Measurement of B_c^+ Production in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV

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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 $B^+ \to J/\psi K^+$ 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 in 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 [1]. The relative role of competing production mechanisms [2–5] is poorly understood and theory is unable to predict all experimentally observed features [6–11]. The study of B_c production offers a promising way of shedding light over these discrepancies and gaining 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 $gg \to B_c + b + \bar{c}$. The production cross sections of the B_c mesons have been calculated in the fragmentation approach [12,13] and in the complete order-α_s^4 approach [14–21], where α_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% [22,23] of the inclusive $b\bar{b}$ cross section [24].

Previously, only the average ratios of B_c^+ to B^+ or B_s^0 cross sections in specific kinematic regions had been measured [25–27], and double-differential cross sections have not yet been measured. The production cross sections of b hadrons show different transverse momentum dependencies [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 and is also important to guide B_c^+ studies at the LHC.

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

$$R(p_T, y) \equiv \frac{d\sigma_{B_c^+}(p_T, y)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{d\sigma_{B^+}(p_T, y)\mathcal{B}(B^+ \to J/\psi K^+)}, \qquad (1)$$

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 fb^{-1} recorded by the LHCb experiment. The B_c^+ and B^+ mesons are reconstructed in the exclusive decays $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$, respectively, with $J/\psi \to \mu^+\mu^-$. The inclusion of charge conjugate modes is implied throughout this Letter.

The LHCb detector [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 $(15 + 29/p_T)$ μm, 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

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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 [33]. 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/ψ meson mass [34]. 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 [35] 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) [36,37]. 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 [38] with a LHCb specific configuration [39]. The generator BCVEGPY [40] is used to simulate B_c^+-meson production. Decays of B_c^+, B^+, and J/ψ mesons are described by EVTGEN [41], and photon radiation is simulated using the PHOTOS package [42]. The decay products are traced through the detector by the GEANT4 package [43,44]. Following Ref. [45], the B_c^+-meson lifetime is set to $\tau_{B_c^+} = 0.509$ ps. The selection requirements are the same for the $B_c^+ \to J/\psi \pi^+$ and $B^+ \to J/\psi K^+$ candidates.

In the preselection, J/ψ 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/ψ candidates with invariant mass between 3.04 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/ψ candidate and the hadron (π 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/ψ-meson mass [34] 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: $\chi^2_{\rm IP}$ of all particles, p_T of muons, p_T of J/ψ and π^+, and the b-meson decay length, decay time, and the vertex fit χ^2 of a fit to the decay tree [46]. The quantity $\chi^2_{\rm IP}$ is defined as the difference in χ^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 ten bins of p_T and three 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

$$R(p_T, y) = \frac{N_{B_c^+}(p_T, y)}{N_{B^+}(p_T, y)} \frac{\epsilon_{B^+}(p_T, y)}{\epsilon_{B_c^+}(p_T, y)}, \tag{2}$$

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

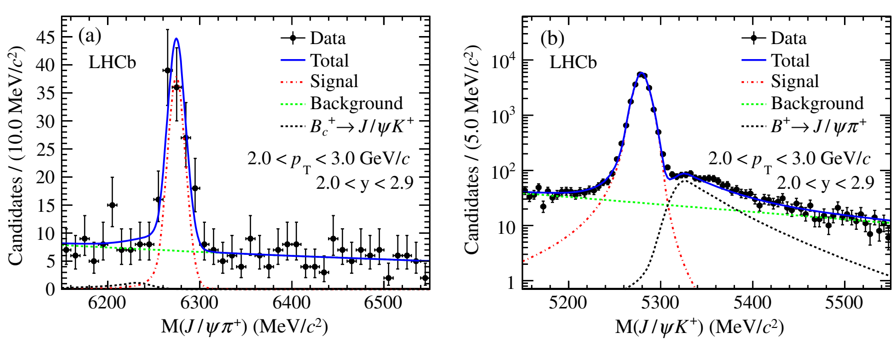

FIG. 1 (color online). Invariant mass distribution of (left) $B_c^+ \to J/\psi \pi^+$ and (right) $B^+ \to J/\psi K^+$ candidates with $2.0 < p_T < 3.0$ GeV/c and $2.0 < y < 2.9$. The results of the fit described in the text are superimposed.

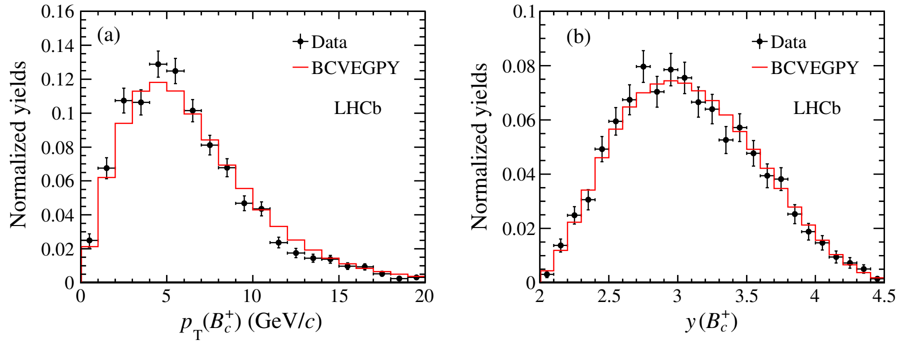

FIG. 2 (color online). Distributions of (left) p_T and (right) y of the B_c^+ signal after event selection. The points with error bars are background-subtracted data, and the solid histogram is the simulation based on the complete order-α_s^4 calculation implemented in the B_c^+ generator BCVEGPY [40]. The uncertainties are statistical.

of B_c^+ candidates reconstructed in $6150 < M_{J/\psi\pi^+} < 6550$ MeV/c^2 and B^+ candidates in $5150 < M_{J/\psi K^+} < 5550$ MeV/c^2. For both $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ decays, the fit includes components for signal, combinatorial background, and Cabibbo-suppressed backgrounds $B_c^+ \to J/\psi K^+$ and $B^+ \to J/\psi\pi^+$. Other sources of backgrounds, such as $B_c^+ \to J/\psi\mu^+\nu_\mu$, are negligible. The $B_c^+ \to J/\psi\pi^+$ 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 $B^+ \to J/\psi K^+$ 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 $\mathcal{B}(B_c^+ \to J/\psi K^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+) = (6.9 \pm 2.0)\%$ for B_c^+ candidates [47] and $\mathcal{B}(B^+ \to J/\psi\pi^+)/\mathcal{B}(B^+ \to J/\psi K^+) = (3.83 \pm 0.13)\%$ 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 3.1×10^3 B_c^+ candidates and 7.1×10^5 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 $\mathcal{B}(B_c^+ \to J/\psi K^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$ is varied within its uncertainty, and the resulting difference (0.1%–0.9%) is taken as systematic uncertainty. The effect of $\mathcal{B}(B^+ \to J/\psi\pi^+)/\mathcal{B}(B^+ \to J/\psi K^+)$ is found to be negligible. 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 2 shows that simulation provides a good description of p_T and y distributions of B_c^+ mesons in the data. The values of $R(p_T, y)$ in the range $0 < p_T < 20$ GeV/c and $2.0 < y < 4.5$ are shown in Fig. 3 and Ref. [49]. 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 $0 < p_T < 20$ GeV/c. The ratios are found to vary as a function of p_T and y. The results are compared with the theoretical predictions in Ref. [49].

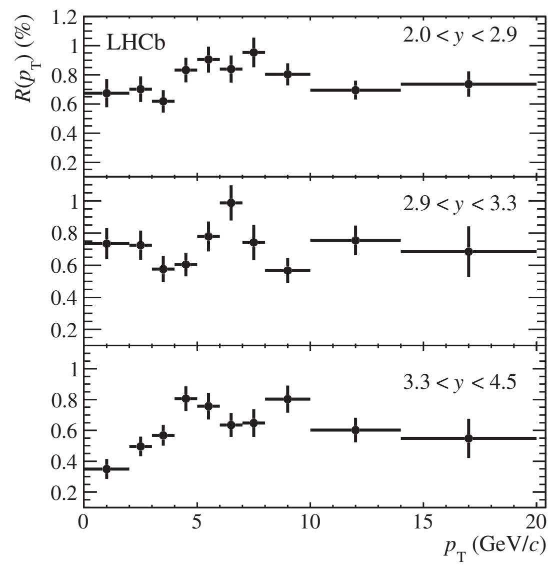

FIG. 3. Ratio $R(p_T, y)$ as a function of p_T in the regions (top) $2.0 < y < 2.9$, (middle) $2.9 < y < 3.3$, and (bottom) $3.3 < y < 4.5$. The error bars on the data show the statistical and systematic uncertainties added in quadrature.

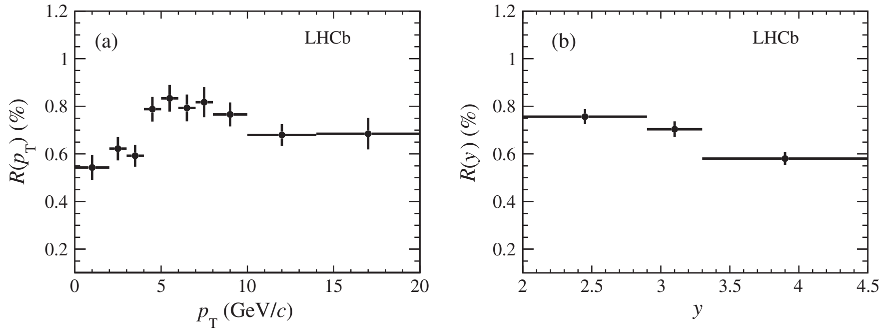

FIG. 4. Ratio (left) $R(p_T)$ as a function of p_T integrated over y in the region $2.0 < y < 4.5$ and (right) $R(y)$ as a function of y integrated over p_T in the region $0 < p_T < 20$ GeV/c. The error bars on the data show the statistical and systematic uncertainties added in quadrature.

The resulting integrated value of R in the region $0 < p_T < 20$ 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 [26], R and its total uncertainty are also reported in the range $4 < p_T < 20$ GeV/c and $2.5 < \eta < 4.5$ 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. The measured transverse momentum and rapidity distributions of the B_c^+ meson are well described by the complete order-α_s^4 calculation. However, the theoretical predictions on the B_c^+ and B^+ production cross sections suffer from big uncertainties [22,54], and the prediction of the branching fraction of the $B_c^+ \to J/\psi\pi^+$ decay has a big spread (see, for example, Ref. [55]); more work on the theoretical side is required to have concluding remarks on the B_c^+ absolute production rate. These results will provide useful information on the B_c^+ production mechanism and help us understand the quarkonium production and, therefore, deepen our understanding of QCD.

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