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Measurement of exclusive b-hadron production at 7 TeV with the CMS experiment

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Measurements of the total and single differential cross sections for B^+ and B^0 mesons produced in pp collisions at $\sqrt{s}$ = 7 TeV are presented. The obtained results are $\sigma(pp \to B^+X) = (28.3 \pm 2.4(\text{stat.}) \pm 2.0(\text{syst.}) \pm 1.1(\text{lumi.}))$ μb for $p_{\mathrm{T}} > 5$ GeV and $|y| < 2.4$ and $\sigma(pp \to B^0X) = (33.2 \pm 2.5(\text{stat.}) \pm 3.1(\text{syst.}) \pm 1.3(\text{lumi.}))$ μb for $p_{\mathrm{T}} > 5$ GeV and $|y| < 2.2$. The results are compared with predictions based on perturbative QCD calculations at leading and next-to-leading order.

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1. Introduction

The study of heavy quark production cross-section in high-energy hadronic interactions plays a critical role as precision tests of next-to-leading order (NLO) Quantum Chromodynamics (QCD) calculations [1] at a higher energy scale than before. Measurements of b-hadron production at the higher energies provided by the Large Hadron Collider (LHC), which are possible thanks to the large $b\bar{b}$ large cross-section at $\sqrt{s}$ = 7 TeV, represent an important new test of theoretical calculations [2, 3]. In addition a good understanding of b-quark production is necessary, since it is an important background to several other analyses, *i.e.* top quark physics, Higgs or Supersymmetry searches, *etc*. These measurements also serve as a validation of the tracking and muon systems.

The data analyzed for the presented results were collected by the multi-purpose experiment CMS (Compact Muon Solenoid) at the LHC [4], which provides since Spring 2010 proton-proton collisions at $\sqrt{s}$ = 7 TeV. The main detector components for the presented measurements are the all-silicon tracker [5] and the muon systems, which use three technologies: drift tubes, cathode strip chambers, and resistive plate chambers.

A trigger system is needed to select the most interesting events minimizing the data taking rate. The CMS first level trigger (L1) consists of custom hardware processors. The High Level Trigger (HLT) processor farm further selects events using a fast object reconstruction.

At CMS the following exclusive b-hadron differential cross sections in transverse momentum (p_{T}) and rapidity (y) have been measured:

- B^+ using the $B^+ \to J/\psi K^+$ decay channel with $J/\psi \to \mu^+\mu^-$ [6],
- B^0 using the $B^0 \to J/\psi K_s$ decay channel with $J/\psi \to \mu^+\mu^-$ and $K_s \to \pi^+\pi^-$ [7],
- B_s using the $B_s \to J/\psi\phi$ decay channel with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. This measurement is reviewed in another contribution to the same proceedings [8].

Other b-hadron exclusive cross section measurements which are underway at CMS are the ones for Λ_b using the decay $\Lambda_b \to J/\psi\Lambda^0(\to p^+\pi^-)$ and $\Sigma_b^{(*)\pm}$ using the decay $\Sigma_b^{(*)\pm} \to \Lambda_b\pi^\pm$.

The common strategy for these measurements is:

- Event selection for the chosen decay channel.
- Extraction of the number of signal events by means of a simultaneous maximum likelihood fit to the distributions of invariant mass of the b-meson candidate decay products and the proper decay length (ct) for every p_{T} or y bin.
- Calculation of the bin-by-bin trigger, reconstruction and event selection efficiencies.
- Calculation of the cross section using the usual formula:

$$\frac{d\sigma(pp \to BX)}{dx^B} = \frac{n_{sig}}{2 \cdot \varepsilon \cdot \mathscr{B} \cdot \mathscr{L} \cdot \Delta x^B}$$

  where x^B can be p_{T}^B or y^B, n_{sig} is the number of signal events, ε is the total efficiency, $\mathscr{B}$ is the branching fraction of the chosen decay channel, taken from the Particle Data Group [9], $\mathscr{L}$ is the integrated luminosity and Δx^B is the bin width. The factor 2 in the denominator accounts for the choice of quoting only the b-hadron cross section, not including its anti-particle.

2. B^+ Production Cross Section

The decay channel $B^+ \to J/\psi K^+$ with $J/\psi \to \mu^+\mu^-$ is used to measure the differential B^+ production cross section. For this analysis 5.8 pb^{-1} of data are used and a very loose trigger requiring two muons without any momentum cut is applied. J/ψ candidates are selected by combining two opposite sign muons, matched to the trigger muon objects that made the event to pass the L1 and HLT requirements, with some acceptance cuts depending on the pseudo-rapidity (η) region as in Ref. [10]. The candidate with a mass closest to the world average J/ψ mass [9] is selected and the mass difference is required to be smaller than 150 MeV. J/ψ candidates are then combined with candidate K^+ tracks to form B^+ candidates using a kinematic fit with a constraint to the world average J/ψ mass. The resulting secondary vertex probability has to be larger than 0.1% and the highest $p_{\rm T}$ combination in the event is chosen.

The efficiency of this event selection is determined from a full Monte Carlo simulation (MC) which uses PYTHIA 6.422 [11] for the event generation, EvtGen [12] for particle decays and GEANT4 [13] for the detector simulation. Corrections factors need to be applied to the trigger and muon reconstruction efficiencies. They are obtained similarly to Ref. [10] with the so called *Tag and Probe* technique. Comparisons between data and MC are used to determine the systematic error in the K^+ track reconstruction [14] and the secondary vertex quality requirement.

Backgrounds are dominated by prompt and non-prompt inclusive J/ψ production. Additional backgrounds, called *peaking* $b\bar{b}$ background, arise from misreconstructed b-hadron decays, such as $B^0 \to J/\psi K_s$, that produce a broad peaking structure in the B^+ candidate invariant mass region below 5.2 GeV.

The simultaneous maximum likelihood fit uses sums of gaussians and exponentials in order to reproduce the shape of the invariant mass and proper decay length distributions for signal and backgrounds. For the proper decay length, the distribution is convoluted with a resolution function (sum of gaussians) common for both signal and background. For more details see Ref. [6]. When fitting in the whole $p_{\rm T}$ and y range (see Fig. 1) a mean life of $c\tau = (481 \pm 22)$ μm (error from the fit) is obtained, in good agreement with the world average [9]. When fitting the data in a particular $p_{\rm T}$ or y bin, to extract the number of signal events in it, the mean life is fixed to the world average value.

For a detailed list of the systematic errors see Ref. [6]. They include errors associated to the fit (up to 5%), to the efficiency calculations, misalignment, the world average branching fractions (3.5%) [9] and the integrated luminosity (now 4%; 11% at the time of publication).

The obtained total cross-section for $p_{\rm T} > 5$ GeV and $|y| < 2.4$ is $\sigma(pp \to B^+X) = (28.3 \pm 2.4(\text{stat.}) \pm 2.0(\text{syst.}) \pm 1.1(\text{lumi.}))$ μb, which is in good agreement with the value obtained with the *MC@NLO* simulation package [15]: $(25.5^{+9.2}_{-5.7})$ μb. The differential cross sections as a function of $p_{\rm T}$ and $|y|$ are shown in Fig. 2 as well as the comparison to MC simulations, which show reasonable agreement in shape and normalization.

3. B^0 Production Cross Section

The decay channel $B^0 \to J/\psi K_s$ with $J/\psi \to \mu^+\mu^-$ and $K_s \to \pi^+\pi^-$ is used to measure the differential B^0 production cross section. A sample of 40 pb^{-1} is used and the trigger with the same

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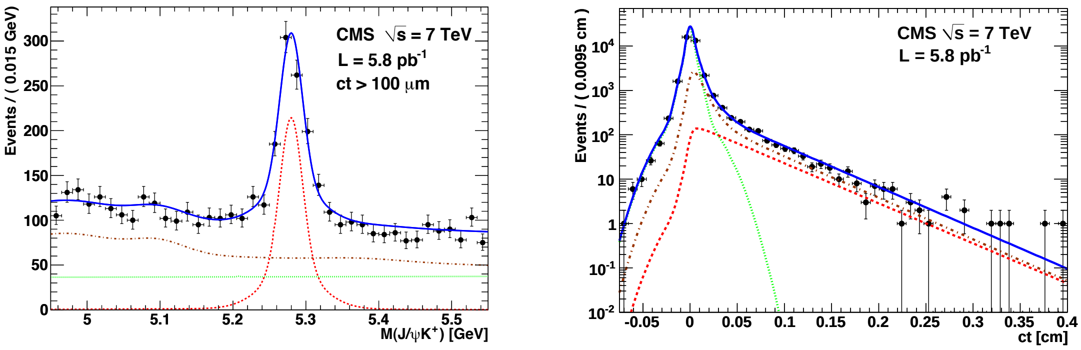

Figure 1: Projections of the fit results for $J/\psi K^+$ in invariant mass (left) and proper decay length (right) for $p_T^B > 5$ GeV and $|y^B| < 2.4$. The sum of all contributions is shown in blue (solid line), the signal is shown in red (dashed), the prompt J/ψ background is shown in green (dotted) and the sum of non-prompt J/ψ, peaking $b\bar{b}$, and $J/\psi\pi^+$ backgrounds are shown in brown (dot-dashed). For better visibility of the individual contributions, the invariant mass plot includes the requirement $ct > 100\,\mu$m.

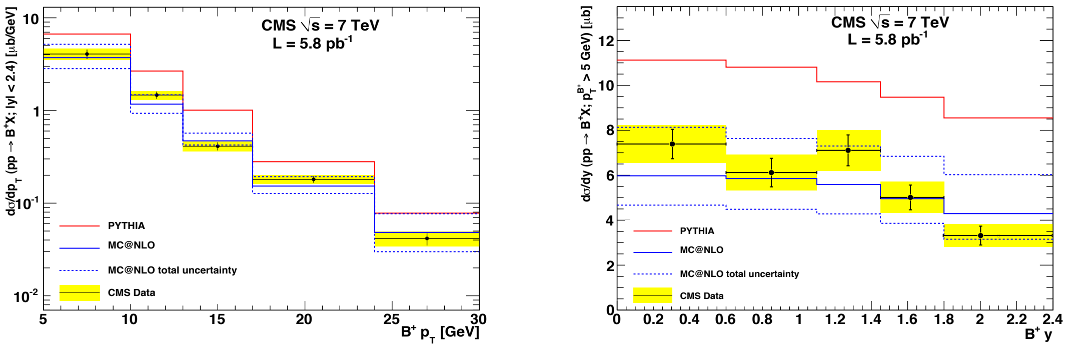

Figure 2: Measured differential cross sections $d\sigma/dp_T^B$ (left) and $d\sigma/dy^B$ (right) for B^+, compared with theory predictions. The error bars are statistical uncertainties, while the (yellow) bands represent the sum in quadrature of statistical and systematic uncertainties, excluding the common branching fraction (3.5%) and luminosity (4%) uncertainties. The solid and dashed blue lines are the *MC@NLO* (CTEQ6M, m_b = 4.75 GeV) prediction and its uncertainty, respectively. The solid red line is the PYTHIA (MSEL 1, D6T, CTEQ6L1) prediction.

requirements on two muons as for the B^+ measurement is applied, with, in most of the data, a loose mass cut around the world average J/ψ mass. The J/ψ candidates are selected in the same way as for the B^+ measurement. K_s candidates are combinations of two tracks giving a vertex with a normalized χ^2 larger than 7 and with its position five standard deviations away from the beam line in the transverse plane. The mass is required to fall within 20 MeV around the world average value. B^0 candidates are selected with a kinematic fit with constraints to the J/ψ and K_s world average masses. The vertex probability is required to be larger than 0.1% and the B^0 mass to differ by less than 0.4 GeV from the world average value. The largest B^0 decay vertex probability combination is chosen.

The muon efficiencies are calculated in the same way as in the B^+ measurement, but the total efficiency also includes the acceptance of the long lived K_s in the CMS tracker and the B^0 reconstruction efficiency (from MC). A kinematic re-weighting and di-muon correlation corrections are also applied, which are obtained by comparing data and MC.

As in the B^+ case the main background sources are prompt and non-prompt J/ψ production as well as the *peaking* $b\bar{b}$ background, mainly from $B^0 \to \chi_{c1} K_s$, $B^0 \to J\psi K^{*0}(\to K_s \pi^0)$, $B^+ \to J/\psi K^{*+}(\to K_s \pi^+)$ and $\Lambda_b \to J/\psi \Lambda^0$.

The maximum likelihood fit to extract the number of signal events uses the same functions as for the B^+ case. The fitting procedure is also similar. The mean life value obtained in the whole p_T and y range fit (Fig. 3) is $c\tau = (479 \pm 22)$ μm (error from the fit) in good agreement with the world average [9].

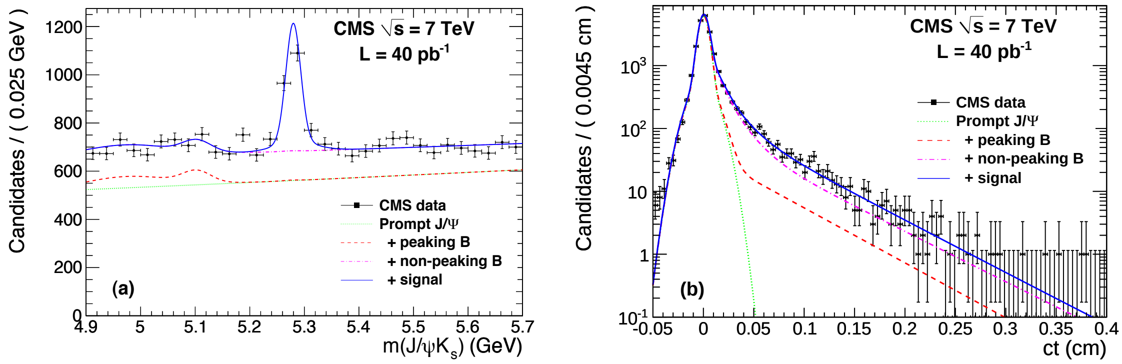

Figure 3: Projections of the fit results for $J/\psi K_s$ in (a) invariant mass and (b) proper decay length for $p_T^B > 5$ GeV and $|y^B| < 2.2$. The sum of all contributions is shown in blue (solid line), the prompt J/ψ background is shown in green (dotted), the sum of the prompt J/ψ and peaking backgrounds are shown in red (dashed) and the sum of all backgrounds is shown in purple (dot-dashed).

For a detailed list of the systematic errors see Ref. [7]. The main contributions are errors associated to the fit (up to 7%), to the efficiency calculations, misalignment, kinematic re-weighting (up to 5%), K_s selection (5%), the world average branching fractions (3.8%) [?] and the integrated luminosity (4%).

The obtained total cross-section for $p_T > 5$GeV and $|y| < 2.2$ is $\sigma(pp \to B^0 X) = (33.2 \pm 2.5(\text{stat.}) \pm 3.1(\text{syst.}) \pm 1.3(\text{lumi.}))$ μb in good agreement with the value obtained with *MC@NLO*: $(25.5^{+9.6}_{-6.2})$ μb. The differential cross sections as a function of p_T and $|y|$ are shown in Fig. 4 as well as the comparison to MC simulations. The measured cross section lies between the central values of the *MC@NLO* and PYTHIA predictions, with a rapidity distribution that falls more slowly than either of the two.

4. Conclusions

CMS has made first measurements of the exclusive total and differential cross sections for B^+, B^0 and B_s at $\sqrt{s}$ = 7 TeV proton-proton collisions. Fig. 5 shows a summary of the measured total

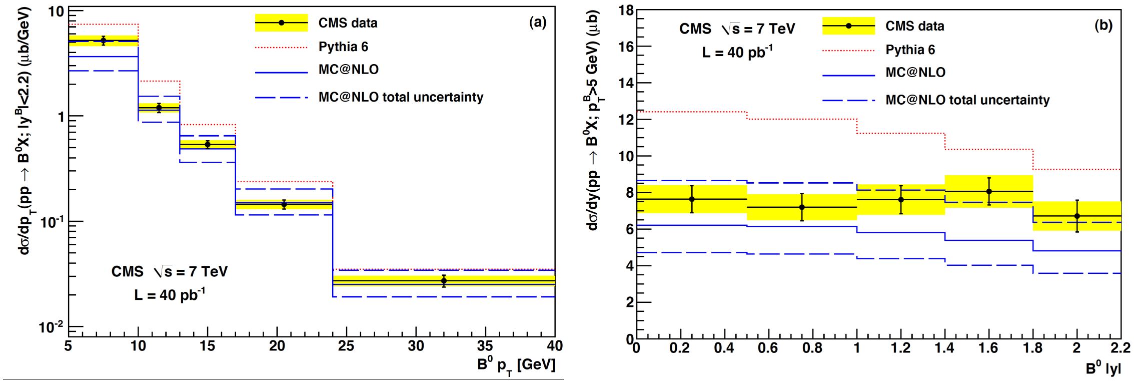

Figure 4: Measured differential cross sections for B^0 (a) $d\sigma/dp_{\mathrm{T}}^B$ and (b) $d\sigma/dy^B$ compared to theoretical predictions. The error bars correspond to the statistical uncertainties and the (yellow) bands represent the uncorrelated systematic uncertainties. Overall uncertainties of 4% for the luminosity and 3.8% for the branching fractions are not shown. The solid and dashed (blue) lines are the *MC@NLO* (CTEQ6M, m_b = 4.75 GeV) prediction and its uncertainty, respectively. The dotted (red) line is the PYTHIA (MSEL 1, CTEQ6L1, Z2) prediction.

cross sections and their comparison to *MC@NLO* predictions, where good agreement can be seen. These results also indicate the good performance of the CMS detector at this early stage of data taking. For updated results see the public CMS B-Physics web page [16].

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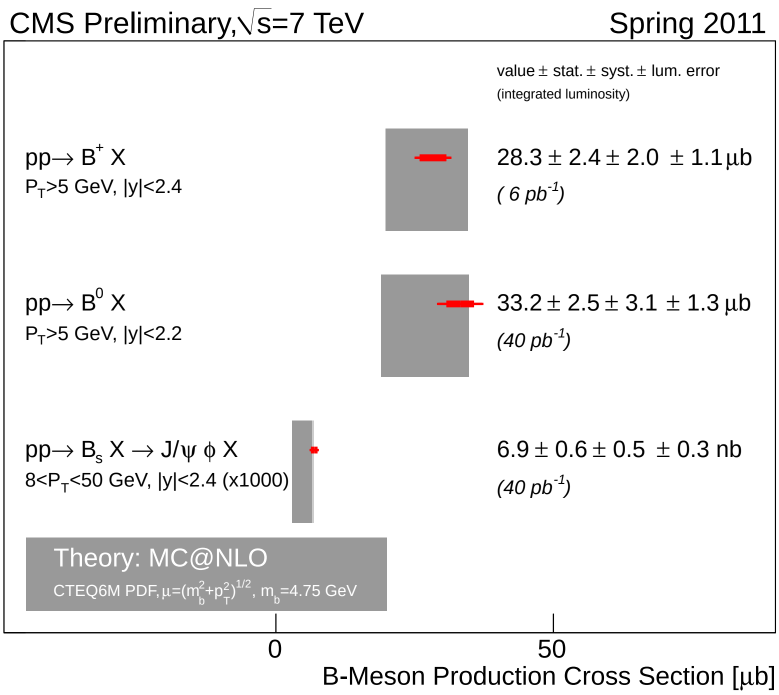

Figure 5: Summary of b-meson cross section measurements performed by CMS with $\sqrt{s}$ = 7 TeV pp collisions at LHC. The inner error bars of the data points correspond to the statistical uncertainty, while the outer (thinner) error bars correspond to the quadratic sum of statistical and systematic uncertainties. The outermost brackets correspond to the total error, including the luminosity uncertainty which is also added in quadrature. Theory predictions at NLO are obtained using *MC@NLO*.

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