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Measurement of the b-hadron production cross section using decays to $D^{*+}\mu^- X$ final states in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

ATLAS Collaboration ⋆

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Abstract

The b-hadron production cross section is measured with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV, using 3.3 pb^{-1} of integrated luminosity, collected during the 2010 LHC run. The b-hadrons are selected by partially reconstructing $D^{*+}\mu^- X$ final states. Differential cross sections are measured as functions of the transverse momentum and pseudorapidity. The measured production cross section for a b-hadron with $p_T > 9$ GeV and $|\eta| < 2.5$ is $32.7 \pm 0.8(\text{stat.})^{+4.5}_{-6.8}(\text{syst.})$ μb, higher than the next-to-leading-order QCD predictions but consistent within the experimental and theoretical uncertainties.
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1. Introduction

The production of heavy quarks at hadron colliders provides a challenging opportunity to test the validity of quantum chromodynamics (QCD) predictions and calculations. The b-hadron production cross section has been predicted with next-to-leading-order (NLO) accuracy for more than twenty years [1,2].

Several measurements were performed with proton–antiproton collisions by the UA1 experiment at the Sp$\bar{\text{p}}$S collider (CERN) at a centre-of-mass energy of $\sqrt{s} = 630$ GeV [3,4], and by

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the CDF and D0 experiments at the Tevatron collider (Fermilab) at $\sqrt{s} = 630$ GeV, 1.8 TeV and 1.96 TeV [5–14]. These measurements made a significant contribution to the understanding of heavy-quark production in hadronic collisions [15], but the theoretical predictions still suffer from large uncertainties, mainly due to the dependence on the factorisation and renormalisation scales.

A measurement of the b-hadron production cross section in proton–proton collisions at the Large Hadron Collider (LHC) provides a further test of QCD calculations for heavy-quark production at higher centre-of-mass energies. Recently the LHCb experiment measured the $b\bar{b}$ and B^+ [16–18] production cross sections in the forward region at $\sqrt{s} = 7$ TeV, the CMS experiment measured the production cross sections for B^+, B^0, B_s^0 mesons, inclusive b-hadrons with muons, and $b\bar{b}$ decays with muons at $\sqrt{s} = 7$ TeV [19–23], and the ALICE experiment measured the $b\bar{b}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV [24].

This paper presents a measurement of the b-hadron (H_b, a hadron containing a b-quark and not a $\bar{b}$-quark) production cross section at a centre-of-mass energy of 7 TeV with the ATLAS detector at the LHC, and its comparison with the NLO QCD theoretical predictions. The measurement requires the partial reconstruction of the b-hadron decay final state $D^{*+}\mu^- X$, with the D^{*+} reconstructed through the fully hadronic decay chain $D^{*+} \rightarrow \pi^+ D^0 (\rightarrow K^- \pi^+)$. This sample was collected by ATLAS between August and October 2010 using events selected by a single-muon trigger, and corresponds to a total integrated luminosity of 3.3 pb^{-1}.

2. The ATLAS detector

The ATLAS detector [25] covers almost the full solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. For the measurement presented in this paper, the inner detector tracking devices, the muon spectrometer and the trigger system are of particular importance.

The inner detector (ID) has full coverage in ϕ and covers the pseudorapidity range $|\eta| < 2.5$. It consists of a silicon pixel detector, a silicon microstrip tracker and a transition radiation tracker composed of drift tubes. These detectors are located at radial distances of 50.5–1066 mm from the interaction point and are surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field. The ID barrel consists of three layers of pixels, four double-layers of single-sided silicon microstrips, and 73 layers of drift tubes, while each ID end-cap has three layers of pixels, nine double-layers of single-sided silicon microstrips, and 160 layers of drift tubes.

The muon spectrometer covers the pseudorapidity range $|\eta| < 2.7$ and is located within the magnetic field produced by three large superconducting air-core toroid systems. The muon spectrometer is divided into a barrel region ($|\eta| < 1.05$) and two end-cap regions ($1.05 < |\eta| < 2.7$), within which the average magnetic fields are 0.5 T and 1 T respectively. Precise measurements are made in the bending plane by monitored drift tube chambers, or, in the innermost layer for $2.0 < |\eta| < 2.7$, by cathode strip chambers. Resistive plate chambers in the barrel and thin gap chambers at $|\eta| < 2.4$ in the end-caps are used as trigger chambers. The chambers are arranged in three layers, such that high p_{T} muons traverse at least three stations with a lever arm of several metres.

A three-level trigger system is used to select interesting events. The first level is hardware-based, and uses a subset of the detector information to reduce the event rate to a design value of at most 75 kHz. This is followed by two software-based trigger levels, together known as the high level trigger, which finally reduce the event rate to about 200 Hz.

3. Outline of the measurement

The first result presented in this paper is the $H_b \to D^{*+}\mu^- X$ production cross section, measured in a limited fiducial acceptance for the $D^{*+}\mu^-$ final state. Given the integrated luminosity $\mathscr{L}$ of the data sample, and the branching ratio $\mathscr{B}$ of the D^{*+} cascade decay $D^{*+} \to \pi^+ D^0 (\to K^-\pi^+)$, the $H_b \to D^{*+}\mu^- X$ cross section is defined as:

$$\sigma\big(pp \to H_b X' \to D^{*+}\mu^- X\big) = \frac{f_b N(D^{*+}\mu^- + D^{*-}\mu^+)}{2\epsilon\mathscr{B}\mathscr{L}} \tag{1}$$

where $N(D^{*+}\mu^- + D^{*-}\mu^+)$ is the total number of reconstructed candidates, f_b is the fraction of candidates originating from the decay $H_b \to D^{*+}\mu^- X$ and ϵ is the signal reconstruction efficiency. The efficiency takes into account reconstruction and muon trigger efficiencies, including the loss of events where the D^{*+} falls within the fiducial acceptance, but the decay products (π or K) cannot be reconstructed because they fall outside the p_{T} and η acceptance. The number N of reconstructed candidates includes both $D^{*+}\mu^-$ and $D^{*-}\mu^+$ combinations: assuming that b- and $\bar{b}$-quarks are produced with the same rate at the LHC, the factor of two is needed to quote the cross section for hadrons containing a b-quark. The value of the branching ratio $\mathscr{B}$ can be obtained by combining the world average values of the branching ratios $D^{*+} \to \pi^+ D^0$ and $D^0 \to K^-\pi^+$ [26], and is $(2.63 \pm 0.04)\%$.

The parameters N, f_b and ϵ are determined as functions of the transverse momentum and pseudorapidity of the $D^{*+}\mu^-$ pairs, in order to measure the differential cross sections. The detailed calculation of these parameters is discussed in the following sections.

To obtain the b-hadron production cross section $\sigma(pp \to H_b X)$, the $H_b \to D^{*+}\mu^- X$ cross section is divided by an acceptance correction α, accounting for the fiducial region in which this is measured, and by the inclusive branching ratio $\mathscr{B}(b \to D^{*+}\mu^- X)$. For this branching ratio the world average value is $(2.75 \pm 0.19)\%$, assuming the world average values of the b-hadronisation fractions [26]. The dominant contributions to the sample are from B^0 mesons, through the decay $B^0 \to D^{*-}\mu^+\nu_\mu$ and its charge conjugate.

4. Event simulation and NLO cross section predictions

Monte Carlo (MC) simulated samples are used to optimise the selection criteria (Section 5) and to evaluate the $D^{*+}\mu^-$ signal composition and reconstruction efficiency (Sections 6 and 7). The different b- and c-quark sources of $D^{*+}\mu^-$ are studied using inclusive samples of $b\bar{b}$ and $c\bar{c}$ events having at least one muon with $p_{\mathrm{T}} > 4$ GeV and $|\eta| < 2.5$ in the final state. Both samples are generated with PYTHIA [27], using the ATLAS AMBT1 tuning [28]. The ATLAS detector response to the passage of the generated particles is simulated with GEANT4 [29,30], and the simulated events are fully reconstructed with the same software used to process the collision data.

To compare the measurements with theoretical predictions, NLO QCD calculations, matched with a leading-logarithmic parton shower MC simulation, are used. Predictions for $b\bar{b}$ production at the LHC at $\sqrt{s} = 7$ TeV are evaluated with two packages: MC@NLO 4.0 [31,32] and POWHEG-HVQ 1.01 [33,34]. MC@NLO is matched with the HERWIG 6.5 [35] MC event generator, while POWHEG is used with both HERWIG 6.5 and PYTHIA 6.4 [27]. For all the predictions, the inclusive branching ratio $\mathscr{B}(b \to D^{*+}\mu^- X)$ is set to the world average value.

The following set of input parameters is used to perform all theoretical predictions:

- CTEQ6.6 [36] parameterisation for the proton parton distribution function (PDF).
- b-Quark mass m_b of 4.75 GeV [26].
- Renormalisation and factorisation scales set to $\mu_r = \mu_f = \mu$, where μ has different definitions for MC@NLO and POWHEG. For MC@NLO:

  $$\mu^2 = m_Q^2 + \frac{(p_{\mathrm{T},Q} + p_{\mathrm{T},\bar{Q}})^2}{4}$$

  where $p_{\mathrm{T},Q}$ and $p_{\mathrm{T},\bar{Q}}$ are the transverse momenta of the produced heavy quark and antiquark, and m_Q is the heavy-quark mass. For POWHEG:

  $$\mu^2 = m_Q^2 + \left(m_{Q\bar{Q}}^2/4 - m_Q^2\right)\sin^2(\theta_Q)$$

  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.
- Heavy-quark hadronisation: cluster model [37] for HERWIG; Lund string model [38] with Bowler modification [39] of the Lund symmetric fragmentation function [40] for PYTHIA.

The following sources of theoretical uncertainties are included in the NLO predictions:

- Scale uncertainty, determined by varying μ_r and μ_f independently to $\mu/2$ and 2μ, with the additional constraint $1/2 < \mu_r/\mu_f < 2$, and selecting the largest positive and negative variations.
- m_b uncertainty, determined by varying the b-quark mass by ±0.25 GeV.
- PDF uncertainty, determined by using the CTEQ6.6 PDF error eigenvectors; the total uncertainty is obtained by varying each parameter independently within these errors and summing the resulting variations in quadrature.
- Hadronisation uncertainty, determined in PYTHIA by using the Peterson fragmentation function [41] instead of the Bowler one, with extreme choices of the b-quark fragmentation parameter: $\epsilon_b = 0.002$ and $\epsilon_b = 0.01$.

In addition to the final comparison with the experimental measurement, these theoretical predictions are used to unfold and extrapolate the measured cross sections (Sections 9 and 10), and to extrapolate to the full kinematic phase space (Section 11). In the following, POWHEG + PYTHIA is used as the default prediction.

5. Data selection and reconstruction of the $D^{*+}\mu^-$ decay

The $D^{*+}\mu^-$ (including its charge conjugate) sample was collected during stable proton–proton collisions. Events were selected by a single-muon trigger, which requires a muon, reconstructed by the high level trigger, with $p_{\mathrm{T}} > 6$ GeV. This trigger was prescaled during the last part of the 2010 data-taking period. Taking into account the prescale factors, this data sample corresponds to an integrated luminosity of 3.3 pb^{-1}.

The D^{*+} candidates are reconstructed through the fully hadronic decay chain $D^{*+} \to \pi^+ D^0(\to K^-\pi^+)$, using only good quality tracks, i.e. tracks with at least five silicon detector hits, and at least one of them in the pixel detector.

The b-hadron and D^0 decay vertices are reconstructed and fitted simultaneously. To perform the vertexing, an iterative procedure based on a fast Kalman filtering method is used. This allows to reconstruct consecutively all the vertices of the same decay chain, using the full information from track reconstruction (particles trajectories with complete error matrices). All pairs of opposite charge particle tracks are fitted to a single vertex to form D^0 candidates, assigning to each track, in turn, the kaon or the pion mass, with the additional requirement $p_T > 1$ GeV for both the kaon and pion candidate; the resulting D^0 candidate is reconstructed by combining the kaon and pion four-momenta. The D^0 path is then extrapolated back and fitted with a track of opposite charge to the candidate kaon, requiring $p_T > 250$ MeV and assigning to it the pion mass, to form the D^{*+} candidate, and with a muon with $p_T > 6$ GeV and $|\eta| < 2.4$ to form the b-hadron vertex. No requirements are made here on the muon charge; only opposite charge combinations $D^{*+}\mu^-$ are used in the analysis, while same charge combinations are used to cross-check the background. The muon is also required to have fired the trigger. To ensure good fit quality, the global χ^2 probability of the combined fit must satisfy $P(\chi^2) > 0.001$. To avoid an additional systematic uncertainty no requirement on the b-hadron vertex decay length is applied.

The D^{*+} candidate is accepted if it satisfies $p_T(K^-\pi^+\pi^+) > 4.5$ GeV and $|\eta(K^-\pi^+\pi^+)| < 2.5$, and either (a) $|m(K^-\pi^+) - m(D^0)| < 64$ MeV in the region $p_T(K^-\pi^+\pi^+) > 12$ GeV and $|\eta(K^-\pi^+\pi^+)| > 1.3$, or (b) $|m(K^-\pi^+) - m(D^0)| < 40$ MeV elsewhere. Here $m(D^0)$ is the world average value for the D^0 mass [26]. This last selection cut is divided into two different kinematic regions due to the changing D^0 mass resolution. The $D^{*+}\mu^-$ candidate must have an invariant mass in the range 2.5–5.4 GeV. The upper invariant mass cut matches the physical requirement of not exceeding the mass of the B-mesons.

Because of the kinematics of the D^{*+} decay, the prompt pion takes only a small fraction of the energy. The D^{*+} signal is therefore studied as a function of the mass difference Δm between the D^{*+} and D^0 candidates. Real D^{*+} mesons are expected to form a peak in Δm around 145.4 MeV, while the combinatorial background gives a rising distribution, starting at the pion mass. The combinatorial background is made of fake $D^{*+}\mu^-$ candidates, created from combinations of tracks which pass the selection cuts, but do not come from a $D^{*+}\mu^-$ signal. Fig. 1(a) shows a clear signal in the distribution of Δm for the reconstructed opposite charge $D^*\mu$ pairs. The dashed histogram shows the corresponding Δm distribution for the same charge combinations $D^{*\pm}\mu^{\pm}$, showing a very small excess around 145.4 MeV, whose origin is described in Section 6.

The opposite charged signal distribution is fitted using a modified Gaussian (G^{mod}), which provides a good description of the tails of the signal distribution. The modified Gaussian has the form:

$$G^{\text{mod}}(x) \propto \exp\left[-0.5 \cdot x^{1+\frac{1}{1+0.5x}}\right] \tag{2}$$

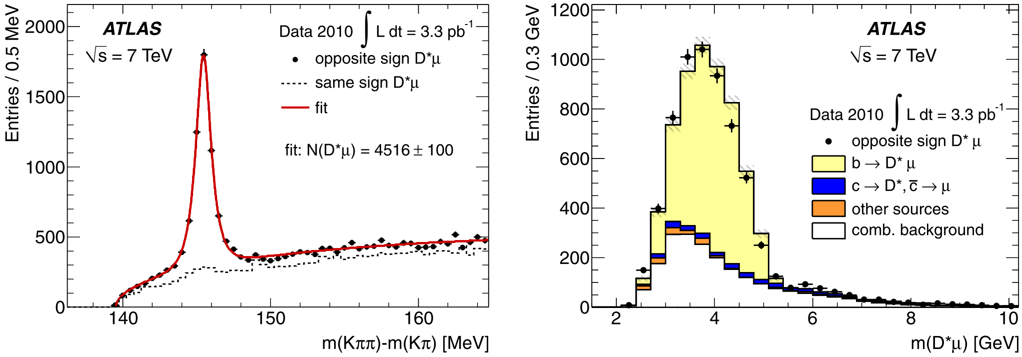
where $x = |(\Delta m - \Delta m_0)/\sigma|$ and Δm_0 and σ, free parameters in the fit, are the mean and width of the Δm peak.

The combinatorial background is fitted with a power function multiplied by an exponential function:

$$B(\Delta m) \propto (\Delta m - m_\pi)^\alpha e^{-\beta(\Delta m - m_\pi)} \tag{3}$$

where α and β are free fit parameters, and m_π is the charged pion mass.

The fitted yield is 4516 ± 100 events, with a fitted $\Delta m_0 = 145.463 \pm 0.015$ MeV, to be compared with the world average value 145.421 ± 0.010 MeV [26], and a fitted $\sigma = 0.49 \pm 0.03$ MeV. The uncertainties on the fitted Δm_0 and σ values are statistical only.



(a)

(b)

Fig. 1. (a) Distribution of the mass difference Δm for $D^*\mu$ combinations of opposite charge (points) and same charge (dashed line). The solid line shows the result of the fit described in the text. (b) Distribution of the opposite charge $D^*\mu$ invariant mass, for mass combinations within $\pm 3\sigma$ of the Δm peak, without applying the invariant mass cut described in the text. The measured distribution is compared with the MC simulation, including the contribution of different sources of signal. The hashed bands show the MC statistical uncertainty.

Table 1
Fitted number of opposite charge $D^*\mu$ pairs for different p_T and $|\eta|$ bins.

$p_T(D^{*+}\mu^-)$	$N(D^{*+}\mu^-)$	$\lvert\eta(D^{*+}\mu^-)\rvert$	$N(D^{*+}\mu^-)$
9–12 GeV	334 ± 33	0.0–0.5	1330 ± 47
12–15 GeV	1211 ± 56	0.5–1.0	1207 ± 47
15–20 GeV	1527 ± 55	1.0–1.5	919 ± 48
20–30 GeV	1049 ± 42	1.5–2.0	890 ± 60
30–45 GeV	310 ± 21	2.0–2.5	317 ± 37
45–80 GeV	76 ± 10		

Fig. 1(b) shows the $D^{*+}\mu^-$ invariant mass distribution selected in a region of 3σ around the Δm peak, without applying any $D^{*+}\mu^-$ invariant mass cut. The measured distribution is compared with the MC $b\bar{b} + c\bar{c}$ simulation described in Section 4, which takes into account the contribution of different physical sources to the $D^{*+}\mu^-$ signal, as discussed in more detail in Section 6. The MC simulation is separately normalised to the number of signal and background events in data. The selection on $m(D^{*+}\mu^-)$ has full efficiency for the signal, while rejecting part of the combinatorial background and physical processes other than a single b-hadron decay.

In order to evaluate differential cross sections, the sample is divided into six $p_T(D^{*+}\mu^-)$ bins and five $|\eta(D^{*+}\mu^-)|$ bins. The Δm distribution in each bin is fitted independently using the same fitting procedure as for the total sample. The number of candidates in each bin is reported in Table 1, together with its statistical uncertainty from the fit.

6. $D^{*+}\mu^-$ sample composition

Various processes contribute to the $D^{*+}\mu^-$ data sample:

- Direct semileptonic decay: $b \to D^{*+}\mu^- X$; this is the signal contribution used for this measurement.

Table 2
Different sources contributing to the $D^{*+}\mu^-$ sample. The uncertainties are due to MC statistics.

Source	Fraction (%)
$b \to D^{*+}\mu^- X$	93.2 ± 0.3
$c \to D^{*+}X, \bar{c} \to \mu^- X'$	3.8 ± 0.2
$b \to D^{*+}\tau^- X, \tau^- \to \mu^- X'$	1.5 ± 0.1
$b \to D^{*+}\bar{D}X, \bar{D} \to \mu^- X'$	0.9 ± 0.1
Others	0.6 ± 0.1

Table 3
Fractions of single b semileptonic decays in different $p_T(D^{*+}\mu^-)$ and $|\eta(D^{*+}\mu^-)|$ bins. The uncertainties are due to MC statistics.

$p_T(D^{*+}\mu^-)$	f_b (%)	$\|\eta(D^{*+}\mu^-)\|$	f_b (%)
9–12 GeV	90.8 ± 1.2	0.0–0.5	93.0 ± 0.5
12–15 GeV	92.7 ± 0.5	0.5–1.0	92.6 ± 0.5
15–20 GeV	93.8 ± 0.4	1.0–1.5	93.4 ± 0.6
20–30 GeV	93.2 ± 0.5	1.5–2.0	93.5 ± 0.6
30–45 GeV	93.8 ± 0.9	2.0–2.5	94.6 ± 0.9
45–80 GeV	93.1 ± 1.9		

- Decays of two c-hadrons, one of them decaying semileptonically: $c \to D^{*+}X, \bar{c} \to \mu^- X'$.
- Direct semileptonic τ decay: $b \to D^{*+}\tau^- X, \tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau (\gamma)$.
- Decays of b-hadrons with two c-hadrons in the final state, one of them decaying semileptonically: $b \to D^{*+}\bar{D}X, \bar{D} \to \mu^- X'$.
- Decays of two b-hadrons, one of them decaying semileptonically: $b \to D^{*+}X, \bar{b} \to \mu X'$. This source contributes to opposite-sign and same-sign charge combinations, depending on the direct or indirect semileptonic decay relative branching ratio and on the neutral b-meson oscillation rate. This explains the small excess observed in Fig. 1(a) in the peak region of the same sign charge Δm distribution.
- A D^{*+} meson accompanied by a fake muon, contributing to both opposite-sign and same-sign charge combinations. The contribution from combinations with misidentified muon charge is negligible.

For the purposes of this measurement, only the direct semileptonic component is of interest. Therefore it is necessary to evaluate the fraction of the reconstructed $D^{*+}\mu^-$ sample that actually originates from direct semileptonic b decays. This is estimated from the MC simulation. The most significant $D^{*+}\mu^-$ contributions are listed in Table 2, together with the MC statistical uncertainty.

The fractions from single b semileptonic decays f_b, evaluated in the various p_T and $|\eta|$ bins of the $D^{*+}\mu^-$ pair, are reported in Table 3, together with the MC statistical uncertainty of the calculations. These values are used for the differential cross section measurements.

7. Reconstruction and muon trigger efficiency

The overall efficiency ϵ for $H_b \to D^{*+}\mu^- X$ decays to enter the $D^{*+}\mu^-$ sample, which includes the reconstruction, muon trigger and selection efficiencies, is evaluated as a product of

Table 4
Overall efficiency ϵ for different $p_T(D^{*+}\mu^-)$ and $|\eta(D^{*+}\mu^-)|$ bins.

$p_T(D^{*+}\mu^-)$	ϵ (%)	$\lvert\eta(D^{*+}\mu^-)\rvert$	ϵ (%)
9–12 GeV	21.2 ± 0.9	0.0–0.5	37.5 ± 0.7
12–15 GeV	26.7 ± 0.6	0.5–1.0	37.2 ± 0.8
15–20 GeV	32.1 ± 0.6	1.0–1.5	29.9 ± 0.8
20–30 GeV	38.8 ± 0.9	1.5–2.0	26.1 ± 0.8
30–45 GeV	45.2 ± 1.7	2.0–2.5	16.1 ± 0.9
45–80 GeV	52 ± 4		

three different components, in order to combine MC and data-driven efficiency calculations. Since the only requirement is the single b detection efficiency, the $b\bar{b}$ MC sample is used. The components are defined as:

$$\epsilon_{\text{reco}} = \frac{N(\text{true } D^{*+}\mu^- \text{ with } \mu \text{ and tracks reconstructed})}{N(\text{true } D^{*+}\mu^-)} \tag{4}$$

$$\epsilon_{\text{trigger}} = \frac{N(\text{true } D^{*+}\mu^- \text{with } \mu \text{ and tracks reconstructed, } \mu \text{ matched to trigger})}{N(\text{true } D^{*+}\mu^- \text{ with } \mu \text{ and tracks reconstructed})} \tag{5}$$

$$\epsilon_{\text{selection}} = \frac{N(\text{true } D^{*+}\mu^- \text{with } \mu \text{ and tracks rec., } \mu \text{ matched to trigger, } D^{*+}\mu^- \text{ selection})}{N(\text{true } D^{*+}\mu^- \text{ with } \mu \text{ and tracks rec., } \mu \text{ matched to trigger})} \tag{6}$$

where the number of true $D^{*+}\mu^-$ pairs is calculated within the fiducial kinematic region $p_T(D^{*+}) > 4.5$ GeV, $p_T(\mu^-) > 6$ GeV, $|\eta(D^{*+})| < 2.5$ and $|\eta(\mu^-)| < 2.4$. Events where the D^{*+} is inside the fiducial region, but its decay products are not fully reconstructed, contribute to ϵ_{reco}.

Both ϵ_{reco} and $\epsilon_{\text{selection}}$ are taken from MC simulation. However $\epsilon_{\text{trigger}}$, which is the fraction of the reconstructed muons that actually satisfied the trigger, is measured directly from data using $J/\psi \to \mu^+\mu^-$ samples [42]. These efficiencies are evaluated for the same data-taking periods used in this measurement.

The overall efficiency ϵ is given by:

$$\epsilon = \epsilon_{\text{reco}}(\text{MC})\epsilon_{\text{trigger}}(\text{data})\epsilon_{\text{selection}}(\text{MC}) \tag{7}$$

The different efficiency components, together with the related statistical uncertainties, are determined as $\epsilon_{\text{reco}} = (48.3 \pm 0.4)\%$, $\epsilon_{\text{trigger}} = (81.9 \pm 0.4)\%$ and $\epsilon_{\text{selection}} = (79.1 \pm 0.5)\%$. The overall efficiency is $(31.3 \pm 0.4)\%$, and the values obtained in $p_T(D^{*+}\mu^-)$ and $|\eta(D^{*+}\mu^-)|$ bins are reported in Table 4. A complete description of the systematic uncertainties follows in Section 8.

8. Systematic uncertainties

The uncertainty in the cross section due to each systematic variation is evaluated by repeating the entire analysis procedure and finding the change in the cross section value. The same strategy is adopted to evaluate bin-by-bin systematic uncertainties for the differential cross section measurements. The following sources are considered:

- Uncertainty of the yields from the fits, obtained by varying the fitting procedure in the following ways:

  - reducing the high end of the Δm range used for the $D^{*+}\mu^-$ signal fit by 4 MeV, from 165 MeV to 161 MeV;
  - changing the background parameterisation function to be $\propto 1 - \exp(-\alpha(\Delta m - m_\pi)^\beta)$, where α and β are free fit parameters, which provides a $P(\chi^2)$ for the fit similar to that with the default background parameterisation.
- Uncertainty of the sample composition estimate: the f_b measurement depends on the b/c cross section ratio used in the MC sample. The ratio of the beauty and charm contributions to the inclusive D^{*+} production, estimated using the life-time information, has been found to be in agreement with the ratio in PYTHIA, within experimental uncertainties. To cover the uncertainties, the MC b/c ratio is varied between 50% and 200% of its nominal value.
- Uncertainties of the muon trigger efficiencies are estimated from $J/\psi \to \mu^+\mu^-$ studies [42].
- Uncertainty on tracking and muon reconstruction efficiency: the uncertainty on ID tracking efficiency is dominated by the detector material description used in MC simulations. This uncertainty is evaluated in studies of minimum bias events [28]. The muon reconstruction uncertainty is evaluated on $Z \to \mu^+\mu^-$ data samples [42]. This systematic uncertainty is dominated by the ID tracking uncertainty.
- Model dependence of the reconstruction efficiency: the efficiency calculation could be affected by differences between the $p_T(D^{*+}\mu^-)$ and $\eta(D^{*+}\mu^-)$ spectra in data and MC simulation. To estimate the systematic uncertainty, the MC distribution is varied, while preserving consistency with the observed data distribution, and the resulting change in efficiency is computed after each variation.
- Uncertainty due to differences in the fit of the D^0 and b-hadron vertices between data and MC simulation: to estimate the systematic uncertainty, the MC $P(\chi^2)$ distribution is varied, while preserving consistency with the observed data distribution, and the resulting change in efficiency is computed after each variation.
- Uncertainty of the difference in D^0 mass resolution between data and MC simulation: the efficiency calculation is corrected to account the difference between D^0 mass resolution in data and MC simulation. To estimate the systematic uncertainty, the error on the data-to-MC ratio of D^0 mass widths is propagated to the efficiency.
- NLO prediction uncertainty: since the NLO predictions are also used as an active part of the analysis for unfolding (Section 9) and acceptance corrections (Section 10), the theoretical uncertainties and the use of different predictions introduce additional systematic uncertainties to the experimental measurements. These are evaluated by repeating the entire analysis, introducing different theoretical uncertainties (Section 4) to the default central prediction (POWHEG + PYTHIA), and using a different theoretical prediction (POWHEG + HERWIG and MC@NLO): positive and negative differences obtained with respect to using the central prediction are separately summed in quadrature. The use of the predictions matched with HERWIG produces visible asymmetries in the uncertainties of the acceptance corrections (Section 10).
- Uncertainty of the luminosity measurement (±3.4%) [43,44].
- Relative uncertainty on the branching fractions of the different decay chains, obtained from the world averages [26]: $b \to D^{*+}\mu^- X$ (±7%), $D^{*+} \to D^0\pi^+$ (±0.7%), $D^0 \to K^-\pi^+$ (±1.3%).

In Sections 9 and 10, tables are shown with these uncertainties quoted after each step of the analysis.

Table 5
Differential cross sections for $H_b \to D^{*+}\mu^- X$ production as a function of $p_{\rm T}$ and $|\eta|$ of the $D^{*+}\mu^-$ pair, in the fiducial kinematical region $p_{\rm T}(D^{*+}) > 4.5$ GeV, $p_{\rm T}(\mu^-) > 6$ GeV, $|\eta(D^{*+})| < 2.5$ and $|\eta(\mu^-)| < 2.4$. The statistical and total systematic uncertainties are shown for each cross section.

$p_{\rm T}(D^{*+}\mu^-)$ [GeV]	$\frac{d\sigma(H_b\to D^{*+}\mu^- X)}{dp_{\rm T}(D^{*+}\mu^-)}$ [nb/GeV]	$\lvert\eta(D^{*+}\mu^-)\rvert$	$\frac{d\sigma(H_b\to D^{*+}\mu^- X)}{d\lvert\eta(D^{*+}\mu^-)\rvert}$ [nb/unit of $\lvert\eta\rvert$]
9–12	$2.78 \pm 0.29^{+0.30}_{-0.30}$	0.0–0.5	$38.4 \pm 1.5^{+3.4}_{-3.4}$
12–15	$8.2 \pm 0.4^{+0.8}_{-0.8}$	0.5–1.0	$34.9 \pm 1.4^{+3.1}_{-3.1}$
15–20	$5.2 \pm 0.2^{+0.5}_{-0.5}$	1.0–1.5	$33.5 \pm 1.8^{+3.4}_{-3.1}$
20–30	$1.47 \pm 0.06^{+0.15}_{-0.14}$	1.5–2.0	$37.2 \pm 2.6^{+4.7}_{-4.2}$
30–45	$0.250 \pm 0.018^{+0.025}_{-0.024}$	2.0–2.5	$21.7 \pm 2.6^{+3.7}_{-3.1}$
45–80	$0.0229 \pm 0.0030^{+0.0023}_{-0.0023}$		

9. Differential cross sections for $H_b \to D^{*+}\mu^- X$ production

Differential cross sections for $H_b \to D^{*+}\mu^- X$ production as a function of the $p_{\rm T}$ and $|\eta|$ of the $D^{*+}\mu^-$ pairs are evaluated by using Eq. (1) and dividing by the bin width. The results are shown in Table 5.

To extract differential cross sections as a function of the $p_{\rm T}$ and $|\eta|$ of the b-hadron, it is necessary to correct the observed $p_{\rm T}(D^{*+}\mu^-)$ and $|\eta(D^{*+}\mu^-)|$ distributions using Monte Carlo simulations, in order to take into account the kinematics of the missing particles from the decay $H_b \to D^{*+}\mu^- X$. This procedure is known as unfolding [45–48]. The unfolding approach used in this paper is based on the iterative method described in Ref. [49], containing elements of Bayesian statistics.

The element F_{ij} of the response matrix F for a b-hadron in a $p_{\rm T}/|\eta|(H_b)$ bin j to decay into a $D^{*+}\mu^-$ in $p_{\rm T}/|\eta|(D^{*+}\mu^-)$ bin i can be interpreted as a conditional probability

$$F_{ij} = P\big(D^{*+}\mu^- \text{ in bin } i \,|\, H_b \text{ in bin } j\big). \tag{8}$$

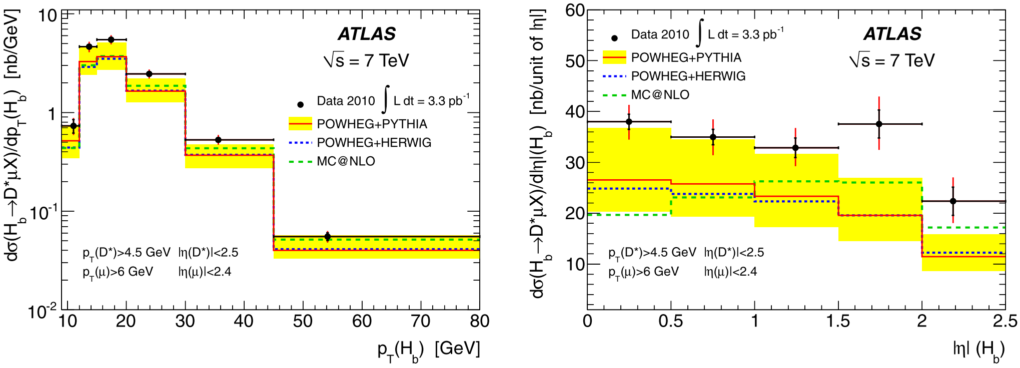
Given an initial set of probabilities p_i for b-hadrons to be found in bin i, using Bayes' theorem one can obtain the expected number of b-hadrons in bin i, given a measured $D^{*+}\mu^-$ distribution:

$$\begin{aligned} N_i^{H_b} &= \sum_{j=1}^{N_{\rm bin}} P\big(H_b \text{ in bin } i \,|\, D^*\mu \text{ in bin } j\big) N_j^{D^{*+}\mu^-} \\ &= \sum_{j=1}^{N_{\rm bin}} \left(\frac{F_{ji}\,p_i}{\sum_k F_{jk}\,p_k}\right) N_j^{D^{*+}\mu^-} \end{aligned} \tag{9}$$

An NLO Monte Carlo sample generated with POWHEG + PYTHIA is used to create the default response matrix F and the initial prior probabilities p. The procedure is repeated with different MC generators, in order to evaluate systematic uncertainties.

The procedure can be iterated, taking as new prior probabilities the solutions of the previous step, i.e. $p_i = N_i^{H_b}/N_{\rm tot}^{H_b}$. After a large number of iterations, the procedure converges on the results obtained with a direct inversion of the response matrix F

$$N_i^{H_b} = \sum_{j=1}^{N_{\rm bin}} \big(F^{-1}\big)_{ij} N_j^{D^{*+}\mu^-} \tag{10}$$



(a)

(b)

Fig. 2. Differential cross section for $H_b \to D^{*+}\mu^- X$ production as a function of (a) p_T and (b) $|\eta|$ of the b-hadron, in the fiducial kinematical region $p_T(D^{*+}) > 4.5$ GeV, $p_T(\mu^-) > 6$ GeV, $|\eta(D^{*+})| < 2.5$ and $|\eta(\mu^-)| < 2.4$. The measurement is compared with the theoretical predictions, as described in the text. The inner error bars of the data points are statistical uncertainties, the outer are statistical + total systematic uncertainties.

This method is known to be sensitive to statistical fluctuations [45], but this effect can be mitigated in the Bayesian method by truncating the procedure after a few iterations.

The number of iterations was therefore optimised in Monte Carlo simulations with test measurements, comparing the values obtained after each iteration to the values expected from the MC-generated information, using a χ^2 test. Two iterations are the optimal solution in this case, providing compatible results even when the response matrix F and the prior probabilities p are generated using different theoretical distributions.

The inversion method and the Bayesian method with a different number of iterations were employed as a check. Within the systematic uncertainties, all the results were found to be in agreement with the chosen default procedure.

A bias could occur in this procedure due to the possible mismodelling of the H_b decays (e.g. D^{**} decays contributing to the missing particles in the final state) in the simulation. It was verified with the simulation that the relevant $D^{*+}\mu^-$ kinematic variables have a small dependence on the specific b-hadron decay, and that a mismodelling of the D^{**} branching ratios does not produce a significant effect. This is expected since the dominant $D^{*+}\mu^-$ contribution arises from direct B^0 decays without an intermediate D^{**}.

Once the H_b distribution is obtained, the differential $H_b \to D^{*+}\mu^- X$ cross sections are determined as a function of p_T and $|\eta|$ of the b-hadron, inside the kinematic region $p_T(D^{*+}) >$ 4.5 GeV, $p_T(\mu^-) > 6$ GeV, $|\eta(D^{*+})| < 2.5$ and $|\eta(\mu^-)| < 2.4$.

Fig. 2 shows the measured differential cross sections, with comparisons to the NLO theoretical predictions. The POWHEG + PYTHIA shaded band refers to the total theoretical uncertainty of the prediction. The differential cross section values are reported in Table 6, together with the statistical and total systematic uncertainties. The individual contributions to the systematic uncertainties are listed in Tables 7 and 8. The comparison with data shows that NLO calculations underestimate the cross section, although the difference is within the combined experimental and theoretical uncertainties.

Table 6

Differential cross sections for $H_b \to D^{*+}\mu^- X$ and $H_b X$ production as a function of p_{T} and $|\eta|$ of the b-hadron, in the fiducial kinematical regions $p_{\mathrm{T}}(D^{*+}) > 4.5$ GeV, $p_{\mathrm{T}}(\mu^-) > 6$ GeV, $|\eta(D^{*+})| < 2.5$ and $|\eta(\mu^-)| < 2.4$, and $p_{\mathrm{T}}(H_b) > 9$ GeV, $|\eta(H_b)| < 2.5$ respectively. The statistical and total systematic uncertainties are shown for each cross section.

$p_{\mathrm{T}}(H_b)$ [GeV]	$\frac{d\sigma(H_b \to D^{*+}\mu^- X)}{dp_{\mathrm{T}}(H_b)}$ [nb/GeV]	$\frac{d\sigma(H_b X)}{dp_{\mathrm{T}}(H_b)}$ [nb/GeV]
9–12	$0.73 \pm 0.12^{+0.09}_{-0.11}$	$(5.8 \pm 0.9^{+0.8}_{-1.0})\cdot 10^3$
12–15	$4.65 \pm 0.27^{+0.50}_{-0.50}$	$(2.37 \pm 0.14^{+0.30}_{-0.33})\cdot 10^3$
15–20	$5.48 \pm 0.19^{+0.57}_{-0.54}$	$(9.1 \pm 0.3^{+1.1}_{-1.1})\cdot 10^2$
20–30	$2.46 \pm 0.08^{+0.26}_{-0.24}$	$212 \pm 7^{+26}_{-26}$
30–45	$0.530 \pm 0.025^{+0.056}_{-0.062}$	$31.3 \pm 1.5^{+3.9}_{-3.9}$
45–80	$0.055 \pm 0.005^{+0.007}_{-0.006}$	$2.78 \pm 0.25^{+0.38}_{-0.33}$

$\lvert\eta(H_b)\rvert$	$\frac{d\sigma(H_b \to D^{*+}\mu^- X)}{d\lvert\eta(H_b)\rvert}$ [nb/unit of $\lvert\eta\rvert$]	$\frac{d\sigma(H_b X)}{d\lvert\eta(H_b)\rvert}$ [μb/unit of $\lvert\eta\rvert$]
0.0–0.5	$38.0 \pm 1.5^{+3.3}_{-3.3}$	$14.3 \pm 0.6^{+1.7}_{-2.7}$
0.5–1.0	$35.0 \pm 1.5^{+3.2}_{-3.2}$	$13.4 \pm 0.6^{+1.8}_{-2.7}$
1.0–1.5	$32.9 \pm 1.9^{+3.3}_{-3.1}$	$13.1 \pm 0.7^{+2.1}_{-2.9}$
1.5–2.0	$37.5 \pm 2.7^{+4.7}_{-4.3}$	$15.8 \pm 1.1^{+2.4}_{-4.4}$
2.0–2.5	$22.3 \pm 2.8^{+3.8}_{-3.2}$	$13.3 \pm 1.6^{+2.5}_{-4.5}$

The integrated $H_b \to D^{*+}\mu^- X$ cross section, inside the kinematic region $p_{\mathrm{T}}(D^{*+}) > 4.5$ GeV, $p_{\mathrm{T}}(\mu^-) > 6$ GeV, $|\eta(D^{*+})| < 2.5$ and $|\eta(\mu^-)| < 2.4$, is:

$$\sigma\big(pp \to H_b X' \to D^{*+}\mu^- X\big) = 78.7 \pm 2.0(\text{stat.}) \pm 7.3(\text{syst.}) \pm 1.2(\mathscr{B}) \pm 2.7(\mathscr{L})\ \text{nb}$$

The integrated Powheg + Pythia prediction, with its theoretical uncertainty, is:

$$\sigma\big(pp \to H_b X' \to D^{*+}\mu^- X\big) = 53^{+18}_{-12}(\text{scale})^{+3}_{-3}(m_b)^{+3}_{-3}(\text{PDF})^{+6}_{-5}(\text{hadr.})\ \text{nb}$$

The corresponding Powheg + Herwig prediction is 51 nb, while MC@NLO predicts 56 nb, with similar theoretical uncertainties to the Powheg + Pythia prediction.

10. Differential cross sections for *b*-hadron production

The b-hadron differential cross sections can be derived from the $H_b \to D^{*+}\mu^- X$ differential cross sections by taking into account the branching ratio $\mathscr{B}(b \to D^{*+}\mu^- X)$ and the necessary decay acceptance corrections. These are evaluated using a Powheg + Pythia simulation in two steps:

- Identification of the H_b kinematic region selected by the D^{*+} and μ^- kinematic cuts. This indicates that only b-hadrons with $p_{\mathrm{T}}(H_b) > 9$ GeV and $|\eta(H_b)| < 2.5$ pass the D^{*+} and μ^- kinematic cuts.

Table 7
$H_b \to D^{*+}\mu^- X$ and H_b cross section relative uncertainties as a function of $p_T(H_b)$, listed as percentages (%).

p_T bin (GeV)	9–12	12–15	15–20	20–30	30–45	45–80
Data statistics	±15.8	±5.9	±3.4	±3.1	±4.7	±9.0
$\sigma(H_b \to D^{*+}\mu^- X)$ and $\sigma(H_b)$ relative systematic error (%)						
$D^*\mu$ fit	±3.5	±1.8	±1.0	±1.4	±1.7	±2.0
f_b	$^{+2.5}_{-3.8}$	$^{+2.3}_{-3.5}$	$^{+1.8}_{-2.8}$	$^{+1.6}_{-2.5}$	$^{+1.4}_{-2.2}$	$^{+1.8}_{-2.9}$
μ trigger	$^{+1.3}_{-1.2}$	$^{+1.3}_{-1.3}$	$^{+1.7}_{-1.6}$	$^{+2.2}_{-2.0}$	$^{+2.5}_{-2.2}$	$^{+2.7}_{-2.5}$
Tracking $+\mu$ reconstruction	$^{+9.1}_{-8.2}$	$^{+9.0}_{-8.1}$	$^{+8.9}_{-8.0}$	$^{+8.7}_{-7.9}$	$^{+8.5}_{-7.7}$	$^{+8.3}_{-7.5}$
MC p_T/η reweight	$^{+0.2}_{-1.3}$	$^{+0.2}_{-1.2}$	$^{+0.4}_{-1.1}$	$^{+0.5}_{-1.1}$	$^{+0.4}_{-1.0}$	$^{+0.2}_{-0.8}$
D^0 and H_b vertices fit	±2.0	±2.0	±2.0	±2.0	±2.0	±2.0
D^0 mass correction	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$
Luminosity	±3.4					
$\mathscr{B}(D^{*+} \to D^0\pi^+)$	±0.7					
$\mathscr{B}(D^0 \to K^-\pi^+)$	±1.3					
$\sigma(H_b \to D^{*+}\mu^- X)$ relative systematic error (%)						
Unfolding	$^{+6.6}_{-10.0}$	$^{+2.3}_{-3.8}$	$^{+1.7}_{-1.5}$	$^{+2.3}_{-1.3}$	$^{+3.2}_{-6.7}$	$^{+9.1}_{-3.5}$
$\sigma(H_b)$ relative systematic error in (%)						
$\mathscr{B}(b \to D^{*+}\mu^- X)$	±7					
Unfolding $\oplus$ acceptance	$^{+3.4}_{-11.3}$	$^{+1.6}_{-6.4}$	$^{+2.3}_{-4.0}$	$^{+0.7}_{-2.5}$	$^{+1.7}_{-4.4}$	$^{+6.0}_{-1.0}$
Total syst. $\sigma(H_b \to D^{*+}\mu^- X)$	$^{+12.9}_{-14.7}$	$^{+10.7}_{-10.8}$	$^{+10.3}_{-9.9}$	$^{+10.4}_{-9.8}$	$^{+10.6}_{-11.7}$	$^{+13.6}_{-10.3}$
Total syst. $\sigma(H_b)$	$^{+13.4}_{-17.1}$	$^{+12.6}_{-14.0}$	$^{+12.5}_{-12.5}$	$^{+12.3}_{-12.1}$	$^{+12.3}_{-12.5}$	$^{+13.5}_{-11.8}$

- Evaluation of a bin-by-bin p_T- and $|\eta|$-decay acceptance α in the H_b allowed kinematic region, defined as

$$\alpha = \frac{\text{number of } H_b(\to D^{*+}\mu^-) \text{ passing the } D^* \text{ and } \mu \text{ kinematic cuts}}{\text{number of } H_b(\to D^{*+}\mu^-) \text{ passing the } H_b \text{ kinematic cuts}} \tag{11}$$

The results are shown in Table 9 for the Powheg + Pythia central prediction. Section 8 describes how the NLO theoretical uncertainties are propagated to this measurement.

The b-hadron differential cross sections as a function of p_T and η, inside the kinematic region $p_T(H_b) > 9$ GeV and $|\eta(H_b)| < 2.5$, can then be calculated according to the formula:

$$\frac{d\sigma(H_b X)}{dp_T(\eta)} = \frac{1}{\alpha_{p_T(\eta)}\mathscr{B}(b \to D^{*+}\mu^- X)} \frac{d\sigma(pp \to H_b X' \to D^{*+}\mu^- X)}{dp_T(\eta)} \tag{12}$$

Fig. 3 shows the b-hadron differential cross section measurements compared with theoretical predictions. The shaded band is the overall theoretical uncertainty of the central Powheg + Pythia prediction. Since the acceptance correction factors have a dependence on p_T and $|\eta|$, as shown in Table 9, the shapes of the b-hadron differential cross sections are different to the $H_b \to D^{*+}\mu^- X$ differential cross sections shown in Fig. 2. The systematic uncertainties are those from the $\sigma(H_b \to D^{*+}\mu^- X)$ measurement described in Section 9, with the addition of the uncertainty of the branching ratio $\mathscr{B}(b \to D^{*+}\mu^- X)$ and the uncertainties of the decay acceptance correction. The b-hadron differential cross section values are reported in Table 6, together with the statistical and total systematic uncertainties, while the individual contributions to the

Table 8
$H_b \to D^{*+}\mu^- X$ and H_b cross section relative uncertainties as a function of $|\eta(H_b)|$, listed as percentages (%). The last column refers to the integrated cross sections.

$\lvert\eta\rvert$ bin	0–0.5	0.5–1	1–1.5	1.5–2	2–2.5	0–2.5
Data statistics	±3.9	±4.3	±5.8	±7.3	±12.5	±2.5
$\sigma(H_b \to D^{*+}\mu^- X)$ and $\sigma(H_b)$ relative systematic error (%)						
$D^*\mu$ fit	±0.7	±0.9	±0.7	±1.2	±1.0	±0.5
f_b	$^{+1.6}_{-2.6}$	$^{+2.0}_{-3.5}$	$^{+1.5}_{-2.4}$	$^{+1.5}_{-2.6}$	$^{+1.3}_{-2.1}$	$^{+1.7}_{-2.8}$
μ trigger	$^{+2.0}_{-1.9}$	$^{+2.1}_{-1.9}$	$^{+1.8}_{-1.6}$	$^{+1.7}_{-1.6}$	$^{+1.6}_{-1.5}$	$^{+1.9}_{-1.9}$
tracking $+\mu$ reconstruction	$^{+7.0}_{-6.5}$	$^{+7.1}_{-6.6}$	$^{+8.5}_{-7.7}$	$^{+11.4}_{-10.0}$	$^{+16.2}_{-13.4}$	$^{+8.6}_{-8.0}$
MC p_T/η reweight	$^{+1.5}_{-0.1}$	$^{+1.2}_{-0.1}$	$^{+1.4}_{-0.1}$	$^{+1.1}_{-0.2}$	$^{+2.0}_{-0.5}$	$^{+1.3}_{-1.3}$
D^0 and H_b vertices fit	±2.0	±2.0	±2.0	±2.0	±2.0	±2.0
D^0 mass correction	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$	$^{+0.8}_{-1.0}$
Luminosity	±3.4					
$\mathscr{B}(D^{*+} \to D^0\pi^+)$	±0.7					
$\mathscr{B}(D^0 \to K^-\pi^+)$	±1.3					
$\sigma(H_b \to D^{*+}\mu^- X)$ relative systematic error (%)						
Unfolding	$^{+1.3}_{-0.9}$	$^{+1.1}_{-1.5}$	$^{+1.4}_{-0.8}$	$^{+0.7}_{-1.0}$	$^{+1.1}_{-2.0}$	–
$\sigma(H_b)$ relative systematic error (%)						
$\mathscr{B}(b \to D^{*+}\mu^- X)$	±7					
Unfolding ⊕ acceptance	$^{+5.1}_{-15.0}$	$^{+7.3}_{-16.2}$	$^{+10.7}_{-19.1}$	$^{+4.8}_{-24.6}$	$^{+4.3}_{-29.6}$	$^{+6.4}_{-17.1}$
Total syst. $\sigma(H_b \to D^{*+}\mu^- X)$	$^{+8.8}_{-8.5}$	$^{+9.0}_{-9.0}$	$^{+10.0}_{-9.4}$	$^{+12.5}_{-11.4}$	$^{+17.1}_{-14.5}$	$^{+10.0}_{-9.8}$
Total syst. $\sigma(H_b)$	$^{+12.2}_{-18.5}$	$^{+13.4}_{-19.7}$	$^{+16.1}_{-22.3}$	$^{+15.0}_{-27.9}$	$^{+18.8}_{-33.5}$	$^{+13.8}_{-20.9}$

Table 9
Decay acceptance α as a function of $p_T(H_b)$ and $|\eta(H_b)|$ for the POWHEG + PYTHIA prediction.

$p_T(H_b)$	α	$\lvert\eta(H_b)\rvert$	α
9–12 GeV	0.005	0.0–0.5	0.096
12–15 GeV	0.071	0.5–1.0	0.095
15–20 GeV	0.219	1.0–1.5	0.091
20–30 GeV	0.422	1.5–2.0	0.086
30–45 GeV	0.614	2.0–2.5	0.061
45–80 GeV	0.723		

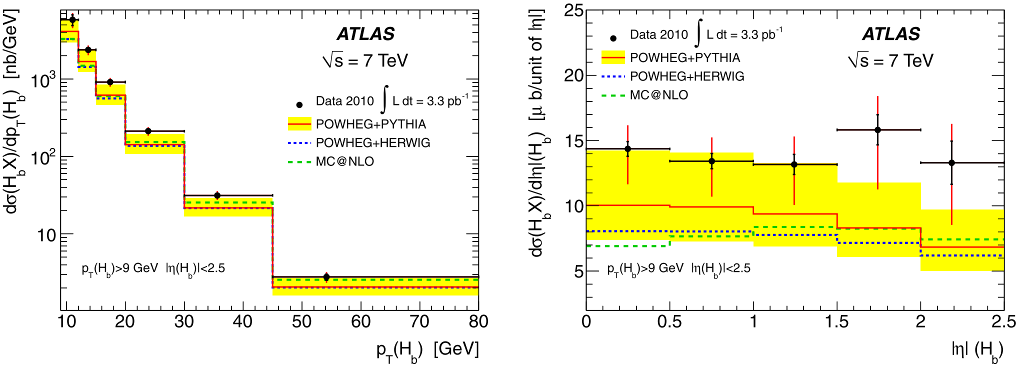
systematic uncertainty are reported in Tables 7 and 8. The combined unfolding and acceptance uncertainties are calculated taking their correlations into account.

The comparison with data shows that NLO calculations underestimate the cross section, although the difference is within the combined experimental and theoretical uncertainties. The b-hadron integrated cross section for $p_T(H_b) > 9$ GeV and $|\eta(H_b)| < 2.5$ is measured as:

$$\sigma(pp \to H_b X) = 32.7 \pm 0.8(\text{stat.}) \pm 3.1(\text{syst.})^{+2.1}_{-5.6}(\alpha) \pm 2.3(\mathscr{B}) \pm 1.1(\mathscr{L})\ \mu\text{b}$$

The integrated POWHEG + PYTHIA prediction, with its theoretical uncertainty, is:

$$\sigma(pp \to H_b X) = 22.2^{+8.9}_{-5.4}(\text{scale})^{+2.1}_{-1.9}(m_b)^{+2.2}_{-2.1}(\text{PDF})^{+1.6}_{-1.5}(\text{hadr.})\ \mu\text{b}$$



(a) (b)

Fig. 3. Differential cross section for H_b production as a function of (a) $p_{\rm T}$ and (b) $|\eta|$ of the b-hadron, in the fiducial kinematical region $p_{\rm T}(H_b) > 9$ GeV, $|\eta(H_b)| < 2.5$. The measurement is compared with the theoretical predictions, as described in the text. The inner error bars of the data points are statistical uncertainties, the outer are statistical + total systematic uncertainties.

The corresponding POWHEG + HERWIG prediction is 18.6 μb, while MC@NLO predicts 19.2 μb, with similar theoretical uncertainties to the POWHEG + PYTHIA prediction.

11. Discussion

Section 10 discusses the measurement of the b-hadron production cross section for $p_{\rm T}(H_b) > 9$ GeV and $|\eta(H_b)| < 2.5$. In order to compare this result with other LHC measurements, we extrapolate this measurement to the full kinematic phase space, extending to regions outside the ATLAS coverage, using the NLO MC theoretical predictions. The multiplicative extrapolation factor is defined as the ratio of the total number of generated b-hadrons to the number of b-hadrons generated with $p_{\rm T}(H_b) > 9$ GeV and $|\eta(H_b)| < 2.5$, and is estimated to be $11.0^{+2.6}_{-1.6}$. The resulting total b-hadron cross section is:

$$\sigma(pp \to H_b X)_{\rm total} = 360 \pm 9({\rm stat.}) \pm 34({\rm syst.}) \pm 25(\mathscr{B}) \pm 12(\mathscr{L})^{+77}_{-69}({\rm accept.} \oplus {\rm extrap.})\ \mu{\rm b}$$

where the combined acceptance and extrapolation uncertainty is calculated taking their correlations into account.

This value can be compared with the inclusive $b\bar{b}$ cross section measurements by LHCb $\sigma(pp \to b\bar{b}X) = 284 \pm 20({\rm stat.}) \pm 49({\rm syst.})$ μb, evaluated in the kinematic region $2 < \eta < 6$ using decays to $D^0\mu^-\bar{\nu}X$ final states [16], and $\sigma(pp \to b\bar{b}X) = 288 \pm 4({\rm stat.}) \pm 48({\rm syst.})$ μb, evaluated using $J/\psi X$ final states in the kinematic region $2.0 < y < 4.5$ [17]. Extrapolations outside the LHCb sensitivity region are done using different theoretical models, without including additional uncertainties. Also ALICE measured the inclusive $b\bar{b}$ cross section in pp collisions, using decays to $J/\psi X$ final states in the kinematic region $|y| < 0.9$ and $p_T > 1.3$ GeV [24]. After extrapolation to the full phase space, they obtain $\sigma(pp \to b\bar{b}X) = 244 \pm 64({\rm stat.})^{+50}_{-59}({\rm syst.})^{+7}_{-6}({\rm extr.})$ μb.

12. Conclusions

The production of b-hadrons (H_b) at the LHC is measured with the ATLAS detector in proton–proton collisions at $\sqrt{s} = 7$ TeV, using 3.3 pb^{-1} of integrated luminosity from the 2010 run. A b-hadron enriched sample was obtained by combining oppositely charged D^* mesons and muons, in events triggered by a muon with p_T exceeding 6 GeV.

Differential cross sections as functions of p_T and $|\eta|$ are produced for both H_b and $H_b \to D^{*+}\mu^- X$ production. These measurements are found to be higher than the NLO QCD predictions, but consistent within the experimental and theoretical uncertainties. The integrated b-hadron cross section for $p_T(H_b) > 9$ GeV and $|\eta(H_b)| < 2.5$ is measured as

$$\sigma(pp \to H_b X) = 32.7 \pm 0.8(\text{stat.}) \pm 3.1(\text{syst.})^{+2.1}_{-5.6}(\alpha) \pm 2.3(\mathscr{B}) \pm 1.1(\mathscr{L})\ \mu\text{b}$$

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