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Complete NRQCD prediction for prompt double J/ψ production at Hadron Collider

Zhi-Guo He* **and Bernd A.Kniehl**
II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
E-mail: zhiguo.he@desy.dekniehl@mail.desy.de

We present our recent work [1] on studying prompt double J/ψ production at hadron collider in the framework of non-relativistic QCD (NRQCD) factorization formalism. We take into account the contribution of all the possible pairings of the Fock states ${}^1S_0^{[8]}, {}^3S_1^{[1,8]}, {}^3P_J^{[1,8]}$ with $J = 0, 1, 2$ in direct J/ψ production and the feed-down contribution from χ_{cJ} and $\psi(2S)$. We find that the ${}^1S_0^{[8]}, {}^3P_J^{[1,8]}$ contribution that has been ignored before leads to a significant enhancement in the region of large invariant mass and rapidity separations of the double J/ψ. The inclusion of their contribution largely softens the conflict between theoretical calculation based on color-singlet model and the measurements by CMS Collaboration at LHC leaving sizable room for the NRQCD predictions at next-to-leading order.

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*Speaker.

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1. Introduction

Since the J/ψ meson was discovered in 1974, studies its production properties have been one of the important subjects in heavy quarkonium physics [2]. The non-relativistic QCD (NRQCD) factorization formalism [3], which is built on the rigorous NRQCD effective field theory [4], has been widely accepted to investigate heavy quarkonium production and decay. In NRQCD factorization formalism the production and decay of heavy quarkonium is factorized into the product of the short-distance coefficients (SDCs) which can be calculated perturbatively and the universal long-distance matrix elements (LDMEs) which are organized as powers of the v [5], the relative velocity of the heavy quark in the meson rest frame. The NRQCD factorization formalism successfully explained the J/ψ yield data at hadron collider [6, 7, 8], however its prediction on J/ψ polarization[9] and the η_c yield [10] at QCD next-to-leading order (NLO) are challenged by the experimental measurements.

Besides the single J/ψ production, the double J/ψ production provides another testing ground on NRQCD factorization. In double J/ψ production the hadronization of charm quark pairs takes twice, so the theoretical predictions are more sensitive to the chosen LDMEs. Therefore, it is also able to test on the validity of the different sets of the LDMEs obtained in the fitting to single J/ψ production data. Moreover, in double J/ψ production, it is believed that both the single parton scattering (SPS) and the double parton scattering (DPS) processes are involved [11]. Pinning down the SPS contribution could help to extract the information of DPS, like the $\sigma_{\rm eff}$, which is related to the transverse structure of proton.

Experimentally, the double J/ψ hadroproduction have been measured by LHCb [12], CMS [13] Collaborations at LHC, and D0 Collaboration [14] at Tevatron. On the theoretical side, the double J/ψ production is pioneered by Barge, et al. in 1995. [15] and then received considerable interest [16, 17, 18, 19, 20, 21, 22, 23] but still less than single J/ψ production. So far only the color-octet (CO) $gg \to 2c\bar{c}(^3S_1^{[8]})$ and color-singlet (CS) $gg \to 2c\bar{c}(^3S_1^{[1]})$ have been studied. Since they are incomplete in NRQCD calculation for prompt double J/ψ production, we denote them by CO^* and CS^*, respectively. It is revealed that the CS^* mainly contributes at low J/ψ transverse momentum, p_T, region, and will be overtook by the CO^* when p_T is large, say $p_T \simeq 16$GeV at LHC [19]. Recently the NLO QCD corrections [22] to the CS^* and relativistic corrections [21] to both the CS^* and CO^* were obtained. It is found that, in the LHCb case, the CS^* prediction to the total cross section is compatible with data, but its prediction to the invariant mass, M, distribution $d\sigma/dM$ largely deviate from the data near the threshold region even after including the -23% relativistic corrections [21]. In CMS case, although the $K-$factor of NLO QCD corrections is larger than 10, the CS^* itself can only account for $2/3$ of the total cross section, let alone the 4 orders of magnitude undershoot the invariant mass distribution for $M > 35$ GeV [22].

2. Framework of NRQCD factorization

In this work, we for the first time, consider the $^1S_0^{[8]}$ and $^3P_J^{[8]}$ with $J = 0,1,2$ contribution to direct double J/ψ production and ψ' feed-down as well as the $^3P_J^{[1]}$ and $^3S_1^{[8]}$ contribution from χ_c feed-down. Note the CS $J/\psi + \chi_{cJ}$ channel are forbidden at $\mathcal{O}(\alpha_s^4)$ because of the charge conjugation conversation. Therefore, there are in total $\binom{8}{2} - 3 = 25$ channels needed to be calculated.

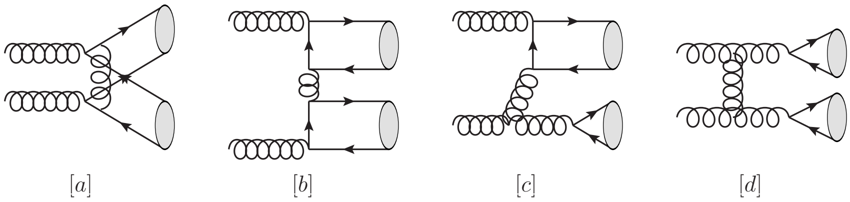


Figure 1: The typical Feynman diagrams for $gg \to c\bar{c}(m) + c\bar{c}(n)$: (a) non-fragmentation Type-I, (b) non-fragmentation Type-II, (c) single-fragmentation, (d) double-fragmentation.

Owing to the factorization theorems of the QCD parton model and NRQCD factorization formalism, we express the prompt double J/ψ hadroproduction cross section as

$$d\sigma(AB \to 2J/\psi + X) = \sum_{i,j,m,n,H_1,H_2} \int dx_1 dx_2 \times f_{i/A}(x_1) f_{j/B}(x_2) d\hat{\sigma}(ij \to c\bar{c}(m)c\bar{c}(n) + X)$$
$$\times \langle \mathcal{O}^{H_1}(m) \rangle \mathrm{Br}(H_1 \to J/\psi + X) \times \langle \mathcal{O}^{H_2}(n) \rangle \mathrm{Br}(H_2 \to J/\psi + X), \quad (2.1)$$

where $f_{i/A}(x)$ is the parton distribution function (PDF) of parton i in hadron A, $d\hat{\sigma}(ij \to c\bar{c}(m)c\bar{c}(n) + X)$ is the SDC, $\langle \mathcal{O}^H(m) \rangle$ is the LDME of $H = J/\psi, \chi_{cJ}, \psi'$, and $\mathrm{Br}(H \to J/\psi + X)$ is the branching fraction with the understanding that $\mathrm{Br}(H \to J/\psi + X) = 1$ if $H = J/\psi$. Because of the smallness of $\mathrm{Br}(\chi_{c0} \to J/\psi\gamma) = 1.27\%$ [24], we neglect the contribution from $H = \chi_{c0}$.

There are in total 72 Feynman diagrams in the partonic sub-process $gg \to c\bar{c}(m) + c\bar{c}(n)$ as shown in Figure.1 for the representative ones. Because of J^{PC} conservation, not all of them contribute for a given combination of m and n. Based on the behaviors of $d\sigma/dp_T^2 \propto 1/p_T^N$ and the topological properties of the contributing Feynman diagrams [see Figs. 1(a)–(d)], we divide the partonic sub-processes into 4 categories: (1) NNLP-I, with $N = 8$, including $m = {}^3S_1^{[1]}$ and $n = {}^3S_1^{[1,8]}, {}^1S_0^{[8]}, {}^3P_J^{[8]}$; (2) NNLP-II, with $N = 8$, too, including $m,n = {}^1S_0^{[8]}, {}^3P_J^{[8]}, {}^3P_J^{[1]}$; (3) NLP, with $N = 6$, including $m = {}^3S_1^{[8]}$ and $n = {}^1S_0^{[8]}, {}^3P_J^{[8]}, {}^3P_J^{[1]}$; and (4) leading power (LP), with $N = 4$, including $m = n = {}^3S_1^{[8]}$. While the NNLP-I and NNPL-II sub-processes exhibit the same p_T scaling, their difference is the topologies of the respective Feynman diagrams. In the latter case, there are the diffraction-like ones as shown in Fig. 1(b), which, we will show later, lead to significant enhancement of the cross section at large value of M.

3. Numerical results

Since we perform the LO evaluation, to be consistent we choose the values of the CO LDMEs that were obtained through the fitting of LO calculation to the J/ψ hadroproduction data [1], the corresponding CTEQ5L PDF [25], and the one-loop running of QCD coupling constant α_s. The renormalization and factorization scales are set to be $\mu_r = \mu_f = m_T = \xi\sqrt{(4m_c)^2 + p_T^2}$ with $m_c = 1.5$ GeV and ξ varying between $1/2$ and 2 about the default value 1 to estimate the theoretical uncertainty. The CS LDMEs are adopted from the potential model results evaluated with the Buchmüller-Tye potential [26]. All the LDMEs appear in our computation are listed in Table 1. The values

[1] In Ref. [27] only the linear combinations $M_r^H = \mathcal{O}^H({}^1S_0^{[8]}) + r\mathcal{O}^H({}^3P_0^{[8]})/m_c^2$ could be determined because of the strong correlations between $\mathcal{O}^H({}^1S_0^{[8]})$ and $\mathcal{O}^H({}^3P_0^{[8]})$ for $H = J/\psi, \psi'$. We find these correlations are very similar in prompt double J/ψ hadroproduction via the NNLP-II and NLP subprocesses.

$\mathcal{O}^{J/\psi}(^3S_1^{[1]})$	$\mathcal{O}^{J/\psi}(^3S_1^{[8]})$	$M_{3.4}^{J/\psi}(^1S_0^{[8]})$	$\mathcal{O}^{\psi'}(^3S_1^{[1]})$	$\mathcal{O}^{\psi'}(^3S_1^{[8]})$	$M_{3.5}^{\psi'}(^1S_0^{[8]})$	$\mathcal{O}^{\chi_{c0}}(^3P_0^{[1]})/m_c^2$	$\mathcal{O}^{\chi_{c0}}(^3S_1^{[8]})$
1.16	3.9×10^{-3}	6.6×10^{-2}	0.758	3.7×10^{-3}	7.8×10^{-3}	4.77×10^{-2}	1.9×10^{-3}

Table 1: Adopted values of LO NRQCD LDMEs in units of GeV^3 [26, 27].

$\mathrm{Br}(\chi_{c1}\to J/\psi\gamma) = 33.9\%$, $\mathrm{Br}(\chi_{c2}\to J/\psi\gamma) = 19.2\%$, and $\mathrm{Br}(\psi'\to J/\psi+X) = 60.9\%$ are taken from the Particle Data Group [24].

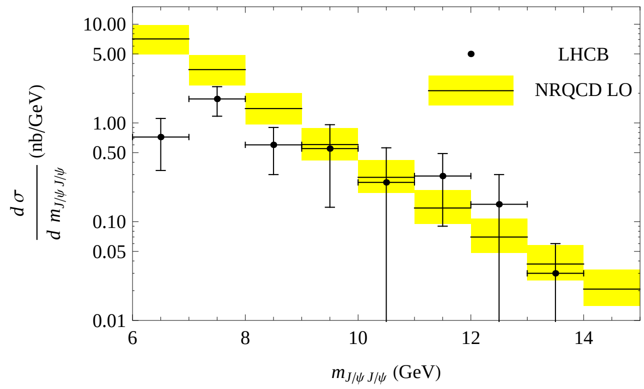
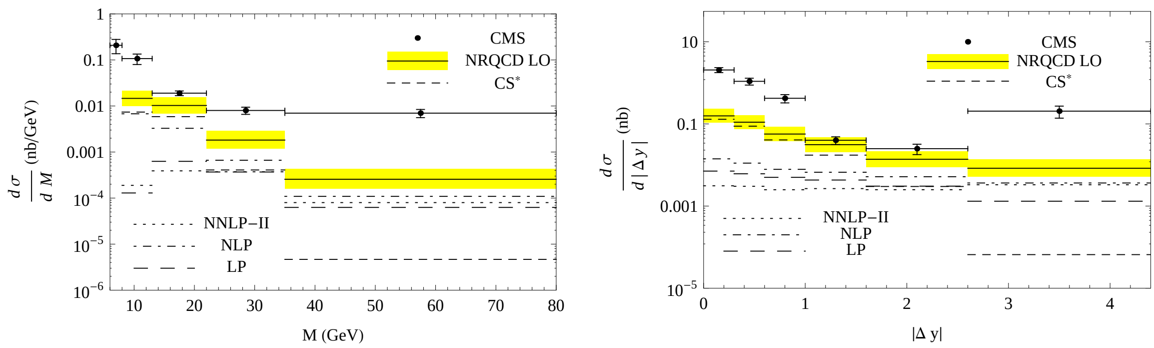


Figure 2: The M distribution of prompt double J/ψ hadroproduction measured by LHCb [12] is compared to the full LO NRQCD prediction (solid lines). The theoretical uncertainty is indicated by the shaded (yellow) bands.

Now we are in a position to compare the NRQCD predictions with the experimental data. At 7 TeV LHC, the LHCb Collaboration measured the double J/ψ production in the rapidity range of $2.0 < y < 4.5$ and $p_T < 10$ GeV for each J/ψ. The total cross section is $\sigma_{tot}^{\mathrm{LHCb}} = 5.1\pm1.0\pm1.1$ nb, which is about 2.6 times smaller than the LO NRQCD prediction $13.2^{+5.2}_{-4.1}$ nb. To check where the excess comes from we also calculate the invariant mass spectrum as shown in Fig. 2. It clearly shows that the conflict between NRQCD prediction and LHCb measurements appears only near the threshold region, in which the perturbative calculation is spoiled by the soft gluon radiations and the relativistic corrections are non-negligible [28]. Near the threshold region $\sigma_{\mathrm{tot}}\propto m_c^{-8}$, which also amplifies the uncertainty in theoretical calculation. When $M\geq 9$ GeV, the NRQCD prediction agree with the data very well.

The CMS Collaboration also measure the double J/ψ production at the same center of mass energy as LHCb Collaboration in the kinematic condition as specified in Eq.(3.3) of Ref [13]. The total cross section is $\sigma_{\mathrm{tot}}^{\mathrm{CMS}} = 1.49\pm0.07\pm0.13$ nb. However, the NRQCD prediction is only $\sigma_{\mathrm{tot}} = 0.15^{+0.08}_{-0.05}$ nb, which is about 1 order of magnitude smaller than the CMS data. We observe that the contribution of the NNLP-I, NNLP-II, NLP, and LP to the center values of σ_{tot} are 97, 13, 27, and 14 fb, respectively; and in σ_{tot} over 36% is made up by the NNLP-II, NLP, and LP processes with half of it coming from χ_{cJ} feed-down via $J/\psi+\chi_{cJ}$ and $\chi_{cJ}+\chi_{cJ}$. The above results indicate that only the CS^* itself is bound to be insufficient even after including the NLO QCD corrections [22].

Besides the total cross section the CMS Collaboration also measured the differential cross section in the M and $|\Delta y|$ bins. In Ref [22], it is found that CS^* prediction for $d\sigma/dM$ at QCD NLO is dramatically below the CMS data by about 2 and 4 orders of magnitude in the last two



(a) (b)

Figure 3: Comparison between CMS [13] measurements of the M (left) and $|\Delta y|$ (right) distribution for prompt double J/ψ hadroproduction and the full LO NRQCD prediction (solid lines), its NNLP-II (dotted lines), NLP (dot-dashed lines), and LP (long-dashed lines) components, and the LO CS* contribution (dashed lines). The theoretical uncertainty in the LO NRQCD prediction is indicated by the shaded (yellow) bands.

bins 22 GeV $<$ M $<$ 35 GeV and 35 GeV $<$ M $<$ 80 GeV, respectively. The Fig. (3a) clearly show that the previous neglected sub-processes largely remedy the conflict between theory and data. After including their contribution, the CMS data are only about 4 and 30 times larger than LO NRQCD predictions in the last two bins, where the NNLP-II, NLP, and LP processes are as the same important approximately. We also study the $|\Delta y|$ distribution shown in Fig. (3b). We observe from Fig. (3b) that the CS^* contribution is mainly around $|\Delta y| = 0$ region, while the $|\Delta y|$ distributions of NLP-II, NLP, and LP sub-processes are more broader. At LO p_T, M and $|\Delta y|$ are related through $M = 2\sqrt{4m_c^2 + p_T^2}\cosh(|\Delta y|/2)$, so the large enhancement in the large M distribution can be understood as follows. For the CS^* sub-process its large $M \gg 2m_{J/\psi}$ region corresponds to the large p_T region where the cross section drops down fast, on the other hand for the NLP-II, NLP, and LP sub-processes their large p_T region correspond to not only the large p_T region but also the moderate p_T region, which feed into the large M region predominately.

At 1.96 TeV Tevatron, D0 Collaboration successfully discriminate the SPS and DPS contributions for $p_T > 4$ GeV and $|\eta| < 2.0$, where η is the pseudo-rapidity of J/ψ yielding $\sigma_{\rm SPS}^{\rm D0} = 70 \pm 6 \pm 22$ fb and $\sigma_{\rm DPS}^{\rm D0} = 59 \pm 6 \pm 22$ fb. The LO CS^* prediction is $\sigma_{\rm tot}^{\rm CS^*} = 51.9$ fb [29]. We estimate that it can be enhanced by around 28% after including the residual contribution of LO NRQCD, which leads to nice agreement.

4. Summary

In summary, in this work, we calculate the complete LO NRQCD prediction on prompt double J/ψ hadroproduction. After comparing it with the LHCb, CMS and D0 measurements we find that the CS^* is an good approximation to describe low p_T region and away from the double J/ψ threshold region. However, in the large M and $|\Delta y|$ region its contribution becomes minor and the contribution of the NLP-II, NLP, LP sub-processes that have been ignored before becomes predominate. Although at LO, the NRQCD predictions can not explain the CMS data at large M and $|\Delta y|$ region yet, we expect a significant enhancement at NLO because of the kinematic cut condition of CMS measurements, which may resolve the conflict.

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