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# Polarization of prompt $J/\psi$ in $pp \to J/\psi + X$ at $\sqrt{s} = 200$ GeV

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Within the framework of the nonrelativistic QCD factorization approach, we compute the cross section and polarization of prompt $J/\psi$ produced from proton-proton collisions at the center-of-momentum energy $\sqrt{s} = 200$ GeV. We present the transverse-momentum distribution in the forward-rapidity region $1.2 < |y| < 2.2$ and the rapidity distribution over the transverse-momentum range $2\ \text{GeV} < p_T < 20$ GeV. The perturbative contributions are computed at leading order in the strong coupling constant. We predict slight transverse polarization of $J/\psi$ in the forward-rapidity region, while that for the midrapidity region is slightly longitudinal. The transverse-momentum distribution agrees well with the PHENIX preliminary data and the color-singlet-model prediction at next-to-leading order in $\alpha_s$, but disagrees with the result from the leading-order color-singlet model or the $s$-channel-cut method.

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## I. INTRODUCTION

As one of the long-standing puzzles in heavy-quarkonium phenomenology, the polarization of prompt $J/\psi$ produced with large transverse momentum ($p_T$) at hadron colliders has not been clearly understood yet. According to the nonrelativistic quantum chromodynamics (NRQCD) factorization approach [1], the dominant production mechanism of $J/\psi$ with large $p_T$ in hadron collisions is the gluon fragmentation into the color-octet spin-triplet $S$-wave heavy-quark-antiquark pair $[Q\bar{Q}_8(^3S_1)]$ that evolves into the meson [2]. Because the corresponding long-distance transition preserves the spin at leading order in $v$, which is the typical velocity of the heavy quark of the meson, the $J/\psi$ should be transverse at large $p_T$ [3]. However, the run II measurement by the Collider Detector at Fermilab (CDF) Collaboration [4] agrees with neither the run I data [5] nor the NRQCD predictions [6–10], although the feeddowns from the $P$-wave spin-triplet states $\chi_{cJ}$ for $J = 0$, 1, and 2 dilute the transverse polarization [9,10]. The problem has not been resolved even after considering corrections in various aspects [11–22]. Therefore, it is worthwhile to see if NRQCD still confronts with experiments of lower center-of-momentum (CM) energies $\sqrt{s}$, where the dominance of the gluon fragmentation may not happen.

In this aspect, the *inclusive* $J/\psi$ production in $pp$ collisions at $\sqrt{s} = 200$ GeV, where the fragmentation does not dominate [23], at the Brookhaven Relativistic Heavy-Ion Collider (RHIC) may provide independent experimental constraints to the $J/\psi$ polarization. Because only a tiny fraction of the PHENIX inclusive $J/\psi$ samples contain the $J/\psi$ from the $B$ decay [24], we can treat this as prompt $J/\psi$. In the case of the cross section, the NRQCD predictions in Refs. [23,25] are consistent with the run 3 PHENIX data [26,27]. As a new production mechanism, the $s$-channel-cut approach [28], which suffers from a criticism [29], also explains the data [30]. The color-singlet-model (CSM) prediction for the direct $J/\psi$ production rate has been computed at next-to-leading order (NLO) in the strong coupling $\alpha_s$ [31,32], including contributions from $cg$ fusion. The NLO CSM prediction agrees with the data for the rapidity distribution, assuming that about 40% of the $J/\psi$ samples are from higher resonances, while it underestimates the data for the $p_T$ distribution. The NLO NRQCD prediction has been found to agree with the data for the $p_T$ distribution [20,21]. In addition to the cross section [33], the PHENIX Collaboration has measured the polarization [34] of the inclusive $J/\psi$. In the midrapidity region $|y| < 0.35$, the PHENIX data for the $J/\psi$ polarization [34] agree with the predictions of both NRQCD [35] and the $s$-channel-cut method [36]. However, the PHENIX preliminary data in Ref. [37] for the forward-rapidity region $1.2 < |y| < 2.2$ disfavor the $s$-channel-cut prediction [36,37]. The PHENIX Collaboration is currently carrying out a comprehensive analysis with the data from the forward-rapidity region. Therefore, it is desirable to provide NRQCD predictions that can be compared with the forthcoming updated PHENIX data for the inclusive $J/\psi$ polarization in the forward-rapidity region.

In this paper, we present an updated NRQCD prediction for the polarization of prompt $J/\psi$ produced in the forward-rapidity region $1.2 < |y| < 2.2$ in $pp$ collisions at $\sqrt{s} = 200$ GeV. The perturbative contributions are computed at LO in $\alpha_s$, like the previous analysis in Ref. [35], in which the cross section and polarization in the midrapidity region $|y| < 0.35$ within the $p_T$ range $1.5\ \text{GeV} < p_T < 5$ GeV are predicted in detail. The PHENIX Collaboration is also preparing to release the rapidity dependence of the $J/\psi$ in both the midrapidity and forward-rapidity regions. In this ongoing analysis, they are using a conservative lower $p_T$ cut $p_T > 2$ GeV to avoid the region where LO NRQCD may break down. We also present a NRQCD prediction for the rapidity dependence of the polarization of prompt $J/\psi$ in the region $|y| < 3$. Except for these changes in the kinematic region, our analysis presented here is very similar to that in Ref. [35] so we do not reproduce details of our strategy to compute observables and explanations on the input parameters given in Ref. [35].

The remainder of this paper is organized as follows. We first present the NRQCD prediction for the $p_T$ dependence of the differential cross section, followed by the NRQCD prediction for the $p_T$ dependence of the polarization parameter $\alpha$ integrated over the forward-rapidity region in Sec. II. The rapidity distributions of the cross section and polarization parameter $\alpha$ integrated over the $p_T$ range 2 GeV $< p_T <$ 20 GeV are given in Sec. III, and we summarize in Sec. IV.

## II. $p_T$ DISTRIBUTIONS

In this section, we provide the NRQCD predictions for the $p_T$ distributions of the production rate and polarization parameter $\alpha$ for the prompt $J/\psi$ produced in $pp$ collisions at $\sqrt{s} = 200$ GeV. The basic strategy to compute the cross section and polarization parameter $\alpha$ can be found in Ref. [35].

The cross section for the prompt $J/\psi$ in $pp$ collisions is computed by including the LO parton processes $ij \to c\bar{c} + k$, with $i, j = g, q, \bar{q}$ and $q = u, d, s$. We use numerical values for the NRQCD matrix elements (ME) given in Ref. [9]. For the parton distribution functions (PDF), we choose MRST98LO [38] as the default value and CTEQ5L [39] for comparison. The transverse mass $m_T = (4m_c^2 + p_T^2)^{1/2}$ is used for both the factorization and renormalization scales $\mu$ with the charm-quark mass $m_c = 1.5$ GeV. $\alpha_s$ is evaluated from the one-loop formula using the value of $\Lambda_{\rm QCD}$ given in each PDF set [38,39]. To estimate theoretical uncertainties, we follow the method given in Ref. [35].

Our prediction for the differential cross section of prompt $J/\psi$ is shown in Fig. 1 as a function of $p_T$. The shaded band indicates the LO NRQCD prediction, and the LO CSM contribution is displayed as a band surrounded by a solid curve. The rate is averaged over the forward-rapidity range $1.2 < |y| < 2.2$, and its explicit normalization is given by

$$\frac{B_{ee}}{2\pi p_T}\langle d^2\sigma/dydp_T\rangle_y = \frac{B_{ee}}{2\pi p_T \times 2}\int_{1.2<|y|<2.2}\frac{d^2\sigma}{dydp_T}dy,$$

where $B_{ee}$ is the branching fraction for $J/\psi \to e^+e^-$ and the factor 2 in the denominator on the right side is from the range of integration $1.2 < |y| < 2.2$.

The result shows that more than 70% of the prompt $J/\psi$'s are direct: At $p_T = 1.5$ GeV (5 GeV), the contributions from direct $J/\psi$, feeddown from $\psi(2S)$, and feeddown from $\chi_{cJ}$ are 83% (71%), 8% (11%), and 10% (19%) of the prompt $J/\psi$'s, respectively. According to Fig. 1, the LO color-singlet ${}^3S_1$ contribution is negligible, which amounts to 4% (2%) of the direct $J/\psi$, while the color-octet ${}^3P_J$ or ${}^1S_0$ and ${}^3S_1$ channels are 94% (81%) and 1.5% (17%), respectively, at $p_T = 1.5$ GeV (5 GeV). The uncertainties are evaluated by considering the variations of $m_c = 1.50 \pm 0.05$ GeV, $m_T/2 \le \mu \le 2m_T$, NRQCD ME, and PDF [38,39] as described in Ref. [35]. The uncertainties from $\mu$ of 83% (98%) dominate over those from $m_c$ [10% (2%)] and those from the NRQCD ME and PDF [7% (0%)] at $p_T = 1.5$ GeV (5 GeV).

The polarization parameter $\alpha$ is defined by $\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L)$, where $\sigma_T$ ($\sigma_L$) is the cross section for

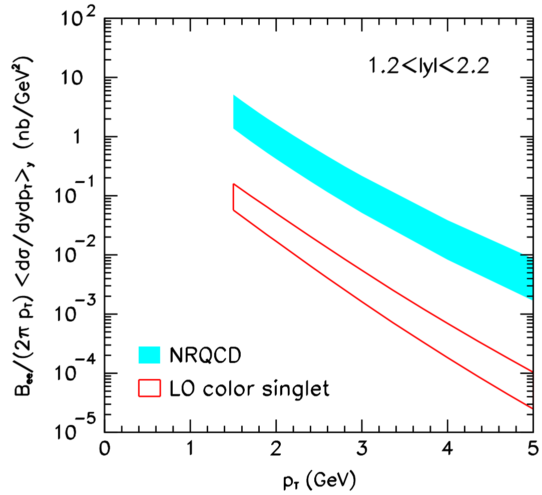


FIG. 1 (color online). The differential cross section of prompt $J/\psi$ with the rapidity $1.2 < |y| < 2.2$ in $pp$ collisions at $\sqrt{s} = 200$ GeV as a function of $p_T$. The shaded band represents the NRQCD prediction and the band surrounded by a solid curve is the color-singlet contribution at LO in $\alpha_s$.

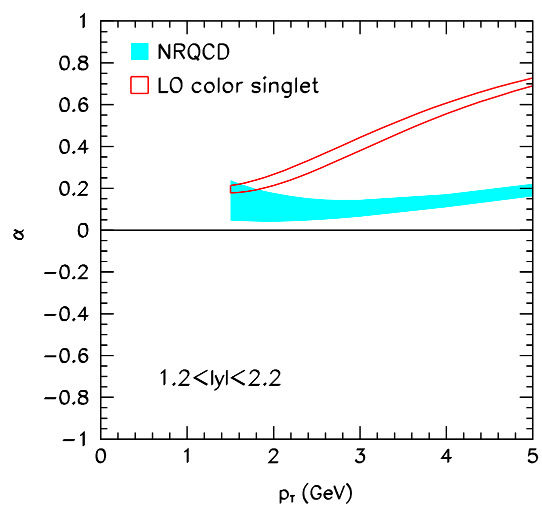


FIG. 2 (color online). The polarization parameter $\alpha$ for the prompt $J/\psi$ with the rapidity $1.2 < |y| < 2.2$ in $pp$ collisions at $\sqrt{s} = 200$ GeV as a function of $p_T$.

the transversely (longitudinally) polarized $J/\psi$. If $J/\psi$ is completely transverse (longitudinal), then $\alpha = +1(-1)$. If $J/\psi$ is unpolarized, then $\alpha = 0$. The polarized cross sections depend on the frame. We choose the hadron CM frame that was employed in the PHENIX analysis.

The $p_T$ dependence of the polarization parameter $\alpha$ integrated over the forward-rapidity region $1.2 < |y| < 2.2$ is shown in Fig. 2 with the same style as Fig. 1. The NRQCD prediction is slightly transverse over the whole range of $p_T$, while the color-singlet contribution gets more transverse as $p_T$ increases. In comparison with the prediction for the midrapidity region, the uncertainties mostly ($\gtrsim 98\%$) come from the NRQCD ME and PDF.

Our results for the polarization agree with the PHENIX preliminary data [37] and are also compatible with the CSM prediction at NLO [32], which has larger uncertainties than the NRQCD prediction. The $s$-channel-cut prediction disagrees with both NRQCD and the PHENIX preliminary data [37].

## III. RAPIDITY DISTRIBUTIONS

In this section, we provide the NRQCD predictions for the rapidity distributions of the production rate and polarization parameter $\alpha$. The PHENIX analysis of the rapidity dependence of the $J/\psi$ is under way with a conservative cut $p_T > 2$ GeV which avoids the kinematic region where the fixed-order calculations may break down. Because the differential cross section at $p_T = 5(20)$ GeV is less than 10% (0.1%) of that for $p_T = 2$ GeV, the total cross section should be insensitive to an upper limit $\gtrsim 10$ GeV and the neglect of the gluon fragmentation can be justified. Our results show that about 79% of the total production rate comes from the direct $J/\psi$, and feeddowns from $\chi_{cJ}$ and $\psi(2S)$ occupy 13% and 8%, respectively. In Fig. 3, we show the NRQCD prediction for the differential cross section integrated over the range $2\text{ GeV} < p_T < 20\text{ GeV}$ as a function of $y$. According to this figure, the LO color-singlet contribution is negligible over the rapidity range $|y| < 3$. The lower cut for $p_T$ severely eliminates the color-octet and color-singlet ${}^3S_1$ contributions to occupy only a few percent of the total production rate, making ${}^3P_J$ and ${}^1S_0$ octet channels dominate. The dominant source of the uncertainties in the rapidity distribution is the scale dependence which occupies about 92% (96%) at $y = 0$ ($|y| = 3$). The contribution of $m_c$ dependence is about 6% (3%) and that of NRQCD ME and PDF is about 3% (1%) at $y = 0$ ($|y| = 3$).

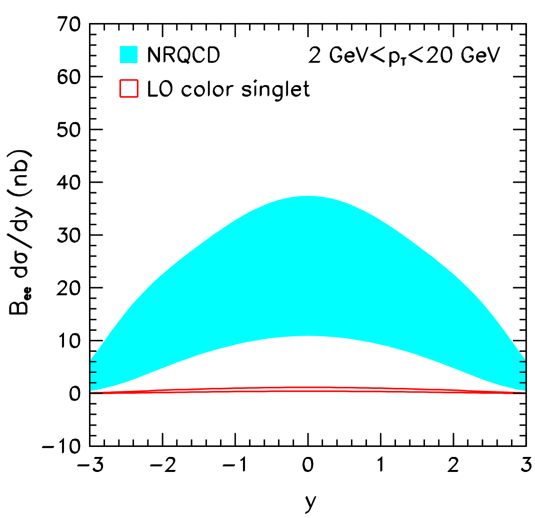


FIG. 3 (color online). The differential cross section of prompt $J/\psi$ with the transverse momentum $2\text{ GeV} < p_T < 20\text{ GeV}$ in $pp$ collisions at $\sqrt{s} = 200$ GeV as a function of $y$.

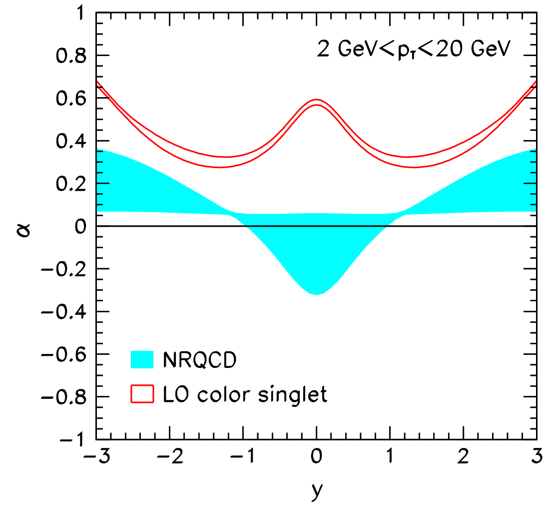


FIG. 4 (color online). The polarization parameter $\alpha$ for the prompt $J/\psi$ with the transverse momentum $2\text{ GeV} < p_T < 20\text{ GeV}$ in $pp$ collisions at $\sqrt{s} = 200$ GeV as a function of $y$.

The rapidity distribution of $\alpha$ integrated over the range $2\text{ GeV} < p_T < 20\text{ GeV}$ is shown in Fig. 4. The LO CSM prediction is always transverse over the whole range of the rapidity. The central values of the NRQCD prediction are slightly longitudinal at the midrapidity region, and there is a turnover around $|y| \approx 1$ from which the NRQCD prediction becomes transverse. The uncertainties of the NRQCD prediction become maximum (minimum) at $y = 0$ ($|y| \approx 1$). Therefore, the uncertainties of the NRQCD prediction for the forward-rapidity region in Fig. 2 are significantly smaller than those for the midrapidity region presented in Fig. 2 of Ref. [35]. More than 96% of the uncertainties of the predictions in Fig. 2 are from the NRQCD ME and PDF. The uncertainties from $\mu$ and $m_c$ are negligible.

## IV. SUMMARY

In summary, we have presented the NRQCD predictions for the $p_T$ and $y$ distributions of the differential cross section and the polarization parameter $\alpha$ for the prompt $J/\psi$ produced in $pp$ collisions at $\sqrt{s} = 200$ GeV.

The $p_T$ and $y$ distributions are given in the kinematic ranges $1.2 < |y| < 2.2$ and $2\ \mathrm{GeV} < p_T < 20\ \mathrm{GeV}$, respectively. While the NRQCD prediction for the prompt $J/\psi$ polarization in the midrapidity region ($|y| < 0.35$) is slightly longitudinal, that in the forward-rapidity region ($1.2 < |y| < 2.2$) is slightly transverse with less theoretical uncertainties. The change in the lower-$p_T$ cut to 2 GeV also reduced the uncertainties in our prediction by avoiding a possible break down of fixed-order calculations at low $p_T$. The LO CSM prediction severely underestimates the differential cross section and shows more transverse $J/\psi$ than that of NRQCD. Our polarization prediction is less transverse than that of the $s$-channel-cut method [36] ($\alpha = 0.36$), but is compatible with the NLO CSM prediction [32], which has larger uncertainties than our results. We anticipate that our NRQCD predictions presented here can be tested against a forthcoming updated analysis by the PHENIX Collaboration.

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