Studies of Onia and Strangeness Production in Proton-proton Collisions at LHCb

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Abstract. Studies of strangeness and quarkonia production in the forward region provide important input to the understanding of QCD models in a kinematic range where they have large uncertainties. The LHCb experiment has collected a dataset corresponding to an integrated luminosity of about 3 fb^{-1} in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV, as well as smaller samples recorded with other LHC operating modes. The latest studies of the production of kaons, Λ baryons, and quarkonia states are presented.

1. Introduction
The LHCb experiment is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of hadrons containing b or c quarks [1].The studies of the production of quarkonia are a stringent test of QCD. Quarkonia production is usually described in the framework of NRQCD, where short-distance calculations are used for the partonic calculations of the production of a heavy quark-antiquark pair and a large distance matrix elements for the evolution of the pair to quarkonia. The NRQCD calculations depend on the colour-singlet (CS) [2] and colour-octet (CO) matrix elements [3] that account for the probability of a heavy quark-antiquark pair, in a particular colour state, to evolve into heavy quarkonium. In proton-proton (pp) collisions quarkonia can be produced directly, through feeddown from higher quarkonia states or in the case charmonium via the decay of b hadrons.

The study of strangeness production provides sensitive tests of soft hadronic interactions in the non-perturbative regime. Both onia and strangeness production in pp-collision act as an important benchmark for the study of the quark-gluon plasma in heavy-ion collisions.

2. Onia production
The differential production cross-sections of prompt J/ψ and Υ mesons at $\sqrt{s} = 8$ TeV has been measured by LHCb [4], in the range of rapidity $2.0 < y < 4.5$ and $p_T < 14$ GeV/c(J/ψ) or $p_T < 15$ GeV/c(Υ) with an integrated luminosity of 51 pb^{-1}. Similar measurements have also been made by LHCb at $\sqrt{s} = 7$ TeV [5] and $\sqrt{s} = 2.76$ TeV [?] The J/ψ and Υ mesons are detected through their decays to $\mu^+\mu^-$ pairs. The fraction of J/ψ mesons from b-hadron decays is measured in the same fiducial region. The yields of both prompt J/ψ mesons and J/ψ from b are determined from a two-dimensional fit in (p_T, y) bins to the distributions of invariant mass and pseudo decay time of the signal candidates, following the approach outlined in ref. [7]. The integrated cross section for prompt J/ψ meson production in the fiducial region is measured to

be $\sigma(\text{prompt} J/\Psi) = 10.94 \pm 0.02 \pm 0.79 \ \mu\text{b}$, where the first error is statistical and the second is systematic, which is experimentally dominated by the timing fit, the trigger and luminosity measurement. The integrated cross section for the production of J/ψ from b in the same fiducial region is $\sigma(J/\Psi \text{ from } b) = 1.28 \pm 0.01 \pm 0.11 \ \mu\text{b}$.

The integrated cross section for Υ production (times the dimuon braching factors $B^{iS} = B(\Upsilon(iS) \to \mu\mu)$) in the range $p_T < 15$ GeV/c and $2.0 < y < 4.5$ are measured to be

$$
\begin{aligned}
\sigma(pp \to \Upsilon(1S)X) \times B^{1S} &= 3.241 \pm 0.018 \pm 0.231 \text{ nb} \\
\sigma(pp \to \Upsilon(2S)X) \times B^{2S} &= 0.761 \pm 0.008 \pm 0.055 \text{ nb} \\
\sigma(pp \to \Upsilon(3S)X) \times B^{3S} &= 0.369 \pm 0.005 \pm 0.027 \text{ nb}.
\end{aligned}
$$

In Figure 1 the measured differential cross-section for the production of prompt J/ψ mesons as a function of p_T are compared to three theoretical models (assuming no polarisation.) Both the NNLO* CSM and the NLO NRQCD models provide reasonable descriptions of the experimental data, whilst the CSM at NLO underestimates the cross-section by an order of magnitude. In Figure 2 shows the $\Upsilon(1S)$ meson differential cross-section as a function of p_T and again the NNLO* CSM model is in agreement. The prompt production of higher states of charmonium
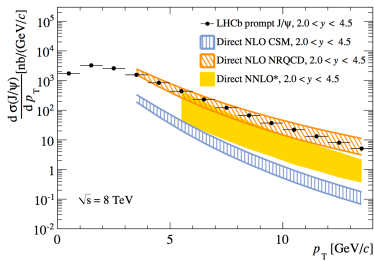

Figure 1. Comparison of the differential cross-section for the production of prompt J/ψ meson as a function of p_T with direct production in an NLO NRQCD [8] (orange diagonal shading), an NNLO* CSM [9] (solid yellow) and an NLO CSM [10] (blue vertical shading).
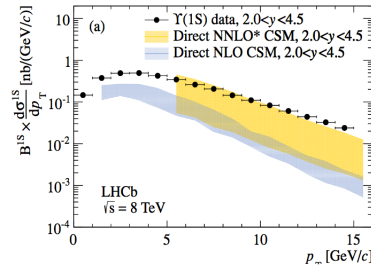

Figure 2. Comparison of the differential production cross-sections times dimuon branching fractions for $\Upsilon(1S)$ mesons as a function of p_T with direct production in an NNLO* CSM [11] (solid yellow) and an NLO CSM [10] (blue vertical shading) model. The points show the measurements reported in this analysis.

(χ_{c0}, χ_{c1} and χ_{c2}) have also been studied at LHCb at $\sqrt{s} = 7$ TeV [12] . In Ref. [12] the χ_c mesons are identified through their decay to $J/\psi(\to \mu\mu)\gamma$, using converted photons. The signal yields are extracted to a fit to the $\Delta M = M(J/\psi\gamma) - M(J/\psi)$ spectrum. The χ_{c0} meson is observed for the first time at high energy hadron collisions. The signal is observed with a statistical significance of 4.3σ with a yield of 705 ± 163, for $4 < p_T^{J/\psi} < 20$ GeV/c. Figure 3 shows the ratio of χ_{c2} to χ_{c1} as a function of p_T with a comparison with a next to leading order [13] and leading order [14] calculations. The major uncertainties in extracting the yields in these measurements are the fitting procedure, the photon efficiency and $p_T^{\chi_c}$ spectrum.

The production of J/ψ meson accompanied by open charm (and pairs of open charm) has been measured by LHCb [16]. The production cross section of J/ψ and open charm mesons in the fiducial volume $2 < y_{J/\psi}, y_C < 4, p_{J/\psi}^T < 12$ GeV/c, $3 < p_C^T < 12$ GeV/c are summarised in Table 1. The major sources of the experimental systematics come from the knowledge of the tracking, luminosity and trigger. In addition the lack of knowledge of the J/ψ polarisation and the charm mesons' branching ratios add a major uncertainty. The predictions from gluon-gluon
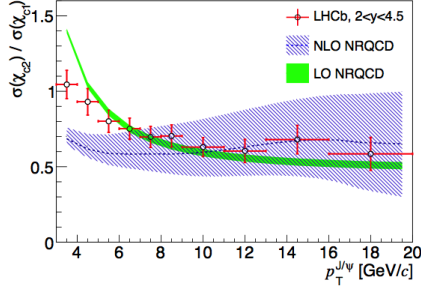
Figure 3. Ratio of χ_{c2} to χ_{c1} cross-sections in the rapidity range $2.0 < y < 4.5$. The results results are compared with the NLO NRQCD calculation from Ref. [13] (blue shading) and the LO NRQCD calculation of Ref. [14] (solid green). The LHCb results are obtained assuming the χ_c mesons are produced unpolarized.
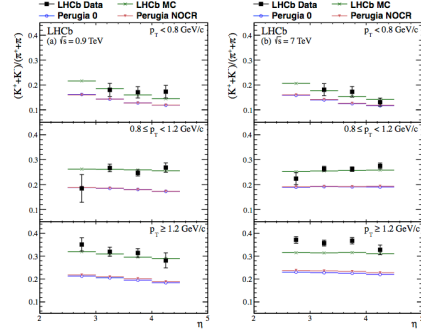

Figure 4. Result for the k/π ratios at $\sqrt{s} = 0.9$ and 7.0 TeV. The data are compared to different tune on the PYTHIA event generator [19].

fusion [17] are significantly smaller than the observed cross section, which are better described with double parton scattering models [18].

Table 1. Production cross-sections for $J/\psi C (= D^0, ...)$. The first uncertainty is statistical, and the second is systematic.

Mode	$\sigma(\text{nb})$
$J/\psi D^0$	$161.0 \pm 3.7 \pm 12.2$
$J/\psi D^+$	$56.6 \pm 1.7 \pm 5.9$
$J/\psi D_s^+$	$30.5 \pm 2.6 \pm 3.4$
$J/\psi \Lambda_c^+$	$43.2 \pm 7.0 \pm 12.0$

3. Strangeness and baryon production

The charged particle species production ratio have been measured at LHCb in three separate p_T regions: $p_T < 0.8$ GeV/c, $0.8 \leq p_T < 1.2$ GeV/c and $p_T \geq 1.2$ GeV/c [15]. For the lowest p_T bin the pseudorapidity range of the measurements is $3.0 < \eta < 4.5$ and $2.5 < \eta < 4.5$ for the higher p_T ranges. The particle identification (PID) algorithm uses information from the RICH and tracking detectors to construct a negative log likelihood for the particle hypothesis. The dominant uncertainty is associated with the understanding of the PID performance. Figure 4 shows the kaon and pion ratio as a function of η in the three p_T ranges. There is a clear rise in the ratio as p_T rises. The data are compared to the predictions of several tunes of the PYTHIA 6.4 [19] generator. The data are higher than the Perugia 0 and NOCR [20] tunes but in agreement with the LHCb tune [21]. LHCb recently published measurements of baryons containing both strange and bottom quarks [22]. In particular LHCb presented the mass measurements of Ξ_b^- and Ω_b^- using the decays $\Xi_b^- \to J/\psi \, \Xi^-$ and $\Omega_b^- \to J/\psi \, \Omega^-$. The mass measurements of the Ω_b^- is of interest given the discrepancy between the CDF [23] and D0 [24] collaborations. The invariant mass distributions are shown in Figure 5 with a signal yield of 111 ± 12 Ξ_b^- and
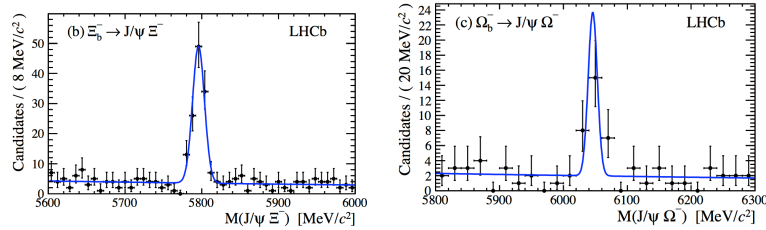
Figure 5. The invariant mass distribution for Ξ_b^- and Ω_b^- candidates. The solid lines are the results of an unbinned likelihood fit.

19 ± 5 Ω_b baryons. The mass measurements are $M(\Xi_b^-) = 5795.8 \pm 0.9 \pm 0.4$ MeV/c^2 and $M(\Omega_b^-) = 6046.0 \pm 2.2 \pm 0.5$ MeV/c^2 and are the most precise to date. The Ω_b^- result is in agreement with the CDF measurement.

4. Summary

LHCb has made many important productions results in the forward rapidity region. The results include evidence for double parton scattering and investigations of excited quarkonia. Since the conference LHCb have published their results on J/ψ polarisation [25]. There are further studies on quarkonia ongoing making using of the full 2011 ($\mathcal{L} = 1.1$ fb^{-1}) and 2012 ($\mathcal{L} = 2.08$ fb^{-1}) datasets as well as data from pA collisions.

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