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b Production Cross Section and Fragmentation Fractions f_s/f_d at LHCb

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The b production cross-section in pp collisions at a center-of-mass energy of 7 TeV is measured with semi-leptonic b decays and with inclusive b decays to J/ψ mesons, yielding total cross-sections of $284 \pm 20 \pm 49$ μb and $288 \pm 4 \pm 48$ μb, respectively.
The ratio of fragmentation fraction f_s/f_d is determined with semi-leptonic b decays and with the exclusively reconstructed hadronic decays $B^0 \to D^- K^+$, $B^0 \to D^- \pi^+$ and $B^0_s \to D^-_s \pi^+$, resulting in $f_s/f_d = 0.268 \pm 0.008 \pm^{0.022}_{0.020}$ and $f_s/f_d = 0.253 \pm 0.017 \pm 0.017 \pm 0.020$, respectively, which are the first determinations of the ratio of fragmentation fractions at the LHC.

The 13th International Conference on B-Physics at Hadron Machines - Beauty2011,
April 04-08, 2011
Amsterdam, The Netherlands

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1. Introduction and LHCb

The b production cross-section at LHCb with a center-of-mass energy of 7 TeV is predicted by Quantum Chromodynamics (QCD), and the measurement of the b production cross-section can be compared to the theoretical predictions to scrutinize QCD. Moreover, knowledge of the yield of B mesons is needed to ascertain the sensitivity in many measurements involving B meson decays, such as CP violation. In these proceedings the b production cross-section is reported as measured with two methods, involving different final states, namely semi-leptonic B decays and inclusive $b \to J/\psi X$ decays. In addition, measurements of the ratio of fragmentation fractions f_u, f_d, f_s, which describe the probability that a b quark will fragment into a B_q meson (where $q = u,d,s$), are presented. Knowledge of the ratio f_s/f_d is crucial to determine all B_s^0 branching fractions at the LHC. The rare decay $B_s^0 \to \mu^+\mu^-$ is the prime example where the uncertainty on f_s/f_d will determine the sensitivity for the search of New Physics. Two determinations of the ratio of fragmentation fractions are presented, involving semi-leptonic B decays and the exclusive hadronic decays $B^0 \to D^-K^+$, $B^0 \to D^-\pi^+$ and $B_s^0 \to D_s^-\pi^+$.

In 2010 the LHCb experiment accumulated a data set that corresponds to a luminosity of about 38 pb^{-1}. The measurements presented here use early data collected by LHCb at various stages of the data-taking period in 2010. The LHCb experiment is a single arm spectrometer, designed to study B decays at the LHC, covering the pseudo-rapidity range $1.8 < \eta < 4.9$. The LHCb detector is optimized to select and accurately measure b hadrons that fly on average 7 mm with a (transverse) momentum of about (5) 100 GeV. The trigger system allows to select events with B decay products at the lowest trigger level (L0) with low transverse momentum, $p_T > 1.2(3.6)$ GeV for muons (hadrons). This reduces the LHC bunch crossing rate of 40 MHz down to 1 MHz. Subsequently, the full event information is shipped to a dedicated CPU farm, where the high level trigger reduces the rate to 2 kHz. A good tracking system is essential to determine the proper lifetime of the B mesons and to accurately determine the momentum of its decay products. The tracking system is divided in a silicon detector close to the interaction region (VELO), a 3.7 Tm dipole magnet, and a tracking system behind the magnet. To distinguish its final states accurately (such as $D_s^+\pi^-$ and D^+K^-), LHCb is equipped with two Ring Imaging Cherenkov (RICH) detectors, before and after the dipole magnet. The calorimeter system enables the selection of hadronic B decays at the lowest trigger level, and in addition provides particle identification for photons, electrons and π^0 mesons. Finally, the muon spectrometer identifies and selects muons both in the trigger and offline.

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2. Measurement of b Production Cross-Section

2.1 Semi-leptonic b-decays

With the first data collected by LHCb in June 2010, corresponding to an integrated luminosity of 12.2 nb^{-1}, the b production cross section was determined using the channel $b \to D^0 X \mu^- \overline{\nu}$ (with $D^0 \to K^-\pi^+$) [2] with branching ratios of $6.84 \pm 0.35\%$ and $3.89 \pm 0.05\%$, respectively.

First, the charged kaons and pions are selected on the basis of their likelihood using the associated Cherenkov photons in the RICH system, and with a transverse momentum p_T larger than 300 MeV. The two tracks must be compatible with originating from a common vertex with $\chi^2 < 6$. A

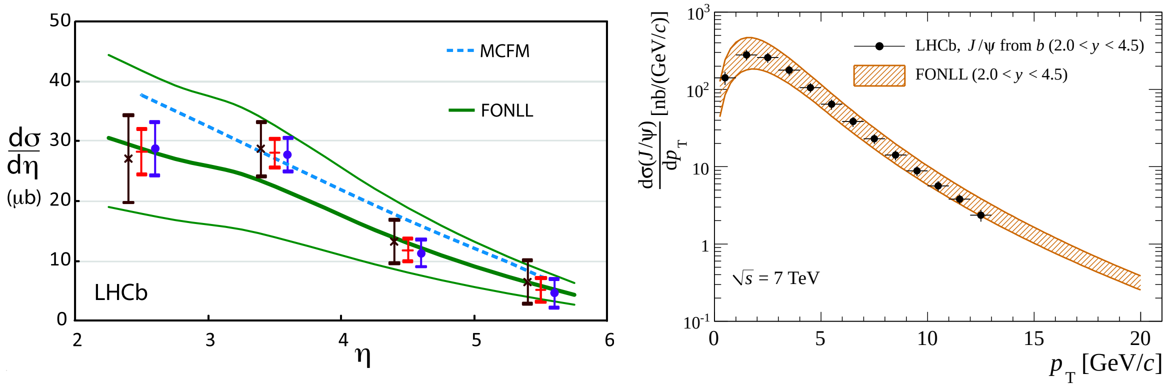

Figure 1: *The b production cross-section is compared to theoretical predictions.*

muon with $p_T > 500$MeV is matched to the D^0 meson by requiring that they originate from a common vertex with $\chi^2 < 5$. The $D^0\mu^-$ invariant mass is required to be between 3 and 5 GeV, consistent with originating from a partially reconstructed b hadron. An unbinned two-dimensional likelihood fit to the $K^-\pi^+$ invariant mass and the logarithm of the impact parameter of the $D^0\mu^-$-pair allows the extraction of the b-yield. The background from false $K^-\pi^+$ combinations is obtained from the D^0-sidebands, whereas the shape of the prompt D^0 yield is found by combining the D^0 with a random track failing the muon identification criteria. The production cross-section of b hadrons (H_b) is determined as follows:

$$\sigma(pp \to H_b X) = \frac{N(D^0\mu^-) + N(\bar{D}^0\mu^+)}{2\mathscr{L}\varepsilon BR(b \to D^0 X \mu^- \bar{\nu}) BR(D^0 \to K^-\pi^+)} = 75.3 \pm 5.4 \pm 13.0\ \mu\text{b}. \tag{2.1}$$

The first error is statistical and the second error is systematic, which is dominated by the uncertainty on the tracking efficiency (10%) and the luminosity determination (10%), followed by the uncertainties in the branching fractions. In the extraction of the cross-section the LEP fragmentation fractions were used, which adds an additional 4.4% to the total systematic uncertainty. Using an extrapolation factor of 3.77 as obtained from Monte Carlo simulations with the Pythia 6.4 program, the following total $b\bar{b}$ cross-section is obtained,

$$\sigma(pp \to H_b X)_{4\pi} = 284 \pm 20 \pm 49\ \mu\text{b}, \tag{2.2}$$

where uncertainties in the extrapolation factor are ignored.

The single differential cross-section as a function of pseudo-rapidity η of the $D^0\mu^-$-pair is shown in Fig. 1. The data are compared with two theories, the first based on improved fixed order next-to-leading order (NLO) with resummation of logarithms to next-to-leading accuracy (FONLL) [3], and the second originating from the *Monte Carlo program for FeMtobarn processes* (MCFM) [4] based on NLO calculations, and using the MSTW8NL parton distribution functions.

2.2 Inclusive J/ψ production

The b cross-section has also been measured with the data sample collected in September 2010, corresponding to an integrated luminosity of 5.2 pb^{-1}, using the channel $b \to J/\psi X$ (with $J/\psi \to \mu^-\mu^+$) [5] with branching ratios of 1.16 ± 0.10% and 5.93 ± 0.06%, respectively.

The J/ψ candidates were selected by requiring good quality charged tracks ($\chi^2 < 4$), with $p_T > 700$ MeV, penetrating the iron of the muon system. The two tracks are required to form a common vertex with a probability larger than 0.5%. The fraction of J/ψ candidates that originate from b-decays is estimated from a two-dimensional likelihood fit to the $\mu^+\mu^-$ invariant mass and pseudo-proper time $t_z = (z_{J/\psi} - z_{PV}) \times M_{J/\psi}/p_{z,J/\psi}$ (where $z_{J/\psi} - z_{PV}$ is the distance in the z-coordinate along the beam-axis between the primary vertex and the J/ψ decay vertex). Four components are extracted from the fit: fake $\mu^+\mu^-$ candidates, prompt J/ψ candidates, J/ψ candidates from b-decays, and prompt J/ψ candidates that are associated to the wrong primary vertex. The last component mimics J/ψ candidates from b-decays and its shape is obtained from associating the J/ψ candidate to the primary vertex of the next event. The shape of J/ψ candidates from b-decays is constrained by using the b hadron pseudo-lifetime.

The integrated cross-section for the production of J/ψ from b hadrons in the region $p_{T,J/\psi} <$ 14 GeV and the rapidity range $2.0 < y_{J/\psi} < 4.5$ is:

$$\sigma(pp \to b\bar{b}X \to J/\psi X') = 1.14 \pm 0.01 \pm 0.16\ \mu\text{b}. \tag{2.3}$$

The first error is statistical and the second error is systematic, which is dominated by the uncertainty in the tracking efficiency (8%) and the luminosity determination (10%). The extrapolation to the full polar angle range is achieved through

$$\sigma(pp \to b\bar{b}X)_{4\pi} = \alpha_{4\pi} \frac{\sigma(pp \to b\bar{b}X \to J/\psi X')}{2BR(b \to J/\psi X')} = 288 \pm 4 \pm 48\ \mu\text{b}, \tag{2.4}$$

where an extrapolation factor $\alpha_{4\pi} = 5.88$ is used as obtained from Monte Carlo simulations with the Pythia 6.4 program. An extra contribution is added to the systematic uncertainty originating from $BR(b \to J/\psi X) = (1.16 \pm 0.10)\%$ and the fragmentation fractions (2%), both taken from LEP. The result is consistent with the b production cross-section obtained with semi-leptonic b-decays as described in the previous section. The single differential cross-section as a function of p_T of the J/ψ candidate is shown in Fig. 1b. The data are compared with FONLL [3] based on improved fixed order NLO and show excellent agreement.

3. Measurement of Ratio of Fragmentation Fractions f_s/f_d

3.1 f_s/f_d from Semi-leptonic b-decays

The fragmentation fractions f_u, f_d, f_s, which describe the probability that a b quark will fragment into a B_q meson (where $q = u,d,s$), respectively, are measured with the first 3 pb^{-1} collected in September 2010. Semi-leptonic decays of the b hadron are used, where the B^0 and B^+ mesons predominantly decay to a combination of the final states $D^0X\mu^-\bar{\nu}$ and $D^+X\mu^-\bar{\nu}$ and where the B_s^0 meson decays predominantly to $D_s^+X\mu^-\bar{\nu}$ [1]. The ratio $f_s/(f_d + f_u)$ is determined as follows

$$\frac{f_s}{f_d + f_u} = \frac{n_{cor}(B_s^0 \to D_sX\mu\nu) + n_{cor}(B_s^0 \to D^0KX\mu\nu)}{n_{cor}(B^{+,0} \to D^+X\mu\nu) + n_{cor}(B^{+,0} \to D^0X\mu\nu)} \frac{\tau_{B^+} + \tau_{B^0}}{2\tau_{B_s^0}}, \tag{3.1}$$

where the n_{cor} are the event yields (including the charge conjugated modes) corrected for relative detector efficiencies, branching ratios of the D mesons and for cross-feeds from decays like $B_s^0 \to D^0KX\mu\nu$ and $B^0 \to D_sX\mu\nu$.

[1] At the time of the conference no results were yet available on the fragmentation fraction f_{Λ_b}, which is the probability that a b quark fragments into a Λ_b baryon, which can be measured using the $\Lambda_cX\mu\nu$ final state.

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The raw event yields are obtained as discussed in Section 2.1, resulting in 27666 ± 187 $D^0 X \mu \nu$, 9257 ± 110 $D^+ X \mu \nu$ and 2192 ± 64 $D_s^+ X \mu \nu$ events. The relative efficiencies are taken from Monte Carlo simulation. The pion, kaon and proton particle identification (PID) efficiency is measured using K_S^0, D^{*-} and Λ^0 control samples. The following ratio of fragmentation fractions is measured,

$$\frac{f_s}{f_d} = 0.268 \pm 0.008^{+0.022}_{-0.020}, \tag{3.2}$$

where the first error is statistical and the second systematic, and assuming $f_u = f_d$. The largest contribution comes from the uncertainty on the D branching ratios (5.5%), followed by the B_s^0 decay modelling to the various excited D_s mesons (3%) and the uncertainty on the contribution from $B_s^0 \to D^0 K X \mu \nu$ decays ($^{+4.1\%}_{-1.1\%}$). The ratio f_s/f_d is found to be consistent with being independent of the transverse momentum of the $D\mu$-pair.

3.2 f_s/f_d from Exclusive Hadronic Decays

The ratio of fragmentation fractions f_s/f_d is also determined with exclusive hadronic B decays, using the full 2010 data set, corresponding to an integrated luminosity of 35 pb^{-1} [6]. The decays $B^0 \to D^- K^+$ and $B_s^0 \to D_s^- \pi^+$ are dominated by colour-allowed tree-diagram amplitudes that are related by SU(3)-symmetry. As a consequence, the ratio of branching ratios is theoretically well-understood, leading to the relation [7]:

$$\frac{f_s}{f_d} = 0.0743 \times \frac{\tau_{B_d}}{\tau_{B_s}} \times \left[\frac{1}{\mathcal{N}_a \mathcal{N}_F} \frac{\varepsilon_{D^- K^+}}{\varepsilon_{D_s^- \pi^+}} \frac{N_{D_s^- \pi^+}}{N_{D^- K^+}} \right], \tag{3.3}$$

where ε denotes the selection efficiency as determined from Monte Carlo simulation (including the B branching fractions) and N denotes the observed event yields. The term $\mathcal{N}_a = 1.00 \pm 0.02$ parametrizes non-factorizable SU(3)-breaking effects and $\mathcal{N}_F = 1.24 \pm 0.08$ is the ratio of the form factors. The Cabibbo favoured decay $B^0 \to D^- \pi^+$ can also be used [8]:

$$\frac{f_s}{f_d} = 0.982 \times \frac{\tau_{B_d}}{\tau_{B_s}} \times \left[\frac{1}{\mathcal{N}_a \mathcal{N}_F \mathcal{N}_E} \frac{\varepsilon_{D^- \pi^+}}{\varepsilon_{D_s^- \pi^+}} \frac{N_{D_s^- \pi^+}}{N_{D^- \pi^+}} \right]. \tag{3.4}$$

but suffers from an additional theoretical uncertainty due to the contribution from "exchange" topologies, parametrized by $\mathcal{N}_E = 0.966 \pm 0.075$.

The three decay modes are topologically identical, with four charged tracks in the final state and are therefore selected with identical kinematic criteria like the p_T of the tracks and of the D meson, and with geometric criteria like the impact parameter χ^2 of the tracks, the vertex fit χ^2 of the D and B vertices and the lifetime of the B meson. The final event samples are selected using the boosted decision tree technique. Subsequently, the D^- and D_s^- are selected with loose PID requirements on the pions and kaons, and a mass cut of $^{+24}_{-40}$ MeV around the D mass. A relatively strong PID requirement is placed on the bachelor particle to suppress the cross feed from $B^0 \to D^- \pi^+$ events under the $B^0 \to D^- K^+$ mass peak. The relative selection efficiencies are estimated from Monte Carlo simulation.

The relative event yields are extracted from unbinned extended maximum likelihood fits to the mass distributions, as shown in Fig. 2. The shapes of the signal and of the partially reconstructed backgrounds are obtained from Monte Carlo simulation and are fixed in the fit. A prominent

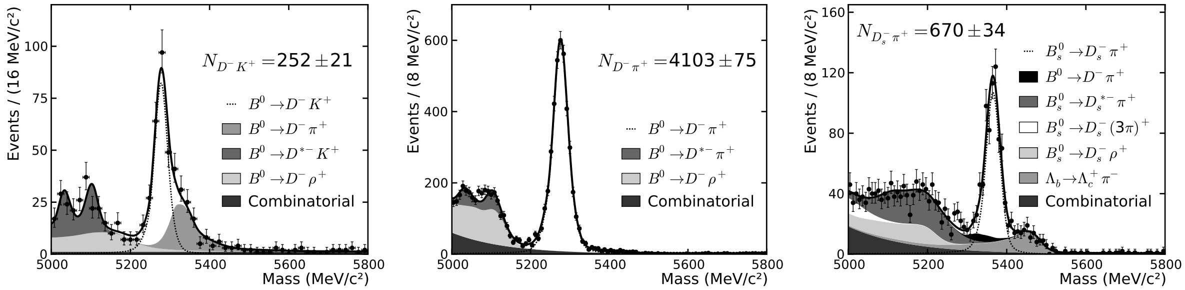

Figure 2: *The mass fits to the decays $B^0\to D^-K^+$, $B^0\to D^-\pi^+$ and $B_s^0\to D_s^-\pi^+$.*

background to $B^0\to D^-K^+$ is $B^0\to D^-\pi^+$ with the bachelor pion misidentified as a kaon. The shape is modeled by using a clean $B^0\to D^-\pi^+$ sample using the kaon mass hypothesis for the bachelor particle, and by taking into account the momentum dependence of the PID criteria.

The resulting value for f_s/f_d as obtained using the decay $B^0\to D^-K^+$ is $f_s/f_d = 0.250\pm 0.024^{\rm stat}\pm0.017^{\rm sys}\pm0.017^{\rm theo}$, whereas using the decay $B^0\to D^-\pi^+$ yields $f_s/f_d = 0.256\pm0.014^{\rm stat}\pm 0.019^{\rm sys}\pm0.026^{\rm theo}$. Taking all correlated errors into account leads to the combined result

$$\frac{f_s}{f_d} = 0.253\pm0.017^{\rm stat}\pm0.017^{\rm sys}\pm0.020^{\rm theo}. \tag{3.5}$$

This is the first measurement of f_s/f_d at the LHC and is in excellent agreement with the determination using semi-leptonic decays as described in the previous Section. In addition, both determinations of f_s/f_d are in agreement with the value from LEP, and the recent update from the Tevatron, suggesting universality of the ratio of fragmentation fractions.

4. Conclusions

The *b* production cross-section is measured with semi-leptonic *b*-decays and with inclusive *b*-decays to J/ψ mesons, yielding consistent results. The ratio fragmentation fraction f_s/f_d is determined with semi-leptonic *b*-decays and with the exclusively reconstructed hadronic decays $B^0\to D^-K^+$, $B^0\to D^-\pi^+$ and $B_s^0\to D_s^-\pi^+$, resulting in the first determination of the ratio of fragmentation fractions at the LHC, which is crucial for the sensitivity in the search for New Physics in the rare decay $B_s^0\to\mu^+\mu^-$ [7].

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