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Review of LHCb Heavy-Quark and Quarkonia Results

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Recent results of heavy-quark and quarkonia from the LHCb experiment are presented, focusing on the production cross-sections of J/ψ and Υ mesons at $\sqrt{s} = 8\,\text{TeV}$, the production ratios of χ_c mesons at $\sqrt{s} = 7\,\text{TeV}$ using converted photons, and the polarisation of prompt J/ψ mesons at $\sqrt{s} = 7\,\text{TeV}$.

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1. Introduction

The studies of heavy-quark and quarkonia in pp collisions are important since they provide essential tests of the QCD models. *e.g.*, the non-relativistic QCD (NRQCD) [1] and the colour-singlet model (CSM) [2]. Great success has been achieved to describe differential production cross-sections of heavy quarkonia [3–5]. However, some open issues still exist, one well-known example is that these theoretical models failed to reproduce the polarisation of J/ψ and $\psi(2S)$ mesons measured by CDF [6]. Therefore, precise measurements of heavy-quark and quarkonia in pp collisions are necessary for a better understanding of QCD, and provide essential constraints and inputs for theoretical models. This note presents recent results in this field from the LHCb experiment [7], based on the data samples taken in 2011 and 2012, focusing on the production of heavy quarkonia [8, 9], and the polarisation of prompt J/ψ mesons [10]. Many other results are not mentioned due to the limit of pages.

2. Productions of heavy quarkonia

Following the previous measurements at $\sqrt{s} = 7\,\text{TeV}$ and $2.76\,\text{TeV}$ [3–5], the double-differential production cross-sections for J/ψ and Υ mesons at $\sqrt{s} = 8\,\text{TeV}$ are measured as functions of the rapidity y and the transverse momentum p_{T} [8], using the data collected in early 2012 with $18\,\text{pb}^{-1}$ ($51\,\text{pb}^{-1}$) for J/ψ (Υ) mesons. Figure 1 shows the invariant mass distributions for J/ψ and Υ mesons, with clean signal peaks and low backgrounds. The prompt J/ψ mesons and J/ψ mesons from b-hadron decays are well separated by combined fits to the invariant mass and the pseudo-proper time t_z [8]. The integrated production cross-sections for prompt J/ψ mesons and J/ψ from b are

$$\sigma(\text{prompt } J/\psi, p_{\text{T}} < 14\,\text{GeV}/c,\ 2.0 < y < 4.5) = 10.94 \pm 0.02 \pm 0.79\,\mu\text{b},$$
$$\sigma(J/\psi \text{ from } b, p_{\text{T}} < 14\,\text{GeV}/c,\ 2.0 < y < 4.5) = 1.28 \pm 0.01 \pm 0.11\,\mu\text{b}.$$

The measured integrated production cross-sections for $\Upsilon(nS)$ time $\mathscr{B}^{nS}$ in the range $2.0 < y < 4.5$ and $p_{\text{T}} < 15\,\text{GeV}/c$ are

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

In both cases the first uncertainty is statistical and the second one systematic.

The left plot of Fig. 2 shows the differential production cross-sections for prompt J/ψ mesons as a function of p_{T} with $2.0 < y < 4.5$. The theoretical predictions shown in this plot are for direct J/ψ meson production. The next-to-leading order (NLO) NRQCD model provides a prediction in good agreement with the data [11, 12]. Considering the contribution of feed-down from higher charmonium states, the prediction of the NNLO* CSM also provide a reasonable description of the data, where NNLO* indicates that the calculations at the next-to-next-leading order are incomplete and some logarithmic terms are neglected [13]. However, the NLO CSM calculation underestimates the production cross-section by an order of magnitude [14]. The results for J/ψ from b are compared in the right plot of Fig. 2 to the calculations based on the FONLL formalism [15, 16]. As already

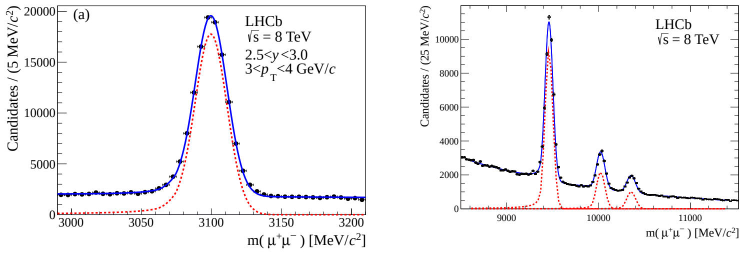

Figure 1: Distributions of dimuon invariant mass for (left) J/ψ mesons with $3.0 < p_{\mathrm{T}} < 4.0\,\mathrm{GeV}/c$ and $2.5 < y < 3.0$, and (right) Υ mesons with $p_{\mathrm{T}} < 15\,\mathrm{GeV}/c$ and $2.0 < y < 4.5$.

observed in J/ψ production measurements at $\sqrt{s} = 7\,\mathrm{TeV}$ [3] and at $\sqrt{s} = 2.76\,\mathrm{TeV}$ [5], good agreements are shown both for the production cross-section as a function of p_{T} and that as a function of y at $\sqrt{s} = 8\,\mathrm{TeV}$.

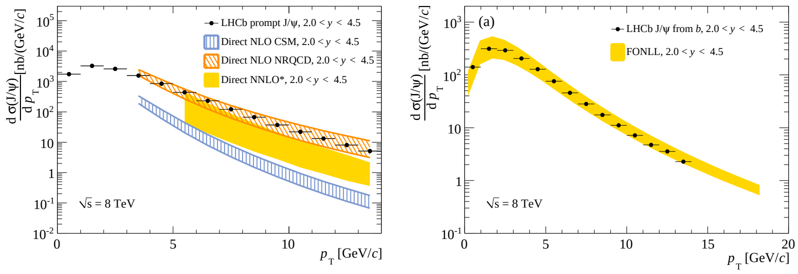

Figure 2: Differential production cross-section for (left) prompt J/ψ mesons and (right) J/ψ from b as a function of p_{T}. Theoretical predictions for direct J/ψ mesons [11–14] are superposed in the left plot, and the prediction of FONLL [15, 16] is superposed in the right plot.

Figure 3 shows the production cross-sections as functions of p_{T} time the dimuon branching fractions $\mathscr{B}^{nS} \equiv \mathscr{B}(\Upsilon(nS) \to \mu^+\mu^-)$ for the three Υ meson states, together with the theoretical predictions of NLO CSM [14] and NNLO* CSM [13]. The NNLO* CSM shows a modest agreement with the data, especially for $\Upsilon(3S)$ mesons, which are expected to suffer less from feed-down. Similar to the case of the prompt J/ψ production, NLO CSM greatly underestimates the production cross-sections.

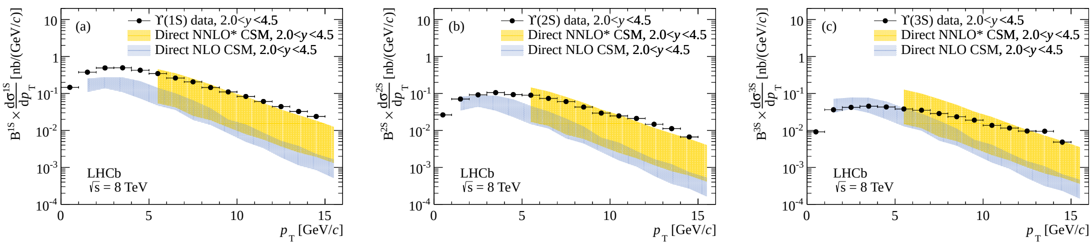

Figure 3: Differential production cross-sections times dimuon branching fractions for (a) $\Upsilon(1S)$, (b) $\Upsilon(2S)$, and (c) $\Upsilon(3S)$ mesons as functions of p_{T}, compared to theoretical predictions for direction production in NLO CSM [14] and NNLO* CSM [13].

It is also important to measure the production of χ_c states. NRQCD calculations with both colour-singlet and colour-octet contributions taken into account give a raito of the χ_{c2} to χ_{c1}

production cross-sections, which is different to the caluclation of CSM. The radiative decay $\chi_c \to J/\psi\,\gamma$ substantially contributes to the prompt J/ψ production [17], and can also have a significant impact on the polarisation of prompt J/ψ [10]. The ratio of prompt χ_{c2} to χ_{c1} production cross-sections $\sigma(pp \to \chi_{c2}X)/\sigma(pp \to \chi_{c1}X)$ at $\sqrt{s} = 7\,\text{TeV}$ was first measured using calorimetric photons, using a data sample of $36\,\text{pb}^{-1}$ collected by the LHCb detector in 2010 [17]. This ratio is updated by a measurement with photons converted into e^+e^- before entering the LHCb magnet, using a data sample of $1.0\,\text{fb}^{-1}$ taken in 2011 [9]. Although the efficiency of converted photons is rather low, the resolution of the invariant mass of $J/\psi\,\gamma$ is greatly improved, as shown in the left plot of Fig. 4. An evidence of χ_{c0} signal is first observed in hadron colliders with a statistical significance of 4.3 σ. The extracted signal yield in the range $4 < p_{\mathrm{T}}^{J/\psi} < 20\,\text{GeV}/c$ is $N(\chi_{c0}) = 705 \pm 163$,

The right plot shows the ratio of χ_{c2} to χ_{c1} production cross-sections as a function of $p_{\mathrm{T}}^{J/\psi}$, together with a comparison to the calculations in NLO NRQCD [18] and in LO NRQCD [19]. Both calculations provide a reasonable description of the data, particularly in high $p_{\mathrm{T}}^{J/\psi}$ region. The ratio of χ_{c0} to χ_{c2} production cross-sections, integrated over $4 < p_{\mathrm{T}}^{J/\psi} < 20\,\text{GeV}/c$, is

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27(\text{stat}) \pm 0.29(\text{syst}) \pm 0.16(p_{\mathrm{T}}\text{ model}) \pm 0.09(\mathscr{B}),$$
$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.787 \pm 0.014(\text{stat}) \pm 0.034(\text{syst}) \pm 0.051(p_{\mathrm{T}}\text{ model}) \pm 0.047(\mathscr{B}),$$

where the first uncertainty is statistical, the second is systematic, the third is due to the p_{T} spectrum of the chosen model, and the fourth is due to the branching fraction uncertainty.

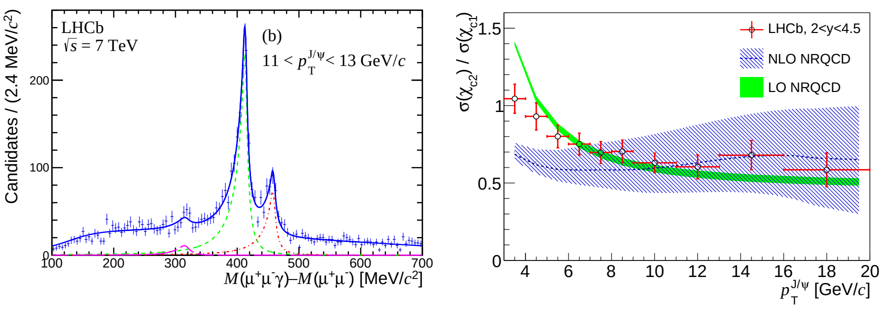

Figure 4: (left) Distribution of $\Delta M \equiv M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ for χ_c candidates with $11 < p_{\mathrm{T}}^{J/\psi} < 13\,\text{GeV}/c$. (right) Ratio of χ_{c2} to χ_{c1} production cross-sections at $\sqrt{s} = 7\,\text{TeV}$ as a function of $p_{\mathrm{T}}^{J/\psi}$ for $2.0 < y < 4.5$, together with the calculations in NLO NRQCD [18] and in LO NRQCD [19].

3. Polarisation measurements of prompt J/ψ mesons

A measurement of prompt J/ψ polarisation in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ is performed, using a dataset of an integrated luminosity of $0.37\,\text{fb}^{-1}$ collected by the LHCb detector in early 2011 [10]. The polarisation parameters are determined as functions of p_{T} and y by a full angular analysis of the decay $J/\psi \to \mu^+\mu^-$.

Figure 5 shows the measured polarisation parameter λ_θ for prompt J/ψ mesons in the helicity frame as a function of p_{T} in the range $2.5 < y < 4.0$, accompanied by the comparison with (left) the ALICE result [20] and (right) theoretical predictions [21–23]. The ALICE result is for inclusive

J/ψ mesons, and the uncertainties are rather large. The measurements of ALICE and LHCb are compatible. The right plot of Fig. 5 shows that our measurement disagrees with the calculations in NLO CSM [21]. For the NLO NRQCD calculations different schemes are used in the three Refs. [21–23] to evaluate the non-perturbative matrix elements. The results show a better agreement with the NLO NRQCD calculations in Ref. [23] than in Ref. [21, 22]. However, one should note that neither NLO CSM nor NLO NRQCD calculations in Ref. [21] includes the effect of feed-down from excited charmonium states, while the feed-down from χ_c and $\psi(2S)$ mesons are taken into account in the NLO NRQCD calculations in Refs. [22, 23].

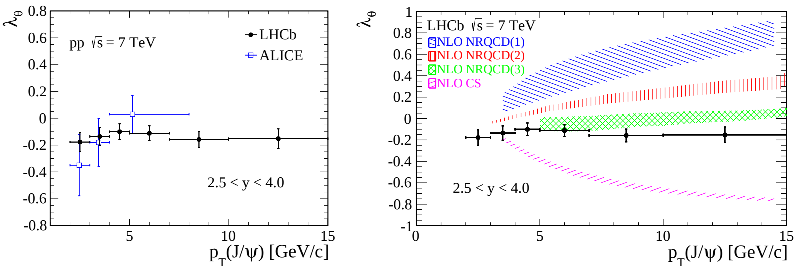

Figure 5: Polarisation parameter λ_θ for prompt J/ψ mesons in the helicity frame, together with (left) the ALICE results [20] and (right) theoretical predictions [21–23].

With the measured polarisation, the prompt J/ψ production cross-sections at $\sqrt{s} = 7\,\text{TeV}$ is updated, which was previously measured in 2011 [3] with large uncertainties due to the unknown polarisation of J/ψ mesons. The updated integrated cross-section in the range $p_{\text{T}} < 14\,\text{GeV}/c$ and $2.0 < y < 4.5$ is $\sigma_{\text{prompt}} = 9.46 \pm 0.04 \pm 0.53^{+0.86}_{-1.10}\,\mu\text{b}$, where the first uncertainty is statistical, the second systematic, and the third asymmetric uncertainties originate from the unknown polarisation of J/ψ mesons with $p_{\text{T}} < 2\,\text{GeV}/c$.

4. Summary

The LHCb experiment has presented a lot of measurements of heavy-quark and quarkonia using the data of pp collisions at 7 TeV and 8 TeV accumulated in 2011 and 2012, among which some recent results are summarised in this note. The production cross-sections of J/ψ and Υ mesons at $\sqrt{s} = 8\,\text{TeV}$ are measured using the dimuon final state [8]. The ratio of χ_{c2} to χ_{c1} production cross-sections is measured at $\sqrt{s} = 7\,\text{TeV}$ using converted photons [9]. The polarisation of prompt J/ψ mesons is determined using a data sample of pp collisions at $\sqrt{s} = 7\,\text{TeV}$ [10].

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