PROCEEDINGS OF SCIENCE

Charmonia production studies at the LHCb experiment

Maksym Teklishyn[∗†]

LAL, Orsay E-mail: teklishy@lal.in2p3.fr

The production of heavy quark-antiquark bound state remains a useful tool for probing Quantum Chromodynamics (QCD) mechanisms. Measurements of the total and differential production cross-sections allow to distinguish the large variety of the existing models, such as non-perturbative QCD and the colour-evaporation model.

We address the most recent results on quarkonia production studies, performed at the LHCb experiment at CERN. The J/ψ production at different $\sqrt{s}$ is studied with the $J/\psi \to \mu\mu$ decay channel. Relative production cross-sections of the χ_c family are found with the $\chi_c \to J/\psi\gamma$ decay channel, using photons converted in detector medium. Results on the $\psi(2S)$ production with two muons in the final states are also addressed.

The XXI International Workshop High Energy Physics and Quantum Field Theory,
June 23 – June 30, 2013
Saint Petersburg Area, Russia

[∗]Speaker.
[†]On behalf of the LHCb collaboration

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PoS(QFTHEP 2013)031

1. Introduction

Describing the heavy quarkonia production is a significant problem from the theoretical point of view. According to effective theory, non-relativistic quantum chromodynamics (NRQCD)prompt, the quarkonia production can be factorised in two steps. Heavy quark-antiquark pair is created at the short distance and then it becomes a bound state at long distances [3]. One should take into account different sources of the $c\bar{c}$ bound state production: direct creation from the parton interactions, decays of the higher charmonium states (prompt production) and charmonium from the b-hadron decays (secondary production). The last source should be considered separately from the first two since its mechanism is very different. Using constraints on the secondary vertices, one can distinguish experimentally between the prompt and secondary charmonium productions. Comparing p_{T} distribution shapes and the absolute cross-section with the existing models, we can study the nature of the heavy quarkonium creation.

2. LHCb detector

The LHCb detector [1] is a single-arm spectrometer. It is one of the four big experiments, installed on the Large Hadron Collider (LHC). The main purpose of the LHCb installation is to study hadrons containing b or c quarks.

The LHCb detector includes a precision tracking system, consists of a silicon-strip vertex detector (VELO), a silicon strip detector, placed before the dipole magnet and the three station of the silicon-strip detectors and straw drift tubes placed behind the magnet. The tracking system has a momentum resolution at the level of $0.4\% - 0.6\%$ up to the 100 GeV/c scale. Two ring-imaging Cherenkov detectors are used to identify the charged hadrons, and photons, electrons and hadrons are identified with a calorimeter system. It consists of the scintillating-pad and preshower detection systems, the electromagnetic and hadronic calorimeters.

In the following analyses the muon trigger is widely used since the $\mu^+\mu^-$ final state is the easiest and cleanest way to study charmonia. However, LHCb can deal with purely hadronic final states which could be used in the $\eta_c(1S)$, $\eta_c(2S)$ and h_c studies [2].

3. Charmonium production measurements

3.1 J/ψ production at different $\sqrt{s}$

Understanding the mechanism of the J/ψ meson production is a challenging theoretical problem. There is a large variety of theories that describe production yields, p_{T} spectra and the polarisation. However, it is still a significant tension between the theoretical predictions and the recent experimental results. At the leading order the Colour Singlet Model (CSM) fails to estimate the J/ψ production by the few orders of magnitude [4]. The calculations based on non-relativistic quantum chromodynamics, supposing the quark-antiquark state to be produced in the colour-octet state, give the right p_{T} spectra and production magnitude but fail to describe the polarisation [5]. With the large rate of the J/ψ production at the Large Hadron Collider, the LHCb detector gives an opportunity to make the measurements in the forward rapidity region $2.0 < y < 4.5$.

Using the LHCb data, collected in 2011–2012 years, we address the results on J/ψ productions at the pp centre-of-mass energies 2.76 TeV, 7 TeV and 8 TeV, using $J/\psi \to \mu^+\mu^-$ decay channel. The corresponding integrated luminosity of the data samples are 70.6 nb^{-1}, 5.2 pb^{-1} and 18.0 pb^{-1} respectively [7, 8, 9].

The total J/ψ cross-section at $\sqrt{s} = 2.76$ TeV [7], integrated over the fiducial volume $0 < p_T < 12$ GeV/c and $2.0 < y < 4.5$, is found to be

$$\sigma(J/\psi,\ \sqrt{s} = 2.76\text{ TeV}) = 5.6 \pm 0.1_{stat} \pm 0.3_{syst}\ \mu\text{b} \tag{3.1}$$

in the frame of non-polarised J/ψ hypothesis. Different polarisation scenarios can modify this result up to 20%. The result is in good agreement with the measurement performed by the ALICE experiment in the forward region [10].

For J/ψ coming from b-hadron decays

$$\sigma(J/\psi \text{ from } b,\ \sqrt{s} = 2.76\text{ TeV}) = 400 \pm 35_{stat} \pm 49_{syst}\text{ nb} \tag{3.2}$$

The prompt J/ψ production cross-section integrated over the fiducial volume $0 < p_T < 14$ GeV/c and $2.0 < y < 4.5$ for $\sqrt{s} = 7$ TeV is found to be

$$\sigma(J/\psi,\ \sqrt{s} = 7\text{ TeV}) = 10.52 \pm 0.04_{stat} \pm 1.40_{syst}\ {}^{+1.64}_{-2.20}\ \mu\text{b}, \tag{3.3}$$

where the last error is related to the polarisation.

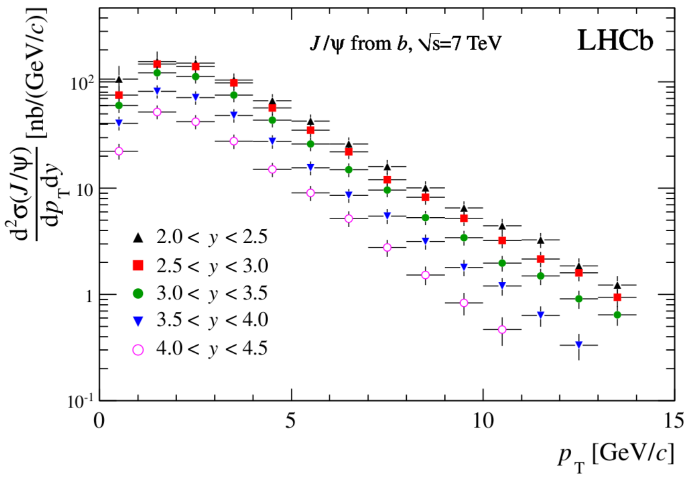

Figure 1: The prompt J/ψ double differential production cross-section at $\sqrt{s} = 7$ TeV as a function of p_T in y bins [8].

The comparison of the J/ψ prompt production at $\sqrt{s} = 7$ TeV with the different theoretical models is given in Fig. 3.1. Theoretical predictions show rather good agreement with the data points at high p_T region even though theoretical uncertainties are still large. At the same time, differential cross-section measurements themselves are not enough to distinguish various theoretical models, thus some results such as J/ψ polarisation should be taken into account [11].

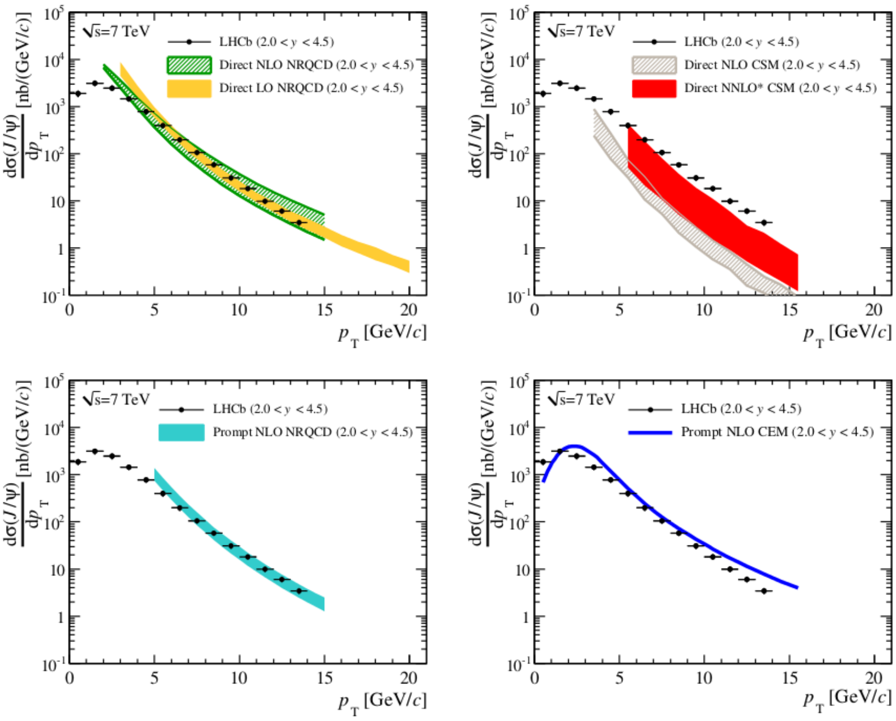

Figure 2: Comparison of the differential prompt J/ψ production at $\sqrt{s} = 7$ TeV for unpolarised J/ψ with: (top, left) direct J/ψ production with NRQCD at LO and NLO; (top, right) direct J/ψ production from CSM at NLO and NNLO; (bottom, left) J/ψ production as predicted by NLO NRQCD; (bottom, right) prompt J/ψ production calculated with CEM at NLO. For more details see [8].

For the same fiducial region, the integrated cross-section for secondary J/ψ is found to be

$$\sigma(J/\psi \text{ from } b,\ \sqrt{s} = 7 \text{ TeV}) = 1.14 \pm 0.01_{stat} \pm 0.16_{syst}\ \mu\text{b}, \tag{3.4}$$

LHCb also performed measurements of the double differential J/ψ cross-section at $\sqrt{s} =$ 8 TeV in the fiducial volume $0 < p_{\mathrm{T}} < 14$ GeV/c and $2.0 < y < 4.5$. For the details see [9].

The assumption of non-polarised J/ψ is made for all J/ψ production results. The J/ψ production cross-section value is updated taking into account polarisation [11].

Summarising results on the inclusive J/ψ production from b-hadron decays, one can compare them with the prediction from the FONLL formalism on Fig. 3.1. It is consistent with the $\sqrt{s}$ dependence of the secondary J/ψ cross-section.

3.2 $\psi(2S)$ production

The measurements of the differential cross-section of the $\psi(2S)$ meson at $\sqrt{s} = 7$ TeV has been performed by the LHCb experiment. The data sample of 2011 year with an integrated luminosity of 36 pb^{-1} was used. Two decay channels were used in the analysis: $\psi(2S) \to \mu^+\mu^-$ and $\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$. Despite the lower signal to background ratio, the second channel is used for the cross-check and to extend accessible phase-space.

Integrated prompt and secondary produced $\psi(2S)$ cross-sections are:

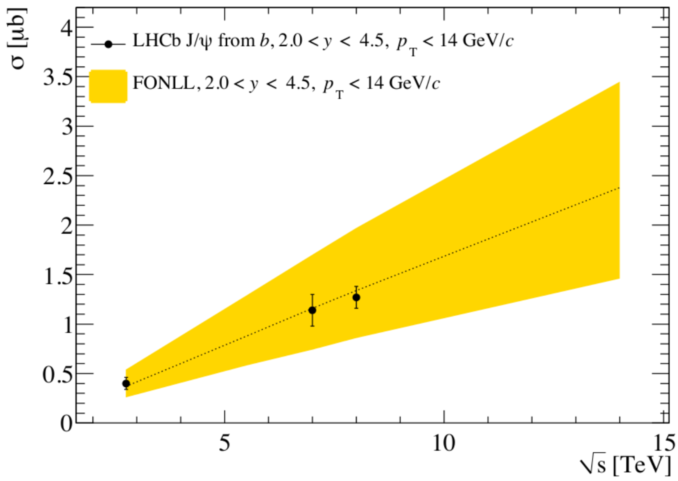

Figure 3: Theoretical predictions in frame of FONLL [12] formalism for the production cross-section for secondary J/ψ in the fiducial volume of $\sqrt{s}$ = 8 TeV analysis. The points represent the measurements at $\sqrt{s}$ = 2.76 [7], 7 [8], and 8 TeV [9].

$$\sigma(\psi(2S),\ \sqrt{s} = 7\ \text{TeV}) = 1.44 \pm 0.01_{stat} \pm 0.12_{syst}\ {}^{+0.20}_{-0.40}\ \mu\text{b} \tag{3.5}$$

$$\sigma(\psi(2S)\ \text{from}\ b,\ \sqrt{s} = 7\ \text{TeV}) = 0.25 \pm 0.01_{stat} \pm 0.02_{syst}\ \mu\text{b}, \tag{3.6}$$

where the third error for prompt $\psi(2S)$ represents the polarisation uncertainty. Non-polarisation hypothesis is assumed for the central value of $\psi(2S)$ prompt cross-section.

3.3 χ_c subfamily

The prompt production of the χ_{c0}, χ_{c1} and χ_{c2} mesons was studied at $\sqrt{s} = 7$ TeV with the LHCb detector. The $\chi_{c0,1,2} \to J/\psi\gamma$ decay channel was used for the analysis, with the photon converted to e^+e^- in the detector medium. This method gives less statistics, comparing to the calorimeter reconstructed photon [15], but the resolution is higher.

Ratios of the prompt production cross-sections in the fiducial volume $4 < p_{\mathrm{T}}^{J/\psi} < 20$ GeV/c and $2.0 < y < 4.5$ at $\sqrt{s} = 7$ TeV are found to be:

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27_{stat} \pm 0.29_{syst} \pm 0.16_{p_{\mathrm{T}}\ \text{model}} \pm 0.09_{\mathscr{B}} \tag{3.7}$$

$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0787 \pm 0.014_{stat} \pm 0.034_{syst} \pm 0.051_{p_{\mathrm{T}}\ \text{model}} \pm 0.047_{\mathscr{B}} \tag{3.8}$$

These results are in agreement with NLO NRQCD predictions and CMS and CDF results although the pseudorapidity ranges are different [17].

4. Conclusions

The brief overview over the latest LHCb results on the charmonium production is given. Using the LHCb installation, we can make a significant investigation in understanding of the heavy quarkonia nature. With the high statistics, provided by LHCb (more than 3 fb^{-1} in 2011-2012 years), many studies of charmonium family have been already performed. However, there are still some gaps in the experimental knowledge of the $c\bar{c}$ bound states, not accessible via $\mu^+\mu^-$ final state, like $\eta_c(1S)$, $\eta_c(2S)$, h_c. Presently, many analyses on heavy quarkonium are upcoming from the LHCb collaboration.

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