PROCEEDINGS OF SCIENCE

Quarkonia Production at LHCb

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We present recent LHCb results in the quarkonia production with three topics. With $1\,\mathrm{fb}^{-1}$ data collected in 2011 with pp collisions at a proton-proton center-of-mass energy $\sqrt{s} = 7\,\mathrm{TeV}$, the ratios of $\sigma(\chi_{c0})/\sigma(\chi_{c2})$ and $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ are measured. With $0.37\,\mathrm{fb}^{-1}$ data collected in 2011, the polarization of prompt J/ψ is measured using an angular analysis of the decay $J/\psi \to \mu^+\mu^-$. Finally the production of J/ψ is studied with the $1.6\,\mathrm{nb}^{-1}$ data collected in 2013 with proton-lead collisions at a proton-nucleon center-of-mass energy $\sqrt{s_{NN}} = 5\,\mathrm{TeV}$. The nuclear modification factor and the forward-backward production ratio are determined for prompt J/ψ and J/ψ from b-hadron decays for the first time.

XV International Conference on Hadron Spectroscopy-Hadron 2013
4-8 November 2013
Nara, Japan

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PoS(Hadron 2013)049

1. Introduction

The measurement of quarkonia provides powerful tests on QCD models, at both perturbative and non-perturbative levels. However, current models cannot describe all experimental measurements well. For example, the prediction of the $\psi(2S)$ cross-section by the Color Singlet Model (CSM) is not compatible with that measured by CDF at the high p_{T} region[1]. In addition, the J/ψ polarization predicted by the Non-relativistic QCD model (NRQCD) and the k_{T} factorization model cannot reproduce the CDF measurement[2]. With the good performance of the LHCb detector, it is expected that LHCb can provide essential and unique contributions in this area.

2. The productions of χ_{c0}, χ_{c1} and χ_{c2}

The χ_{cJ} production is measured using the decay of $\chi_{cJ} \to J/\psi\gamma$, where the photon converts into a pair of oppositely charged electrons in the detector material before the magnet. This measurement is based on 1 fb^{-1} data collected by LHCb in 2011. Since the energy resolution of the converted photon is better than that reconstructed with the calorimeter photons as used in the previous measurement[3], a clean separation of the χ_{c1} and χ_{c2} peaks is allowed.

The signal yields for χ_{cJ} are determined by the fit to the spectrum of the invariant mass difference between χ_{cJ} and J/ψ: $\Delta M = M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$. The χ_{cJ} is selected with the rapidity $2.0 < y < 4.5$ and the transverse momentum of J/ψ is required to be in the region of $4 < {p_{\mathrm{T}}}^{J/\psi} < 20\,\mathrm{GeV}/c$. Figure 1(left) shows the fit to ΔM in the data after the background subtraction, and the first evidence of χ_{c0} at hadron collider is also reported with a statistical significance of 4.4σ.

The ratios of the cross sections of χ_{c0}, χ_{c1} and χ_{c2} are measured as

$$\begin{aligned}\sigma(\chi_{c0})/\sigma(\chi_{c2}) &= 1.19 \pm 0.27(\mathrm{stat}) \pm 0.29(\mathrm{syst}) \pm 0.16(p_{\mathrm{T}}\ \mathrm{model}) \pm 0.09(\mathscr{B}) \\ \sigma(\chi_{c2})/\sigma(\chi_{c1}) &= 0.787 \pm 0.014(\mathrm{stat}) \pm 0.034(\mathrm{syst}) \pm 0.051(p_{\mathrm{T}}\ \mathrm{model}) \pm 0.047(\mathscr{B}),\end{aligned} \tag{2.1}$$

where the systematics is dominated by the photon efficiency, the total fit function modelling, the p_{T} spectrum choice and the uncertainty of $\mathscr{B}(\chi_{cJ} \to J/\psi\gamma)$. The results are in agreement with the NRQCD predictions[4, 5]. The ratio of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is measured as a function of ${p_{\mathrm{T}}}^{J/\psi}$, as shown in Figure 1(right). The result is in agreement with the NRQCD predictions in the high p_{T}

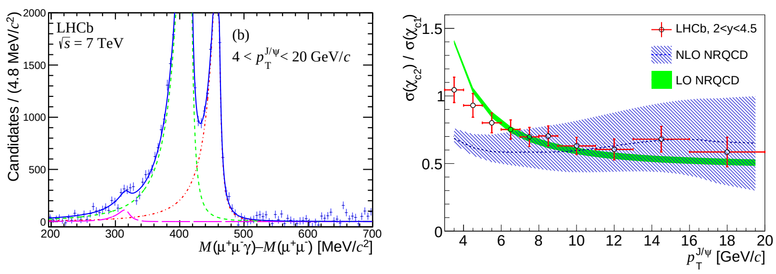

Figure 1: (Left)The ΔM distribution after background subtraction: total fitted function (blue solid curve), χ_{c1} signal (green dashed curve), χ_{c2} signal (red dot-dashed curve) and χ_{c0} signal (purple lone-dashed curve). (Right) The measured $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ as a function of ${p_{\mathrm{T}}}^{J/\psi}$ and the theoretical predictions[4, 5].

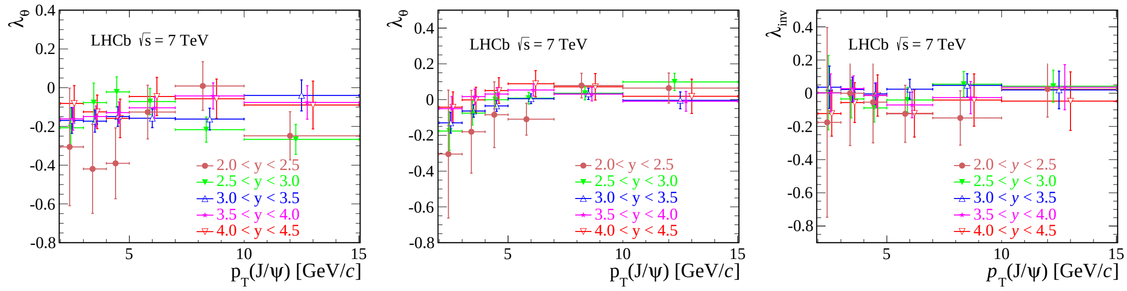

Figure 2: The measured λ_θ in HX frame (left), CS frame(middle) and the measured λ_{inv} (right).

region and it is also compatible with the results measured by CDF[6] and CMS[7]. The simulation sample, which is used to estimate the efficiency, is generated with the unpolarized χ_{cJ} assumption. If the efficiency is corrected to the angular distribution under the polarization hypotheses, a better agreement will be achieved between the LHCb result and that measured by CDF and CMS.

3. J/ψ polarization

The measurement of CDF[2] show that the NLO NRQCD model predicts the J/ψ production very well, but not for the polarization. The polarization parameters $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})$ are defined in the full angular distribution

$$\frac{d^2N}{d\cos\theta d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos^2 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi, \tag{3.1}$$

where the angles θ and ϕ are defined in Ref.[8]. This analysis is based on 0.37 fb^{-1} data collected by LHCb in 2011 at $\sqrt{s} = 7$ TeV and J/ψ candidates are reconstructed by the decay of $J/\psi \to \mu^+\mu^-$ selected similar to Ref.[9]. The polarization parameters $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})$ are determined by 2D fits to θ and ϕ distributions of the J/ψ candidates after the background subtraction.

The polarization parameters are measured in different frames as functions of p_{T} and y of J/ψ, as shown in Figure 2. The weighted average value is $\lambda_\theta = -0.145 \pm 0.027$ in helicity frame. The LHCb result is consistent with that measured by ALICE[10] and favors the prediction of the NLO NRQCD[11] including the feed-down contribution of the $^3P_J^{[8]}$ state, which is better than other predictions[12, 13].

Using the measured polarization, the prompt J/ψ cross-section production is updated

$$\sigma(\text{prompt } J/\psi; p_{\text{T}} < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 9.46 \pm 0.04(\text{stat}) \pm 0.53(\text{syst})^{+0.86}_{-1.10}\,\mu\text{b}, \tag{3.2}$$

where, comparing with the previous measurement[9], the changes of the center value and the second uncertainty term are caused by the updated determination of the luminosity and the track efficiency, and the third uncertainty term is due to the polarization of J/ψ mesons.

4. J/ψ production in pPb collisions

In the proton-lead collisions, the effect of cold nuclear matter can be characterized by the

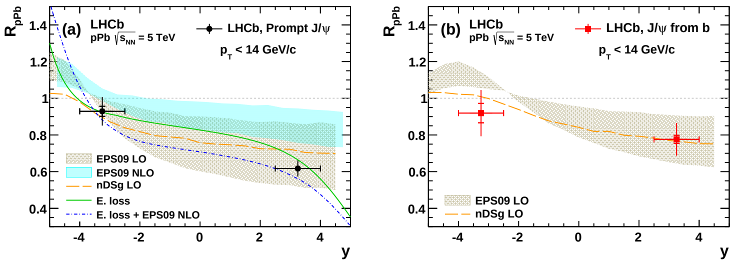

Figure 3: Nuclear modification factor $R_{p\mathrm{Pb}}$ as a function of y for (a) prompt J/ψ and (b) J/ψ from b decays. The theoretical predictions includes Ref.[15] (yellow dashed line and brown band), Ref.[16] (blue band) and Ref.[17] (green solid and blue dash-dotted lines)

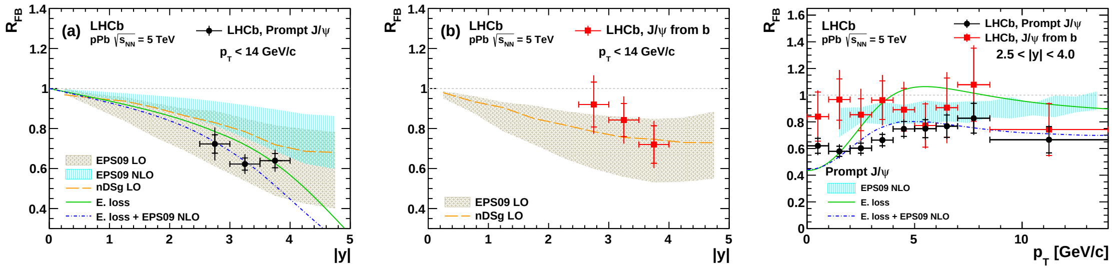

Figure 4: Forward-backward production ratio as a function of y for prompt J/ψ (left) and J/ψ from b decays (middle) and as a function of p_{T} (right). The theoretical predictions includes Ref.[15] (yellow dashed line and brown band), Ref.[16] (blue band) and Ref.[17, 18] (green solid and blue dash-dotted lines)

nuclear modification factor $R_{p\mathrm{Pb}}$ and the forward-backward production ratio R_{FB}

$$R_{p\mathrm{Pb}}(y,\sqrt{s_{NN}}) \equiv \frac{1}{A}\frac{d\sigma_{p\mathrm{Pb}}(y,\sqrt{s_{NN}})/dy}{d\sigma_{pp}(y,\sqrt{s_{NN}})/dy}; \quad R_{\mathrm{FB}}(y,\sqrt{s_{NN}}) \equiv \frac{R_{p\mathrm{Pb}}(+|y|,\sqrt{s_{NN}})}{R_{p\mathrm{Pb}}(-|y|,\sqrt{s_{NN}})}, \tag{4.1}$$

where all the variables are defined in Ref.[14]. In 2013, LHCb takes $1.6\,\mathrm{nb}^{-1}$ data for forward and backward pPb collisions. J/ψ mesons are reconstructed by the decay $J/\psi \to \mu^+\mu^-$ and selected with $p_{\mathrm{T}} < 14\,\mathrm{GeV}/c$ and $1.5 < y < 4.0$ ($-5.0 < y < -2.5$) for forward (backward) collisions. The pseudo decay time $t_z = M_{J/\psi} \times (z_{J/\psi} - z_{\mathrm{PV}})/p_z$[14] is used to separate the prompt J/ψ from J/ψ from b decays. The integrated production cross-sections of prompt J/ψ and J/ψ from b decays are measured as

$$\begin{aligned}
\sigma_{\mathrm{Fwd}}(\text{prompt } J/\psi) &= 1028.2 \pm 13.6(\mathrm{stat}) \pm 88.6(\mathrm{syst})\,\mu\mathrm{b} \\
\sigma_{\mathrm{Fwd}}(J/\psi \text{ from } b) &= 150.1 \pm 4.2(\mathrm{stat}) \pm 12.6(\mathrm{syst})\,\mu\mathrm{b} \\
\sigma_{\mathrm{Bwd}}(\text{prompt } J/\psi) &= 1141.9 \pm 49.8(\mathrm{stat}) \pm 98.4(\mathrm{syst})\,\mu\mathrm{b} \\
\sigma_{\mathrm{Bwd}}(J/\psi \text{ from } b) &= 119.7 \pm 8.3(\mathrm{stat}) \pm 10.0(\mathrm{syst})\,\mu\mathrm{b}
\end{aligned} \tag{4.2}$$

where the systematic uncertainty is dominated by the luminosity, the fit model and the discrepancy between the data and simulation samples. The differential productions as functions of p_{T} and y for prompt J/ψ and J/ψ from b decays are measured for the first time. As shown in Figure 3 and 4, the measured $R_{p\mathrm{Pb}}$ and R_{FB} show clear suppression of prompt J/ψ production in the forward region. The $R_{p\mathrm{Pb}}$ and R_{FB} for J/ψ from b show a first indication of b-hadron suppression in pPb collisions. The results agree with theoretical predictions.

5. Conclusion

With the good performance of the LHCb detector, some of the measurements of the quarkonia production are performed. The ratio of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is measured as a function of p_{T} of J/ψ and the result is in good agreement with NRQCD predictions. The polarization of prompt J/ψ is measured and the theoretical models cannot reproduce the results well. In addition, for the first time, the productions, nuclear modification factors and the forward-backward production ratios of prompt J/ψ and J/ψ from b in pPb collisions are measured.

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