Inclusive and exclusive B-hadron production cross sections at 7 TeV with CMS

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Abstract. Measurements of the inclusive B production cross section and the total and differential cross sections for B^+, B^0 and B_s mesons in pp collisions at $\sqrt{s} = 7$ TeV are presented. Results are compared with QCD predictions at leading and next-to-leading order.

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INTRODUCTION

The CMS [1] experiment at the LHC recorded proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV throughout 2010, accumulating an integrated luminosity of $L = 40$ pb^{-1}. Among the very first measurements was the precise determination of the inclusive B production cross section with only 60 nb^{-1}. The cross sections of several exclusive B decays were measured with the full dataset from 2010.

The understanding of the production properties of b quarks is important for at least two reasons: first, it allows us to test next-to-leading-order (NLO) predictions of perturbative Quantum Chromodynamics (QCD). Already now, the measurements provide a precision which is beyond the theoretical uncertainties. Second, b quarks constitute a major source of backgrounds for searches for the Higgs boson, Supersymmetry and other models of physics beyond the Standard Model. A good understanding of b quark production in all aspects is therefore a prerequisite for an important fraction of the CMS physics program.

INCLUSIVE B PRODUCTION CROSS SECTION WITH MUONS

This measurement [2] is based on leptonic decays of B hadrons with a branching ratio of BR($b \to \mu + X$)=10%. The data for this analysis has been collected with a low-threshold single-muon trigger with $p_t > 3$ GeV. The effective integrated luminosity corresponds to 85 nb^{-1}. In order to facilitate a measurement at very low transverse momenta, jets are reconstructed with tracks only. Track-jets with $p_t > 1$ GeV and muons with $p_t > 6$ GeV and pseudo-rapidity $|\eta| < 2.1$ have been selected.

The fraction of b-jets is extracted with a binned likelihood fit to the distribution of the relative transverse momentum of muon with respect to the jet axis (p_t^{rel}), defined as

$$p_t^{\text{rel}} = |\vec{p}_\mu \times \vec{p}_j| / |\vec{p}_j|. \quad (1)$$

The quantity $p_t^{\rm rel}$ allows to distinguish b-jets from non-b-jets because of the large B hadron mass of $m_b \approx 5$ GeV which can significantly deflect the muons from the jet direction and therefore creates a large $p_t^{\rm rel}$. The distribution of the $p_t^{\rm rel}$ templates as well as the result of the likelihood fit is shown in Figure 1 (left). The $p_t^{\rm rel}$ templates are derived from simulation (beauty and charm) or taken directly from data (light flavor templates). The result in the given kinematic region is

$$\sigma(\mathrm{pp} \to \mathrm{b} + \mathrm{X} \to \mu + \mathrm{X}') = 1.32 \pm 0.01(\mathrm{stat}) \pm 0.3(\mathrm{syst}) \pm 0.15(\mathrm{lumi})\mu\mathrm{b}. \qquad (2)$$

The predicted cross-section by the MC@NLO [3, 4] Monte Carlo generator is

$$\sigma_{MC@NLO} = 0.84^{+0.36}_{-0.19}(\mathrm{scale}) \pm 0.08(\mathrm{m_b}) \pm 0.04(\mathrm{pdf})\mu\mathrm{b} \qquad (3)$$

while the PYTHIA generator [5] predicts $\sigma_{PYTHIA} = 1.8\mu$b. The differential cross-section as function of the muon transverse momentum and the comparison with the prediction is shown in Figure 1 (right). The cross section is overestimated by PYTHIA and underestimated by MC@NLO. In general, there seems to be a reasonable agreement, especially in the high p_t region.

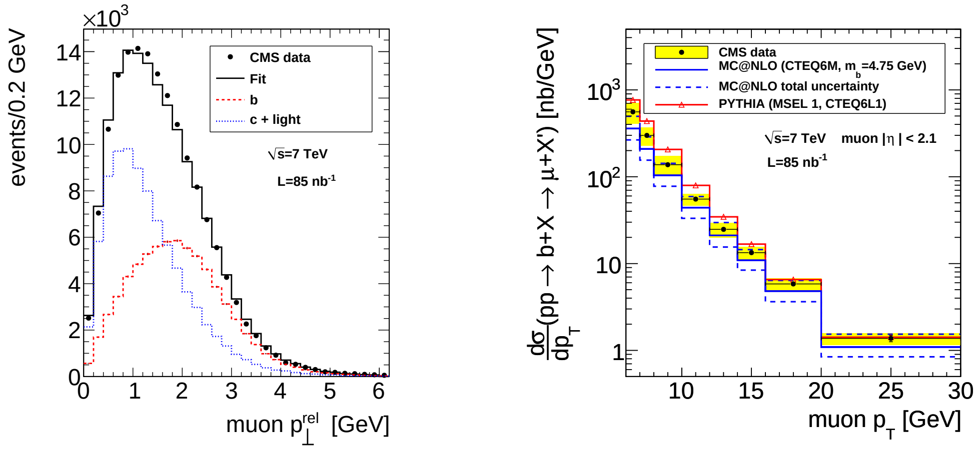

FIGURE 1. Left: Distribution of the muon $p_t^{\rm rel}$ for b (red) and c+light flavor (blue) templates. The black line shows the result of the likelihood fit, while the markers represent the data. Right: Differential cross section $\frac{d\sigma}{dp_t^{\mu}}(\mathrm{pp} \to \mathrm{b} + \mathrm{X} \to \mu + \mathrm{X}', |\eta^{\mu}| < 2.1)$. The markers represent data while the yellow band indicates the measurement uncertainty which is calculated as the quadratic sum of statistical and systematic uncertainties, not including the luminosity uncertainty. The theoretical prediction from MC@NLO is shown in blue, while PYTHIA is shown in red.

INCLUSIVE B PRODUCTION CROSS SECTION WITH B-TAGGED JETS

This measurement [6] uses b-tagged jets without requiring the presence of any muons in contrast to the study in the previous section. Jets are reconstructed with the anti-kT algorithm [7] (with $R = 0.5$) using particle flow objects as input [8]. The jets are selected in the kinematic region $18 < p_t < 300$ GeV and $|y| < 2.0$.

The identification of b-jets is performed with a secondary vertex based b-tagging algorithm [9, 10]. In this algorithm the tracks are first associated to a jet with a cone of $\Delta R < 0.3$ where $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$. Then, these tracks are input to a vertex search using the adaptive vertex fitting technique [11] in which outlying tracks are removed. In the final step, the distance between the primary and secondary vertex (decay length significance) is used to discriminate between b-jets and other jets. The applied cut on the decay length significance corresponds to a b-tagging efficiency of 60% and a mistag efficiency of 0.1% at $p_t = 100$ GeV. The purity of the b-tagged sample is determined in a data-driven template fit, using the distribution of the invariant mass of the secondary vertex

The result is shown in Figure 2 as a stand-alone measurement (left) and as a ratio to the inclusive jet p_t spectrum (right). The latter has the advantage that the uncertainties due to the jet energy and luminosity cancel. From this we can conclude that between 1% and 5% of all jets are b-jets, depending on the momentum. Figure 2 also shows the theory predictions based on MC@NLO and PYTHIA. It is found that PYTHIA seems to do a better job describing the shape of the distribution within the uncertainties.

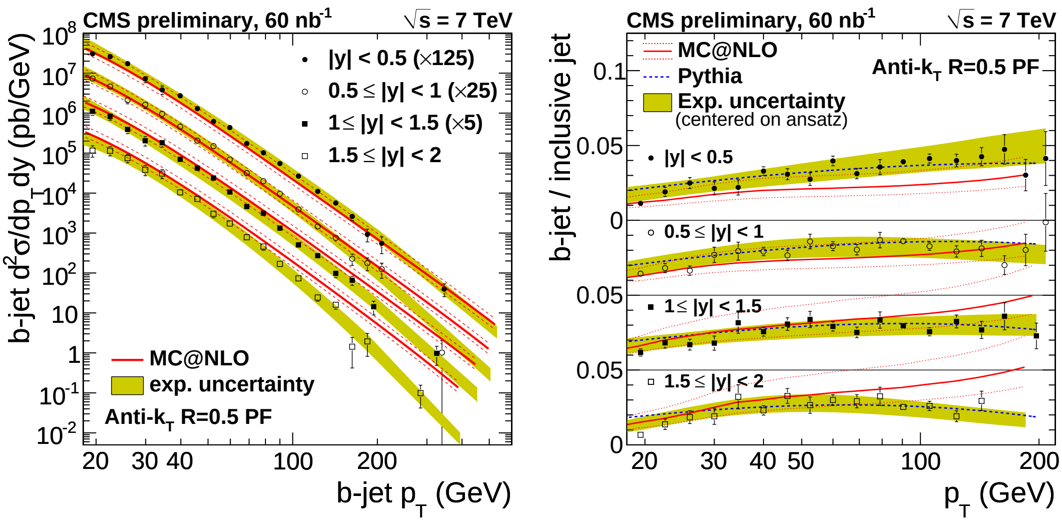

FIGURE 2. Left: measured b-jet cross section compared to the MC@NLO calculation. Right: measured b-jet cross section as a ratio to the inclusive jet cross section. Theory predictions are from PYTHIA and MC@NLO.

This was the first CMS precision measurement applying secondary vertex based b-tagging. The fact that this was possible already with 60 nb^{-1} demonstrates the excellent performance of the CMS detector and the Monte Carlo Simulation.

EXCLUSIVE B DECAY CHANNELS

CMS also performed exclusive measurements of the production of B^+, B_d^0 and B_s^0 mesons in the following decay modes:

- $B^+ \to J/\psi K^+$ with $J/\psi \to \mu^+\mu^-$ [12]
- $B_d^0 \to J/\psi K_s$ with $J/\psi \to \mu^+\mu^-$ and $K_s \to \pi^+\pi^-$ [13]
- $B_s^0 \to J/\psi\phi$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ [14]

The analysis of B^+ has been done with an integrated luminosity of 5.8 pb^{-1} while B_d^0 and B_s^0 have been measured with the full 2010 dataset corresponding to 40 pb^{-1}. All three measurements follow a similar strategy. Data are selected with a di-muon trigger and its efficiency is determined from a tag and probe method [15]. Two oppositely charged muons are required to form a good J/ψ decay vertex and the invariant di-muon mass has to lie within 150 MeV of the world average J/ψ mass.

K_s or ϕ candidates are reconstructed requiring two oppositely charged tracks to be compatible with a common vertex and to lie within 10 MeV of the world average ϕ mass or within 20 MeV within the world average K_s mass, respectively. The candidates for K^+, K_s or ϕ are then combined with the two muons to form candidates of B^+, B_d^0 and B_s^0 mesons, respectively. At this stage, a kinematically constraint vertex fit is performed in which the J/ψ mass, and K_s mass are constraint to the world average value. The probability of this fit is required to be larger than 1%.

To extract the number of signal and background events, a two dimensional unbinned maximum likelihood fit is applied using the proper decay length and the invariant mass distributions of the B meson candidates. The proper decay length is defined as $c\tau = (m_B/p_t^B)L_{xy}$ where L_{xy} is the transverse decay length, defined as $L_{xy} = (\vec{s}\cdot\vec{p}_t^B)/|\vec{p}_t^B|$. $\vec{s}$ is the vector pointing from the primary vertex to the B decay vertex. The parameters of the probability density functions for the background are obtained directly from data, where possible, using signal-free sidebands, otherwise they are extracted from the Monte Carlo Simulation.

The resulting total cross sections are shown in Figure 3 in comparison to the predictions from MC@NLO. The measurement has also been performed in bins of p_t and η to obtain differential cross sections. These results are available in [12, 13, 14].

The conclusion is that there is good agreement with the expectations within the uncertainties. However, already at this stage the measurement uncertainties are smaller than those of the theory predictions, which are dominated by scale uncertainties.

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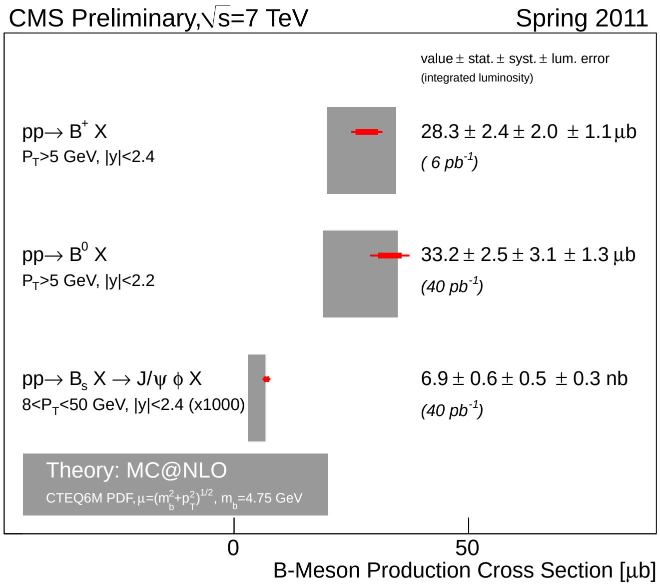

FIGURE 3. Summary of B meson cross section measurements performed by CMS with 7 TeV pp collisions at LHC. The inner error bars of the data points correspond to the statistical uncertainty, while the outer (thinner) error bars correspond to the quadratic sum of statistical and systematic uncertainties. The outermost brackets correspond to the total error, including a luminosity uncertainty which is also added in quadrature. Theory predictions at NLO are obtained using MC@NLO.

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