PROCEEDINGS OF SCIENCE

Production and properties of b-hadrons

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A representative sample of recent results in Heavy-Flavour Physics, obtained with the experiments housed at the CERN Large Hadron Collider (LHC), and based on proton-proton collision data collected in 2010 and 2011 at a center-of-mass energy of 7 TeV, is reviewed. Particular emphasis is given to recent measurements of production and properties of b-flavoured hadrons.

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1. Introduction

The LHC mission includes, besides the searches for signals of New Physics and for the missing bricks of the Standard Model (SM), a wide program of Heavy-Flavour Physics. This particular field is studied with both the general purpose experiments, ATLAS and CMS, and a dedicated detector at forward rapidities, LHCb. Also the heavy-ions collision dedicated experiment, ALICE, has a Heavy-Flavour Physics program complementary to its main purpose.

The importance of precision measurements of production and properties of b-hadrons is due to multiple reasons. Measurements of Heavy-Flavour production provide a testing ground for Quantum Chromodynamics (QCD) calculations in a new energy regime. While next-to-leading order (NLO) contributions dominate at LHC, large theoretical uncertainties remain due to factorization and renormalization scales. Moreover, b-jet identification is crucial in searches for New Physics, as many SM processes are known to have b-hadrons in their final state, and several scenarios beyond the SM foresee predominant couplings to the heaviest known quarks and leptons. Measurements of b-hadron properties provide important tests of the SM and any deviation from the predicted values would be an indirect indication of New Physics.

A representative sample of recent results in Heavy-Flavour Physics, obtained with the experiments housed at the CERN Large Hadron Collider (LHC), and based on proton-proton collision data collected in 2010 and 2011 at a center-of-mass energy of 7 TeV, and made public in the last six months, is reviewed herein. Other subjects, such as quarkonia, excited states, rare decays and CP violation measurements at the LHC, are widely covered by other contributions at HQL2012.

2. Results from the ATLAS Experiment

A detailed description of the ATLAS detector can be found in a dedicated document [1]. The ATLAS Collaboration observed the production of $B_c^\pm$ meson decaying to $J/\psi\pi^\pm \to \mu^+\mu^-\pi^\pm$ [2]. As the $B_c^\pm$ meson is composed of a charm and a beauty quark-antiquark pair, both contributing to final states with competing decay modes, it is an unique probe for heavy quark dynamics non accessible to $b\bar{b}$ or $c\bar{c}$ bound states. This measurement is based on 4.3 fb^{-1} of pp-collision data collected in 2011. The event selection is based on a $J/\psi \to \mu^+\mu^-$ enriched sample, where muon pairs of opposite charge with common vertex and invariant mass in the J/ψ region are selected from a single-muon and di-muon trigger sample. Eight Monte Carlo (MC) samples are used to optimize the event selection criteria: $B_c^\pm \to J/\psi\pi^\pm$ signal and direct J/ψ production, J/ψ production in decays of b-hadrons, $B_c^\pm \to J/\psi K^\pm$, $B_c^\pm \to J/\psi\rho^\pm(\pi^\pm\pi^0)$, $B_c^\pm \to J/\psi\mu^\pm\nu$, $B_c^\pm \to J/\psi\pi^\pm\pi^0$, $B_c^\pm \to J/\psi\pi^\pm\pi^\mp\pi^\pm$ backgrounds. A candidate pion is fitted to a common vertex together with the muon pair, combinatorial background is reduced by means of track impact parameter with respect to the event primary vertex. An extended unbinned maximum likelihood fit is performed to extract the mean mass, resolution, and number of $B_c^\pm$ signal candidates from the data. The $B_c^\pm$ mass returned by the fit is 6282 ± 7 MeV$/c^2$, which is consistent with the world average of 6277 ± 6 MeV$/c^2$. The signal mass resolution is 36 ± 9 MeV$/c^2$, and the mass resolution determined from the Monte Carlo is 43 ± 7 MeV$/c^2$. The total number of observed signal events is 82 ± 17 over a background of 140 ± 5 events. The quoted errors are statistical only.

Also the production of Λ_b^0 was measured through the decay $\Lambda_b^0 \to J/\psi\Lambda \to \mu^+\mu^- p^+\pi^-$, as well as the complementary final state for $\bar{\Lambda}_b^0$ [3]. Understanding the production of Λ_b^0 and its decay modes is crucial because its lifetime is accurately predicted by Heavy Quark Effective Theory and perturbative QCD. This measurement is based on 1.2 fb^{-1} of pp-collision data collected in 2011. Besides a J/ψ selection analogous to the one described in the $B_c^\pm$ measurement, a candidate proton and a candidate pion of opposite charged are used to form a neutral Λ^0 baryon, which is then fit to a common vertex together with the candidate $J/\psi \to \mu^+\mu^-$. Both the $\Lambda^0 \to p^+\pi^-$ and $\bar{\Lambda}^0 \to p^-\pi^+$ hypotheses are tried, choosing the one with the best vertex significance. Background is reduced requiring a proper decay time of the candidate Λ_b^0 larger than 0.35 ps. The signal yield is extracted via an extended unbinned maximum likelihood fit to the $\mu^+\mu^- p^\pm\pi^\mp$ invariant mass. The Λ^0 mass returned by the fit is 5620.6 ± 1.6 MeV$/c^2$, which is consistent with the world average of 5620.2 ± 1.6 MeV$/c^2$. The signal mass resolution is 37.2 ± 2.0 MeV$/c^2$. The total number of observed signal events is 579 ± 31 over a background of 699 ± 33 events. The quoted errors are statistical only.

The mass and lifetime of the Λ_b^0 baryon have been measured by ATLAS using 4.9 fb^{-1} of pp-collision data collected in 2011 [4]. As the $\Lambda_b^0 \to J/\psi\Lambda \to \mu^+\mu^- p^+\pi^-$ decay is charachterized by a topology very similar to the one of $B^0 \to J/\psi K_S^0 \to \mu^+\mu^-\pi^+\pi^-$, the procedure can be validated by means of an accurate measurement of the B^0 mass and lifetime. The main backgrounds for this measurement are the combinatorial background of prompt J/ψ production together with charged tracks, and the non-prompt J/ψ's from decays of B-mesons. The possibility of sample contamination from misidentified B^0 mesons is taken into account by attempting a $B^0 \to J/\psi K_S^0 \to \mu^+\mu^-\pi^+\pi^-$ topology fit to the candidate event. The signal yield, and the Λ_b^0 mass and lifetime are extracted simultaneously from a combined fit to the invariant mass distribution of the four selected tracks and to the candidate baryon decay distance measured with respect to the event primary vertex. The Λ_b^0 lifetime and mass are measured to be 1.449 ± 0.036 (stat) ± 0.017 (syst) ps, and 5619.7 ± 0.7 (stat) ± 1.1 (syst) MeV$/c^2$, respectively. These results are consistent with the world average values, as well as with recent measurements by LHCb which are not included in the world average value [5].

These measurements are complemented by the one of the average b-hadrons lifetime [6], providing a sound testbench for the teorethical predictions of Heavy Quark Expansion, which calculate lifetimes up to a percent level accuracy. This measurement is based on 35 pb^{-1} of pp-collision data collected in 2010. A high-quality J/ψ inclusive sample is selected therein, whose non-prompt fraction is assumed to be produced in the decays of B^0, $B^\pm$, B_s^0, $B_c^\pm$, Λ_b^0. An average of the lifetimes can be measured with a partial reconstruction of their decay, using the J/ψ vertex. The non-prompt fraction can be separated by exploiting their displaced decay vertex. In particular, the signed projection L_{xy} of the flight distance on the candidate J/ψ transverse momentum is used to calculate a pseudo-proper decay time of the b-hadron. The average lifetime of b-hadrons is extracted from data by performing an unbinned maximum likelihood fit simultaneously to the J/ψ invariant mass and the pseudo-proper decay time and its value is 1.489 ± 0.016 (stat) ± 0.043 (syst) ps.

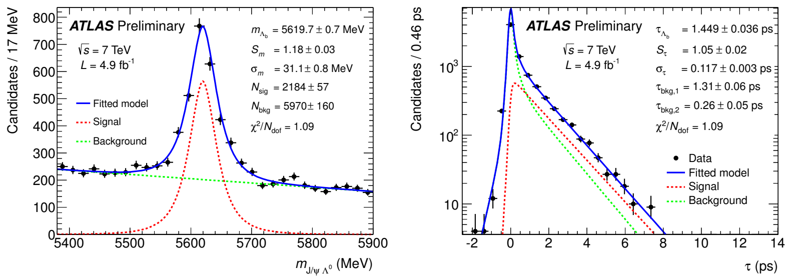

Figure 1: Projections of the fitted PDF onto the mass (left) and the proper decay time (right) axes for ATLAS Λ_b^0 candidates. The displayed errors are statistical only.

3. Results from the CMS Experiment

A detailed description of the CMS detector can be found in a dedicated document [7]. The CMS Collaboration measured the inclusive production of b-jets with two complementary analyses. The experimental measurement of the b-quark production cross section has been pursued with interest at hadron colliders because of discrepancies between theoretical predictions and experimental results. Both studies were performed on pp-collision data collected in 2010: a jet analysis, selecting events with a b-jet, and a muon analysis, requiring in addition a muon in the b-jet [8]. Despite the difference in the corresponding integrated luminosity (34 pb^{-1} and 3 pb^{-1}, respectively), the precisions of the two measurements are similar and dominated by their specific yet comparable systematic uncertainties. The inclusive jet data were collected using a combination of minimum bias and single-jet triggers. For the muon analysis, the events are required to pass a trigger selection that accepts events with high p_T central muons. Jets are reconstructed using a particle-flow algorithm, which uses the information from all CMS sub-detectors to reconstruct different types of particles produced in the event. The b-jets are identified by finding the secondary decay vertex of the b-hadrons. In the muon analysis, a muon is required to be included in the most energetic b-tagged jet. The two b-jet cross-section measurement samples are essentially statistically independent. The signal is extracted via a fit to the secondary vertex mass in the jet analysis and a fit to the muon p_T relative to the jet axis in the muon analysis, and the cross section measurement is extracted on a double-differential basis, as a function of p_T and rapidity, and compared to MC predictions at NLO, as shown in Figure 2 for the jet analysis.

A complementary analysis, based on 17.9 pb^{-1} of pp-collision data collected in 2010, makes use of an inclusive dimuon sample [9]. Events are selected from a double muon trigger sample, by requiring a pair of muons associated to the same vertex and with an invariant mass far from the known resonances. Two different transverse momentum thresholds are chosen. The fraction of signal events ($pp \to b\bar{b}X \to \mu^+\mu^-X'$) in the data is obtained from a fit to the 2D distribution of the impact parameters of the two muons. For this purpose, reconstructed muons in events simulated with PYTHIA are separated into four different classes, defined according to their origin: b-hadrons, including sequential decays (B), c-hadrons (C), prompt muons (P), and decays-in-flight of light flavour hadrons (D). The single-particle distributions of the transverse impact parameter d_{xy} are

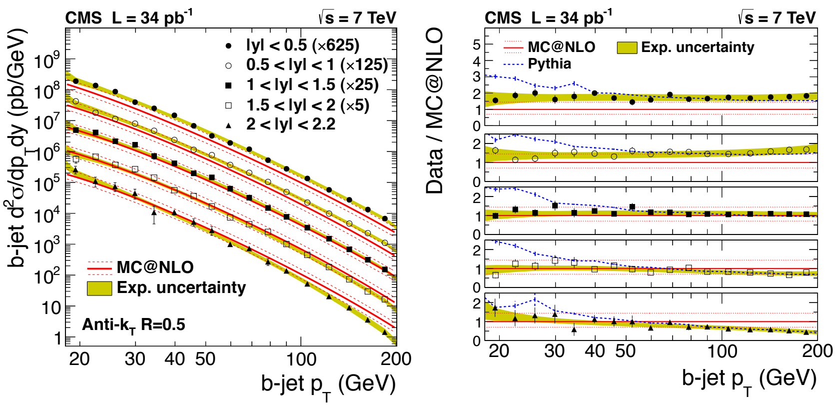

Figure 2: Measured b-jet cross section from the jet analysis, multiplied by the arbitrary factors shown in the figure for easier viewing, compared to the MC@NLO calculation (left) and as a ratio to the MC@NLO calculation (right). The experimental systematic uncertainties are shown as a shaded band and the statistical uncertainties as error bars.

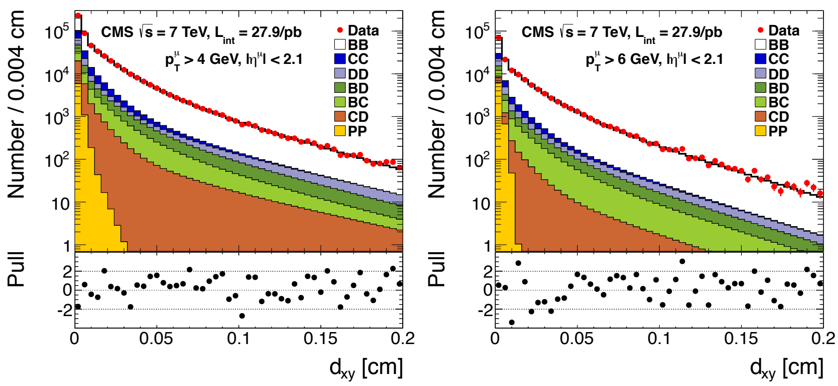

Figure 3: Projected d_{xy} distributions from data with the results of the fit for muons with $p_{\mathrm{T}} > 4$ GeV$/c$ (left) and $p_{\mathrm{T}} > 6$ GeV$/c$ (right). The distribution from each dimuon source is shown by the histograms. The pulls from the fit are shown too.

obtained for each class from simulation and fit using analytical functions. From these functions, the 2D templates are built symmetrically. The measured cross section for muon $p_{\mathrm{T}} > 4$ GeV$/c$ and pseudorapidity $|\eta| < 2.1$ is 25.7 ± 0.1 (stat) $\pm\, 2.2$ (syst) $\pm\, 1.0$ (lumi) nb, while the one for muon $p_{\mathrm{T}} > 6$ GeV$/c$ and pseudorapidity $|\eta| < 2.1$ is 5.03 ± 0.05 (stat) $\pm\, 0.46$ (syst) $\pm\, 0.20$ (lumi) nb. Both results are compatible with MC@NLO predictions of 19.7 ± 0.3 (stat)$^{+6.5}_{-4.1}$ (syst) nb and 4.40 ± 0.14 (stat)$^{+1.10}_{-0.84}$ (syst) nb, respectively, within the uncertainties of the NLO calculations and the measurements.

The CMS Collaboration measured also the production cross section of Λ_b^0 in the $J/\psi\Lambda \rightarrow \mu^+\mu^- p^+\pi^-$ final state, as well as the $\Lambda_b^0/\bar{\Lambda}_b^0$ production ratio on 1.9 fb^{-1} of pp-collision data collected in 2011 [10]. This is the first measurement of the production cross section of a b-baryon at the LHC, using fully reconstructed $J/\psi\Lambda$ decays. One particular aspect of this study is the possibility to measure baryon/antibaryon asymmetries which are predicted in baryon transport models

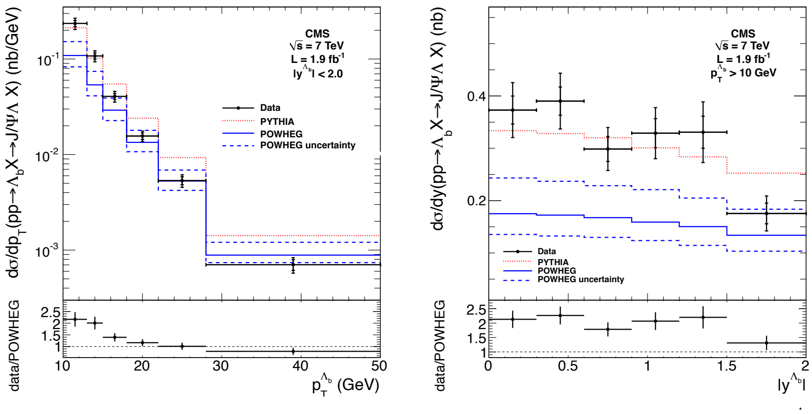

Figure 4: Measured differential cross sections times branching fraction as a function of Λ_b^0 transverse momentum (left) and rapidity (right) compared to the theoretical predictions from PYTHIA and POWHEG. The inner error bars correspond to the statistical uncertainties and the outer ones represent the uncorrelated systematic uncertainties added in quadrature to the statistical uncertainties. The dashed lines show the uncertainties on the POWHEG predictions.

from the symmetric pp initial state at the LHC. The selection of candidate Λ_b^0 is analogous to the one described in the ATLAS measurements, with the main difference in assigning the "proton" hypothesis to the highest p_{T} track in the Λ^0 candidate instead of testing both the options. The signal yield is extracted from a fit to the Λ_b^0 invariant mass. The cross section is calculated in a double-differential way and shown in Figure 3, while the measured $\Lambda_b^0/\bar{\Lambda}_b^0$ production ratio is consistent with unity in the whole kinematic range under study.

4. Results from the LHCb Experiment

A detailed description of the LHCb detector can be found in a dedicated document [11]. The LHCb Collaboration could perform the world best measurements of the masses of b-hadrons on 35 pb^{-1} of pp-collision data collected in 2010 [12]. The trigger and the momentum scale calibration are based on di-muon resonances, in particular the J/ψ one, and the measurement relies on the exclusive decays $B^{\pm} \to J/\psi K^{\pm}$, $B^0 \to J/\psi K^{*0}(K^+\pi^-)$, $B^0 \to J/\psi K_S^0(\pi^+\pi^-)$, $B_s^0 \to J/\psi\phi(K^+K^-)$ and $\Lambda_b^0 \to J/\psi\Lambda$. Ring imaging Cherenkhov detectors are used to enhance particle identification. The masses are measured from a fit to the invariant mass distribution of the charged tracks used to reconstruct the candidate event: $m_{B^{\pm}} = 5279.38 \pm 0.11\ (\mathrm{stat}) \pm 0.33\ (\mathrm{syst})\ \mathrm{MeV}/c^2$, $m_{B^0} = 5279.58 \pm 0.15\ (\mathrm{stat}) \pm 0.28\ (\mathrm{syst})\ \mathrm{MeV}/c^2$, $m_{B_s^0} = 5366.90 \pm 0.28\ (\mathrm{stat}) \pm 0.23\ (\mathrm{syst})\ \mathrm{MeV}/c^2$, and $m_{\Lambda_b^0} = 5619.19 \pm 0.70\ (\mathrm{stat}) \pm 0.30\ (\mathrm{syst})\ \mathrm{MeV}/c^2$.

The LHCb Collaboration completed the first observation of the $B_c^{\pm} \to J/\psi\pi^{\pm}\pi^{\mp}\pi^{\pm}$ decay and measured its branching fraction relative to $B_c^{\pm} \to J/\psi\pi^{\pm}$ using 0.8 fb^{-1} of pp-collision data collected in 2011 [13]. The three-pions final state fraction is expected to be approximately twice than the single-pion one, but shows greater detection difficulties because of the reduced detector acceptance. A muon pair is used to create a candidate J/ψ with vertex and mass constraints, and is then combined with one or three candidate pions. The signal yield is extracted via a fit to the candi-

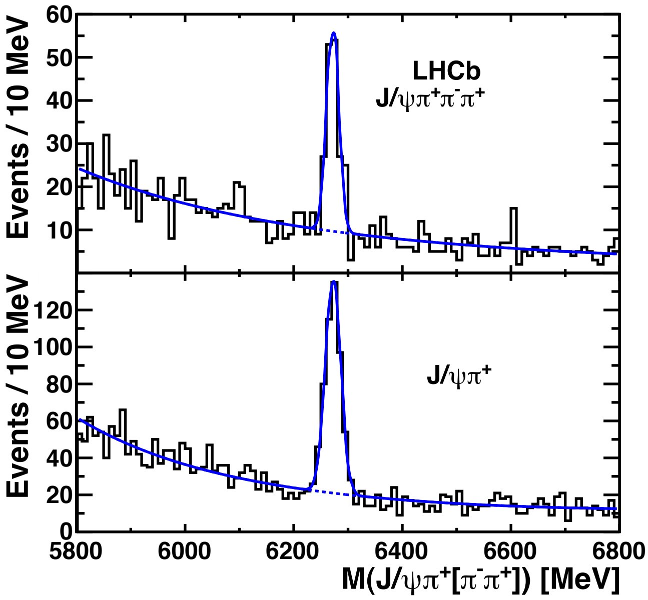

Figure 5: Invariant mass distribution of $B_c^\pm \to J/\psi\pi^\pm\pi^\mp\pi^\pm$ (top) and $B_c^\pm \to J/\psi\pi^\pm$ (bottom) candidates. The maximum likelihood fits of $B_c^\pm$ signals are superimposed.

date $B_c^\pm$ invariant mass. The main backgrounds come from combinatorial association of track and particles from different B-mesons. The measured ratio between the three-pions and the single-pion decay modes is 2.41 ± 0.30 (stat) ± 0.33 (syst).

The measurement of relative branching fraction of decays of B-mesons to final states with a J/ψ or a $\psi(2S)$ can help in enlarging the statistics which could be used to study rare processes. This measurement was performed by the LHCb Collaboration on 0.37 fb^{-1} of pp-collision data collected in 2011 [14]. The event selection is analogous to the one of the measurement of the masses of b-hadrons, with the restriction to the exclusive decays $B^\pm \to J/\psi K^\pm$, $B^0 \to J/\psi K^{*0}(K^+\pi^-)$, and $B_s^0 \to J/\psi\phi(K^+K^-)$. The combinatorial background is reduced by requiring a large lifetime of the candidate meson in terms of a decay length larger than 0.1 mm. The number of candidates is calculated with an unbinned likelihood fit to invariant mass distribution, and the branching fractions are unfolded taking into account the corresponding selection efficiencies. The measured $\mathcal{B}(B \to \psi(2S)X)/\mathcal{B}(B \to J/\psi X)$ is 0.594 ± 0.006 (stat) ± 0.016 (syst) ± 0.015 ($\mathcal{B}_{\psi\to\mu\mu}$) for $B^\pm$, 0.476 ± 0.014 (stat) ± 0.010 (syst) ± 0.012 ($\mathcal{B}_{\psi\to\mu\mu}$) for B^0, and 0.489 ± 0.026 (stat) $\pm$ 0.021 (syst) ± 0.012 ($\mathcal{B}_{\psi\to\mu\mu}$) for B_s^0.

5. Results from the ALICE Experiment

A detailed description of the ALICE detector can be found in a dedicated document [15]. The interest of ALICE Collaboration in Heavy-Flavour physics in pp-collisions is driven by its being an essential baseline for the corresponding measurements in heavy ion collisions. In the latter, heavy quarks are produced at early stages of the collision and then experience the full evolution of

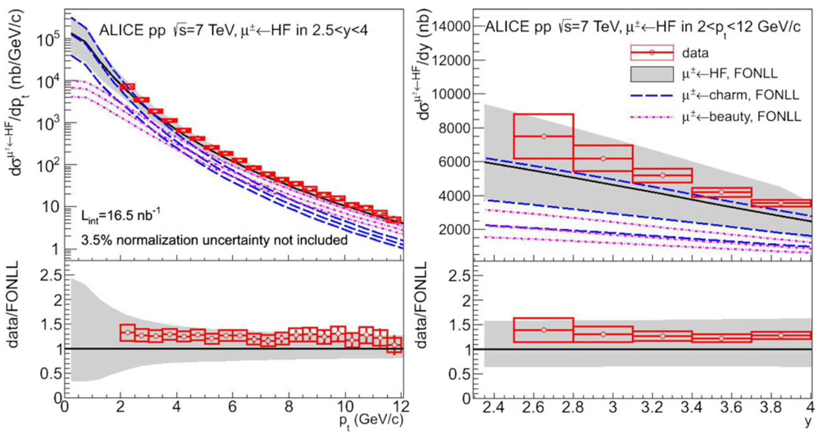

Figure 6: Left: p_{T}-differential production cross section of muons from Heavy-Flavour decays in the rapidity range $2.5 < y < 4$. Right: y-differential production cross section of muons from Heavy-Flavour decays, in the range $2 < p_{\mathrm{T}} < 12$ GeV$/c$. In both panels, the error bars (empty boxes) represent the statistical (systematic) uncertainties. A 3.5% normalization uncertainty is not shown. The solid curves are FONLL calculations and the bands display the theoretical systematic uncertainties.

the extremely hot and dense, strongly interacting medium. The modification of the Heavy-Flavour transverse momentum distributions measured in heavy ion collisions with respect to those measured in pp-collisions is considered as a sensitive probe of this medium.

The particular arrangement of ALICE subdetectors allows to use muons or electrons in two complementary kinematic regions. A measurement of the muon production due to Heavy-Flavour decays in the forward region, at rapidities between 2.5 and 4, was performed by the ALICE Collaboration on a 16.5 nb^{-1} sample of pp-collision data collected in 2010 with minimum-bias and single muon triggers [16]. Muon track p_{T} is used as discriminator of Heavy-Flavour production. MC PYTHIA simulations are used to create background templates of muons from light mesons, baryons, resonances, muons produced in the front absorber in decays of secondary hadrons and misidentified hadrons. These templates are normalized to data. The production cross section of muons from Heavy-Flavour is measured in a double-differential way and compared to theoretical predictions from Fixed Order plus Next-to-Leading Logarithms (FONLL), as shown in Figure 6. FONLL perturbative QCD calculations are in good agreement with data within experimental and theoretical uncertainties, data being close to the upper limit of the model calculations. Both transverse momentum and rapidity dependence of the HF decay muon production cross section are well described by the model predictions.

A complementary measurement was performed using electrons in the central region, from 2.6 nb^{-1} of pp-collision data collected in 2010 with minimum-bias triggers [17]. This is the first measurement of beauty production at ALICE, which follows an inclusive measurement of beauty and charm production with an analogous technique. Electrons from b-hadrons are selected by requiring a large impact parameter of the electron track measured in the Inner Tracking System. Electron identification is based on dE/dx in the TPC, time-of-flight and information from TRD's. The back-

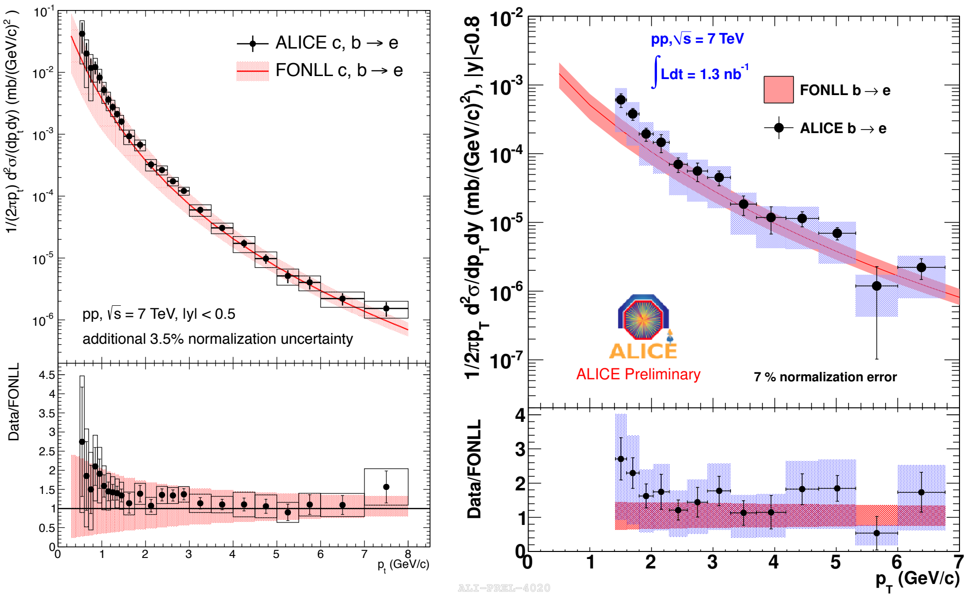

Figure 7: The measured electron spectrum from Heavy-Flavour hadron decays is compared to a FONLL calculation for inclusive charm and beauty semileptonic decays on an absolute scale in the upper panel (left) and exclusive beauty semileptonic decays (right). The ratio of the measured spectrum to the FONLL pQCD calculation is shown in the lower panel.

ground is composed by the so-called "electron cocktail", which is calculated from measured meson spectra, including light neutral meson decays, photon conversion in beam pipe, di-electron vector meson decays, heavy quarkonia (parametrized from other LHC measurements) and QCD photons (calculated from theory). The background is subtracted from inclusive electron p_{T} spectrum, the contribution from charmed hadrons is subtracted thanks to exclusive measurement of D-mesons production cross-section at ALICE. The double-differential production cross section is compared to FONLL predictions, which provide a good description of the measured spectra, as shown in Figure 7. These measurements, together with the electron spectra measured in Pb-Pb collisions, allow the extraction of a nuclear modification factor, showing a strong suppression of electrons from Heavy-Flavour decays in central collisions.

The last study included in this review is the measurement of the non-prompt J/ψ production at ALICE, based on 5.6 nb^{-1} of pp-collision data collected in 2010 with minimum-bias triggers [18]. The determination of non-prompt J/ψ fraction allows extrapolation of b-hadrons production cross section. Pairs of opposite-charge tracks identified as electrons are fitted to a common vertex to build a J/ψ candidate. A simultaneous unbinned maximum likelihood fit allows the extraction of the signal yield from electron-positron invariant mass, and the separation of the non-prompt fraction using pseudo-proper decay length. The measured non-prompt fraction within acceptance, including a selection on $p_T > 1.3$ GeV$/c$, is 0.147 ± 0.037 (stat)$^{+0.018}_{-0.027}$ (syst)$^{+0.025}_{-0.021}$ (syst,ψ polarization). The measured b-hadrons production cross section is compared to analogous measurements from other experiments in Figure 8.

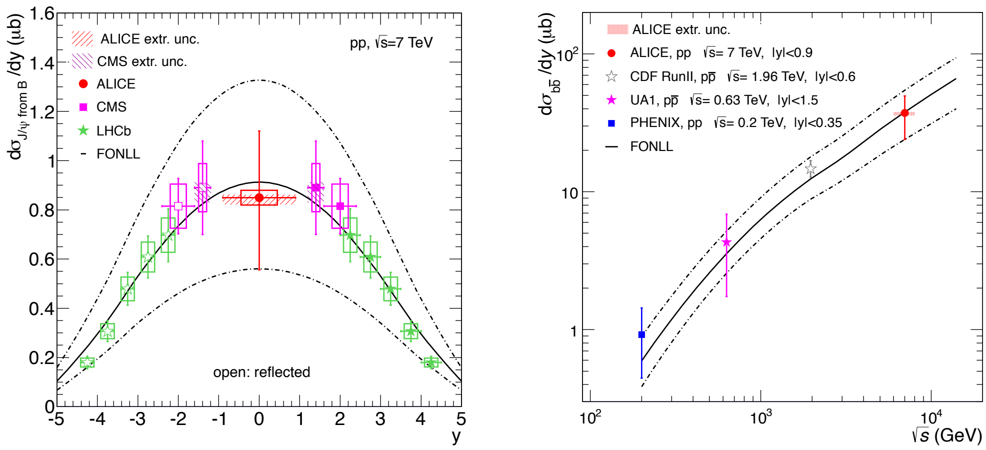

Figure 8: (Left) The differential production cross section for non-prompt J/ψ's. The error bars represent the quadratic sum of the statistical and systematic errors, while the systematic uncertainties on luminosity and branching ratio are shown as boxes. The CMS values were obtained by integrating the published data measured for $1.2 < |y| < 1.6$ and $1.6 < |y| < 2.4$. The results obtained in the forward region by LHCb are reflected with respect to $y = 0$ (open symbols). The FONLL calculation (and its uncertainty) is represented by solid (dashed) lines. (Right) Differential $b\bar{b}$ production cross section at mid-rapidities in pp and $p\bar{p}$ collisions as a function of $\sqrt{s}$.

6. Summary

The LHC excellent performance in 2010 and 2011 allowed all the experiments to perform high-quality studies in Heavy-Flavour physics. The dedicated B-physics experiment, LHCb, is giving us numerous interesting results covering the main subjects in Heavy-Flavour physics. Also the general-purpose experiments, ATLAS and CMS, and the Heavy-Ion collisions experiment, ALICE, produced interesting measurements which complement those from LHCb. Further results are expected to be made public in next months, allowing a better understanding of the field.

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