Study of Charmonium production in pp collisions at the LHC energies

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Abstract. We perform a detail study of $J/\psi$ and $\psi(2S)$ production in $p - p$ collisions at different LHC energies using non-relativistic QCD (NRQCD) model of heavy quarkonium productions in the high $p_T$ region. The feeddown to $J/\psi$ and $\psi(2S)$ from B meson has been implemented using Fixed-Order Next-to-Leading Logarithm (FONLL) formalism. We also include the contribution from $\chi_{cJ}$ and $\psi(2S)$ decays to $J/\psi$ where the $p_T$ distributions of $\chi_{cJ}$ have been calculated using NRQCD. The corresponding results are then compared with the available data at LHC energies. It is found that the data are well reproduced for $p_T > 4$ GeV within the theoretical uncertainties arising due to the choice of the factorization scale. We also predict the transverse momentum distributions of $J/\psi$ and $\psi(2S)$ both from the direct and feeddown processes at the upcoming LHC energies of $\sqrt{s} = 5.5$ TeV and 13 TeV.
1. Introduction

The understanding of the quarkonia (bound states of $Q$ and $\bar{Q}$) productions has been a long-term effort both experimentally and theoretically. The quarkonia production mechanism in $p−p$ collisions is qualitatively understood by the models based on the Quantum Chromodynamics (QCD), in particular, in the non-relativistic QCD (NRQCD) [1]. A remarkable progress has been made in quarkonia production studies during last decade based on NRQCD formalism [2, 3, 4, 5, 6, 7, 8]. The picture of the NRQCD formalism is as follows. The orbital splittings in case of quarkonium bound states are smaller than the heavy quark mass $m_Q$ which suggests that all the other dynamical scales of these systems are smaller than $m_Q$. So, the velocity $v$ of the heavy constituents in these systems is believed to be a small quantity, $v << 1$. Therefore, a hierarchy of scales: $m_Q >> m_Qv >> m_Qv^2$ as observed in a non-relativistic (NR) system also holds for quarkonia. Here, $m_Q$ fixes the distance range for $Q\bar{Q}$ creation and annihilation processes, momentum $m_Qv$ is inversely proportional to the spatial size of the bound state and the kinetic energy $m_Qv^2$ determines the typical interaction time scale. These different distance scales make quarkonia study interesting and challenging and NRQCD keeps track of these scale hierarchy.

The quarkonia production in NRQCD is a two step process: First, the creation of the $Q\bar{Q}$ pair in a hard scattering at short distances which are process-dependent, is to be calculated perturbatively as an expansions in the strong coupling constant $\alpha_s$. Note that $Q\bar{Q}$ states can be in the color-singlet(CS) [9, 10, 11] as well as in a color-octet(CO) [12, 13, 14] states. Second, the $Q\bar{Q}$ pair evolves into the quarkonium state with the probabilities that are given by the supposedly universal nonperturbative long-distance matrix elements (LDMEs) which have to be extracted from experiments. For CO states, this evolution process also involves the nonperturbative emission of soft gluons to form a CS states. The crucial feature of this formalism is that the complete structure of the $Q\bar{Q}$ Fock space, which is spanned by the states $n=2^{S+1}L^{[i]}_J$ with spin $S$, orbital angular momentum $L$, total angular momentum $J$, and color multiplicity $i = 1, 8$.

FONLL [15, 16] formalism is dedicated to calculate the production cross-sections of $J/\psi$ and $\psi(2S)$ from B meson decays which can be used as the feeddown contributions from B meson to the $J/\psi$ and $\psi(2S)$ productions. FONLL includes next-to-leading log resummation at high $p_T$ and it only addresses single inclusive production cross-sections. All other kinematic variables such as rapidity are integrated over.

In recent times, the charmonium production in $p–p$ collisions has been measured at $\sqrt{s} = 2.76$ TeV and 7 TeV by ALICE [17, 18] and LHCb [19, 20] collaborations at extreme forward rapidities of $2.5 < y < 4$ and $2 < y < 4.5$, respectively. Both experiments utilized the dimuon decay channel of $J/\psi$ and $\psi(2S)$ for these measurements since this decay channel is cleaner than the di-electron channel. The ALICE Muon Spectrometer uses a Front Absorber (FA) of radiation length $10 \lambda_{int}$ to cut down the hadron background since this set-up also collects data in Pb-Pb collisions. Thus, this spectrometer has a mass resolution of around $\sim 70$ MeV due to the multiple coulomb scattering and energy loss of the muons inside the FA. In addition, the cross-section measurements are inclusive in nature i.e. the contribution due to the B feeddown cannot be measured separately. On the other hand, LHCb does not employ any absorber and has a mass resolution of $\sim 20$ MeV. In addition, the contribution of B feeddown has been measured separately from the displaced vertex technique at LHCb [19, 20].
In the present work, the charmonium cross-sections have been calculated at $\sqrt{s} = 2.76$ TeV and 7 TeV within the framework of NRQCD and FONLL. These calculations have been compared with the experimental values and predictions have been made for $\sqrt{s} = 5.5$ TeV and 13 TeV. This is done since the center-of-mass energy for 2015 $p-p$ collisions at LHC will be 13 TeV and the designed goal for the Pb-Pb collisions at LHC is 5.5 TeV per nucleon. Thus, we provide the predictions for the $p-p$ reference at $\sqrt{s} = 5.5$ TeV which can be used as the baseline for the calculation of $R_{AA}$ in Pb-Pb collisions in future.

The organization of the paper is as follows. In Sec. II, we give a brief description of the theoretical model of NRQCD. Results will be presented in Sec. III followed by summary and discussion in Sec. IV.

2. $p_T$ spectrum in $p+p$ collisions

The factorization formalism of the NRQCD provides a theoretical framework for studying the heavy quarkonium production and decay. According to the NRQCD factorization formalism, the cross section for direct production of a resonance $H$ in a collision of particle $A$ and $B$ can be expressed as

$$d\sigma_{A+B\rightarrow H+X} = \sum_{a,b,n} \int dx_a dx_b G_{a/A}(x_a, \mu_F) G_{b/B}(x_b, \mu_F) \times d\sigma(a+b\rightarrow Q\bar{Q}(n)+X) \langle O^H(n) \rangle,$$

where $G_{a/A}(G_{b/B})$ is the partonic distribution function (PDF) of the incoming partons $a$ ($b$) in the incident hadron $A$ ($B$) which depends on the large light-cone momentum fraction $x_a$ ($x_b$) and the factorization scale $\mu_F$. The transverse mass of the resonance $H$ is $m_T = \sqrt{p_T^2 + m_H^2}$, where $m_H \sim 2m_Q$ is the mass of resonance $H$. The short distance contribution $d\sigma(a+b\rightarrow Q\bar{Q}(n)+X)$ can be calculated within the framework of perturbative QCD (pQCD). On the other hand, $\langle O^H(n) \rangle$ are nonperturbative LDMEs and to be extracted from experiment.

To calculate the short distance contribution i.e. the heavy quark pair production from the reaction of the type $a+b\rightarrow c+d$, where $a$, $b$ refer to light incident parton, $c$ refers to $Q\bar{Q}$ pair and $d$ is the light final state parton. The differential cross section for the reaction of the above type can be written as [21]

$$\frac{d\sigma}{dp_T dy} = \int dx_a G_{a/A}(x_a, \mu_F) G_{b/B}(x_b, \mu_F) \times 2p_T x_a x_b \frac{d\sigma}{dt}(ab\rightarrow cd),$$

where, $\sqrt{s}$ being the total energy in the center-of-mass and $y$ is the rapidity of the $Q\bar{Q}$ pair. In our numerical computation, we use CTEQ6 [22] for the initial partonic distribution functions. The invariant differential cross section is given by

$$\frac{d\sigma}{dt} = \frac{|\mathcal{M}|^2}{16\pi s^2},$$

where $\hat{s}$, $\hat{t}$ and $\hat{u}$ are the parton level Mandelstern variables. The value of the momentum fraction $x_b$ can be written as,

$$x_b = \frac{1}{\sqrt{s}} \frac{x_a \sqrt{\hat{s}} m_T e^{-y} - m_H^2}{x_a \sqrt{\hat{s}} - m_T e^y}.$$
The minimum value of $x_a$ is

$$x_{\text{amin}} = \frac{1}{\sqrt{s}} \frac{\sqrt{s} m_T e^y - m_H^2}{\sqrt{s} - m_T e^{-y}}$$  \hspace{1cm} (5)$$

The LDMEs are predicted to scale with a definite power of the relative velocity $v$ of the heavy constituents inside $Q\bar{Q}$ bound states. In the limit $v << 1$, the production of quarkonium is based on the $^3S_1^{[1]}$ and $^3P_j^{[1]} (J = 0, 1, 2)$ CS states and $^3S_1^{[8]}$, $^3S_1^{[8]}$ and $^3P_j^{[8]}$ CO states. In our calculations, we used the expressions for the short distance CS cross-sections given in Refs. \[13\]-\[14\] and the CO cross-sections given in Refs. \[13\]-\[14\].

In this paper we calculate the $p_T$ distribution of $J/\psi$ and $\psi(2S)$ in $p-p$ collisions at CERN LHC energies. For $J/\psi$ production in $p-p$ collisions, three sources need to be considered: direct $J/\psi$ production, feeddown contributions to the $J/\psi$ from the decay of heavier charmonium states, predominantly from $\psi(2S), \chi_{c0}, \chi_{c1}$ and $\chi_{c2}$ and $J/\psi$ from B hadron decays. Sum of the first two sources are called "prompt $J/\psi$" and third source will be called "$J/\psi$ from B". On the other hand, $\psi(2S)$ has no significant feeddown contributions from higher mass states. We call this direct contribution as "prompt $\psi(2S)$" to be consistent with the experiments. The other source to $\psi(2S)$ production is from B hadron decays and we call it "$\psi(2S)$ from B". The sum of the prompt $J/\psi(\psi(2S))$ and $J/\psi(\psi(2S))$ from B will be called "inclusive $J/\psi(\psi(2S))$".

We will be comparing the theoretical predictions with the measured production cross-sections of prompt $J/\psi$ and $\psi(2S)$ from LHCb collaboration and inclusive $J/\psi$ and $\psi(2S)$ from ALICE collaboration at different LHC energies.

The direct production cross section of $J/\psi$ can be written as the sum of the contributions \[13\]-\[14\].

$$d\sigma(J/\psi) = d\sigma(Q\bar{Q}(^3S_1^{[1]})) < O(Q\bar{Q}(^3S_1^{[1]}) \rightarrow J/\psi) > + d\sigma(Q\bar{Q}(^1S_0^{[8]})) < O(Q\bar{Q}(^1S_0^{[8]}) \rightarrow J/\psi) > + d\sigma(Q\bar{Q}(^3S_1^{[8]})) < O(Q\bar{Q}(^3S_1^{[8]}) \rightarrow J/\psi) > + d\sigma(Q\bar{Q}(^3P_j^{[8]})) < O(Q\bar{Q}(^3P_j^{[8]}) \rightarrow J/\psi) > + ... \hspace{1cm} (6)$$

Similar expression holds for direct $\psi(2S)$ production. The production cross-section for $\chi_{cJ}$ can be written as \[13\]:

$$d\sigma(\chi_{cJ}) = d\sigma(Q\bar{Q}(^3P_j^{[1]})) < O(Q\bar{Q}(^3P_j^{[1]}) \rightarrow \chi_{cJ}) > + d\sigma(Q\bar{Q}(^3S_1^{[8]})) < O(Q\bar{Q}(^3S_1^{[8]}) \rightarrow \chi_{cJ}) > + ... \hspace{1cm} (7)$$

Here, we have taken into account the contributions from all three $\chi_{cJ}(\chi_{c0}, \chi_{c1}$ and $\chi_{c2}$) mesons to $J/\psi$.

To calculate the direct charmonia and feeddown contributions from heavier states as well as from B decays, we use the following branching ratios: $B(J/\psi|\psi(2S)) \rightarrow \mu^+\mu^- = 0.0593[0.0078], B(\psi(2S) \rightarrow J/\psi) = 0.603, B(\chi_{cJ} \rightarrow J/\psi) = 0.0130, 0.348, 0.198$ for $J = 0, 1, 2$, respectively and $B(B \rightarrow J/\psi(\psi(2S))) = 0.116[0.283]$. We choose the factorization and renormalization scales $\mu_F = \mu_R = \mu_0$, where $\mu_0 = \sqrt{p_T^2 + 4m_c^2}$ with $m_c = 1.4$ GeV. The LDMEs \[24\] for CS and CO which we have used for our calculations are given in the Table I. The central values of LDMEs are taken for our calculations. FONLL \[15\]-\[16\]-\[25\] calculation is used to estimate the contribution from B decays to $J/\psi$ and $\psi(2S)$ productions.
3. Results

The shaded band in Fig. 1(a) represents the NRQCD predictions for prompt differential cross-section of $J/\psi$ as a function of $p_T$ for the rapidity interval $2 < y < 4.5$ at $\sqrt{s} = 7$ TeV. The uncertainty limits on the calculated values correspond to the variation of the factorization scale $\mu_F$. This uncertainty due to the factorization scale was estimated by performing the calculations for $\mu_F = \mu_R = \mu_0/2$ (upper bound) and $\mu_F = \mu_R = 2\mu_0$ (lower bound). This scale variation has two effects on the cross-sections.

First, for the same value of $x$, the PDFs at a higher scale are smaller in the region of interest. Second, with the increase of the scale, $\alpha_s$ decreases. These uncertainties were calculated for the direct production as well as for the feeddown contributions from $\psi(2S)$, $\chi_{c0}$, $\chi_{c1}$ and $\chi_{c2}$. However, in the figure, the feeddown contributions have been shown by lines which correspond to the calculated values for the central values of LDMEs and $\mu_F$. The experimental data from LHCb [19] for the prompt $J/\psi$ differential cross-sections has also been shown in the figure. It may be noted that the calculated values for the direct production underpredicts the experimental values and the good agreement has been found after the inclusion of the feeddown contributions. This indicates that the feeddown from the higher states have significant contributions at LHC energies. The NRQCD calculations are unable to describe the experimental data for $p_T < 4$ GeV since in this domain the perturbative approximation fails. In Fig. 1(b), the measured values from LHCb [20] and calculated values from NRQCD for $\psi(2S)$ differential cross-sections as a function of $p_T$ has been shown. The uncertainty band arises due to the same reasons as discussed for $J/\psi$. It is important to note that for $\psi(2S)$ there is no contribution from the higher excited charmonium states. Thus, the prompt and direct production is the same. In the present framework of NRQCD, the calculated direct production cross-sections for $\psi(2S)$ reproduce the measured values quite well for $p_T > 4$ GeV.

| LDMEs | Numerical value | scaling order |
|-------|-----------------|---------------|
| $< \mathcal{O}(Q\bar{Q}(\bar{3}S^1_1) \rightarrow J/\psi) >$ | 1.2 GeV$^3$ | $m_c^3$ |
| $< \mathcal{O}(Q\bar{Q}(\bar{3}S^1_1) \rightarrow \psi(2S)) >$ | 0.76 GeV$^3$ | $m_c^3$ |
| $< \mathcal{O}(Q\bar{Q}(\bar{3}P^0_{11}) \rightarrow \chi_{c0}) >/m_c^2$ | 0.054 GeV$^3$ | $m_c^3$ |
| $< \mathcal{O}(Q\bar{Q}(\bar{3}P^1_{11}) \rightarrow \chi_{c1}) >/3m_c^2$ | 0.054 GeV$^3$ | $m_c^5$ |
| $< \mathcal{O}(Q\bar{Q}(\bar{3}P^2_{11}) \rightarrow \chi_{c2}) >/5m_c^2$ | 0.054 GeV$^3$ | $m_c^5$ |

Table 1. LDMEs [21]
Figure 1. (Color online) Differential production cross-section vs. $p_T$ for (a) $J/\psi$ and (b) $\psi(2S)$ has been compared with the LHCb data in the rapidity interval $2 < y < 4.5$ and at $\sqrt{s} = 7$ TeV [19, 20]. For LHCb data, the vertical error bars represent the statistical errors while the boxes correspond to the systematic uncertainties. We have shown the sum of all contributions with a green band which is obtained by varying the renormalization scale from $\mu_F = \mu_R = \mu_0/2$ to $\mu_F = \mu_R = 2\mu_0$ and we have shown the direct, feeddown contributions to prompt $J/\psi$ and $\psi(2S)$ only by lines which are for central $\mu_F = \mu_R = \mu_0$ values.

These calculations were also carried out for ALICE data which corresponds to the rapidity interval of $2.5 < y < 4$ at $\sqrt{s} = 2.76$ TeV [17] and $7$ TeV [18]. However, ALICE collaboration has reported the inclusive $J/\psi$ cross-section which include the B feeddown along with the prompt contribution. The B feeddown to $J/\psi$ and $\psi(2S)$ was calculated from FONLL and added to the prompt contribution calculated within the present NRQCD framework.

Figs. 2(a) and 2(b) show the comparison between the calculated and measured values for the differential cross-sections of $J/\psi$ at $\sqrt{s} = 2.76$ TeV and 7 TeV, respectively. The agreement has been found to be good at both the energies for $p_T > 4$ GeV. Fig. 2(c) also shows a good agreement for $\psi(2S)$ at $\sqrt{s} = 7$ TeV. The experimental data for $\psi(2S)$ at $\sqrt{s} = 2.76$ TeV is not available.

ALICE collaboration has also reported the ratio of the differential cross-sections of $\psi(2S)$ to $J/\psi$ at $\sqrt{s} = 7$ TeV [18]. These measured and calculated values are shown in Fig. 3. The agreement is reasonable for $p_T > 4$ GeV except for the $p_T$ bin of 6-8 GeV. The experimental data shows a clear dip for this bin while the calculated values show a smooth increasing trend in the domain of $3.5 < p_T < 12$ GeV.

Thus, there is a good agreement between the experimental values from LHCb and ALICE collaborations and calculated values from NRQCD framework for $p_T > 4$ GeV. This observation has prompted us to calculate the differential production cross-sections for $J/\psi$ and $\psi(2S)$ at $\sqrt{s} = 5.5$ TeV and 13 TeV. It may be noted that in 2015, the center-of-mass energy for $p - p$ collisions at LHC will be 13 TeV. The predicted cross-section for $J/\psi$ and $\psi(2S)$ for this energy is shown in Figs. 4(a) and 4(b), respectively.

ALICE collaboration will be collecting the maximum statistics at $\sqrt{s_{NN}} = 5.5$ TeV for Pb-Pb collisions at LHC. The measurement of $J/\psi$ and $\psi(2S)$ cross-sections in $p - p$ collisions at this energy is not available which is crucial for the measurement of the suppression of production cross-section for these resonances. Thus, the values have
Figure 2. (Color online) Same as Fig. 1 with the inclusion of B decay and the data are from ALICE [17, 18] in the rapidity interval $2.5 < y < 4$ for (a) $J/\psi$ at $\sqrt{s} = 2.76$ TeV, (b) $J/\psi$ at $\sqrt{s} = 7$ TeV and (c) $\psi(2S)$ at $\sqrt{s} = 7$ TeV.

Figure 3. (Color online) Inclusive $\psi(2S)$ to $J/\psi$ production cross-section ratio vs. $p_T$ compared to the ALICE data in the rapidity interval $2.5 < y < 4$ and at $\sqrt{s} = 7$ TeV [18].

been calculated for $J/\psi$ and $\psi(2S)$ at this energy and shown in Figs. 2(a) and 2(b), respectively.
4. Summary and Discussion

In summary, we have calculated the prompt and inclusive production cross-sections of $J/\psi$ and $\psi(2S)$ at LHC energies within the framework of NRQCD and FONLL. We employ NRQCD to calculate the contributions from direct production and from the decays of heavier charmonium states such as $\psi(2S)$, $\chi_{c0}$, $\chi_{c1}$ and $\chi_{c2}$. The feeddown to $J/\psi$ and $\psi(2S)$ from B meson has been implemented using FONLL calculation. The experimental values from LHCb and ALICE collaborations and calculated values from NRQCD and FONLL are in good agreement for $p_T > 4$ GeV. We have also given the predictions for the production cross-sections of $J/\psi$ and $\psi(2S)$ at $\sqrt{s} = 5.5$ TeV and 13 TeV in the rapidity interval $2.5 < y < 4$ in $p-p$ collisions. We also note that there is the fragmentation process which contributes to the charmonium production at high $p_T$ [8]. Inclusion of this process may improve the results and the parameters (such as $m_c$, $\mu_0$ etc.) may be marginally adjusted to reproduce the data. Recently, there is a work where the entire $p_T$ region of the production cross-sections has been well reproduced with the CGC+NRQCD formalism [26, 27]. The authors discussed the feeddown contribution from B decays and it is estimated to be 10% of any other
contribution in the low $p_T$ region. But for completeness we include this (along with the other feeddown contributions) as this is important as far as the ALICE data are concerned because the cross-section from B decay cannot be measured separately in ALICE. In future we intend to adopt the CGC formalisms \cite{26,27} for quarkonium production in the low $p_T$ region to cover the entire $p_T$ range with the inclusion of all the feeddown contributions.

ACKNOWLEDGEMENTS

It is a pleasure to thank Matteo Cacciari for helpful discussion about FONLL. The work of B. P. was supposed by CSIR, India (File No. 09/489(0085)/2010-EMR-I).

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