ratio of CKM elements that govern the decays, 0.077. This value also agrees with previously measured ratios of branching fractions of B^+ [28], B^0 [29] and B_s^0 [30] decays with similar topology, $\mathscr{B}(B \to DK)/\mathscr{B}(B \to D\pi)$, although $\mathscr{B}(B_s^0 \to D_s^- K^+)/\mathscr{B}(B_s^0 \to D_s^-\pi^+)$ seems to be low [31].

The ratio of branching fractions $\mathscr{B}(B_c^+ \to B_s^0\pi^+)/\mathscr{B}(B_c^+ \to J/\psi\pi^+)$ can be estimated using the results $(\sigma(B_c^+)/\sigma(B^+)) \times \mathscr{B}(B_c^+ \to J/\psi\pi^+)/\mathscr{B}(B^+ \to J/\psi K^+) = (0.68 \pm 0.10 \pm 0.03 \pm 0.05)\,\%$ [6] and knowledge on $\mathscr{B}(B^+ \to J/\psi K^+)$ [23] and f_s/f_d [26] (and assuming $f_d = f_u$). This results in the estimate $\mathscr{B}(B_c^+ \to B_s^0\pi^+)/\mathscr{B}(B_c^+ \to J/\psi\pi^+) = 88 \pm 21$, where we neglected the small differences in the analyses with corresponding differences in the fiducial regions. The predictions for this ratio vary widely, and this result seems to slightly favour the prediction based on QCD sum rules.

Assuming a value for $\mathscr{B}(B_c^+ \to J/\psi\pi^+)$ around 0.15 % this then leads to a branching fraction for $B_c^+ \to B_s^0\pi^+$ of about 10 % which is the largest exclusive branching fraction of any known weak B meson decay.

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