Measurement of $B_c^+$ production in proton-proton collisions at $\sqrt{s} = 8$ TeV

The LHCb collaboration

Abstract

Production of $B_c^+$ mesons in proton-proton collisions at a center-of-mass energy of 8 TeV is studied with data corresponding to an integrated luminosity of 2.0 fb$^{-1}$ recorded by the LHCb experiment. The ratio of production cross-sections times branching fractions between the $B_c^+ \to J/\psi \pi^+$ and $B_c^+ \to J/\psi K^+$ decays is measured as a function of transverse momentum and rapidity in the regions $0 < p_T < 20$ GeV/$c$ and $2.0 < y < 4.5$. The ratio integrated within this kinematic range is measured to be $(0.683 \pm 0.018 \pm 0.009)\%$, where the first uncertainty is statistical and the second systematic.

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In the Standard Model, the $B_c$ mesons are the only states formed by two heavy quarks of different flavor, the $\bar{b}$ and the $c$ quarks. The production of $B_c$ mesons in hadron collisions implies the simultaneous production of $b\bar{b}$ and $c\bar{c}$ pairs, therefore it is rarer than that of other $b$ mesons. The production of $b\bar{b}$ and $c\bar{c}$ quarkonium states in hadron collisions has been studied for two decades, however, significant puzzles remain \cite{1}. The relative role of competing production mechanisms \cite{2 –5} is poorly understood and theory is unable to predict all experimentally observed features \cite{6 –11}. The study of $B_c$ production offers a promising way of shedding light over these discrepancies and gaining an insight on the underlying physics. In proton-proton ($pp$) collisions at the Large Hadron Collider (LHC), $B_c$ mesons are expected to be mainly produced through the gluon-gluon fusion process $gg \rightarrow B_c + b + \bar{c}$. The production cross-sections of the $B_c$ mesons have been calculated in the fragmentation approach \cite{12, 13} and in the complete order-$\alpha_s^4$ approach \cite{14–21}, where $\alpha_s$ is the strong-interaction coupling. In the latter approach, the total production cross-section of the $B_c$ ground state, $B_c^+$, at a center-of-mass energy of 8 TeV, integrated over the whole phase space and including contributions from intermediate excited states, is predicted to be about 0.2\% \cite{22, 23} of the inclusive $b\bar{b}$ cross-section \cite{24}.

Previously only the average ratios of $B_c^+$ to $B^+$ or $B^0$ cross-sections in specific kinematic regions had been measured \cite{25 –27}. The production cross-sections of $b$-hadrons show different transverse momentum dependencies \cite{28 –31}. A precise measurement of $B_c^+$ production as a function of transverse momentum and rapidity will provide useful information on the largely unknown production mechanism of the $B_c^+$ meson and other bound states of heavy quarks.

In this Letter we report on the first measurement of the double differential ratio of inclusive production cross-sections multiplied by branching fractions,

$$R(p_T, y) \equiv \frac{d\sigma_{B_c^+}(p_T, y) B(B_c^+ \rightarrow J/\psi \pi^+)}{d\sigma_{B^+}(p_T, y) B(B^+ \rightarrow J/\psi K^+)},$$

where transverse momentum $p_T$ and rapidity $y$ refer to the $b$ meson. The cross-section includes contributions from excited states. We use a sample of $pp$ collision data at 8 TeV, corresponding to an integrated luminosity of $2.0 \text{fb}^{-1}$ recorded by the LHCb experiment. The $B_c^+$ and $B^+$ mesons are reconstructed in the exclusive decays $B_c^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$ respectively, with $J/\psi \rightarrow \mu^+ \mu^-$. The inclusion of charge conjugate modes is implied throughout this Letter.

The LHCb detector \cite{32} 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 of the magnet. The combined tracking system provides a momentum measurement with a relative uncertainty that varies from 0.4\% at low momentum, $p$, to 0.6\% at 100 GeV/c. The minimum distance of a track to a primary vertex, the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu$m, where $p_T$ is in GeV/c. Different types of charged
hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The trigger consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, in which all charged particles with $p_T > 300$ MeV/c are reconstructed. Events are first required to pass the hardware trigger, which requires one or two muons with high $p_T$. In the subsequent software trigger, the event is required to have one muon with high $p_T$ and large IP with respect to all primary $pp$ interaction vertices (PVs), or a pair of oppositely charged muons with an invariant mass consistent with the known $J/\psi$ meson mass. Finally, the tracks of two or more of the final state particles are required to form a vertex that is significantly displaced from the PVs. A multivariate algorithm is also used to identify secondary vertices consistent with the decay of a $b$ meson.

The $b$-meson candidate selection is performed in two steps, a preselection and a final selection on the output of a multivariate classifier based on a boosted decision tree algorithm (BDT). Simulated $B_c^+$ and $B^+$ decays are used to optimize the $b$-meson candidate selection. Production of $B^+$ mesons is simulated using PYTHIA 6.4 with an LHCb specific configuration. The generator Bcvegpy is used to simulate $B_c^+$ meson production. Decays of $B_c^+$, $B^+$ and $J/\psi$ mesons are described by EVTGEN and photon radiation is simulated using the PHOTOS package. The decay products are traced through the detector by the GEANT4 package. Following Ref., the $B_c^+$ meson lifetime is set to $\tau_{B_c^+} = 0.509$ ps. The selection requirements are the same for $B_c^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$ candidates.

In the preselection, $J/\psi$ candidates are formed from pairs of oppositely charged particles with $p_T$ larger than 0.55 GeV/c, with a good quality of the track fit and identified as muons. The two muons are required to originate from a common vertex. The $J/\psi$ candidates with invariant mass between 3.04 GeV/$c^2$ and 3.14 GeV/$c^2$ are combined with a charged particle that has $p_T > 1.0$ GeV/c, a good quality of the track fit and is separated from any PV. The pion mass hypothesis is assigned to the track for the selection of the $B_c^+$ candidate and the kaon hypothesis for that of the $B^+$ candidate. The $J/\psi$ candidate and the hadron ($\pi$ or $K$) are required to originate from a common vertex. To improve the $b$-meson mass resolution, the mass of the muon pair is constrained to the known $J/\psi$ meson mass in this vertex fit. The $b$-meson candidates are required to have a decay time larger than 0.2 ps, and to point toward the primary vertex.

In the final selection, the BDT is trained using a simulated $B_c^+$ signal sample and background events populating the data mass sideband $6376 < M_{J/\psi \pi^+} < 6600$ MeV/$c^2$. The following variables are used as input to the BDT: $\chi^2_{IP}$ of all particles; $p_T$ of muons, $J/\psi$ and $\pi^+$; and the $b$-meson decay length, decay time, and the vertex fit $\chi^2$ of a fit to the decay tree. The quantity $\chi^2_{IP}$ is defined as the difference in $\chi^2$ of a given primary vertex reconstructed with and without the considered particle. The selection value on the BDT output is chosen to maximize the signal significance $N_S/\sqrt{N_S + N_B}$, where $N_S$ and
$N_B$ are the expected numbers of signal and background events, respectively. The same BDT requirements are used for the $B^+$ meson.

The $B_c^+$ and $B^+$ candidates are subdivided into 10 bins of $p_T$ and 3 bins of $y$. Bin sizes are chosen to contain approximately the same number of signal candidates, except for the highest $p_T$ bin. The differential production ratio $R$ is measured as

$$R(p_T, y) = \frac{N_{B_c^+}(p_T, y) \epsilon_B(p_T, y)}{N_{B^+}(p_T, y) \epsilon_B(p_T, y)},$$

where $N_B(p_T, y)$ is the number of reconstructed signal decays and $\epsilon_B(p_T, y)$ is the total efficiency in a given $(p_T, y)$ bin, including geometrical acceptance, reconstruction, selection and trigger effects.

In each $p_T$ and $y$ bin, the number of signal decays is determined by performing an extended maximum likelihood fit to the unbinned invariant mass distribution of $B_c^+$ candidates reconstructed in $6150 < M_{J/\psi K^+} < 6550$ MeV/$c^2$ and $B^+$ candidates in 5150 < $M_{J/\psi K^+}$ < 5550 MeV/$c^2$. For both $B_c^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$ decays, the fit includes components for signal, combinatorial background, and Cabibbo-suppressed backgrounds $B_c^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow J/\psi \pi^+$. Other sources of backgrounds, such as $B_c^+ \rightarrow J/\psi \mu^+\nu_\mu$, are negligible. The $B_c^+ \rightarrow J/\psi \pi^+$ signal is described by a double-sided Crystal Ball (DSCB) function, which is an empirical function with a Gaussian core and power-law tails on both sides. The $B^+ \rightarrow J/\psi K^+$ signal is described by the sum of two DSCB functions, to account for different mass resolutions in different kinematic regions. The tail parameters are determined from simulation. The combinatorial background is described by an exponential function. The shapes of the Cabibbo-suppressed backgrounds are determined from simulation. The ratios of the yield of the Cabibbo-suppressed background to that of the signal are fixed to the central value of $\mathcal{B}(B_c^+ \rightarrow J/\psi K^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) = (6.9 \pm 2.0)\%$ for $B_c^+$ candidates [47], and $\mathcal{B}(B^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (3.83 \pm 0.13)\%$ for $B^+$ candidates [48], respectively.

As an example, Fig. 1 shows the $B_c^+$ and $B^+$ mass distributions together with the fit results for the bin $2.0 < p_T < 3.0$ GeV/$c$ and $2.0 < y < 2.9$. The mass resolution is approximately 11 MeV/$c^2$ for $B_c^+$ signals and 8.7 MeV/$c^2$ for $B^+$ signals. Summing over all bins, a total signal yield of $3.1 \times 10^3$ $B_c^+$ candidates and $7.1 \times 10^5$ $B^+$ candidates is obtained. In each $(p_T, y)$ bin the total efficiency is determined from simulation and ranges from 2.4% to 23.2% for $B_c^+$ candidates and from 3.6% to 33.5% for $B^+$ candidates.

The systematic uncertainties associated with the signal shape in each bin (0.1% - 2.6%) are estimated by comparing the ratios between input signal yields and fit results in simulation. The uncertainties from the combinatorial background shape (0.1% - 4.4%) are determined by varying the fit function. The input value for the ratio of branching fractions $\mathcal{B}(B_c^+ \rightarrow J/\psi K^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$ is varied within its uncertainty and the resulting difference (0.1% - 0.9%) is taken as systematic uncertainty. The systematic uncertainty associated with the relative trigger efficiency is estimated to be 1%. Other effects, such as the $(p_T, y)$ binning scheme, the shapes of the Cabibbo-suppressed backgrounds, the $B_c^+$ lifetime uncertainty and the uncertainty of tracking efficiency, are negligible.
Figure 1: Invariant mass distribution of (left) $B_c^+ \rightarrow J/\psi \pi^+$ and (right) $B^+ \rightarrow J/\psi K^+$ candidates with $2.0 < p_T < 3.0 \text{ GeV}/c$ and $2.0 < y < 2.9$. The results of the fit described in the text are superimposed.

Figure 2: Distributions of (left) $p_T$ and (right) $y$ of the $B_c^+$ signal after event selection. The points with error bars are background-subtracted data, and the solid histogram is the simulation based on the complete order-$\alpha_s^4$ calculation, implemented in the $B_c^{+}$ generator BCVEGPY \cite{bcvegpym}. The uncertainties are statistical.

Figure 2 shows that simulation provides a good description of $p_T$ and $y$ distributions of $B_c^+$ mesons in data. The values of $R(p_T,y)$ in the range $0 < p_T < 20 \text{ GeV}/c$ and $2.0 < y < 4.5$ are shown in Table 1 and Fig. 3. Figure 4 shows the ratio $R(p_T)$ integrated over $y$ in the region $2.0 < y < 4.5$ and $R(y)$ integrated over $p_T$ in the region $0 < p_T < 20 \text{ GeV}/c$. The ratios are found to vary as a function of $p_T$ and $y$.

The resulting integrated value of $R$ in the region $0 < p_T < 20 \text{ GeV}/c$ and $2.0 < y < 4.5$ is measured to be

$$R = (0.683 \pm 0.018 \pm 0.009)\%,$$

where the first uncertainty is statistical and the second systematic. To enable comparison with the previous LHCb measurement \cite{lhcb}, $R$ and its total uncertainty are also reported in
Table 1: $R(p_T, y)$ in units of $10^{-2}$ as a function of $p_T$ and $y$. The first uncertainty is statistical and the second systematic.

| $p_T$ (GeV/c) | $2.0 < y < 2.9$ | $2.9 < y < 3.3$ | $3.3 < y < 4.5$ | $2.0 < y < 4.5$ |
|---------------|-----------------|-----------------|-----------------|-----------------|
| $0 < p_T < 2$ | $0.67 \pm 0.10 \pm 0.01$ | $0.73 \pm 0.10 \pm 0.01$ | $0.35 \pm 0.06 \pm 0.01$ | $0.54 \pm 0.05 \pm 0.01$ |
| $2 < p_T < 3$ | $0.70 \pm 0.09 \pm 0.02$ | $0.72 \pm 0.09 \pm 0.02$ | $0.50 \pm 0.06 \pm 0.01$ | $0.62 \pm 0.05 \pm 0.01$ |
| $3 < p_T < 4$ | $0.62 \pm 0.08 \pm 0.01$ | $0.58 \pm 0.08 \pm 0.01$ | $0.57 \pm 0.07 \pm 0.02$ | $0.59 \pm 0.05 \pm 0.01$ |
| $4 < p_T < 5$ | $0.83 \pm 0.08 \pm 0.02$ | $0.60 \pm 0.07 \pm 0.01$ | $0.81 \pm 0.08 \pm 0.02$ | $0.79 \pm 0.05 \pm 0.01$ |
| $5 < p_T < 6$ | $0.90 \pm 0.09 \pm 0.02$ | $0.78 \pm 0.09 \pm 0.01$ | $0.76 \pm 0.09 \pm 0.02$ | $0.83 \pm 0.06 \pm 0.01$ |
| $6 < p_T < 7$ | $0.84 \pm 0.09 \pm 0.01$ | $0.99 \pm 0.11 \pm 0.02$ | $0.64 \pm 0.08 \pm 0.01$ | $0.79 \pm 0.06 \pm 0.01$ |
| $7 < p_T < 8$ | $0.95 \pm 0.10 \pm 0.01$ | $0.74 \pm 0.11 \pm 0.01$ | $0.65 \pm 0.09 \pm 0.01$ | $0.82 \pm 0.06 \pm 0.01$ |
| $8 < p_T < 10$ | $0.80 \pm 0.08 \pm 0.01$ | $0.57 \pm 0.08 \pm 0.01$ | $0.80 \pm 0.09 \pm 0.02$ | $0.77 \pm 0.05 \pm 0.01$ |
| $10 < p_T < 14$ | $0.70 \pm 0.06 \pm 0.01$ | $0.75 \pm 0.09 \pm 0.01$ | $0.60 \pm 0.08 \pm 0.01$ | $0.68 \pm 0.05 \pm 0.01$ |
| $14 < p_T < 20$ | $0.74 \pm 0.09 \pm 0.01$ | $0.68 \pm 0.15 \pm 0.03$ | $0.55 \pm 0.13 \pm 0.02$ | $0.68 \pm 0.07 \pm 0.01$ |
| $0 < p_T < 20$ | $0.76 \pm 0.03 \pm 0.01$ | $0.70 \pm 0.03 \pm 0.01$ | $0.58 \pm 0.03 \pm 0.01$ | $0.68 \pm 0.02 \pm 0.01$ |

the range $4 < p_T < 20$ GeV/c and $2.5 < y < 4.5$ as $(0.698 \pm 0.023)\%$. The previous LHCb measurement of $R$ at 7 TeV of Ref. [26] is updated using the recent measurement of the $B_c^+$ lifetime [45] to be $(0.61 \pm 0.12)\%$.

In summary, we present the first measurement of the $B_c^+$ double differential production cross-section ratio with respect to that of the $B^+$ meson. The measurement is performed in three bins of rapidity and ten bins of $p_T$ in $pp$ collisions at $\sqrt{s} = 8$ TeV on a data sample collected with the LHCb detector. The relative production rates of $B_c^+$ and $B^+$ mesons are found to depend on their transverse momentum and rapidity.

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Figure 3: Ratio $R(p_T, y)$ as a function of $p_T$ in the regions (top left) $2.0 < y < 2.9$, (top right) $2.9 < y < 3.3$, and (bottom left) $3.3 < y < 4.5$. The error bars on the data show the statistical and systematic uncertainties added in quadrature.

Figure 4: Ratio (left) $R(p_T)$ as a function of $p_T$ integrated over $y$ in the region $2.0 < y < 4.5$ and (right) $R(y)$ as a function of $y$ integrated over $p_T$ in the region $0 < p_T < 20 \text{ GeV/c}$. The error bars on the data show the statistical and systematic uncertainties added in quadrature.
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