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Contents

1 Introduction

The b-hadron production cross-section has been predicted with next-to-leading-order (NLO) accuracy for more than twenty years [1, 2] and more recently it has been predicted with fixed order plus next-to-leading-logarithms (FONLL) calculations [3, 4]. Several measurements were performed with proton–antiproton collisions by the UA1 collaboration at the S$p\bar{p}$S collider (CERN) at a centre-of-mass energy of $\sqrt{s}$ = 630 GeV [5, 6] and by the CDF and D0 collaborations at the Tevatron collider (Fermilab) at $\sqrt{s}$ = 630 GeV, 1.8 TeV and 1.96 TeV [7–16]. These measurements made a significant contribution to the understanding of heavy-quark production in hadronic collisions [17]. However, the dependence of the theoretical predictions for b-quark production on the factorisation and renormalisation scales and the b-quark mass m_b [2] results in theoretical uncertainties of up to 40% and, therefore, it is important to perform precise measurements of b-hadron production cross-sections. In addition, measurements of b-hadron production cross-sections are of theoretical interest at higher $\sqrt{s}$ [18] and for B mesons of higher transverse momentum (p_{T}) [19].

Measurements of the b-hadron production cross-section in proton–proton collisions at the Large Hadron Collider (LHC) provide further tests of QCD calculations for heavy-quark production at higher centre-of-mass energies and in wider transverse momentum (p_{T}) and rapidity (y) ranges, thanks to the extended coverage and excellent performance of the LHC detectors. Recently the LHCb collaboration measured b-hadron production cross-sections using $B^{\pm} \to J/\psi\, K^{\pm}$, $b \to J/\psi\, X$ and semileptonic b-hadron decays in the forward rapidity region at $\sqrt{s}$ = 7 TeV [20–22]. The CMS collaboration measured the production cross-sections for B^{+}, B^{0}, B_s mesons, Λ_b baryons, and inclusive b-hadron production using $b \to$

$J/\psi\, X$ decays, semileptonic decays, and b-hadron jets at $\sqrt{s} = 7$ TeV [23–30]. ATLAS has measured b-hadron production cross-sections using semileptonic decays [31, 32], $b \to J/\psi\, X$ decays [33] and b-hadron jets [34].

This paper presents a measurement of the B^+ production cross-section using the decay channel $B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+$ in pp collisions at $\sqrt{s} = 7$ TeV, as a function of B^+ transverse momentum and rapidity. The ATLAS and CMS detectors provide coverage in the central rapidity region, so their measurements are complementary to the LHCb measurements. With 2.4 fb^{-1} of data collected by the ATLAS detector, this analysis extends the measurement of the B^+ cross-section up to p_{T} of about 100 GeV, allowing comparisons with NLO predictions in four rapidity regions in the range $|y| < 2.25$ to be made. The results are reported for B^+ meson production, but are derived from both charged states, under the assumption that in the phase space accessible by this measurement the B^+ and B^- production cross-sections are equal. This assumption is in agreement with the predictions of NLO Monte Carlo generators and is also valid within the precision of the measurement.

2 The ATLAS detector

The ATLAS experiment [35] uses a general-purpose detector [1] consisting of an inner tracker, a calorimeter and a muon spectrometer. A brief outline of the components that are most relevant for this analysis is given below. The inner detector (ID) directly surrounds the interaction point; it includes a silicon pixel detector (Pixel), a silicon microstrip detector (SCT) and a transition radiation tracker (TRT), and is embedded in an axial 2 T magnetic field. The ID covers the range $|\eta| < 2.5$ and is enclosed by a calorimeter system containing electromagnetic and hadronic sections. The calorimeter is surrounded by a large muon spectrometer (MS) inside an air-core toroidal magnet system that contains a combination of monitored drift tubes (MDTs) and cathode strip chambers (CSCs), designed to provide precise position measurements in the bending plane in the range $|\eta| < 2.7$. In addition, resistive plate chambers (RPCs) and thin gap chambers (TGCs) with a coarse position resolution but a fast response time are used primarily to trigger muons in the ranges $|\eta| < 1.05$ and $1.05 < |\eta| < 2.4$, respectively. RPCs and TGCs are also used to provide position measurements in the non-bending plane and to improve pattern recognition and track reconstruction. Momentum measurements in the MS are based on track segments formed in at least two of the three stations of the MDTs and the CSCs.

The ATLAS trigger system [36] has three levels: the hardware-based Level-1 trigger and the two-stage High Level Trigger (HLT), comprising the Level-2 trigger and Event Filter (EF). At Level-1, the muon trigger searches for patterns of hits satisfying different p_{T} thresholds using the RPCs and TGCs. The region-of-interest (RoI) around these Level-1 hit patterns then serves as a seed for the HLT muon reconstruction, in which dedicated

[1] ATLAS uses a right-handed coordinate system (x, y, z) with its origin at the nominal interaction point. The z-axis is along the beam pipe, the x-axis points to the centre of the LHC ring and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle.

algorithms are used to incorporate information from both the MS and the ID, achieving a position and momentum resolution close to that provided by the offline muon reconstruction.

3 Data and Monte Carlo samples

The analysis is based on data collected at the LHC during the proton–proton running period in the early 2011 (April–August) with a dimuon trigger that required the presence of at least two muon candidates with $p_{\mathrm{T}} > 4$ GeV. Later run periods are not considered because this trigger was prescaled. Selected events are required to have occurred during stable LHC beam conditions and the ID, as well as the MS, must have been fully operational. The collected data correspond to an integrated luminosity of 2.4 fb^{-1} with an uncertainty of 1.8% [37].

In the analysis two Monte Carlo (MC) samples are used. The first sample simulates the signal $B^{\pm} \to J/\psi\, K^{\pm} \to \mu^{+}\mu^{-}\, K^{\pm}$, while the second simulates $b\bar{b}$ production, with $b\bar{b} \to J/\psi\, X \to \mu^{+}\mu^{-}\, X$, including the signal and also the backgrounds which are relevant for the analysis. Both samples were generated with Pythia 6 [38] using the 2011 ATLAS tune [39]. The response of the ATLAS detector was simulated [40] using Geant4 [41]. Additional pp interactions in the same and nearby bunch crossings (pile-up) were included in the simulation.

The MC samples are used in several parts of the analysis. The first is the extraction of the fit models for signal and background. The second is the construction of efficiency maps for the muon trigger and reconstruction. The third is the estimation of the signal reconstruction efficiency and the kinematic acceptance of the selection criteria applied to the final-state particles in each p_{T} and rapidity interval used in the analysis. In the MC samples generated with Pythia, the decay $J/\psi \to \mu^{+}\mu^{-}$ is isotropic. In order to take into account that the J/ψ meson is produced with zero helicity in the $B^{\pm}$ rest frame, in the analysis a weight proportional to $\sin^{2}\theta^{*}$ is applied to each event, where θ^{*} is the μ^{+} angle relative to the $B^{\pm}$ direction in the J/ψ rest frame.

To compare the cross-section measurements with theoretical predictions, NLO QCD calculations matched with a leading-logarithmic parton shower MC simulation are used. Predictions for $b\bar{b}$ production are evaluated with two packages: Powheg-hvq (Powheg-Box 1.0) [42, 43] and MC@NLO 4.01 [44, 45]. For the hadronisation process, Powheg is matched with Pythia, which uses the Lund string model [46] with the Bowler modification [47] of the Lund symmetric fragmentation function [48]. MC@NLO is matched with Herwig [49], which uses a cluster model for hadronisation [50]. The b-quark production cross-section is also calculated in the FONLL theoretical framework [19], permitting direct comparison with the data assuming the world average of the hadronisation fraction $f_{\bar{b}\to B^{+}} = 0.401 \pm 0.008$ [51]. The theoretical uncertainties associated with the Powheg, MC@NLO and FONLL predictions are discussed in section 7 where the comparisons to the measured cross-sections are made.

4 Event selection and reconstruction

Events for the analysis were selected with a trigger that requires two muon RoIs at Level-1. A full track reconstruction of dimuon candidates was performed by the HLT where both muons are required to have $p_{\mathrm{T}} > 4$ GeV and fullfill additional requirements, loosely selecting events compatible with J/ψ meson decays into a muon pair.

Events selected by the trigger are required to have at least one reconstructed primary vertex with a minimum of three associated tracks. Tracks reconstructed in the ID which are matched to tracks reconstructed in the MS are selected as muon candidates. Muon candidates are required to have sufficient numbers of hits in the Pixel, SCT and TRT detectors to ensure accurate ID measurements. The same selection criteria are applied to tracks selected as potential $K^{\pm}$ candidates.

Events are required to contain at least one pair of reconstructed oppositely signed muons that fit successfully to a common vertex, using a vertexing algorithm [52]. The momenta of the muons and the dimuon invariant mass are calculated from the refitted track parameters returned by the vertexing algorithm. Muon pairs with a common vertex are considered as $J/\psi \to \mu^+\mu^-$ candidates if their invariant mass lies in the mass range 2.7–3.5 GeV. Because of the trigger requirements on muons, the reconstructed J/ψ candidate must have rapidity $|y| < 2.25$ and the reconstructed muons $p_{\mathrm{T}} > 4$ GeV and $|\eta| < 2.3$. To ensure that the muon pair from the J/ψ candidate is the one that triggered the event, an (η, ϕ) match between the trigger muons and those of the J/ψ candidate is required. If multiple J/ψ candidates are found in the event, all are considered in the formation of $B^{\pm}$ candidates.

The muon tracks of the selected J/ψ candidates are again fitted to a common vertex with an additional third track with p_{T} greater than 1 GeV. The three-track vertex fit is performed by constraining the muon tracks to the J/ψ mass [51]. The $K^{\pm}$ mass is assigned to the third track and the $\mu^+\mu^-K^{\pm}$ invariant mass is calculated from the refitted track parameters returned by the vertexing algorithm. Regarding the quality of the three-track vertex fit, the χ^2 per degree of freedom must be $\chi^2/N_{\mathrm{d.o.f.}} < 6$, which is found to select about 99% of signal events while rejecting background events. We retain B^+ and B^- candidates with $p_{\mathrm{T}} > 9$ GeV and $|y| < 2.25$ in the mass range 5.040–5.800 GeV. After this selection, the average candidate multiplicity is 1.3. The multiple $B^{\pm}$ candidates result mainly from random combinations of tracks with selected J/ψ mesons produced promptly in pp collisions. Such combinations result in non-resonant background and do not affect the estimation of the signal yield.

5 Cross-section determination

The differential cross-section for B^+ meson production in pp collisions times branching ratio to the final state is given by

$$\frac{\mathrm{d}^2\sigma(pp \to B^+X)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \cdot \mathscr{B} = \frac{N^{B^+}}{\mathscr{L} \cdot \Delta p_{\mathrm{T}} \cdot \Delta y} , \tag{5.1}$$

where $\mathscr{B}$ is the total branching ratio of the signal decay, which is $(6.03 \pm 0.21) \times 10^{-5}$, obtained by combining the world-average values of the branching ratios for $B^+ \to J/\psi\, K^+$

and $J/\psi \to \mu^+\mu^-$ [51], N^{B^+} is the number of $B^+ \to J/\psi\, K^+$ signal decays produced, $\mathscr{L}$ is the integrated luminosity of the data sample and Δp_{T}, Δy are the widths of p_{T} and y intervals. Assuming that B^+ and B^- mesons are produced in equal numbers, N^{B^+} is derived from the average yield of the two reconstructed charged states in a (p_{T}, y) interval, after correcting for detector effects and acceptance,

$$N^{B^+} = \frac{1}{A}\frac{N^{B^+}_{\mathrm{reco}}}{\varepsilon^{B^+}} = \frac{1}{A}\frac{N^{B^-}_{\mathrm{reco}}}{\varepsilon^{B^-}} = \frac{1}{A}\frac{N^{B^\pm}_{\mathrm{reco}}}{\varepsilon^{B^+} + \varepsilon^{B^-}} \ , \tag{5.2}$$

where $N^{B^\pm}_{\mathrm{reco}}$ is the number of reconstructed signal events, obtained from data with a fit to the invariant mass distribution of $B^\pm$ candidates, A is the acceptance of the kinematic selection of the final-state particles of the signal decay, obtained from MC simulation, and ε^{B^+}, ε^{B^-} are the reconstruction efficiencies for the $B^\pm$ signal decays. Separate efficiency is needed for B^+ and B^- signal decays, because the different interaction cross-sections of K^+ and K^- with the detector material result in different reconstruction efficiencies for the two charged mesons. The reconstruction efficiencies for B^+ and B^- are obtained from MC simulation. In the following, ε^{B^-} is implicitly referred to, together with ε^{B^+}. The efficiency for B^+ events is defined as the product of trigger, muon reconstruction (ID and MS), kaon reconstruction and vertexing efficiencies,

$$\varepsilon^{B^+} = \varepsilon^{J/\psi}_{\mathrm{trigger}} \cdot \varepsilon^{\mu^+} \cdot \varepsilon^{\mu^-} \cdot \varepsilon^{K^+}_{\mathrm{ID}} \cdot \varepsilon^{\mu\mu K}_{\mathrm{vertex}} = \varepsilon^{J/\psi}_{\mathrm{trigger}} \cdot \varepsilon^{\mu^+}_{\mathrm{MS}} \cdot \varepsilon^{\mu^-}_{\mathrm{MS}} \cdot (\varepsilon^{\mu}_{\mathrm{ID}})^2 \cdot \varepsilon^{K^+}_{\mathrm{ID}} \cdot \varepsilon^{\mu\mu K}_{\mathrm{vertex}} \ .$$

In the above equation, $\varepsilon^{\mu^+}_{\mathrm{MS}}$ and $\varepsilon^{\mu^-}_{\mathrm{MS}}$ are the efficiencies for reconstructing μ^+ and μ^- in the MS, which differ for muons of low p_{T} and large $|\eta|$ because of the bending of tracks in the toroidal magnetic field. This effect is to large extent symmetric for a simultaneous change of sign in the muon charge and in η. The trigger efficiency, $\varepsilon^{J/\psi}_{\mathrm{trigger}}$, depends on the ability of the trigger to identify muons of given p_{T} and η as decay products of a J/ψ meson. The trigger efficiency includes independent and correlated terms between the two muons [53]. The efficiency ε^{B^+} for a given (p_{T}, y) interval is obtained from MC-simulated signal events from the fraction

$$\varepsilon^{B^+} = \frac{N^{B^+}_{\mathrm{MC,reco}}}{N^{B^+}_{\mathrm{MC,\,gen}}} \ , \tag{5.3}$$

where the denominator is the number of signal events generated in a given interval of the generated p_{T} and y and the numerator is the number of signal events that pass the trigger and the offline selection requirements in the same (p_{T}, y) interval of the reconstructed variables. Bin-to-bin migration effects are included in the efficiency definition of eq. (5.3). The trigger and muon reconstruction efficiencies are measured in the data using auxiliary single muon and dimuon triggers and tag-and-probe methods [53] and the simulation is corrected with per-event weights to reproduce the efficiencies measured with data. The derived weights, $w^{\mu^+}_{\mathrm{MS}}$, $w^{\mu^-}_{\mathrm{MS}}$, $w^{J/\psi}_{\mathrm{trigger}}$, are applied in each reconstructed MC-simulated signal event, so that $N^{B^+}_{\mathrm{MC,\,reco}}$ in eq. (5.3) is now defined as

$$N^{B^+}_{\mathrm{MC,\,reco}} = \sum_{i=1}^{N^{\mathrm{events}}_{\mathrm{MC}}} (w^{\mu^+}_{\mathrm{MS}})_i \cdot (w^{\mu^-}_{\mathrm{MS}})_i \cdot (w^{J/\psi}_{\mathrm{trigger}})_i \ , \tag{5.4}$$

where $N_{\rm MC}^{\rm events}$ is the number of reconstructed MC-simulated signal events before applying the weights derived from data. The efficiency for reconstructing muons in the ID, $\varepsilon_{\rm ID}^{\mu}$, and the vertexing efficiency, $\varepsilon_{\rm vertex}^{\mu\mu K}$, are found to be equal to 99% and are well reproduced by the MC simulation. The reconstruction efficiency for hadrons in the ID was verified in ref. [54] for data and simulation; for the kaons used in this analysis, the efficiency is obtained from simulation.

The number of reconstructed $B^{\pm}$ mesons is obtained using a binned maximum likelihood fit to the invariant mass distribution of the selected candidates. The probability density function (pdf) for the signal is defined as the sum of two Gaussians of relative fraction f_1 and corresponding widths σ_1, σ_2, both centred at the reconstructed $B^{\pm}$ mass. The pdf for the background consists of three components to model the following three sources of background:

- $B^{\pm} \to J/\psi\,\pi^{\pm}$, where the kaon mass is wrongly assigned to the pion; this decay is Cabibbo suppressed with a relative fraction of 4.9% [51] with respect to the signal decay; it produces a resonant structure in the signal region that is modelled with a Crystal Ball function (see appendix E of ref. [55].

- $B^{\pm/0} \to J/\psi\,K^{*\pm/0} \to J/\psi\,(K\pi)^{\pm/0}$ and $B^{\pm/0} \to J/\psi\,(K\pi)^{\pm/0}$, where the final-state pion is not associated to the decay vertex, creating a resonant structure displaced from the $B^{\pm}$ mass by about m_{π}, where m_{π} is the mass of the pion; these partially reconstructed B-decays are modelled with a complementary error function.

- Combinatorial background from random combinations of J/ψ (produced promptly in pp collisions or in feed-down from B-decays) with a track; it is modelled with an exponential function. The background from muon pairs not originating from J/ψ decays is negligible after the full $B^{\pm}$ candidate selection.

The extraction of the signal yield is done in two steps. First, the shapes of the signal and the resonant background pdfs, which depend on the $p_{\rm T}$ and y of the $B^{\pm}$ meson candidate, are obtained by fitting the invariant mass distribution of signal and background events from MC samples in each $(p_{\rm T}, y)$ interval. Then the invariant mass distribution of the data is fitted in the same $(p_{\rm T}, y)$ interval. The parameters for the shape of the signal pdf (σ_1, σ_2 and f_1) and the resonant backgrounds are fixed to the results of the fits to MC event samples. The relative normalisation of the $B^{\pm} \to J/\psi\,\pi^{\pm}$ decay to the signal is fixed to the fraction of the world-average values for their branching ratios, and is corrected for the difference in acceptance for the two decay modes. The reconstructed mass $m_{B^{\pm}}$ is obtained from data for the full $p_{\rm T}$ range in a rapidity interval by fitting the invariant mass distribution of the selected candidates, and is fixed throughout the fits in $p_{\rm T}$ intervals. Therefore, when fitting the data in each $(p_{\rm T}, y)$ interval, the free parameters are the normalisation of the signal, the normalisation of the partially reconstructed B-decays, and the slope of the combinatorial background. The results of the fits to the invariant mass distributions of the selected $B^{\pm}$ candidates from data are exemplified in figure 1 for an interval of intermediate $p_{\rm T}$ and central rapidity. The stability of the fit was tested with simulated samples of signal and background with statistical size similar to our data and no evidence of bias in the fit was found.

The total number of signal $B^{\pm}$ events observed in data in the full p_{T} and y range covered by the analysis, 9 GeV $< p_{\mathrm{T}} <$ 120 GeV and $|y| < 2.25$, before acceptance and efficiency corrections, is about 125600. These events populate four intervals in $|y|$ and eight intervals in p_{T} for the differential cross-section measurement. The acceptance correction, A, has a small dependence on y and ranges from 4% to 85% from the low to the high p_{T} intervals. The efficiency ε^{B^+} has a dependence on both y and p_{T} and ranges from 25% to 40%. The relative difference between the efficiencies for reconstructing B^+ and B^- mesons, $(\varepsilon^{B^+} - \varepsilon^{B^-})/\varepsilon^{B^+}$, has a dependence on p_{T} and ranges from 5% to 2%.

The assumption of equal B^+ and B^- production is tested by fitting the invariant mass distribution of B^+ and B^- candidates separately. The resulting yields, before applying efficiency corrections, are 63530 ± 840 and 62090 ± 840 respectively, where the quoted uncertainties are statistical. Taking into account the different efficiencies for reconstructing B^+ and B^- mesons, the ratio of B^+/B^- is found to be consistent with unity, within the statistical precision of this test.

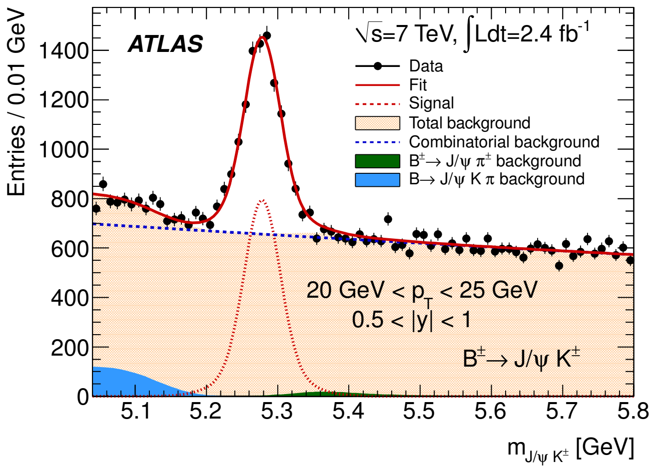

Figure 1. The observed invariant mass distribution of $B^{\pm}$ candidates, $m_{J/\psi K^{\pm}}$, with transverse momentum and rapidity in the range 20 GeV $< p_{\mathrm{T}} <$ 25 GeV, $0.5 < |y| < 1$ (dots), compared to the binned maximum likelihood fit (solid line). The error bars represent the statistical uncertainty. Also shown are the components of the fit as described in the legend.

6 Systematic uncertainties

Various sources of systematic uncertainty on the measurement of the B^+ production cross-section are considered and discussed below:

1. **Trigger.** The trigger efficiency is obtained from data in bins of p_{T} and $q \cdot \eta$ of the muon, where q is the muon charge, using a tag-and-probe method [53]. Then, the correction weights for the trigger efficiency $w^{J/\psi}_{\mathrm{trigger}}$ (see eq. (5.4)) are obtained from the

fraction of the measured efficiency from data over the expectation from simulation in each $(p_{\mathrm{T}}, q{\cdot}\eta)$ bin. As the statistical components of the uncertainty associated with the weights for the trigger efficiency are dominant, the uncertainties on the cross-section are derived from a series of pseudo-experiments by allowing the weights to fluctuate randomly under a Gaussian assumption, according to their assigned uncertainty.

2. **Fit.** For the fit method, three sources of systematic uncertainty are identified and considered to be uncorrelated. These are the shape of the signal pdf, the reconstructed $B^{\pm}$ mass and the shape of the background pdf. Below, the procedure to estimate the systematic uncertainty from each source is described, and the resulting uncertainties are added quadratically to obtain the total systematic uncertainty from the fit method in each (p_{T}, y) interval.

   (a) *Uncertainty on shape of the signal pdf.* This uncertainty is estimated with variations of the fit model, where the values of the signal pdf parameters σ_1, σ_2, f_1 are varied independently within their uncertainties derived from the fit to signal events from MC simulation. From these variations of the fit model, the largest absolute value of the signal yield variation is taken as the systematic uncertainty from the signal pdf shape, in order to account for the large correlations of these parameters. Two alternative pdfs were considered (three Gaussians, two Crystal Ball + Gaussian) and no significant differences in the signal yield were observed. Among the various sources of systematic uncertainty considered for the fit method, the signal pdf is dominant and its contribution ranges from 1% to 8%.

   (b) *Uncertainty on the $B^{\pm}$ mass value.* The reconstructed mass $m_{B^{\pm}}$ is obtained from data by fitting the invariant mass distribution of all candidates with $p_{\mathrm{T}} >$ 9 GeV in each of the four rapidity intervals. The resulting values are used to fix this parameter when performing the fits in the various (p_{T}, y) intervals and their statistical uncertainties (0.4–1.0 MeV) are used to estimate the systematic uncertainty on the signal yield. The fits in the various (p_{T}, y) intervals are repeated varying the value of $m_{B^{\pm}}$ within its statistical uncertainty. The observed difference in the signal yield is smaller than 1%.

   (c) *Uncertainty on the shape of the background pdf.* The fit includes three components for the description of the background (see below), and each contributes as a possible source of uncertainty. In order to account for the large correlations between the three components, the systematic uncertainty assigned to the background modelling for each (p_{T}, y) interval is obtained after varying each component independently, and taking the largest observed difference in the signal yield.

      i. Combinatorial background: with a polynomial instead of exponential shape for the combinatorial bacground; the observed relative difference in the signal yield ranges from 0.1% to 4%, where the larger change is observed for higher values of y and p_{T}.

ii. $B^{\pm} \to J/\psi\,\pi^{\pm}$: for the resonant background from $B^{\pm} \to J/\psi\,\pi^{\pm}$, the dominant uncertainty comes from the relative branching fraction of this decay with respect to the signal, which has an uncertainty of 10% [51]. Varying this fraction in the fit within its uncertainty was found to have a small effect on the signal yield (∼1%).

iii. Partially reconstructed B-decays: the resonant background from partially reconstructed B-decays is modelled with a complementary error function. When varying its parameters within their uncertainties from the fits to background events from MC simulation, the observed difference in the signal yield is smaller than 1%.

3. **Kaon track reconstruction.** The efficiency of hadron reconstruction is determined from MC simulation and validated with data [54], with the uncertainty dominated by the material description. The uncertainty ranges with increasing rapidity from 2% to 4% for the kaons used in this analysis.

4. **Acceptance.** The acceptance in each (p_{T}, y) interval has a relative uncertainty ranging from 1% to 4%, due to the size of the MC sample, which is assigned as systematic uncertainty.

5. **Muon reconstruction.** The muon reconstruction efficiency is obtained from data in bins of p_{T} and $q \cdot \eta$ of the muon, using a tag-and-probe method [53]. Then, the correction weights w^{μ}_{MS} (see eq. (5.4)) are obtained from the fraction of the measured efficiency from data over the expectation from simulation in each $(p_{\mathrm{T}}, q \cdot \eta)$ bin. The uncertainties associated with the weights for the muon reconstruction efficiency are mainly statistical, so the same procedure as for the trigger efficiency is used to estimate the systematic uncertainty on the cross-section. In addition, there is also an uncertainty coming from the efficiency for reconstructing a muon in the ID with the selection criteria used in this analysis. This efficiency is found to be 99% with a systematic uncertainty of 0.5% for each muon.

6. **$B^{\pm}$ vertex-finding efficiency.** The vertex quality requirement has an efficiency of ∼99% and is fairly independent of p_{T} and y. It was estimated with data by comparing the signal yields in four rapidity intervals before and after applying this requirement and is found to be consistent with the expectation from MC simulation. A systematic uncertainty of 2% is assigned to the cross-section, as the maximum difference observed between the estimate from data and the expectation from MC simulation for this efficiency.

7. **Branching ratio.** The total branching ratio of the selected decay, obtained by combining the branching ratios of the decays $B^{\pm} \to J/\psi K^{\pm}$ and $J/\psi \to \mu^{+}\mu^{-}$, has an uncertainty of 3.4% [51].

8. **Luminosity.** The luminosity calibration is based on data from van der Meer scans and has an uncertainty of 1.8% [37].

9. **Signal efficiency.** The efficiency correction factor for $B^{\pm}$ signal events is obtained from MC simulation (eq. (5.3)). The systematic uncertainty assigned to this factor has two components, which are added in quadrature:

   (a) *Uncertainty from the size of the MC sample.* The sample used for the estimation of the efficiency correction factor corresponds to a luminosity similar to that of the data sample. Due to the size of this sample, the efficiency estimation has an uncertainty that is small ($\sim$1%) in most intervals and becomes significant in the high-p_{T} interval 70–120 GeV ($\sim$10%). It is added quadratically to the rest of the sources of uncertainty.

   (b) *Uncertainty from K^+/K^- efficiency asymmetry.* The efficiencies for reconstructing K^+ and K^- mesons are obtained from simulation and their relative difference is found to be $\sim$3.5%. This difference is verified with data and the statistical uncertainty of the estimate from data is used to assign a systematic uncertainty of 1%, which propagates to the cross-section through the sum of efficiencies $(\varepsilon^{B^+} + \varepsilon^{B^-})$ in eq. (5.2).

The range of these uncertainties is summarised in table 1. Their breakdown in (p_{T}, y) intervals is given in figure 2. In the same figure, the total systematic uncertainty, including the uncertainties from the luminosity and branching ratio, is compared to the statistical precision of the measurement. In most intervals, the systematic uncertainty dominates.

Additional sources of systematic uncertainty were examined, but were found to be less significant and were neglected. Residual effects related to final-state radiation have been determined to be smaller than 1% and are neglected. Differences in the underlying kinematic distributions modelled by the Pythia and NLO generators, including parton distribution

	Relative uncertainty [%]			
Source	$\lvert y\rvert < 0.5$	$0.5 < \lvert y\rvert < 1$	$1 < \lvert y\rvert < 1.5$	$1.5 < \lvert y\rvert < 2.25$
Statistical uncertainty	2.2–14	2.5–17	3.2–22	3.8–24
Total systematic uncertainty	6.7–14	6.5–13	6.9–16	7.6–18
1. Trigger	3.8–7.4	3.2–6.2	3.4–7.0	3.6–8.8
2. Invariant mass fit	1.8–3.4	1.7–5.3	2.4–8.9	2.6–7.6
3. Kaon reconstruction	2.2	2.2–2.4	2.5–2.9	3.5–4.0
4. Acceptance	0.9–3.5	0.9–3.6	1.0–4.2	1.0–5.8
5. Muon reconstruction	0.5–1.3	0.5–1.7	0.5–2.1	0.6–5.4
6. $B^{\pm}$ vertexing	2.0	2.0	2.0	2.0
7. Branching ratio	3.4	3.4	3.4	3.4
8. Luminosity	1.8	1.8	1.8	1.8
9. Signal efficiency	1.3–10	1.3–9.1	1.3–9.5	1.2–12

Table 1. The statistical and total systematic uncertainties on the cross-section measurement in different ranges of rapidity y. The contributions from the various sources of systematic uncertainty are also given. The range of values quoted for some of the uncertainties represent the lower and upper limit of the uncertainty over the p_{T} range in a given rapidity range.

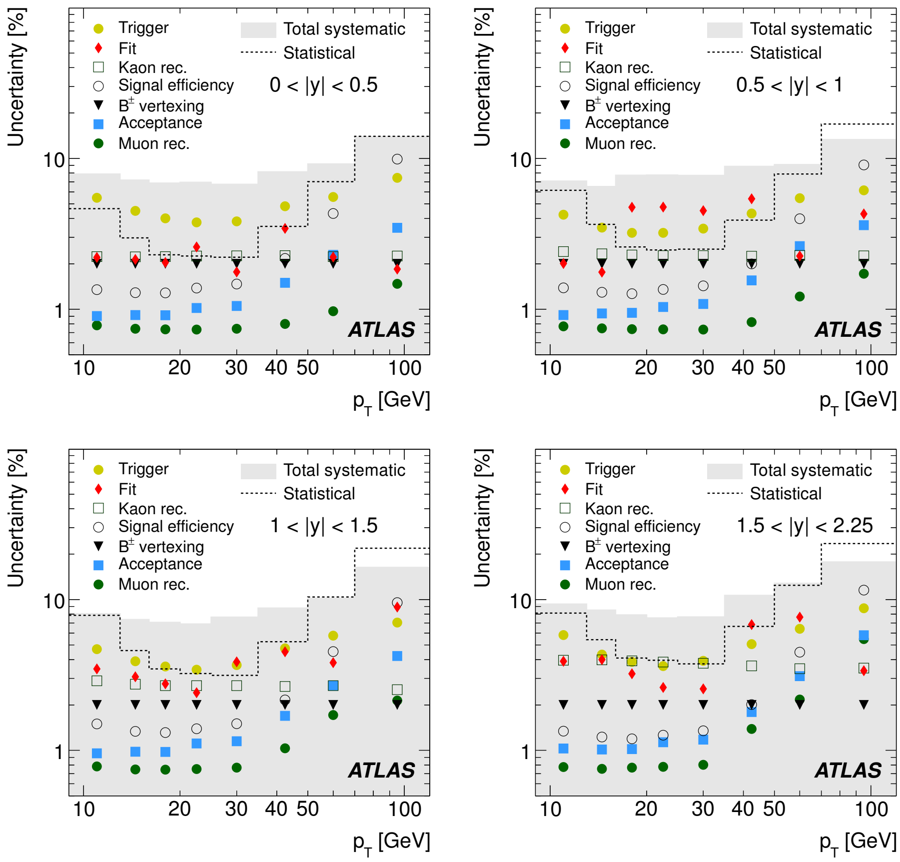

Figure 2. Relative systematic uncertainties on the cross-section determination as a function of p_{T} for different rapidity ranges. The total systematic uncertainty (solid area), including uncertainties from luminosity (1.8%) and branching ratio (3.4%), is compared to the statistical uncertainty (dashed line).

functions, were considered. The impact on the acceptance and the signal efficiency was estimated by reweighting the kinematic distributions of PYTHIA to those of POWHEG and MC@NLO. The largest effect is seen in the high-rapidity intervals ($1.5 < |y| < 2.25$), where the maximum relative difference observed is 1%, with a statistical uncertainty of the same order, while in most (p_{T}, y) intervals the effect is very small ($\sim$0.1%). Bin-to-bin migration of signal events due to finite detector resolution is studied with MC simulation. It is found to be a small effect (<0.5%), which is included in the definition of signal efficiency (eq. (5.3)). Potential effects in the calculation of the signal efficiency due to the difference between the momentum scales in data and MC simulation are expected to be larger in the lower p_{T} intervals used in this analysis, where they were estimated to be smaller than 0.5%.

7 Cross-section results

Using eq. (5.1), the differential cross-section for B^+ production times the product of branching ratios $\mathscr{B}$ is obtained as a function of p_T and y of the B^+ meson and the results are shown in tables 2 and 3, averaged over each (p_T, y) interval. The double-differential cross-section is integrated over p_T to obtain the differential cross-section $\mathrm{d}\sigma/\mathrm{d}y$, or over rapidity to obtain $\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}$, and results are reported in tables 4 and 5. When summing over the intervals in p_T or rapidity, the systematic uncertainty from each source is calculated from the linear sum of the contributions from each interval, as they are correlated. Tabulated results of the measurements presented in this paper are available in HepData [56].

p_T interval [GeV]	$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} \cdot \mathcal{B}(B^+ \to J/\psi K^+) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)$ [pb/GeV] $0 < \lvert y\rvert < 0.5$	$0.5 < \lvert y\rvert < 1$
9–13	24.5 ± 1.1 ± 1.7	21.7 ± 1.3 ± 1.4
13–16	8.7 ± 0.3 ± 0.6	8.5 ± 0.3 ± 0.5
16–20	3.76 ± 0.09 ± 0.22	3.9 ± 0.10 ± 0.27
20–25	1.54 ± 0.04 ± 0.09	1.57 ± 0.04 ± 0.11
25–35	0.467 ± 0.010 ± 0.027	0.468 ± 0.012 ± 0.033
35–50	0.097 ± 0.003 ± 0.007	0.095 ± 0.004 ± 0.008
50–70	0.0165 ± 0.0012 ± 0.0014	0.0178 ± 0.0014 ± 0.0015
70–120	0.00188 ± 0.00026 ± 0.00025	0.00202 ± 0.00034 ± 0.00026

Table 2. Differential cross-section measurement for B^+ production multiplied by the branching ratio to the final state, averaged over each (p_T, y) interval in the rapidity range $|y| < 0.5$ and $0.5 < |y| < 1$. The first quoted uncertainty is statistical, the second uncertainty is systematic.

p_T interval [GeV]	$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} \cdot \mathcal{B}(B^+ \to J/\psi K^+) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)$ [pb/GeV] $1 < \lvert y\rvert < 1.5$	$1.5 < \lvert y\rvert < 2.25$
9–13	23.6 ± 1.9 ± 1.7	22.3 ± 1.8 ± 1.9
13–16	8.0 ± 0.4 ± 0.5	7.1 ± 0.4 ± 0.6
16–20	3.29 ± 0.11 ± 0.20	2.90 ± 0.12 ± 0.21
20–25	1.32 ± 0.04 ± 0.08	1.08 ± 0.04 ± 0.07
25–35	0.408 ± 0.013 ± 0.028	0.312 ± 0.012 ± 0.022
35–50	0.073 ± 0.004 ± 0.006	0.055 ± 0.004 ± 0.006
50–70	0.0135 ± 0.0014 ± 0.0013	0.0097 ± 0.0012 ± 0.0012
70–120	0.00095 ± 0.00021 ± 0.00015	0.00083 ± 0.00019 ± 0.00014

Table 3. Differential cross-section measurement for B^+ production multiplied by the branching ratio to the final state, averaged over each (p_T, y) interval in the rapidity range $1 < |y| < 1.5$ and $1.5 < |y| < 2.25$. The first quoted uncertainty is statistical, the second uncertainty is systematic.

Using the world-average values for the branching ratio $\mathscr{B}$, the differential cross-sections obtained are compared to predictions of Powheg (+Pythia) and MC@NLO (+Herwig)

p_{T} interval [GeV]	$\frac{d\sigma}{dp_{\mathrm{T}}} \cdot \mathcal{B}(B^+ \to J/\psi K^+) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)$ [pb/GeV] $\|y\| < 2.25$
9–13	103 ± 4 ± 8
13–16	36.0 ± 0.8 ± 2.3
16–20	15.3 ± 0.3 ± 1.0
20–25	6.1 ± 0.1 ± 0.4
25–35	1.81 ± 0.03 ± 0.12
35–50	0.348 ± 0.008 ± 0.028
50–70	0.062 ± 0.003 ± 0.005
70–120	0.0061 ± 0.0006 ± 0.0007

Table 4. Differential cross-section measurement for B^+ production multiplied by the branching ratio to the final state, averaged over each p_{T} interval in the rapidity range $|y| < 2.25$. The first quoted uncertainty is statistical, the second uncertainty is systematic.

$\|y\|$ interval	$\frac{d\sigma}{dy} \cdot \mathcal{B}(B^+ \to J/\psi K^+) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)$ [pb] 9 GeV $< p_{\mathrm{T}} <$ 120 GeV
0.0–0.5	154 ± 5 ± 10
0.5–1.0	143 ± 6 ± 9
1.0–1.5	144 ± 8 ± 10
1.5–2.25	132 ± 7 ± 11

Table 5. Differential cross-section measurement for B^+ production multiplied by the branching ratio to the final state, averaged over each y interval in the p_{T} range 9 GeV$< p_{\mathrm{T}} <$ 120 GeV. The first quoted uncertainty is statistical, the second uncertainty is systematic.

and the FONLL approximations. For POWHEG and MC@NLO the CT10 [57] parameterisation for the parton distribution function of the proton is used, while for FONLL calculations the CTEQ6.6 [58] parameterisation is used. In all cases, a b-quark mass of 4.75 ± 0.25 GeV is used, with the renormalisation and factorisation scales, μ_r, μ_f, set to $\mu_r = \mu_f = \mu$, where μ has different definitions for the POWHEG, MC@NLO and FONLL predictions.[1] The predictions are quoted with uncertainties due to the b-quark mass and renormalisation and factorisation scales. Uncertainties from factorisation and renormalisation scales are estimated by varying them independently up and down by a factor of two [19].

POWHEG and MC@NLO predictions are compared with the double-differential cross-section measurement in figure 3. To allow a better comparison between the measured cross-sections and the NLO predictions, figure 4 shows their ratio for each rapidity range separately for POWHEG and MC@NLO. The data are in good agreement with POWHEG in all rapidity intervals. MC@NLO, however, predicts a lower production cross-section at low

[1]For POWHEG: $\mu^2 = m_Q^2 + (m_{Q\bar{Q}}^2/4 - m_Q^2)\sin^2\theta_Q$, where $m_{Q\bar{Q}}$ is the invariant mass of the $Q\bar{Q}$ system and θ_Q is the polar angle of the heavy quark in the $Q\bar{Q}$ rest frame. For MC@NLO: $\mu^2 = m_Q^2 + (p_{\mathrm{T},\,Q} + p_{\mathrm{T},\,\bar{Q}})^2/4$, where $p_{\mathrm{T},\,Q}$ and $p_{\mathrm{T},\,\bar{Q}}$ are the transverse momenta of the produced heavy quark and antiquark respectively, and m_Q is the heavy-quark mass. For FONLL: $\mu = \sqrt{m_Q^2 + p_{\mathrm{T},\,Q}^2}$.

p_{T} and a p_{T} spectrum that is softer than the data for $|y| < 1$ and harder than the data for $|y| > 1$. In the integration of the four rapidity intervals, this effect averages out and the prediction of the cross-section $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$ is compatible with data.

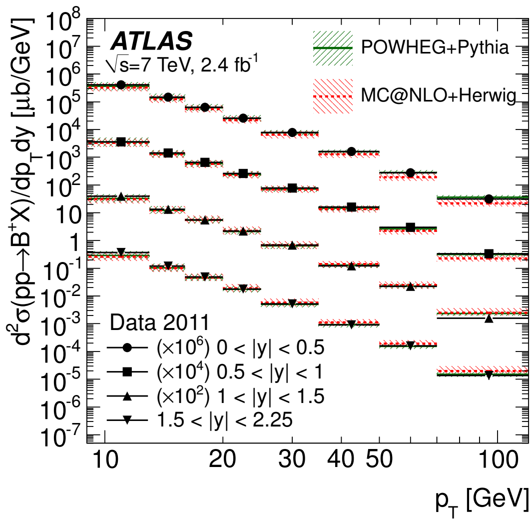

Figure 3. Double-differential cross-section of B^+ production as a function of p_{T} and y, averaged over each (p_{T}, y) interval and quoted at its centre. The data points are compared to NLO predictions from POWHEG and MC@NLO. The shaded areas around the theoretical predictions reflect the uncertainty from renormalisation and factorisation scales and the b-quark mass.

The FONLL prediction is compared with the measured differential cross-section $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$ in figure 5. In this figure, the results from CMS [23] for B^+ meson production as a function of p_{T}, covering the rapidity range $|y| < 2.4$, are shown for comparison. The FONLL prediction is in good agreement with the data concerning the behaviour in rapidity and p_{T}, within the theoretical uncertainties.

All available predictions for $\mathrm{d}\sigma/\mathrm{d}y$ are compared with data in figure 6. The measured cross-section has a small rapidity dependence and is in agreement with the predictions within their uncertainties. The theoretical uncertainties in all cases are large ($\sim$30%) and are similar for the POWHEG, MC@NLO and FONLL predictions.

The integrated B^+ production cross-section in the kinematic range 9 GeV $< p_{\mathrm{T}} <$ 120 GeV and $|y| < 2.25$ is:

$$\sigma(pp \to B^+X) = 10.6 \pm 0.3\ (\text{stat.}) \pm 0.7\ (\text{syst.}) \pm 0.2\ (\text{lumi.}) \pm 0.4\ (\mathscr{B})\ \mu\text{b}.$$

The FONLL prediction, with its theoretical uncertainty from the renormalisation and factorisation scale and the b-quark mass, is:

$$\sigma(pp \to bX) \cdot f_{\bar{b}\to B^+} = 8.6^{+3.0}_{-1.9}\ (\text{scale}) \pm 0.6\ (m_b)\ \mu\text{b}\ ,$$

where $f_{\bar{b}\to B^+} = (40.1 \pm 0.8)\%$ [51] is the world-average value for the hadronisation fraction. The corresponding predictions of POWHEG and MC@NLO are 9.4 μb and 8.8 μb, respectively, with theoretical uncertainties similar to those of the FONLL prediction.

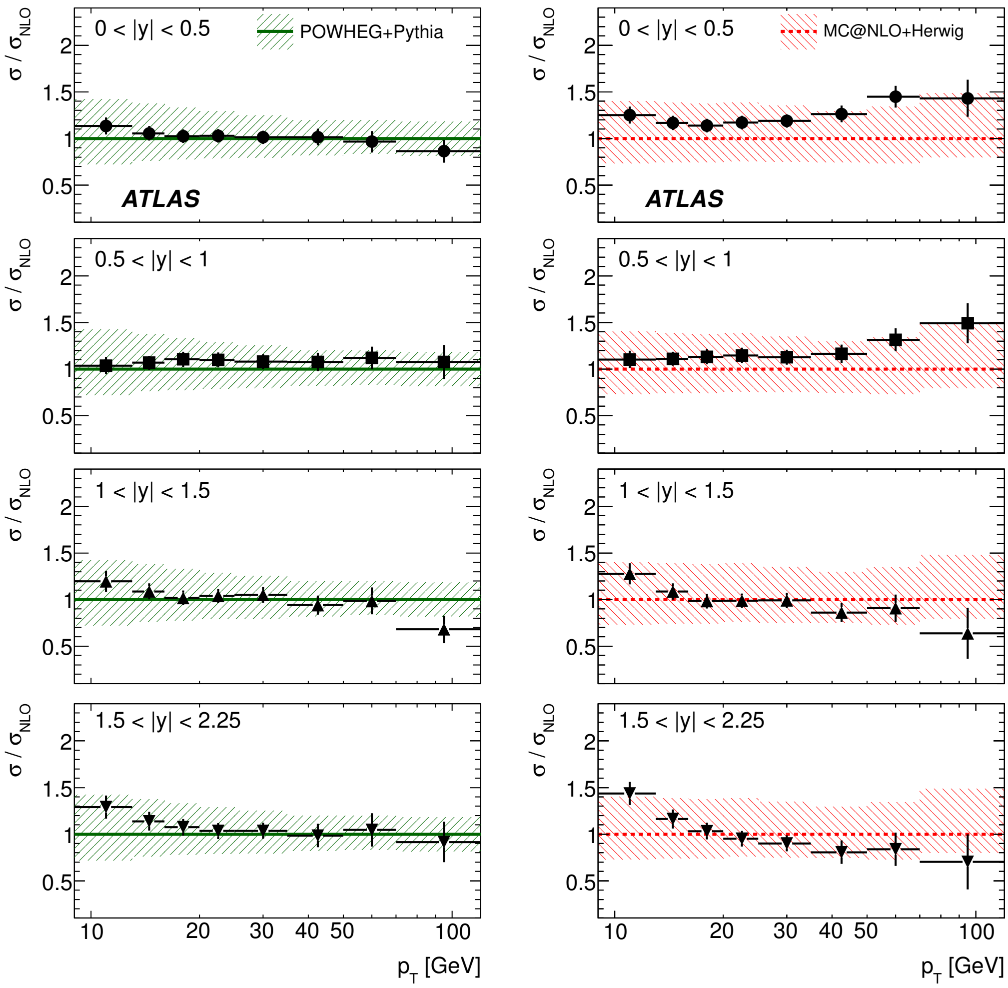

Figure 4. Ratio of the measured cross-section to the theoretical predictions ($\sigma/\sigma_{\rm NLO}$) of Powheg (left) and MC@NLO (right) in eight $p_{\rm T}$ intervals in four rapidity ranges. The points with error bars correspond to data with their associated uncertainty, which is the combination of the statistical and systematic uncertainty. The shaded areas around the theoretical predictions reflect the uncertainty from renormalisation and factorisation scales and the b-quark mass.

8 Conclusions

The differential cross-section for B^+ meson production has been studied with 2.4 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV, recorded in 2011 with the ATLAS detector at the LHC. The cross-section was measured as a function of transverse momentum and rapidity in the range 9 GeV $< p_{\rm T} <$ 120 GeV and $|y| < 2.25$, and quoted with a total uncertainty of 7%–30% with the main source of uncertainty being systematic. The next-to-leading-order QCD calculation is compatible with the measured differential cross-section. The predictions are obtained within the Powheg and MC@NLO frameworks and are quoted with an uncertainty from renormalisation and factorisation scales and b-quark mass of the order of 20%–40%. Within these uncertainties, Powheg+Pythia is in agreement with

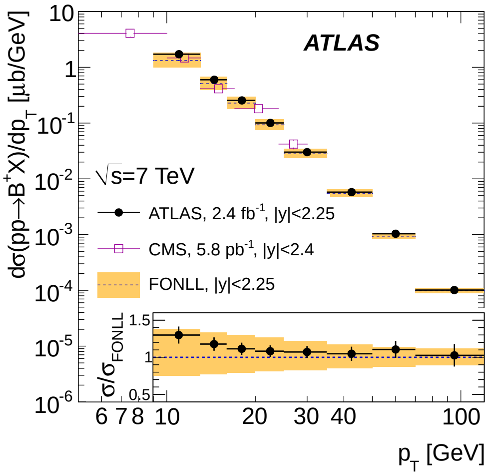

Figure 5. Differential cross-section of B^+ production vs p_{T}, integrated over rapidity. The solid circle points with error bars correspond to the differential cross-section measurement of ATLAS with total uncertainty (statistical and systematic) in the rapidity range $|y| < 2.25$, averaged over each p_{T} interval and quoted at its centre. For comparison, data points from CMS are also shown, for a measurement covering $p_{\mathrm{T}} < 30$ GeV and $|y| < 2.4$ [23]. Predictions of the FONLL calculation [19] for b-quark production are also compared with the data, assuming a hadronisation fraction of $f_{\bar{b}\to B^+}$ of $(40.1 \pm 0.8)\%$ [51] to fix the overall scale. Also shown is the ratio of the measured cross-section to the predictions of the FONLL calculation ($\sigma/\sigma_{\mathrm{FONLL}}$). The upper and lower uncertainty limits on the prediction were obtained considering scale and b-quark mass variations.

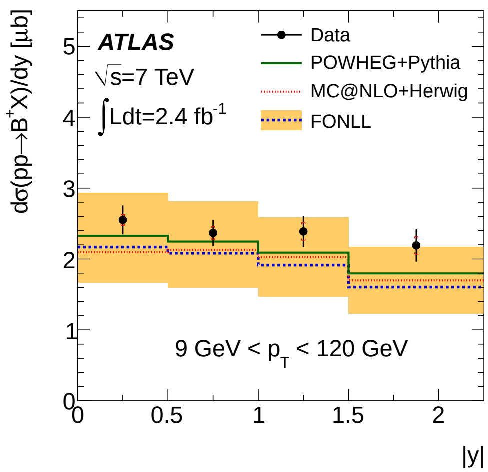

Figure 6. Differential cross-section of B^+ production vs rapidity, integrated over p_{T}. Points with error bars correspond to the differential cross-section measurement with total uncertainty (lines on the error bars indicate the statistical component) in the p_{T} range 9 GeV $< p_{\mathrm{T}} <$ 120 GeV, averaged over each rapidity interval and quoted at its centre. POWHEG, MC@NLO and FONLL predictions are also given for comparison. The FONLL prediction is quoted with upper and lower uncertainty limits, which were obtained considering scale and b-quark mass variations. The relevant uncertainties of the predictions of POWHEG and MC@NLO are of the same order and are not shown.

the measured integrated cross-sections and with the dependence on p_{T} and y. At low $|y|$, MC@NLO+HERWIG predicts a lower production cross-section and a softer p_{T} spectrum than the one observed in data, while for $|y| > 1$ the predicted p_{T} spectrum becomes harder than observed in data. The FONLL calculation for $\sigma(pp \to b\,X)$ is compared to the data, assuming a hadronisation fraction $f_{\bar{b}\to B^+}$ of $(40.1 \pm 0.8)\%$ [51], and is in good agreement with the measured differential cross-section $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$, within the theoretical uncertainty.

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