PROCEEDINGS OF SCIENCE

Heavy flavour production in pp collisions at LHCb

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These proceedings summarise recent LHCb results on heavy-flavour production in pp collisions. The production cross-sections of $\Upsilon(nS)$ are measured using pp collision data at centre-of-mass energy of $\sqrt{s}$ = 5 TeV, the production cross-sections of J/ψ are also measured at the same energy point. In addition, the production cross-sections of $\chi_{c1}(3872)$ relative to the $\psi(2S)$ meson are measured using pp collision data at centre-of-mass energy of $\sqrt{s}$ = 8 and 13 TeV

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1. Introduction

The production of heavy quark-antiquark resonances (quarkonia) at hadron colliders can better us understands of strong interaction, which is described by Quantum Chromodynamics (QCD). Based on the assumption of factorization, the production process can be separated into two steps, the generation of a heavy quark pair ($Q\overline{Q}$) through the interaction of partons, and the subsequent hadronization of the quark pair into the quarkonium state. The first step can be calculated within perturbative QCD, while the latter one is nonperturbative and needs to be described by phenomenological models. In the Colour Singlet Model [6, 8, 9, 12, 13, 15, 16], the intermediate $Q\overline{Q}$ state is assumed to be colourless, and has the same spin-parity quantum numbers as the final state quarkonium. On the other hand, in the Colour Evaporation Model [15, 17, 18, 21], the probability of forming a specific quarkonium state is assumed to be independent of the color of the $Q\overline{Q}$ pair. In the nonrelativistic QCD (NRQCD) approach [7, 10, 11], intermediate $Q\overline{Q}$ states with all possible colour-spin-parity quantum numbers may evolve into the desired quarkonium. The transition probabilities from $Q\overline{Q}$ states to quarkonium, described by long-distance matrix elements (LDMEs) in NRQCD, are nonperturbative and are determined by fitting to experimental data. The LDMEs are assumed to be independent of the production mechanism and kinematics.

The LHCb detector [1, 5] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The high integrated luminosity and excellent performance of the detector make the LHCb an ideal laboratory for production measurements. In these proceedings, the latest measurements on heavy flavour production in pp collisions at LHCb are presented [2–4].

2. Measurement of $\Upsilon(nS)$ production cross-sections at $\sqrt{s} = 5$ TeV

The production cross-sections of $\Upsilon(nS)$ mesons, namely $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$, in pp collisions at $\sqrt{s} = 5$ TeV are measured with a data sample corresponding to an integrated luminosity of $9.13 \pm 0.18\ \mathrm{pb}^{-1}$ collected by the LHCb detector [3]. The $\Upsilon(nS)$ mesons are reconstructed in the decay mode $\Upsilon(nS) \to \mu^+\mu^-$.

The double-differential cross-section times the $\Upsilon(nS) \to \mu^+\mu^-$ branching fraction ($\mathcal{B}$) of $\Upsilon(nS)$ production in a given (p_{T},y) bin is defined as

$$\mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-) \times \frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}} \times \mathrm{d}y} = \frac{N(\Upsilon(nS) \to \mu^+\mu^-)}{\mathcal{L} \times \varepsilon \times \Delta p_{\mathrm{T}} \times \Delta y}, \tag{1}$$

where $N(\Upsilon(nS) \to \mu^+\mu^-)$ is the yield of $\Upsilon(nS) \to \mu^+\mu^-$ signal decays, ε is efficiency correction factor in a (p_{T},y) bin, $\mathcal{L}$ is the integrated luminosity, and Δp_{T} and Δy are the interval widths of the $\Upsilon(nS)$ transverse momentum and rapidity, respectively.

The cross-section times branching fraction integrated over y or p_{T} is shown in Fig. 1. The differential cross-section times branching fraction as a function of p_{T} for $\Upsilon(1S)$ mesons for y integrated over 2.0–4.5 are compared with the NRQCD predictions [14] in Fig. 2. The data points are plotted at the p_{T} average points in each bin. Good agreement is observed between NRQCD predictions and the measured distribution.

The double-differential cross-sections integrated over the kinematic range of $p_{\mathrm{T}} < 20$ GeV/c and $2.0 < y < 4.5$ are

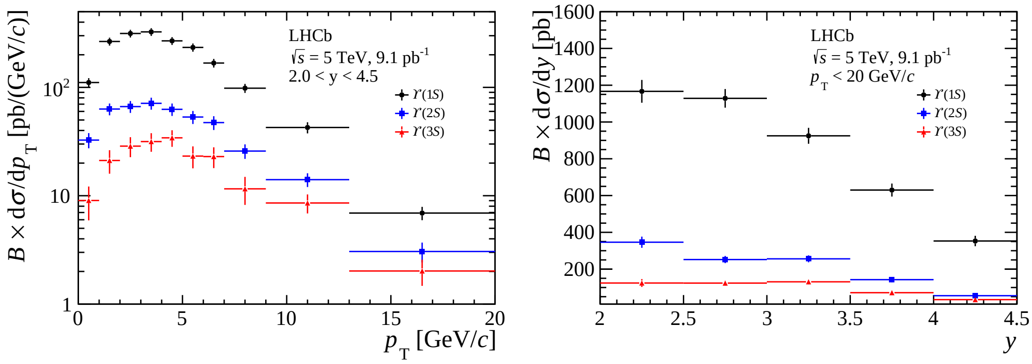

Figure 1: Differential cross-section times branching fraction (left) as a function of p_T for y integrated from 2.0 to 4.5 and (right) as a function of y for p_T integrated from 0 to 20 GeV/c, for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states.

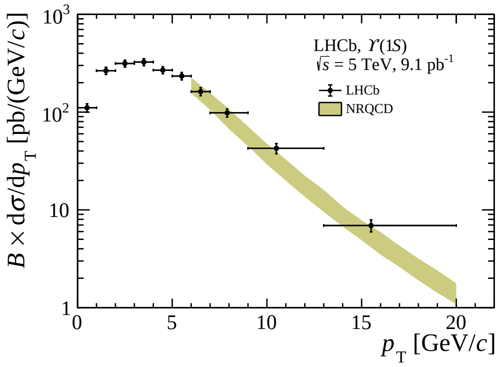

Figure 2: Differential cross-section of $\Upsilon(1S)$ mesons as a function of p_T, compared with the NRQCD prediction of Ref. [14].

$$\sigma(\Upsilon(1S)) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 2101 \pm 33\ (\text{stat}) \pm 83\ (\text{syst})\ \text{pb}, \tag{2}$$
$$\sigma(\Upsilon(2S)) \times \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 526 \pm 20\ (\text{stat}) \pm 21\ (\text{syst})\ \text{pb}, \tag{3}$$
$$\sigma(\Upsilon(3S)) \times \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 242 \pm 16\ (\text{stat}) \pm 10\ (\text{syst})\ \text{pb}. \tag{4}$$

3. Measurement of J/ψ production cross-sections at $\sqrt{s}$ = 5 TeV

In pp collisions J/ψ mesons can be produced either directly from hard collisions of partons, through the feed-down of excited charmonium states, or via decays of beauty hadrons. The J/ψ mesons from the first two sources originate from the primary pp collision vertex (PV) and are called *prompt* J/ψ mesons, while those from the last source originate from decay vertices of beauty hadrons, which are typically separated from the PV, and are called *nonprompt* J/ψ mesons.

The differential cross-sections for prompt and nonprompt J/ψ mesons in pp collisions were measured in the rapidity range $2.0 < y < 4.5$ using a data sample collected by the LHCb experiment, corresponding to an integrated luminosity of 9.13 ± 0.18 pb^{-1}, assuming unpolarised J/ψ mesons [2].

The measured double-differential cross-sections for prompt and nonprompt J/ψ mesons are shown in Fig. 3 for the range $0 < p_{\mathrm{T}} < 14$ GeV/c and $2.0 < y < 4.5$ with Δp_{T} between 1 and 4 GeV/c and $\Delta y = 0.5$.

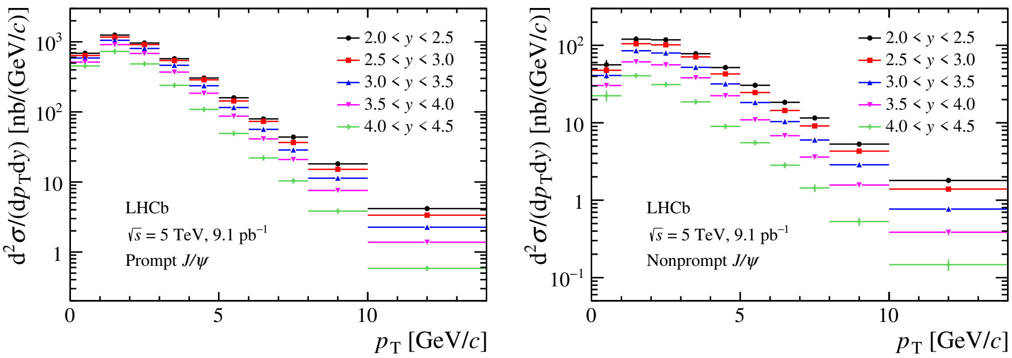

Figure 3: Differential cross-section (left) for the prompt J/ψ and (right) for the nonprompt J/ψ.

By integrating the double-differential results over p_{T} or y, the single-differential cross-sections $\sigma/\mathrm{d}p_{\mathrm{T}}$ and $\sigma/\mathrm{d}y$ are obtained, and are compared with NRQCD calculations and colour glass condensate (CGC) effective theory results [19, 20], as shown in Fig. 4.

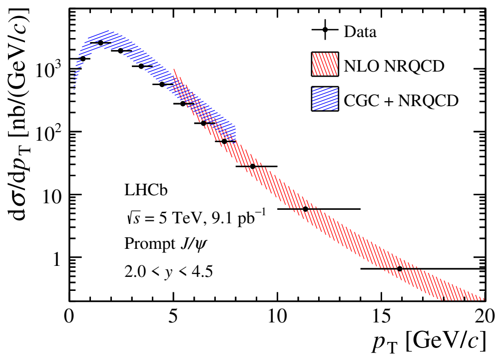

Figure 4: Differential cross-section of prompt J/ψ mesons as a function of p_{T}, compared with the NRQCD and CGC prediction [19, 20].

By integrating the double-differential results over p_{T} and y, the integrated cross-sections for prompt and nonprompt J/ψ mesons in the range $0 < p_{\mathrm{T}} < 20$ GeV/c and $2.0 < y < 4.5$.

$$\sigma_{prompt J/\psi} = 8.154 \pm 0.010\ (\text{stat}) \pm 0.283\ (\text{syst})\ \mu\text{b}, \tag{5}$$

$$\sigma_{nonprompt J/\psi} = 0.820 \pm 0.003\ (\text{stat}) \pm 0.034\ (\text{syst})\ \mu\text{b}. \tag{6}$$

4. Measurement of $\chi_{c1}(3872)$ productions at $\sqrt{s} = 8$ and 13 TeV

The production cross-section of the $\chi_{c1}(3872)$ state relative to the $\psi(2S)$ meson, where both decay to $J/\psi\pi^+\pi^-$ with J/ψ decaying to $\mu^+\mu^-$ final state, is measured using proton-proton collision data collected with the LHCb experiment at centre-of-mass energies of $\sqrt{s}$ = 8 and 13 TeV, corresponding to integrated luminosities of 2.0 and 5.4 fb^{-1} [4].

The cross-section is determined in intervals of the $J/\psi\pi^+\pi^-$ transverse momentum, p_{T}, and rapidity, y, within the ranges $4 < p_{\mathrm{T}} < 20$ GeV/c and $2.0 < y < 4.5$.

The cross-section ratios for promptly and nonpromptly produced mesons measured with the 8 and 13 TeV data samples as a function of p_{T} and y are shown in Figs. 5 and 6 respectively. The double ratio of the prompt $\chi_{c1}(3872)$ and $\psi(2S)$ production cross-sections between 13 and 8 TeV is also calculated using the measured cross-section ratio for 8 TeV and the combined ratio for 13 TeV, as shown in Fig. 7.

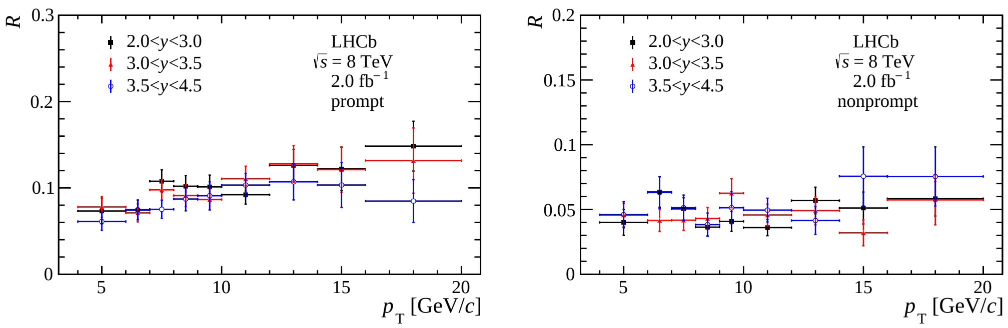

Figure 5: Ratios (R) of differential cross-section times the branching ratio to the $J/\psi\pi^+\pi^-$ final state between $\chi_{c1}(3872)$ and $\psi(2S)$ mesons from (left) prompt production and (right) nonprompt production, for the $\sqrt{s}$ = 8 TeV sample as a function of p_{T} in intervals of rapidity.

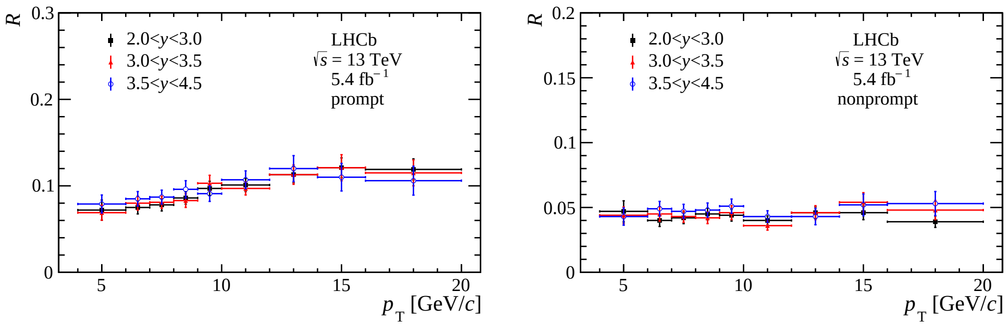

Figure 6: Ratios (R) of differential cross-section times the branching ratio to the $J/\psi\pi^+\pi^-$ final state between $\chi_{c1}(3872)$ and $\psi(2S)$ mesons from (left) prompt production and (right) nonprompt production, for the $\sqrt{s}$ = 13 TeV sample as a function of p_{T} in intervals of rapidity.

5. Summary

The LHCb detector plays an important role in heavy flavour production measurements. Recently, $\Upsilon(nS)$ production at 5 TeV, J/ψ production at 5 TeV and $\chi_{c1}(3872)$ production at 8 and 13 TeV have been measured in LHCb. The measurements of these quantities are paramount in order to improve the data-driven LDMEs and our understanding of QCD. Also, the possibility of measuring the production cross-sections of exotic states can shed some light on their internal structure and binding mechanisms.

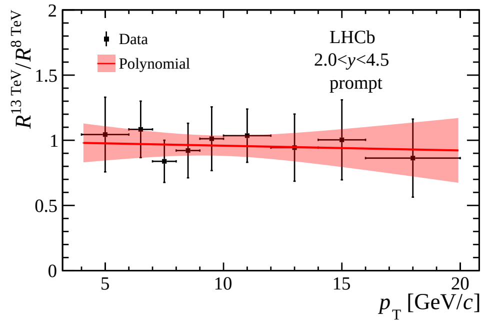

Figure 7: Double ratio of the prompt $\chi_{c1}(3872)$ production cross-section relative to that of $\psi(2S)$ mesons between 13 and 8 TeV as a function of p_T integrated over $2.0 < y < 4.5$. A first-order polynomial of the form $a_0+a_1p_T$ is used to fit the double ratio, yielding $a_0 = 0.99\pm0.23$ and a slope of $a_1 = (4\pm23)\times10^{-3}$ GeV/c^{-1}.

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