Published for SISSA by Springer

Received: *January 18, 2011*
Accepted: *March 3, 2011*
Published: *March 18, 2011*

Inclusive b-hadron production cross section with muons in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$

The CMS collaboration

Abstract: A measurement of the b-hadron production cross section in proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ is presented. The dataset, corresponding to $85\,\mathrm{nb}^{-1}$, was recorded with the CMS experiment at the LHC using a low-threshold single-muon trigger. Events are selected by the presence of a muon with transverse momentum $p_{\mathrm{T}}^{\mu} > 6\,\mathrm{GeV}$ with respect to the beam direction and pseudorapidity $|\eta^{\mu}| < 2.1$. The transverse momentum of the muon with respect to the closest jet discriminates events containing b hadrons from background. The inclusive b-hadron production cross section is presented as a function of muon transverse momentum and pseudorapidity. The measured total cross section in the kinematic acceptance is $\sigma(\mathrm{pp} \to \mathrm{b} + X \to \mu + X') = 1.32 \pm 0.01(\mathrm{stat}) \pm 0.30(\mathrm{syst}) \pm 0.15(\mathrm{lumi})\mu\mathrm{b}$.

Keywords: Hadron-Hadron Scattering

doi:10.1007/JHEP03(2011)090

Contents

1 Introduction

Measurements of b-hadron production in proton-proton (pp) collisions at the Large Hadron Collider (LHC) are important tests of Quantum Chromodynamics (QCD) in a new kinematical region. Results on b-hadron production in proton-antiproton collisions at the lower center-of-mass energies, $\sqrt{s}$, of the CERN S$\bar{\text{p}}$pS Collider [1] and the Tevatron [2–5] have aroused substantial interest because of tensions between the experimental results and the theoretical expectations [6, 7]. First results at the LHC from pp collisions at $\sqrt{s} = 7\,\text{TeV}$ have been reported by the LHCb collaboration for the forward rapidity region using semi-inclusive decays [8] and by the CMS collaboration in the central rapidity region using fully reconstructed B^+ hadron decays [9].

The b-quark production cross section in hadron collisions has been computed at next-to-leading order (NLO) in perturbative QCD [10–12]. The observed large scale dependence of the NLO results is considered to be a symptom of large contributions from higher orders: small-x effects [13, 14], where $x \sim m_\text{b}/\sqrt{s}$, are possibly relevant in the low-p_T domain, while multiple-gluon radiation leads to large logarithms of p_T/m_b and may be important at high p_T [15]. The resummed logarithms of p_T/m_b at next-to-leading-logarithmic accuracy have been matched to the fixed-order NLO calculation for massive quarks [16]. At the non-perturbative level, the b-hadron p_T spectrum depends strongly on the parametrization of the fragmentation function [17]. The b-quark production cross section has also been studied in the general-mass variable-flavor-number scheme [18] and the k_T factorization QCD approach [19, 20].

In this paper we present an inclusive measurement of the production of b hadrons decaying into muons and jets based on 85 nb^{-1} of data recorded by the CMS experiment using a low-threshold single-muon trigger. Muons from b-hadron decays are distinguished from backgrounds based on their transverse momentum relative to a nearby jet ($p_{\perp}^{\rm rel}$).

In section 2 a brief overview of the CMS detector is given. Section 3 discusses the Monte Carlo (MC) simulation used. Section 4 describes the event selection and analysis methodology. The systematic errors are addressed in section 5 and the results are presented in section 6.

2 The CMS detector

A detailed description of the CMS detector can be found in ref. [21]. The subdetectors used for the present analysis are the inner tracker, consisting of silicon pixel and silicon strip layers, and the muon detectors. The inner tracker is immersed in a 3.8 T axial magnetic field. The pixel tracker consists of three barrel layers and two endcap disks at each barrel end. The strip tracker has 10 barrel layers and 12 end-cap disks at each barrel end. Muons are measured in gas-ionization detectors embedded in the steel return yokes. In the barrel, there is a drift tube system interspersed with resistive plate chambers (RPCs), and in the end-caps there is a cathode strip chamber system, also interspersed with RPCs. The first-level (L1) trigger used in this analysis is based on the muon system alone, while the high-level trigger (HLT) uses additional information from the inner tracker.

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal LHC beam collision point, the x axis pointing towards the center of the LHC ring and the z axis pointing along the counterclockwise beam direction. The polar angle θ is measured from the positive z axis and the pseudorapidity is defined by $\eta = -\ln\tan(\theta/2)$. The azimuthal angle ϕ is measured from the positive x axis in the plane perpendicular to the beam.

3 Monte Carlo simulation

The MC event generator PYTHIA 6.422 [22] is used (with MSEL=1) to compute efficiencies and kinematic distributions. PYTHIA and MC@NLO 3.4 [23, 24] and CASCADE [25] predictions are compared with the experimental results. The programs were run with their default parameter settings, except when mentioned otherwise.

The PYTHIA event sample was simulated with the CTEQ6L1 [26] PDF, a b-quark mass $m_{\rm b} = 4.8$ GeV, and Peterson et al. fragmentation functions [27] for c and quarks with parameters $\varepsilon_{\rm c} = 0.05$ and $\varepsilon_b = 0.005$. The underlying event is simulated with the D6T tune [28]. Pileup events were not included in the simulation and play a negligible role in the data sample used for this measurement.

For comparison, additional event samples were generated where the EVTGEN [29] program was used to decay the b hadrons. Events generated by the PYTHIA program were passed through a detailed MC simulation of the CMS detector response based on GEANT4 [30].

The MC@NLO package has a NLO matrix element calculation interfaced to the parton shower algorithms of the HERWIG [31] package. A b quark mass of $m_{\mathrm{b}} = 4.75\,\mathrm{GeV}$ and the CTEQ6M PDF set [26] were used. The CASCADE generator uses off-shell LO matrix elements and follows the k_{T} factorization approach with CCFM low-x evolution [14]. The unintegrated CCFM parton distribution set A0 [32] and $m_{\mathrm{b}} = 4.75\,\mathrm{GeV}$ were used.

Events generated with MC@NLO and CASCADE are studied only at the generator level and are not passed through the detailed detector simulation. Semileptonic b-hadron decays are the dominant source of muons in b events for this measurement. Simulated events were reweighted to reproduce the branching ratio $B(b \to \mu\nu_{\mu}X) = 10.95\%$ [33].

The results have been also compared with an analytical FONLL calculation [16, 34], using the CTEQ6.6 [35] PDF set, $m_{\mathrm{b}} = 4.75\,\mathrm{GeV}$ and a Kartvelishvili fragmentation function [36] with parameter $\alpha = 24.2$.

4 Data selection and analysis

This analysis is based on data collected in 2010 when the collider and detector were fully operational and fulfilled the following requirements: (1) Stable beam conditions, (2) stable magnetic field inside CMS at the nominal value, (3) operational L1 and HLT, and (4) inner tracker and muon stations at their nominal high-voltage settings. The data sample used in this analysis corresponds to an integrated luminosity of $\mathcal{L} = 85 \pm 9\,\mathrm{nb}^{-1}$ [37].

The events of interest are selected by a very loose single-muon trigger path. The L1 muon trigger makes no explicit requirement on the muon momentum transverse to the z axis, p_{T}, although muons with $p_{\mathrm{T}} < 3\,\mathrm{GeV}$ do not have sufficient momentum to be reconstructed in the barrel region of the muon system.

In the HLT, a standalone muon reconstruction (with information from the muon detectors only) is seeded by the parameters of the L1 muon candidate. If the standalone muon candidate has $p_{\mathrm{T}} > 3\,\mathrm{GeV}$ it serves as a seed in the global muon reconstruction, where a track in the inner tracker is linked to the standalone muon, and further selection requirements are applied on the transverse momentum ($p_{\mathrm{T}} > 3\,\mathrm{GeV}$) and the impact parameter with respect to the beam spot in the transverse plane ($|d_0| < 2\,\mathrm{cm}$).

The offline event selection requires a reconstructed primary vertex with more than three tracks and at least one muon candidate with $p_{\mathrm{T}} > 6\,\mathrm{GeV}$ and pseudorapidity $|\eta| < 2.1$ that fulfills a tight muon selection similar to that in ref. [38]. The muon candidates are required to be reconstructed by two independent algorithms, one starting from segments in the muon chambers and one starting from inner-tracker information. The inner track must be measured with at least 10 hits in the inner tracker, two of which must be on pixel layers. The inner-track fit and the global muon fit (including all inner tracker and muon detector hits) are required to have a χ^2 of less than 10 per degree of freedom and at least two muon segments matching the inner track must be found. Only muon candidates with transverse impact parameter with respect to the primary vertex $|d_0| < 2\,\mathrm{mm}$ and longitudinal impact parameter with respect to the primary vertex $|d_z| < 1\,\mathrm{cm}$ are accepted.

In events passing the trigger and event selections, all tracks including the muon are clustered into track-jets [39] by the anti-k_{T} jet algorithm [40] with $R = 0.5$. The tracks are

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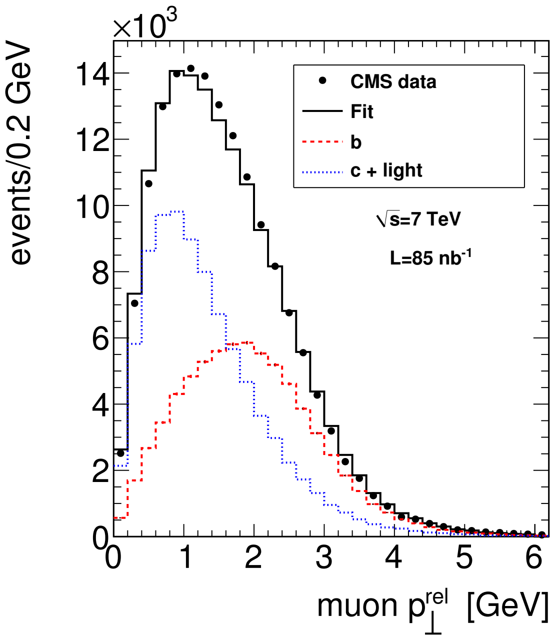

Figure 1. Distribution of muon transverse momentum $p_{\perp}^{\mathrm{rel}}$ with respect to the closest track-jet in data and results of the maximum likelihood fit. The black full circles correspond to the data distribution, while the black line is the result of the fitting procedure. The red dashed and the blue dotted line are the simulated b and cudsg distributions, respectively.

selected with the following requirements: $0.3 < p_{\mathrm{T}} < 500\,\mathrm{GeV}$, $|z_0| < 2\,\mathrm{cm}$, and hits in at least 2 (5) layers of the pixel (pixel and strip) detector. Only jets containing a muon are accepted as b-jet candidates.

The jet direction and jet energy E are calculated by summing the four-momenta of all tracks in the jet except the muon. The pion mass hypothesis is assumed for calculating the energy associated with a track. The jet is required to contain at least one track and to have a transverse energy $E_T = E \sin\theta_{\mathrm{jet}}$ of at least 1 GeV, where θ_{jet} is the polar angle of the jet direction.

The efficiency for identifying b jets is determined in MC simulation for events in which the muon from a b-hadron decay falls into the kinematic region of this measurement. The efficiency for finding a jet containing the muon rises with the muon p_{T} from 74% at 6 GeV to almost 100% for events containing a muon with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$. The fraction of events in which the reconstructed jet containing the muon is not matched to the b jet at the generator level is smaller than 7% in the lowest muon transverse momentum bin and asymptotically reaches a value of 2% at large p_{T}.

From the momenta of the selected muon ($\vec{p}_\mu$) and the associated track-jet ($\vec{p}_j$), the relative transverse momentum of the muon with respect to its track-jet is calculated as $p_{\perp}^{\mathrm{rel}} = |\vec{p}_\mu \times \vec{p}_j|/|\vec{p}_j|$.

A total of 157 783 data events pass the selection. If an event contains more than one muon of either charge, only the muon with the largest transverse momentum p_{T}^{μ} is kept. This affects 0.5% of all data events.

4.1 Fitting procedure

A fit to the observed $p_{\perp}^{\rm rel}$ spectrum, based on distributions obtained from simulation (signal and $c\bar{c}$) and data (the remaining background), is used to determine the fraction of signal events among all events passing the event selection. A binned log-likelihood fit is performed, which takes into account the finite size of the MC simulated sample [41].

The distributions used in the fitting algorithm are determined separately for the full sample and for each bin in muon transverse momentum and pseudorapidity. Since the shape of the $p_{\perp}^{\rm rel}$ distribution in c and light-quark/gluon (udsg) events cannot be distinguished by the fit, the two background components are combined and a fit discriminating the signal component against a single background component is implemented. The udsg background is dominated by hadrons misidentified as muons (mainly in-flight decays) and is determined in data. Hadrons satisfying all muon track selection criteria (without muon detector requirements) are weighted by the misidentification probability and used instead of muons to determine $p_{\perp}^{\rm rel}$. The misidentification probability has been measured in data [42]. The c background is determined from MC simulation. Muons from sources other than b, c and udsg events are neglected. The largest contribution to the muon event sample from these sources is expected in the highest $p_{\rm T}^{\mu}$ bin (3%, from W decays).

The result of the fit in the full sample is displayed in figure 1. A b fraction of 46% is observed. Extensive tests to validate the fitting procedure were performed [43] with repeated fits of MC pseudo-experiments obtained by appropriate random variations. A satisfactory performance of the fit was observed: the fit result does not show a significant bias and the errors are properly calculated by the fitter. The stability of the fit was proven by repeated fits with varied binning. The signal fractions have also been determined with particle flow jets [44] and with a fit to the muon impact parameter distribution. The results are consistent with the fit using track-jets within the systematic uncertainty.

5 Systematic uncertainties

The systematic uncertainties of this analysis are dominated by the shapes of the $p_{\perp}^{\rm rel}$ distributions used in the fitting procedure.

The signal $p_{\perp}^{\rm rel}$ distribution is validated with data through a control sample enriched in b decays. Selecting muons with a large impact parameter significance of $|d_0|/\sigma_{d_0} > 12$, where d_0 is the uncertainty of the impact parameter measurement, results in an event sample with an expected b fraction of about 85%. Small adjustments of the shape of the distributions by rescaling $p_{\perp}^{\rm rel}$ improve the agreement between data and simulation in the b-enriched region and in the full sample. They result in variations of the measured cross section of up to 21% that are taken as a systematic uncertainty.

The background consists of contributions from $c\bar{c}$ events and from light-quark and gluon events, where a hadron is misidentified as a muon. Both contributions are similar in shape and magnitude. The c fraction of the background is expected to rise with increasing muon $p_{\rm T}$. The fit does not separately determine the c and udsg content of the sample. Two effects can introduce a systematic uncertainty. (1) The udsg distribution determined

source	cross section uncertainty (%)
Trigger efficiency	5
Muon reconstruction efficiency	3
Hadron tracking efficiency	2
b $p_{\perp}^{\mathrm{rel}}$ shape uncertainty	≤ 21
Background $p_{\perp}^{\mathrm{rel}}$ shape uncertainty	2–14
Background composition	3–6
Production mechanism	2–5
Fragmentation	1–4
Decay	3
Underlying event	10
Luminosity	11

Table 1. Summary of systematic cross section uncertainties. The systematic uncertainty can vary depending on the muon transverse momentum and pseudorapidity as indicated by the range.

from data could be biased. Using the PYTHIA-derived udsg background introduces a difference to the reference fit of 2–14%, depending on the muon transverse momentum and pseudorapidity bin. (2) If the c fraction of the non-b background in the data was different from the value used in combining the backgrounds, the fitted b fraction could change. The MC-simulation predicts a c fraction of 50–70% in the non-b background depending on the muon transverse momentum. This fraction depends on the modeling of charm semileptonic decays and on the hadron misidentificaton probability. Varying the c vs. udsg fraction by ±20% leads to a systematic uncertainty of 3–6%.

The muon trigger efficiency has been determined from data with an uncertainty of 5% using independent triggers. The muon reconstruction efficiency is known to a precision of 3%. The tracking efficiency for hadrons is known with a precision of about 4% [45], which induces a systematic uncertainty of 2% on the number of events passing the event selection.

In PYTHIA, the production of a $\mathrm{b\bar{b}}$ pair can be separated into flavor creation (19% of the selected events), flavor excitation (56%), and gluon splitting (25%). The event selection efficiencies are 71%, 72%, and 76%, respectively. Reweighting the events from the different production processes to reflect the difference between PYTHIA and HERWIG leads to a systematic uncertainty of 2–5%, depending on the muon transverse momentum.

The uncertainty of the b quark fragmentation is studied by varying the parameter ε_{b} between 0.003 and 0.010, which results in a systematic uncertainty of 1–4% on the reconstruction efficiency. A sample generated with EVTGEN is used to investigate the uncertainty in modeling the b-hadron decay properties. A systematic uncertainty of 3% is found. Varying the fraction of prompt $\mathrm{b} \to \mu$ decays with respect to $\mathrm{b} \to \mathrm{c} \to \mu$ decays within its uncertainty [33] changes the measured cross section by 1%. Neither the muon trigger efficiency nor the track-jet finding is affected significantly by the variation of the fragmentation and decay parameters.

The track-jet reconstruction can be affected by the underlying event. Using simulated event samples with different MC tunes (D6T [28], Pro-Q20 [46], and CW [47]) for the efficiency and acceptance calculation changes the cross section of the order of 10 %.

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At the present stage of the CMS experiment, the integrated luminosity recorded is known with an accuracy of 11% [37].

Table 1 summarizes the systematic uncertainties.

6 Results

The inclusive production cross section for b quarks decaying into muons is calculated as

$$\sigma \equiv \sigma(\mathrm{pp} \to \mathrm{b} + X \to \mu + X') = \frac{N_{\mathrm{b}}}{\mathcal{L}\,\varepsilon},$$

where N_{b} is the number of selected b events in data. No distinction is made between positive and negative muons; N_{b} includes the process $\mathrm{pp} \to \bar{\mathrm{b}} + X \to \mu + X'$. The efficiency ε includes the trigger efficiency, $(88 \pm 5)\%$, the muon reconstruction efficiency, $(94 \pm 3)\%$, and the efficiency for associating a track-jet to the reconstructed muon, $(77 \pm 8)\%$.

The result of the inclusive production cross section for b quarks decaying into muons within the kinematic range $p_{\mathrm{T}}^{\mu} > 6\,\mathrm{GeV}$ and $|\eta^{\mu}| < 2.1$ is

$$\sigma = 1.32 \pm 0.01(\mathrm{stat}) \pm 0.30(\mathrm{syst}) \pm 0.15(\mathrm{lumi})\mu\mathrm{b},$$

where the first uncertainty is statistical, the second is systematic, and the third is associated with the estimation of the integrated luminosity. For comparison, the inclusive b-quark production cross section predicted by MC@NLO is

$$\sigma_{\mathrm{MC@NLO}} = 0.95^{+0.41}_{-0.21}(\mathrm{scale}) \pm 0.09(m_{\mathrm{b}}) \pm 0.05(\mathrm{pdf})\mu\mathrm{b},$$

where the first uncertainty is due to variations in the QCD scale, the second to the b-quark mass, and the third to the parton distribution function. The value of the scale uncertainty is obtained by varying the QCD renormalization and factorization scales as described in ref. [7]. The b-quark mass was varied between 4.5 GeV and 5.0 GeV and the uncertainty induced by the parton distribution function was evaluated using the eigenvector sets as described in ref. [26]. The PYTHIA prediction using the parameters described in section 3 is 1.9 μb.

The differential cross section is calculated from

$$\left.\frac{d\sigma(\mathrm{pp} \to \mathrm{b} + X \to \mu + X')}{dx}\right|_{\mathrm{bin}\ i} = \frac{N_{\mathrm{b}}^{i}}{\mathcal{L}\,\varepsilon^{i}\,\Delta x^{i}},$$

where x stands for the muon transverse momentum or the muon pseudorapidity, and Δx^{i} denotes the width of bin i. The number N_{b}^{i} of selected b events in data and the efficiency ε_{i} are determined separately for each bin.

The results of the differential b-quark production cross section as a function of the muon transverse momentum and pseudorapidity are shown in figure 2 and summarized in table 2. The data lie between the PYTHIA and the MC@NLO predictions. The observed shapes of the kinematic distributions are described reasonably well by both programs. The integral of the differential cross section is consistent with the cross section determined from the full sample.

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p_T^μ [GeV]	N_b	ε	$d\sigma/dp_T$ [nb/GeV]	stat (%)	syst (%)
6–7	26351 ± 523	0.55 ± 0.01	559	2	27
7–8	16016 ± 359	0.63 ± 0.01	299	2	23
8–10	16459 ± 332	0.70 ± 0.01	138	2	21
10–12	7136 ± 209	0.76 ± 0.02	55	3	15
12–14	3330 ± 146	0.79 ± 0.02	25	4	19
14–16	1871 ± 102	0.82 ± 0.04	13	5	15
16–20	1685 ± 99	0.85 ± 0.04	5.8	6	14
20–30	969 ± 82	0.83 ± 0.04	1.4	8	13
η^μ	N_b	ε	$d\sigma/d\eta$ [nb]	stat	syst
(-2.1,-1.5)	8452 ± 262	0.61 ± 0.02	271	3	18
(-1.5,-0.9)	9843 ± 276	0.63 ± 0.02	307	3	23
(-0.9,-0.3)	12476 ± 321	0.68 ± 0.02	356	3	23
(-0.3, 0.3)	11508 ± 315	0.64 ± 0.02	349	3	27
(0.3, 0.9)	11918 ± 312	0.68 ± 0.02	344	3	23
(0.9, 1.5)	9330 ± 272	0.61 ± 0.02	299	3	24
(1.5, 2.1)	8397 ± 255	0.62 ± 0.02	265	3	17

Table 2. Differential cross sections $d\sigma/dp_T^\mu$ for $|\eta^\mu| < 2.1$ in bins of muon transverse momentum and $d\sigma/d\eta^\mu$ for $p_T^\mu > 6$ GeV in bins of muon pseudorapidity. The number of b events (N_b, including $\bar{b}$ events) determined by the fit, the efficiency (ε) of the online and offline event selection, and the differential cross section, together with its relative statistical and systematic uncertainties, are given. A common uncertainty on the luminosity of 11% is not included.

The ratio of the measured differential cross section and the MC@NLO prediction is shown in figure 3. The PYTHIA, CASCADE and FONLL results are shown in the same figure, divided by the MC@NLO prediction. The FONLL uncertainties were obtained by varying scales, b-quark mass and parton distribution as done for MC@NLO.

7 Conclusions

A measurement of the inclusive b-hadron production cross section in the central rapidity region in proton-proton collisions at $\sqrt{s} = 7$ TeV has been performed. The measurement is based on a data sample corresponding to an integrated luminosity of 85 nb^{-1} recorded by the CMS experiment during the first months of data taking in 2010 with a low-threshold single-muon trigger.

The result for the total inclusive production cross section of b hadrons decaying into muons within the visible kinematic range is

$$\sigma(\mathrm{pp} \to \mathrm{b} + X \to \mu + X') = 1.32 \pm 0.01(\mathrm{stat}) \pm 0.30(\mathrm{syst}) \pm 0.15(\mathrm{lumi})\mu\mathrm{b},$$

where $p_T^\mu > 6\,\mathrm{GeV}, |\eta^\mu| < 2.1$. The measured cross section is approximately 1.4 times higher than the NLO predictions, but the difference is less than the theoretical and experimental uncertainties. Differential cross sections have been measured as a function of

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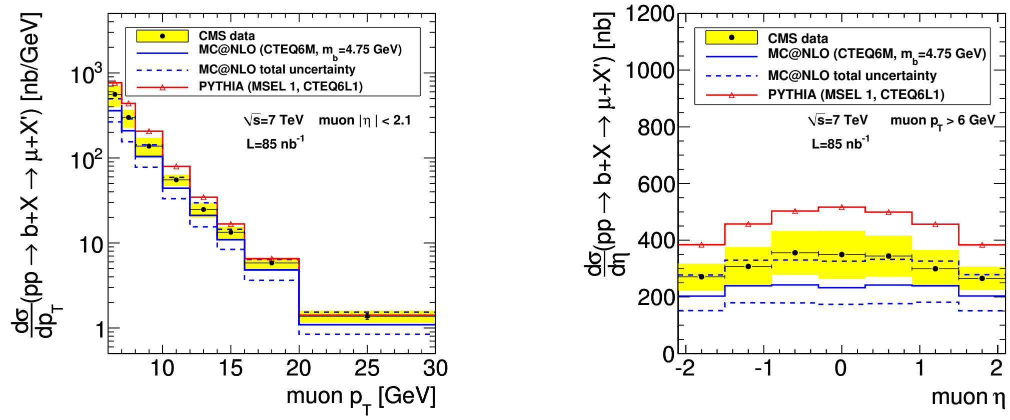

Figure 2. Differential cross section (left) $\frac{d\sigma}{dp_T^\mu}(\text{pp} \to \text{b} + X \to \mu + X', |\eta^\mu| < 2.1)$, and (right) $\frac{d\sigma}{d\eta^\mu}(\text{pp} \to \text{b} + X \to \mu + X', p_T^\mu > 6\,\text{GeV})$. The two possible muon charges are not distinguished; the cross section includes the process $\text{pp} \to \bar{\text{b}} + X \to \mu + X'$. The black points are the CMS measurements. Vertical error bars showing the statistical error are smaller than the point size in most bins, the horizontal bars indicate the bin width. The yellow band shows the quadratic sum of statistical and systematic uncertainties. The systematic uncertainty (11%) of the luminosity measurement is not included. The solid blue line shows the MC@NLO result and the dashed blue lines illustrate the theoretical uncertainty as described in the text. The solid red line with markers shows the PYTHIA result.

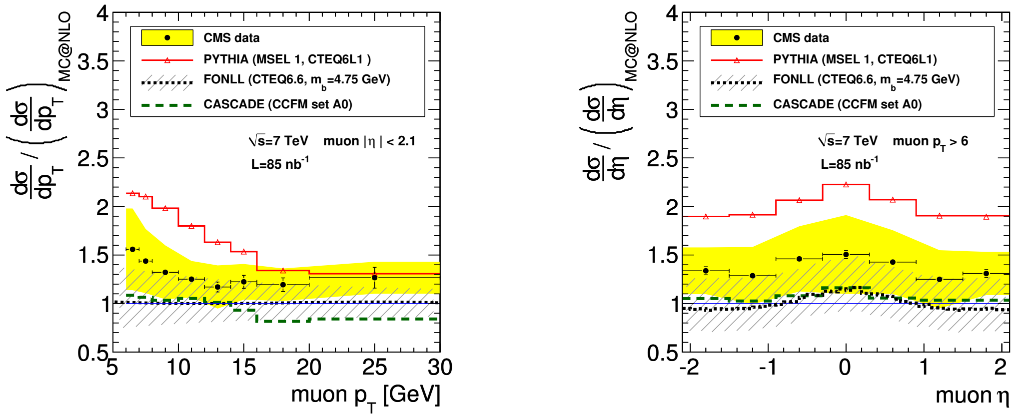

Figure 3. Differential cross section (left) $\frac{d\sigma}{dp_T^\mu}(\text{pp} \to \text{b} + X \to \mu + X', |\eta^\mu| < 2.1)$, and (right) $\frac{d\sigma}{d\eta^\mu}(\text{pp} \to \text{b} + X \to \mu + X', p_T^\mu > 6\,\text{GeV})$ divided by their MC@NLO predictions. The two possible muon charges are not distinguished; the cross section includes the process $\text{pp} \to \bar{\text{b}} + X \to \mu + X'$. The black points are the CMS measurements. Vertical error bars showing the statistical error are smaller than the point size in most bins, the horizontal bars indicate the bin width. The yellow band shows the quadratic sum of statistical and systematic uncertainties. The systematic uncertainty (11%) of the luminosity measurement is not included. Superimposed are the FONLL result (black dotted line) with uncertainties (hatched band), the CASCADE result (green, dashed line) and the PYTHIA result (red line with markers), divided by the MC@NLO cross section.

muon transverse momentum and pseudorapidity. The observed shapes are reasonably well described by NLO QCD. A similar pattern was recently found by this collaboration in the measurement of b production using fully reconstructed B^+ meson decays [9].

Acknowledgments

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

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