FERMILAB-PUB-11-299-CMS

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2010-087
2011/01/04

CMS-BPH-10-004

Measurement of the B^+ Production Cross Section in pp Collisions at $\sqrt{s} = 7\,\text{TeV}$

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Abstract

Measurements of the total and differential cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$ for B^+ mesons produced in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ are presented. The data correspond to an integrated luminosity of $5.8\,\text{pb}^{-1}$ collected by the CMS experiment operating at the LHC. The exclusive decay $B^+ \to J/\psi\, K^+$, with $J/\psi \to \mu^+\mu^-$, is used to detect B^+ mesons and to measure the production cross section as a function of p_T^B and y^B. The total cross section for $p_T^B > 5\,\text{GeV}$ and $|y^B| < 2.4$ is measured to be $28.1 \pm 2.4 \pm 2.0 \pm 3.1\,\mu\text{b}$, where the first uncertainty is statistical, the second is systematic, and the last is from the luminosity measurement.

Submitted to Physical Review Letters

*See Appendix A for the list of collaboration members

The study of heavy-quark production in high-energy hadronic interactions plays a critical role in testing next-to-leading order (NLO) Quantum Chromodynamics (QCD) calculations [1]. The first such measurements were made more than two decades ago by the UA1 Collaboration at the CERN S$\bar{\text{p}}$pS collider [2, 3] operating at a center of mass energy of $\sqrt{s} = 0.63\,\text{TeV}$, while more recent measurements have been made by the CDF and D0 Collaborations at the Fermilab Tevatron for $\sqrt{s} = 1.8$ and $1.96\,\text{TeV}$ [4–11]. Substantial progress has been achieved in the understanding of heavy-quark production at Tevatron energies [12], but large theoretical uncertainties remain due to the dependence on the renormalization and factorization scales. Particularly important in the perturbative expansion are terms that scale as powers of $\ln(\sqrt{s}/m_{\text{b}})$ at low transverse momentum p_{T} of the b quark [13, 14], or as powers of $\ln(p_{\text{T}}/m_{\text{b}})$ when $p_{\text{T}} \gg m_{\text{b}}$ [15], where m_{b} is the mass of the b quark. Measurements of b-hadron production at the higher energies provided by the Large Hadron Collider (LHC) represent an important new test of theoretical calculations [16, 17].

Recently, the LHCb Collaboration measured the production cross section for b hadrons at the LHC in the forward region using partially reconstructed decays [18]. This Letter presents the first measurement of exclusive B^+ production in pp collisions at $\sqrt{s} = 7\,\text{TeV}$. A sample of $\text{B}^+ \to \text{J}/\psi\,\text{K}^+$ decays, with $\text{J}/\psi \to \mu^+\mu^-$, is reconstructed in $5.84 \pm 0.64\,\text{pb}^{-1}$ of data collected by the Compact Muon Solenoid (CMS) experiment operating at the LHC; here and throughout this paper, charge conjugation is implied. The signal yield in bins of transverse momentum p_{T}^{B} and rapidity $|y^{\text{B}}|$ is measured with a maximum likelihood fit to the reconstructed invariant mass M_{B} and proper decay length ct of the B^+ candidates. These yields are corrected for detection efficiencies and luminosity to compute the differential production cross sections $d\sigma/dp_{\text{T}}^{\text{B}}$ and $d\sigma/dy^{\text{B}}$. The results are compared to theoretical predictions based on NLO QCD.

A detailed description of the CMS detector can be found elsewhere [19]. The main subdetectors used in this analysis are the silicon tracker and the muon systems. The tracker is immersed in a 3.8 T magnetic field generated by a superconducting solenoid of 6 m internal diameter, and consists of 1440 silicon pixel and 15 148 silicon strip detector modules. The momenta of charged particles (tracks) are measured in the tracker over the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln\tan\frac{\theta}{2}$ and θ is the polar angle of the track relative to the counterclockwise beam direction. An impact parameter resolution of $\sim 15\,\mu\text{m}$ and a p_{T} resolution of about 1.5% are achieved for particles with p_{T} up to 100 GeV. Muons are identified in the range $|\eta| < 2.4$ by gas-ionization detectors embedded in the steel return yoke. The barrel and endcap regions are instrumented with drift tubes and cathode strip chambers, respectively, interspersed with resistive plate chambers. The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in less than 1 μs. The High Level Trigger (HLT) processor farm further decreases the event rate to less than 300 Hz before data storage. The events used in the measurement reported in this Letter were collected with a trigger requiring the presence of two muons at the HLT, with no explicit momentum threshold.

Reconstruction of $\text{B}^+ \to \text{J}/\psi\,\text{K}^+$ candidates begins by identifying $\text{J}/\psi \to \mu^+\mu^-$ decays. The muon candidates are required to have at least one reconstructed segment in the muon system that matches the extrapolated position of a track reconstructed in the tracker. Muons within $|\eta| < 2.4$ that fire the trigger are selected and further required to satisfy a kinematic threshold that depends on pseudorapidity: $p_{\text{T}}^{\mu} > 3.3\,\text{GeV}$ for $|\eta^{\mu}| < 1.3$; $p^{\mu} > 2.9\,\text{GeV}$ for $1.3 < |\eta^{\mu}| < 2.2$; and $p_{\text{T}}^{\mu} > 0.8\,\text{GeV}$ for $2.2 < |\eta^{\mu}| < 2.4$. Candidate J/ψ mesons are reconstructed by combining pairs of oppositely charged muons having an invariant mass within 150 MeV of the nominal J/ψ mass [20]. If more than one muon pair in an event satisfies this selection, the one closest to the J/ψ mass is selected.

Candidate B^+ mesons are reconstructed by combining a J/ψ candidate with a track having $p_T > 0.9\,\text{GeV}$, at least four hits in the tracker (of which one must be in the pixel detector), and a track-fit χ^2 less than five times the number of degrees of freedom. A kinematic fit is performed to the dimuon-track combination, constraining the dimuon mass to equal the J/ψ mass and assuming the third track to be a kaon. The selected events must have a resulting χ^2 confidence level greater than 0.1% and a reconstructed B^+ mass satisfying $4.95 < M_B < 5.55\,\text{GeV}$. In events with at least one B^+ candidate, the average number of such candidates is approximately 1.7. When multiple candidates exist, the one with the highest p_T is retained, which results in the correct choice 95% of the time in simulated events containing a true signal decay. A total of 35 406 B^+ candidates pass all the selection criteria.

The efficiencies corresponding to this selection, defined as the fraction of $B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+$ decays produced with $p_T^B > 5\,\text{GeV}$ and $|y^B| < 2.4$ that pass all the criteria, range from a few percent for $p_T^B \sim 5\,\text{GeV}$, to approximately 40% for $p_T^B > 24\,\text{GeV}$, as determined in large samples of signal events generated by PYTHIA 6.422 [21], decayed by EVTGEN [22], and processed by a detailed simulation of the CMS detector based on GEANT4 [23]. The efficiencies for hadron-track reconstruction [24] and the vertex quality requirement are found to be consistent between data and simulation within the available precision, which is used to set the systematic uncertainty of these quantities. Correction factors for trigger and muon-reconstruction efficiencies are obtained from a large sample of inclusive $J/\psi \to \mu^+\mu^-$ decays using a technique similar to that described in [25], where one muon is identified with stringent quality requirements and the second muon is identified using information either exclusively from the tracker (to measure the trigger and muon-identification efficiencies) or from the muon system (to measure the silicon tracker efficiency). The correction factors are determined in bins of muon p_T and η, and are applied independently to each muon in simulated B^+ decays to determine the corrected efficiencies.

The proper decay length of each B^+ candidate is calculated as $ct = (M_B/p_T^B)L_{xy}$, where the transverse decay length L_{xy} is the vector $\vec{s}$ pointing from the primary vertex [26] to the secondary vertex projected onto the B^+ transverse momentum: $L_{xy} = (\vec{s} \cdot \vec{p}_T^B)/|\vec{p}_T^B|$. The core resolution on ct is approximately 30 μm for correctly reconstructed signal decays.

Backgrounds are dominated by prompt and non-prompt inclusive J/ψ production. Additional backgrounds arise from misreconstructed b-hadron decays, such as $B \to J/\psi K^*(892)$, that produce a broad peaking structure in the region $M_B < 5.2\,\text{GeV}$. A study of the sidebands of the dimuon invariant mass distribution confirms that the contamination from muon pairs that do not originate from the decay of a J/ψ meson is negligible after all selection criteria are applied.

The number n_{sig} of signal B^+ and B^- decays in each p_T^B and $|y^B|$ bin (defined in Table 1) is obtained using an unbinned extended maximum-likelihood fit to M_B and ct. The likelihood for event j is obtained by summing the product of yield n_i and probability density $\mathcal{P}_i$ for each of the signal and background hypotheses i. Five individual components are considered: signal, $B^+ \to J/\psi\pi^+$, $b\bar{b}$ events that peak in M_B, non-prompt J/ψ, and prompt J/ψ. The extended likelihood function is then the product of likelihoods for all events:

$$\mathcal{L} = \exp\left(-\sum_i n_i\right) \prod_j \left[\sum_i n_i \mathcal{P}_i(M_B;\, \vec{\alpha}_i)\mathcal{P}_i(ct;\, \vec{\beta}_i)\right]. \quad (1)$$

The probabilities $\mathcal{P}_i$ are the probability density functions (PDFs) with shape parameters $\vec{\alpha}_i$ for M_B, and $\vec{\beta}_i$ for ct, evaluated separately for each of the i fit components. The yields n_i are then determined by maximizing the quantity $\ln\mathcal{L}$ with respect to the yields and a subset of the PDF parameters. The yield for $J/\psi\pi^+$ is constrained to equal the $J/\psi K^+$ yield times the ratio

Table 1: Bin ranges for p_T^B and $|y^B|$, signal yields n_{sig}, efficiencies ϵ, and measured differential cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$, compared to the MC@NLO [27] and PYTHIA predictions. The uncertainties in the measured cross sections are statistical and systematic, respectively, excluding the common branching fraction (3.5%) and luminosity (11%) uncertainties. The last range of p_T^B is unbounded, so it is quoted as an integrated cross section in μb for $p_T^B > 30$ GeV.

p_T^B (GeV)	n_{sig}	ϵ (%)	$d\sigma/dp_T^B$ (μb/GeV)	MC@NLO	PYTHIA
5–10	223 ± 26	1.56 ± 0.02	$4.07 \pm 0.47 \pm 0.31$	$2.76^{+1.09}_{-0.62}$	4.92
10–13	236 ± 21	7.62 ± 0.11	$1.47 \pm 0.13 \pm 0.09$	$0.88^{+0.23}_{-0.19}$	2.07
13–17	169 ± 17	14.6 ± 0.2	$0.412 \pm 0.041 \pm 0.026$	$0.37^{+0.04}_{-0.07}$	0.81
17–24	207 ± 17	23.3 ± 0.6	$0.181 \pm 0.015 \pm 0.012$	$0.12^{+0.04}_{-0.04}$	0.22
24–30	56 ± 9	31.9 ± 1.5	$0.042 \pm 0.007 \pm 0.004$	$0.035^{+0.020}_{-0.003}$	0.06
> 30	44 ± 8	33.4 ± 2.0	$0.188 \pm 0.034 \pm 0.018$	$0.15^{+0.07}_{-0.01}$	0.20
$\lvert y^B \rvert$	n_{sig}	ϵ (%)	$d\sigma/dy^B$ (μb)	MC@NLO	PYTHIA
0.00–0.60	187 ± 17	3.01 ± 0.06	$7.39 \pm 0.65 \pm 0.53$	$4.45^{+1.51}_{-0.99}$	8.9
0.60–1.10	164 ± 17	3.81 ± 0.08	$6.11 \pm 0.64 \pm 0.47$	$4.55^{+1.37}_{-0.99}$	8.6
1.10–1.45	207 ± 20	5.92 ± 0.12	$7.11 \pm 0.69 \pm 0.59$	$4.50^{+1.47}_{-1.07}$	8.0
1.45–1.80	203 ± 22	8.24 ± 0.15	$5.01 \pm 0.55 \pm 0.42$	$4.21^{+1.81}_{-1.09}$	7.7
1.80–2.40	176 ± 22	6.31 ± 0.12	$3.31 \pm 0.42 \pm 0.28$	$2.62^{+1.07}_{-0.59}$	4.8

of branching fractions for the two decay modes [20]. Correlations between M_B and ct have been found to be at the level of a few percent. They are therefore assumed to have a negligible impact on the fit, and potential biases arising from this assumption are taken into account in the systematic uncertainty of the fitted signal yield.

The PDFs are constructed from common functions, with shape parameters obtained from data when possible. The M_B PDFs are the sum of three (two) Gaussians for the signal ($J/\psi\pi$) with parameters obtained from simulation; an exponential for both prompt and non-prompt J/ψ that allows for possible curvature in the shape of the combinatorial background; and a combination of two Gaussians and an exponential for the peaking background. The resolution on M_B for signal decays is approximately 30 MeV. The ct PDFs are a single exponential convolved with the resolution function to describe the signal, $J/\psi\pi$, and peaking background components, where the lifetime is allowed to be different for the latter; the sum of two exponentials convolved with the resolution function for the non-prompt J/ψ component; and the pure resolution function for the prompt J/ψ component. The resolution function is common for signal and background, and is described by the sum of two or three Gaussian functions, depending on p_T^B and $|y^B|$.

The fit proceeds in several steps so that all background shapes are obtained directly from data, except for the peaking component. This technique relies on the assumption that in the signal-free region $5.40 < M_B < 5.55$ GeV (upper sideband) there are only two contributions: prompt and non-prompt J/ψ background (ignoring the small contribution from $J/\psi\pi$). To obtain the effective lifetime of the non-prompt J/ψ background, the ct distribution is fitted for events in the inclusive B^+ sample defined by $p_T^B > 5$ GeV and $|y^B| < 2.4$ that lie in the M_B upper sideband region, allowing the resolution function parameters to vary freely. The resolution function is then fixed and the B^+ lifetime in the inclusive sample is obtained by fitting ct and M_B simultaneously. The result, $c\tau = 481 \pm 22\,\mu$m (statistical uncertainty only), is in good agreement with the

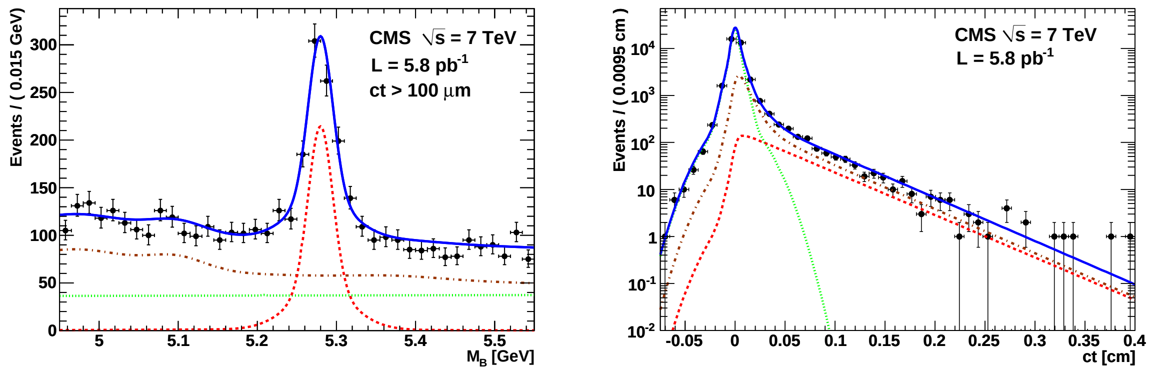

Figure 1: Projections of the fit results in M_{B} (left) and ct (right) for $p_{\mathrm{T}}^{\mathrm{B}} > 5\,\mathrm{GeV}$ and $|y^{\mathrm{B}}| < 2.4$. The curves in each plot are the sum of all contributions (solid blue line); signal (dashed red); prompt J/ψ (dotted green); and the sum of non-prompt J/ψ, peaking $\mathrm{b\bar{b}}$, and $\mathrm{J}/\psi\pi^{+}$ (dot-dashed brown). For better visibility of the individual contributions, the M_{B} plot includes a requirement of $ct > 100\,\mu\mathrm{m}$.

world-average value of $491 \pm 9\,\mu\mathrm{m}$ [20]. With the effective lifetime for signal and non-prompt background fixed, the resolution function parameters are then determined separately in each bin of $p_{\mathrm{T}}^{\mathrm{B}}$ and $|y^{\mathrm{B}}|$. Finally, with all ct resolution and background lifetime parameters fixed, the signal and background yields are fitted in each bin, together with the parameters describing the shape of the prompt and non-prompt J/ψ components in M_{B}.

Several studies have verified the accuracy and robustness of the fit strategy. A set of 400 pseudoexperiments was performed where signal and background events were generated randomly from the PDFs in each bin. No biases were observed on the yields, and the fit uncertainties were also seen to be estimated properly. Having established that the nominal fit procedure is free of inherent biases, other potential biases caused by residual correlations between M_{B} and ct were studied by mixing together fully simulated signal and background events to produce 100 pseudoexperiments. Again, no significant evidence of bias in the signal yield was found. The observed deviations (a few percent) between fitted and generated yields are taken as the systematic uncertainty due to potential biases in the fit method.

Table 1 summarizes the fitted signal yield in each bin of $p_{\mathrm{T}}^{\mathrm{B}}$ and $|y^{\mathrm{B}}|$, while Fig. 1 shows the fit projections for M_{B} and ct from the inclusive sample with $p_{\mathrm{T}}^{\mathrm{B}} > 5\,\mathrm{GeV}$ and $|y^{\mathrm{B}}| < 2.4$. The total number of signal events is 912 ± 47, where the error is statistical only.

The differential cross sections for B^{+} production as a function of $p_{\mathrm{T}}^{\mathrm{B}}$ and y^{B} (averaged for positive and negative rapidities) are defined as

$$\frac{d\sigma(\mathrm{pp}\to\mathrm{B}^{+}\mathrm{X})}{dp_{\mathrm{T}}^{\mathrm{B}}} = \frac{n_{\mathrm{sig}}(p_{\mathrm{T}}^{\mathrm{B}})}{2\,\epsilon(p_{\mathrm{T}}^{\mathrm{B}})\,\mathcal{B}\,\mathcal{L}\,\Delta p_{\mathrm{T}}^{\mathrm{B}}}, \qquad \frac{d\sigma(\mathrm{pp}\to\mathrm{B}^{+}\mathrm{X})}{dy^{\mathrm{B}}} = \frac{n_{\mathrm{sig}}(|y^{\mathrm{B}}|)}{2\,\epsilon(|y^{\mathrm{B}}|)\,\mathcal{B}\,\mathcal{L}\,\Delta y^{\mathrm{B}}}, \tag{2}$$

where $n_{\mathrm{sig}}(p_{\mathrm{T}}^{\mathrm{B}})$ and $n_{\mathrm{sig}}(|y^{\mathrm{B}}|)$ are the fitted signal yields in the given bin, $\epsilon(p_{\mathrm{T}}^{\mathrm{B}})$ and $\epsilon(|y^{\mathrm{B}}|)$ are the efficiencies in each bin for a B^{+} meson produced with $p_{\mathrm{T}}^{\mathrm{B}} > 5\,\mathrm{GeV}$ and $|y^{\mathrm{B}}| < 2.4$ to pass all the selection criteria, $\Delta p_{\mathrm{T}}^{\mathrm{B}}$ is the bin size in $p_{\mathrm{T}}^{\mathrm{B}}$, and $\Delta y^{\mathrm{B}} = 2\,\Delta|y^{\mathrm{B}}|$ is the bin size in y^{B}. The total branching fraction $\mathcal{B}$ is the product of the individual branching fractions $\mathcal{B}(\mathrm{B}^{+}\to\mathrm{J}/\psi\,\mathrm{K}^{+}) = (1.014 \pm 0.034) \times 10^{-3}$ and $\mathcal{B}(\mathrm{J}/\psi\to\mu^{+}\mu^{-}) = (5.93 \pm 0.06) \times 10^{-2}$ [20]. The factor of two in the denominator of Eq. 2 takes into account the choice of quoting the cross section for a single charge (taken to be B^{+}), while n_{sig} includes both charge states. All efficiencies, $\epsilon(p_{\mathrm{T}}^{\mathrm{B}})$ or $\epsilon(|y^{\mathrm{B}}|)$,

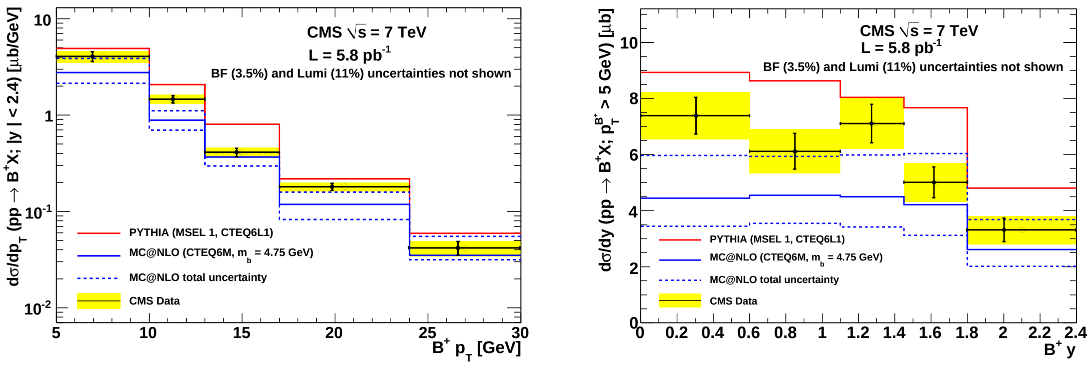

Figure 2: Measured differential cross sections $d\sigma/dp_T^B$ (left) and $d\sigma/dy^B$ (right) compared with the theory predictions. The error bars are the statistical uncertainties, while the (yellow) band represents the sum in quadrature of statistical and systematic uncertainties, excluding the common branching fraction and luminosity uncertainties. The solid and dashed blue lines are the MC@NLO prediction and its uncertainty, respectively. The solid red line is the PYTHIA prediction.

are calculated separately in each bin, and account for bin-to-bin migrations (a few percent) due to the resolution on the measured momentum and rapidity.

The cross section is affected by several sources of systematic uncertainty arising from the signal yields, efficiencies, branching fractions, and luminosity. Uncertainties of the signal yields arise from potential fit biases and imperfect knowledge of the PDF parameters (2–5%), ct resolution function (1–2%), and the effects of final-state radiation on the signal shape in M_B ($< 1\%$). Uncertainties of the trigger (2%), muon identification (1%), and tracking (1–4%) efficiencies are all determined directly from data. The contribution (1–4%) related to the B^+ momentum spectrum is evaluated by reweighting the shape of the p_T^B distribution generated with PYTHIA to match the spectrum predicted by MC@NLO 3.4 [27]. An uncertainty of 1.5% is assigned to the efficiency of the vertex quality requirement, which is cross-checked in data by performing a fit on the inclusive sample after removing this selection. The effect of tracker misalignment on the cross sections due to variations in the signal yields and efficiencies is estimated to be approximately 2% using samples simulated with a different alignment than the nominal one. The total systematic uncertainty of the cross section measurement in each bin is computed as the sum in quadrature of the individual uncertainties, and is summarized in Table 1. In addition, there are common uncertainties of 3.5% from the branching fractions and 11% from the luminosity measurement [28].

The differential cross sections as functions of p_T^B and y^B are shown in Fig. 2 and Table 1. They are compared with the predictions of MC@NLO using a b-quark mass of 4.75 GeV, renormalization and factorization scales $\mu = \sqrt{m_b^2 + p_T^2}$, and the CTEQ6M parton distribution functions [29]. The uncertainty on the predicted cross section is calculated by varying the renormalization and factorization scales by a factor of two, m_b by ± 0.25 GeV, and by using the CTEQ6.6 parton distribution set. For reference, the prediction of PYTHIA is also included, using a b-quark mass of 4.8 GeV, CTEQ6L1 parton distributions [29], and the D6T tune to simulate the underlying event. The total integrated cross section for $p_T^B > 5$ GeV and $|y^B| < 2.4$ is calculated as the sum over all p_T^B bins and is found to be $28.1 \pm 2.4 \pm 2.0 \pm 3.1\ \mu$b, where the first uncertainty is statistical, the second is systematic (including the branching fraction uncertainty), and the last is from the luminosity measurement. Systematic uncertainties that are uncorrelated between bins are added quadratically, while correlated uncertainties are added linearly. This result lies between the predictions of MC@NLO, $19.1^{+6.5}_{-4.0}$ (scale)$^{+1.7}_{-1.4}$ (mass) $\pm$ 0.6 (PDF) μb, and PYTHIA (36.2 μb).

In summary, the first measurements of the total and differential cross sections for B^+ mesons produced in pp collisions at $\sqrt{s} = 7$ TeV, using the decay $B^+ \to J/\psi K^+$, have been presented. The measurements cover a range in p_T^B from 5 GeV to greater than 30 GeV, and the rapidity range $|y^B| < 2.4$. The result is in reasonable agreement with theoretical predictions in terms of shape, but has an absolute normalization approximately 1.5 times larger than the MC@NLO calculation.

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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