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Measurement of the B0s Production Cross Section with B0s → J/ Decays in pp Collisions at √s = 7 TeV

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Measurement of the B_s^0 Production Cross Section with $B_s^0 \to J/\psi\phi$ Decays in pp Collisions at $\sqrt{s} = 7$ TeV

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The B_s^0 differential production cross section is measured as functions of the transverse momentum and rapidity in pp collisions at $\sqrt{s} = 7$ TeV, using the $B_s^0 \to J/\psi\phi$ decay, and compared with predictions based on perturbative QCD calculations at next-to-leading order. The data sample, collected by the CMS experiment at the LHC, corresponds to an integrated luminosity of 40 pb^{-1}. The B_s^0 is reconstructed from the decays $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. The integrated B_s^0 cross section times $B_s^0 \to J/\psi\phi$ branching fraction in the range $8 < p_T^B < 50$ GeV/c and $|y^B| < 2.4$ is measured to be $6.9 \pm 0.6 \pm 0.6$ nb, where the first uncertainty is statistical and the second is systematic.

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The measurements of differential cross sections for heavy-quark production in high-energy hadronic interactions are critical input for the underlying next-to-leading order (NLO) quantum chromodynamics (QCD) calculations [1]. While progress has been achieved in the understanding of heavy-quark production at Tevatron energies [2–10], large theoretical uncertainties remain due to the dependence on the renormalization and factorization scales. Measurements of b-hadron production at the higher energies provided by the LHC represent an important new test of theoretical approaches that aim to reduce the scale dependence of NLO QCD calculations [11,12]. The Compact Muon Solenoid (CMS) experiment, that covers a rapidity range complementary to the specialized b-physics experiment LHCb [13], recently measured the cross sections for production of B^+ [14] and B^0 [15] in pp collisions at $\sqrt{s} = 7$ TeV. This paper presents the first measurement of the production of B_s^0, with B_s^0 decaying into $J/\psi\phi$, and adds information to improve the understanding of b-quark production at this energy. Data and theoretical predictions are compared to NLO predictions of heavy-quark production.

The decay channel $B_s^0 \to J/\psi\phi$ is of wide interest as the production rate offers a sensitive indirect search of physics beyond the standard model at the LHC. This decay proceeds via the $b \to c\bar{c}s$ transition that probes the CP-violating phase related to B_s^0-$\bar{B}_s^0$ mixing. The standard model predicts this phase to be close to zero [16] while new phenomena may alter the observed phase [17].

A sample of exclusive $B_s^0 \to J/\psi\phi$ decays, with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$, is reconstructed from the data collected in 2010 by the CMS experiment, corresponding to an integrated luminosity of 39.6 ± 1.6 pb^{-1}. The differential production cross sections, $d\sigma/dp_T^B$ and $d\sigma/dy^B$, are determined as functions of the transverse momentum p_T^B and rapidity $|y^B|$ of the reconstructed B_s^0 candidate. The differential cross sections are calculated from the measured signal yields (n_{sig}), corrected for the overall efficiency (ϵ), bin size (Δx, with $x = p_T^B, |y^B|$), and integrated luminosity (L),

$$\frac{d\sigma(pp \to B_s^0 \to J/\psi\phi)}{dx} = \frac{n_{\text{sig}}}{2 \cdot \epsilon \cdot \mathcal{B} \cdot L \cdot \Delta x}, \tag{1}$$

where $\mathcal{B}$ is the product of the branching fractions for the decays of the J/ψ and ϕ mesons. In each bin the signal yield is extracted with an unbinned maximum likelihood fit to the $J/\psi\phi$ invariant mass and proper decay length ct of the B_s^0 candidates. The factor of 2 in Eq. (1) is required since we report the result as a cross section for B_s^0 production alone, while both B_s^0 and $\bar{B}_s^0$ are included in n_{sig}. The size of the bins is chosen such that the statistical uncertainty on n_{sig} is comparable in each of them.

A detailed description of the CMS detector can be found elsewhere [18]. The primary components used in this analysis are the silicon tracker and the muon systems. The tracker operates in a 3.8 T axial magnetic field generated by a superconducting solenoid having an internal diameter of 6 m. The tracker consists of three cylindrical layers of pixel detectors complemented by two disks in the forward and backward directions. The radial region between 20 and 116 cm is occupied by several layers of silicon strip detectors in barrel and disk configurations, ensuring at least nine hits in the pseudorapidity range $|\eta| < 2.4$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle of the track measured from the positive z-axis of a right-handed coordinate system, with the origin at the nominal interaction point, the x-axis pointing to the center of the LHC, the y-axis pointing up (perpendicular to the LHC plane), and the z-axis along the counterclockwise-beam direction. An impact parameter resolution around

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15 μm and a $p_{\rm T}$ resolution around 1.5% are achieved for charged particles with transverse momenta up to 100 GeV/c. Muons are identified in the range $|\eta| < 2.4$, with detection planes made of drift tubes, cathode strip chambers, and resistive plate chambers, embedded in the steel return yoke.

The first level of the CMS trigger system uses information from the crystal electromagnetic calorimeter, the brass/scintillator hadron calorimeter, and the muon detectors to select the most interesting events in less than 1 μs. The high level trigger employs software algorithms and a farm of commercial processors to further decrease the event rate using information from all detector subsystems. The events used in the measurement reported in this paper were collected with a trigger requiring the presence of two muons at the high level trigger, with no explicit momentum threshold.

Reconstruction of $B_s^0 \to J/\psi\phi$ candidates begins by identifying $J/\psi \to \mu^+\mu^-$ decays. The muon candidates must have one or more reconstructed segments in the muon system that match the extrapolated position of a track reconstructed in the tracker. Furthermore, the muons are required to lie within a kinematic acceptance region defined as $p_{\rm T}^{\mu} > 3.3$ GeV/c for $|\eta^{\mu}| < 1.3$; total momentum $p^{\mu} > 2.9$ GeV/c for $1.3 < |\eta^{\mu}| < 2.2$; and $p_{\rm T}^{\mu} > 0.8$ GeV/c for $2.2 < |\eta^{\mu}| < 2.4$. Two oppositely charged muon candidates are paired and are required to originate from a common vertex using a Kalman vertex fit. The muon pair is required to have a transverse momentum $p_{\rm T} > 0.5$ GeV/c and an invariant mass within 150 MeV/c^2 of the world average J/ψ mass value [19], which corresponds to more than 3 times the measured dimuon invariant mass resolution [20].

Candidate ϕ mesons are reconstructed from pairs of oppositely charged tracks with $p_{\rm T} > 0.7$ GeV/c that are selected from a sample with the muon candidate tracks removed. The tracks are required to have at least five hits in the silicon tracker detectors, and a track χ^2 per degree of freedom less than 5. Each track is assumed to be a kaon and the invariant mass of a track pair has to be within 10 MeV/c^2 of the world average ϕ-meson mass [19].

The B_s^0 candidates are formed by combining a J/ψ with a ϕ candidate. The two muons and the two kaons are subjected to a combined vertex and kinematic fit [21], where in addition the dimuon invariant mass is constrained to the nominal J/ψ mass. The selected candidates must have a resulting χ^2 vertex probability greater than 2%, an invariant mass between 5.20 and 5.65 GeV/c^2, and must be in the kinematic range $8 < p_{\rm T}^B < 50$ GeV/c and $|y^B| < 2.4$. For events with more than one candidate, the one with the highest vertex-fit probability is selected, which results in the correct choice 97% of the time, as determined from simulated signal events.

The proper decay length of each selected B_s^0 candidate is calculated using the formula $ct = c(M_B/p_{\rm T}^B)L_{xy}$, where the transverse decay length L_{xy} is the length of the vector $\vec{s}$ pointing from the primary vertex [22] to the secondary vertex projected onto the B_s^0 transverse momentum: $L_{xy} = (\vec{s} \cdot \vec{p}_T^{\,B})/p_{\rm T}^B$, with M_B being the reconstructed mass of the B_s^0 candidate. Candidate B_s^0 mesons are accepted within the range $-0.05 < ct < 0.35$ cm.

A total of 6200 events pass all the selection criteria. The efficiency of the B_s^0 reconstruction is computed with a combination of techniques using the data and large samples of simulated signal events generated using PYTHIA 6.422 [23]. The decays of unstable particles are described by the EVTGEN [24] simulation. Long-lived particles are then propagated through a detailed description of the CMS detector based on the GEANT4 [25] package. The trigger and muon reconstruction efficiencies are obtained from a large sample of inclusive $J/\psi \to \mu^+\mu^-$ decays in data using a (tag-and-probe) technique similar to that described in Ref. [20], where one muon (the tag) is identified with stringent quality requirements, and the second muon (the probe) 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 tracking efficiency). The dimuon efficiencies are calculated as the product of the single-muon efficiencies obtained with this method. Corrections to account for correlations between the two muons (1%–3%) are obtained from simulation studies. The correction factors are determined in bins of single muon $p_{\rm T}^{\mu}$ and η^{μ} and are applied independently to each muon from a $B_s^0 \to J/\psi\phi$ decay in the simulation to determine the total corrected efficiency. The probabilities for the muons to lie within the kinematic acceptance region and for the ϕ and B_s^0 candidates to pass the selection requirements are determined from the simulated events. The efficiencies for hadronic track reconstruction [26] and the vertex-quality requirement are found to be consistent between real data and simulated events within their uncertainties (up to 5%). The total efficiency of this selection, defined as the fraction of $B_s^0 \to J/\psi\phi$ decays produced with $8 < p_{\rm T}^B < 50$ GeV/c and $|y^B| < 2.4$ that pass all criteria, ranges from 1.3% for $p_{\rm T}^B \approx 8$ GeV/c to 19.6% for $p_{\rm T}^B > 23$ GeV/c.

The two main background sources are prompt and nonprompt J/ψ production. The latter background is mainly composed of B^+ and B^0 mesons that decay to a J/ψ and a higher-mass K-meson state (such as the K_1^+). Such events tend to contribute to the low-mass side of the M_B mass distribution. Inspection of a large variety of potential background channels confirms that there is no single dominant component and that the channel $B^0 \to J/\psi K^*(892)$ [with $K^*(892)^0 \to K^+\pi^-$], which *a priori* is kinematically similar to the signal decay and more abundantly produced, is strongly suppressed by the restriction on the K^+K^- invariant mass. A study of the sidebands of the dimuon invariant mass distribution confirms that the contamination from events without a J/ψ decay to two muons is negligible after all selection criteria have been applied.

The signal yields in each p_T^B and $|y^B|$ bin, given in Table I, are 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 the yield n_i and the probability density functions (PDF) $\mathcal{P}_i$ and $\mathcal{Q}_i$ for each of the signal and background hypotheses i. Three individual components are considered: signal, nonprompt $b \to J/\psi X$, and prompt J/ψ. The extended likelihood function is then the product of likelihoods for each event j:

$$\mathcal{L} = \exp\left(-\sum_{i=1}^{3} n_i\right)\prod_j\left[\sum_{i=1}^{3} n_i\mathcal{P}_i(M_B;\vec{\alpha}_i)\mathcal{Q}_i(ct;\vec{\beta}_i)\right]. \quad (2)$$

The PDFs $\mathcal{P}_i$ and $\mathcal{Q}_i$ are parameterized separately for each fit component with shape parameters $\vec{\alpha}_i$ for M_B and $\vec{\beta}_i$ for ct. The yields n_i are then determined by minimizing the quantity $-\ln\mathcal{L}$ with respect to the signal yields and a subset of the PDF parameters [27]. Possible correlations between M_B and ct are found to be less than 2%. Therefore, they are assumed to have a negligible impact on the fit, and potential biases arising from this assumption are accounted for in the systematic uncertainty on the fitted signal yield as described below.

The PDFs are constructed from basic analytical functions that satisfactorily describe the variable distributions from simulated events. Shape parameters are obtained from data when possible. The M_B PDF is the sum of two Gaussian functions for the signal, a second-order polynomial for the nonprompt J/ψ that allows for possible curvature in the shape, and a first-order polynomial for prompt J/ψ. The resolution on M_B is approximately 20 MeV$/c^2$ near the B_s^0 mass.

For the signal, the ct PDF is a single exponential parameterized in terms of a proper decay length $c\tau$. It is convolved with a resolution function that is a combination of two Gaussian functions to account for a dominant core and small outlier distribution; the core fraction is varied in the fit and found to be consistently larger than 95%. The ct distribution for the nonprompt J/ψ background is described by a sum of two exponentials, with effective lifetimes that are allowed to be different. The "long-lifetime exponential" corresponds to decays of b-hadrons to a J/ψ plus some charged particles that survive the ϕ selection, while the "short-lifetime exponential" accounts for events where the muons from the J/ψ decay are wrongly combined with hadron tracks originating from the pp collision point. The exponential functions are convolved with a resolution function with the same parameters as the signal. For the prompt J/ψ component the pure resolution function is used. The core resolution in ct is measured in data to be 45 μm.

All background shapes are obtained directly from data, while the signal shape in M_B is taken from a fit to reconstructed signal events from the simulation. The effective lifetime and resolution function parameters for prompt and nonprompt backgrounds are extracted, using the full data sample irrespective of p_T^B and $|y^B|$, from regions in M_B that are separated by more than 4 times the width of the observed B_s^0 signal from the mean B_s^0 peak position (M_B sidebands): $5.20 < M_B < 5.29$ GeV$/c^2$ and $5.45 < M_B < 5.65$ GeV$/c^2$. A comparison of the PDF shapes for the different sideband regions in simulated events confirms that their average over the signal-free regions is a good representation of the background in the signal region. With the lifetimes for signal and nonprompt background fixed from this first step, the resolution function parameters are then determined separately in each p_T^B and $|y^B|$ bin, from the M_B sidebands. The signal and background yields in each p_T^B and $|y^B|$ bin are determined in a final iteration, using the full M_B range, with all parameters floating except

TABLE I. Signal yield n_{sig}, efficiency $\epsilon(\%)$, and measured differential cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$, compared to the MC@NLO and PYTHIA predictions, in different p_T^B and $|y^B|$ intervals. The uncertainty on n_{sig} is statistical only while the uncertainties on the measured cross sections are statistical and systematic, respectively, excluding the common luminosity of 4% and the 1.4% from the J/ψ and ϕ branching fractions.

			$d\sigma/dp_T^B$ (nb/GeV$/c$)		
p_T^B (GeV$/c$)	n_{sig}	ϵ (%)	Data	MC@NLO	PYTHIA
8–12	138 ± 16	1.28 ± 0.05	1.172 ± 0.136 ± 0.113	0.719	1.513
12–16	176 ± 17	5.26 ± 0.23	0.364 ± 0.035 ± 0.034	0.240	0.515
16–23	162 ± 16	11.9 ± 0.6	0.085 ± 0.008 ± 0.008	0.074	0.144
23–50	86 ± 11	19.6 ± 1.1	0.007 ± 0.001 ± 0.001	0.008	0.010
			$d\sigma/dy^B$ (nb)		
$\|y^B\|$	n_{sig}	ϵ (%)	Data	MC@NLO	PYTHIA
0.00–0.80	151 ± 15	2.75 ± 0.09	1.484 ± 0.147 ± 0.148	1.040	2.281
0.80–1.40	144 ± 15	4.65 ± 0.18	1.123 ± 0.117 ± 0.102	1.023	2.051
1.40–1.70	129 ± 15	5.68 ± 0.31	1.634 ± 0.190 ± 0.160	0.929	1.833
1.70–2.40	139 ± 17	3.26 ± 0.20	1.316 ± 0.161 ± 0.139	0.801	1.559

the background lifetimes and the lifetime resolution functions, which are fixed to the results of the fit to the M_B sidebands. It has been verified that leaving all parameters floating changes the signal yield by an amount smaller than the systematic uncertainty assigned to the fit procedure.

Many detailed studies have been conducted to validate the accuracy and robustness of the fit procedure. A large number of pseudoexperiments were performed, each corresponding to the yields observed in each p_T^B and $|y^B|$ bin for a data sample corresponding to an integrated luminosity of $40\ \text{pb}^{-1}$, where signal and background events were generated randomly from the PDFs in each bin. The fit yields were found to be unbiased and their uncertainties estimated properly. The effects of residual correlations between M_B and ct were studied by mixing fully simulated signal and background events to produce pseudoexperiments. The observed deviations between the fitted and generated yields (1%–2%) are taken as the systematic uncertainty due to potential biases in the fit method.

Figure 1 shows the fit projections for M_B and ct from the inclusive sample with $8 < p_T^B < 50\ \text{GeV}/c$ and $|y^B| < 2.4$. When plotting M_B, the selection $ct > 0.01$ cm is applied for better visibility of the individual contributions. The number of signal events in the entire data sample is 549 ± 32, where the uncertainty is statistical only. The obtained proper decay length of the signal, $c\tau = 478 \pm 26\ \mu\text{m}$, is within 1.4 standard deviations of the world average value [19], even though this analysis was not optimized for lifetime measurements.

Table I summarizes the fitted signal yield in each bin of p_T^B and $|y^B|$. The differential cross section is calculated according to Eq. (1), using the product of the branching fractions $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.93 \pm 0.06) \times 10^{-2}$ and $\mathcal{B}(\phi \to K^+K^-) = (48.9 \pm 0.5) \times 10^{-2}$ [19]. All efficiencies are calculated separately in each bin, and account for bin-to-bin migrations (less than 1%) due to the finite resolution of the measured momentum and rapidity.

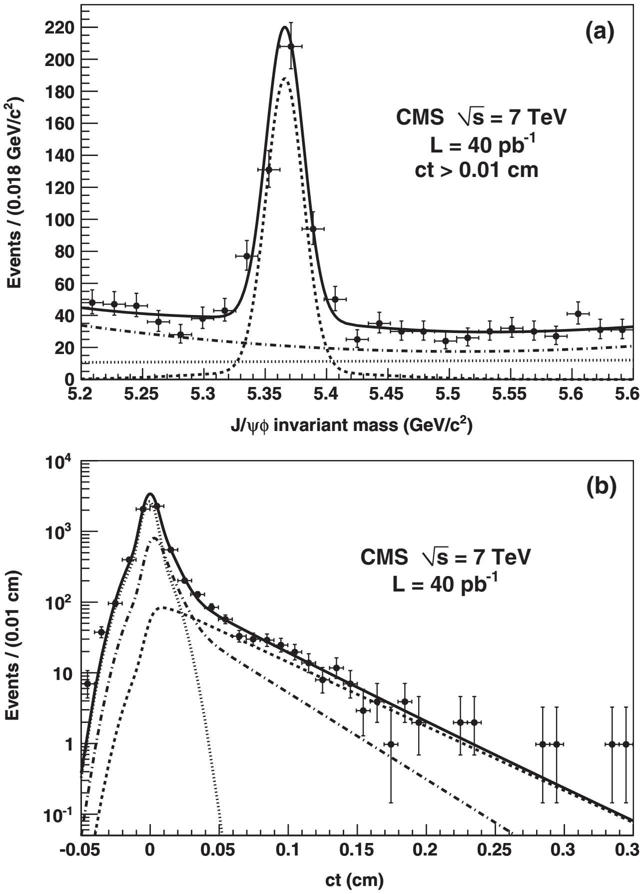

FIG. 1. Projections of the fit results in M_B (a) and ct (b) for $8 < p_T^B < 50\ \text{GeV}/c$ and $|y^B| < 2.4$. The curves in each plot are the sum of all contributions (solid line), signal (dashed line), prompt J/ψ (dotted line), and nonprompt J/ψ (dotted-dashed line). For better visibility of the individual contributions, plot (a) includes the requirement $ct > 0.01$ cm.

The cross section measurement is affected by several sources of systematic uncertainty arising from uncertainties on the fit, efficiencies, branching fractions, and integrated luminosity. In every bin the total uncertainty is about 11%. Uncertainties on the muon efficiencies from the trigger, identification, and tracking are determined directly from data (3%–5%). The uncertainty of the method employed to measure the efficiency in the data has been estimated from a large sample of full-detector simulated events (1%–3%). The tracking efficiency for the charged kaons has been shown to be consistent with simulation. A conservative uncertainty of at most 9% in each bin has been assigned for the hadronic track reconstruction (adding linearly the uncertainties on the two kaon tracks [26]), which includes the uncertainty due to misalignment of the silicon detectors. The uncertainty on the fit procedure arising from potential biases and imperfect knowledge of the PDF parameters is estimated by varying the parameters by 1 standard deviation (2%–4%). The contribution related to the B_s^0 momentum spectrum (1%–3%) is evaluated by reweighting the shape of the p_T^B distribution generated with PYTHIA to match the spectrum predicted by MC@NLO [28]. An uncertainty of 1% is assigned to the variation of the selection criteria applied to the vertex-fit probability, the transverse momentum of the kaons, the B_s^0 transverse momentum, and the K^+K^- invariant mass window. An uncertainty is added to account for the limited number of simulated events (at most 3% in the highest p_T^B bin). The total uncorrelated systematic uncertainty on the cross section measurement is computed in each bin as the sum in quadrature of the individual uncertainties, and is summarized in Table I. In addition, there are common uncertainties of 4% from the integrated luminosity measurement [29] and 1.4% from the J/ψ and ϕ branching fractions. As the reported result is a measurement of the B_s^0 cross

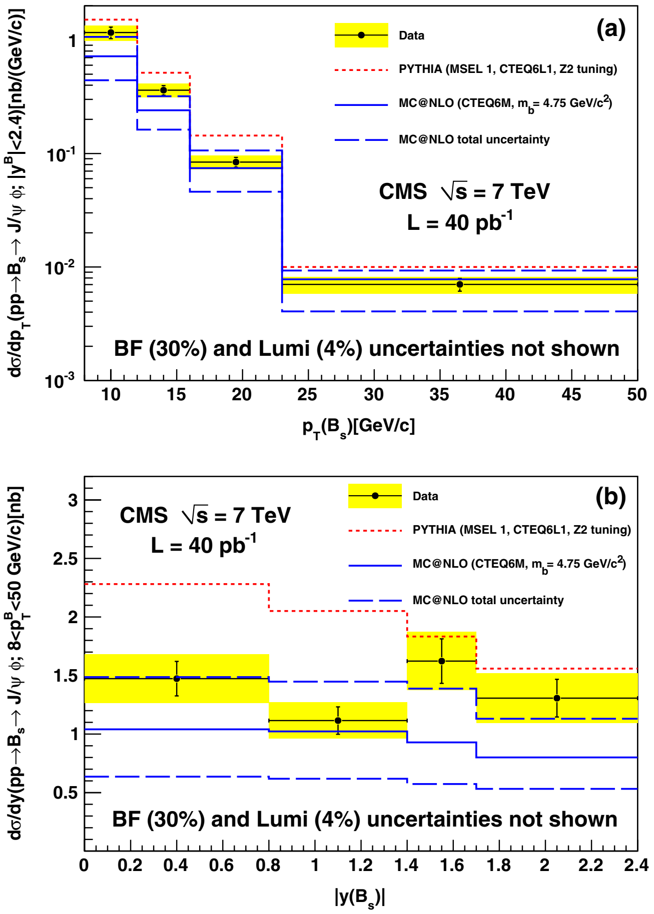

FIG. 2 (color online). Measured differential cross sections $d\sigma/dp_T^B$ (a) and $d\sigma/dy^B$ (b) compared with theoretical predictions. The (yellow) band represents the sum in quadrature of statistical and systematic uncertainties. The dotted (red) line is the PYTHIA prediction; the solid and dashed (blue) lines are the MC@NLO prediction and its uncertainty, respectively. The common uncertainties of 4% on the data points, due to the integrated luminosity, and of 30% on the theory curves, due to the $B_s^0 \to J/\psi\phi$ branching fraction, are not shown.

section times the $B_s^0 \to J/\psi\phi$ branching fraction, the 30% uncertainty on the $B_s^0 \to J/\psi\phi$ branching fraction [19] is not included in the result.

The differential cross sections times branching fractions as functions of p_T^B and $|y^B|$ are listed in Table I and plotted in Fig. 2, together with predictions from MC@NLO and PYTHIA. The predictions of MC@NLO use the renormalization and factorization scales $\mu = \sqrt{m_b^2c^4 + p_T^2c^2}$, where p_T is the transverse momentum of the b quark, a b-quark mass of $m_b = 4.75\ \text{GeV}/c^2$, and the CTEQ6M parton distribution functions [30]. The uncertainty on the MC@NLO cross section is obtained simultaneously varying the renormalization and factorization scales by factors of two, varying m_b by $\pm 0.25\ \text{GeV}/c^2$, and using the CTEQ6.6 parton distribution function set. The prediction of PYTHIA uses the CTEQ6L1 parton distribution functions [30], a b-quark mass of $4.8\ \text{GeV}/c^2$, and the Z2 tune [31] to simulate the underlying event. The total integrated B_s^0 cross section times $B_s^0 \to J/\psi\phi$ branching fraction for the range $8 < p_T^B < 50\ \text{GeV}/c$ and $|y^B| < 2.4$ is measured to be $6.9 \pm 0.6 \pm 0.6$ nb, where the first uncertainty is statistical and the second is systematic. The statistical and systematic uncertainties are derived from the bin-by-bin uncertainties and propagated through the sum. The measured total cross section lies between the theoretical predictions of MC@NLO ($4.6^{+1.9}_{-1.7} \pm 1.4$ nb) and PYTHIA (9.4 ± 2.8 nb), where the last uncertainty is from the $B_s^0 \to J/\psi\phi$ branching fraction [19]. Also the previous CMS cross section measurements of B^+ [14] and B^0 [15] production in pp collisions at $\sqrt{s} = 7$ TeV gave values between the two theory predictions, indicating internal consistency amongst the three different B-meson results.

In summary, the first measurements of the B_s^0 differential cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$, in the decay channel $B_s^0 \to J/\psi\phi$ and in pp collisions at $\sqrt{s} = 7$ TeV, have been presented. The results cover the kinematical window $|y^B| < 2.4$ and $8 < p_T^B < 50\ \text{GeV}/c$. They add complementary information to previous results in moving towards a comprehensive description of b-hadron production at $\sqrt{s} = 7$ TeV.

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