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Exploring J/ψ Production Mechanism at the Future Electron-Ion Collider

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We propose to use transverse momentum $p_{\rm T}$ distribution of J/ψ production at the future Electron Ion Collider (EIC) to explore the production mechanism of heavy quarkonia in high energy collisions. We apply QCD and QED collinear factorization to the production of a $c\bar{c}$ pair at high $p_{\rm T}$, and non-relativistic QCD factorization to the hadronization of the pair to a J/ψ. We evaluate J/ψ $p_{\rm T}$-distribution at both leading and next-to-leading order in strong coupling, and show that production rates for various color-spin channels of a $c\bar{c}$ pair in electron-hadron collisions are very different from that in hadron-hadron collisions, which provides a strong discriminative power to determine various transition rates for the pair to become a J/ψ. We predict that the J/ψ produced in electron-hadron collisions is likely unpolarized, and the production is an ideal probe for gluon distribution of colliding hadron (or nucleus). We find that the J/ψ production is dominated by the color-octet channel, providing an excellent probe to explore the gluon medium in large nuclei at the EIC.

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J/ψ production has been a focus of theoretical and experimental interest since its discovery over 45 years ago.[1,2] In particular, understanding its production mechanism and using it as a probe to QCD matter are among the most active research subjects in particle and nuclear physics.[3,4] The challenge is to understand the nonperturbative transition from a produced $c\bar{c}$ pair to a physical J/ψ. The non-relativistic QCD (NRQCD) factorization approach[5] to describe J/ψ production in hadronic collisions is by far the most phenomenologically successful one, although there are still challenges to understand the polarization of produced J/ψ and to resolve the difference between various sets of non-perturbative long distance matrix elements (LDMEs) extracted from the world data.[6–10] These LDMEs characterize the transition rates for various color-spin states of a produced $c\bar{c}$ pair to become a J/ψ and should be process-independent. The universality of these LDMEs, which has not been confirmed, not even the sign, is a critical test of the NRQCD factorization approach to the J/ψ production.[11,12]

The J/ψ production has been studied in every possible high energy collisions from e^+e^-,[13,14] photon-hadron,[15–17] and hadron-hadron (hh) collisions.[18–24] New ideas have been proposed to study J/ψ production more differentially, such as measuring a J/ψ within a produced jet[25–28] as well as its polarization.[28] With the recent decision to build the Electron-Ion Collider (EIC)[29] in US and the proposal of an EIC in China (EicC),[30] in this Letter, we propose to use transverse momentum $p_{\rm T}$ distribution of single inclusive J/ψ production at the EIC to explore and to test the J/ψ production mechanism. Unlike the traditional semi-inclusive deep inelastic scattering (SIDIS), we do not require to measure the scattered electron and define the $p_{\rm T}$ of produced J/ψ in the electron-hadron frame. With a single observed hard scale, $p_{\rm T}$, we apply QCD and QED collinear factorization to colliding hadron and electron, respectively, and NRQCD factorization to the hadronization of produced $c\bar{c}$ pair to a physical J/ψ. The inclusiveness from not measuring the scattered electron helps us to eliminate a major uncertainty of QED radiative corrections in SIDIS.[31] We also discuss the similarity and difference from tagging or not tagging the scattered electron.

In this Letter, we perform explicit calculations of short-distance hard parts of J/ψ production at both leading order (LO) and next-to-leading order (NLO) in strong coupling constant $\alpha_{\rm s}$. We use the recently

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developed dipole subtraction method[32] to deal with the QCD divergences for heavy quarkonium production. With its high design luminosity,[29] we find from our NLO results that J/ψ can be produced at a wide range of $p_{\rm T}$ with a large number of events (>1000) at the EIC. Most importantly, we find that the single inclusive J/ψ production at the EIC is very sensitive to the difference between all available sets of LDMEs, which could provide new insights into the J/ψ production mechanism. In addition, we are confident to predict that the J/ψ produced at the EIC is likely unpolarized, and the production is dominated by gluon initiated partonic subprocesses. With the dominance of producing color-octet $c\bar{c}$ pairs, the $p_{\rm T}$-distribution of J/ψ production at the EIC could be an excellent probe to explore the dense gluon medium in large nuclei, which should further motivate the measurement of single inclusive J/ψ production at the EIC.

Factorization and NLO Calculation. We consider single inclusive J/ψ production in electron-hadron (eh) collisions, $e + h \to J/\psi(p) + X$, where the scattered outgoing electron is unobserved/integrated over. Single inclusive jet production in eh collisions without observing the outgoing electron was introduced in Ref. [33]. Additional studies of the same process were carried out at NLO[34–36] and even at NNLO[37] in recent years. A key difference between the jet production and J/ψ production at high $p_{\rm T}$ is that a J/ψ is identified in the final-state, and its non-perturbative hadronization process might be interfered by the presence of soft gluons from the beam jet of the colliding hadron. Following the arguments given for QCD collinear factorization at both leading power and next-to-leading power production of J/ψ at high $p_{\rm T}$ in hadron-hadron collisions,[38–41] we are confident that the impact of such soft gluon interactions should be suppressed by powers of $\Lambda_{\rm QCD}/p_{\rm T}$. Although there is no all-order proof of NRQCD factorization to represent the hadronization of a $c\bar{c}$ pair to a J/ψ by an expansion of local LDMEs organized by powers of $\alpha_{\rm s}$ and the pair's relative velocity, the factorization was found valid up to two-loop calculations.[38,39] In this Letter, as an Ansatz, we apply NRQCD factorization for the J/ψ hadronization. With a single hard scale $p_{\rm T}$, the same factorization formalism for J/ψ production in hadron-hadron collisions should also apply for electron-hadron collisions,

$$\frac{d\sigma_{eh\to J/\psi(p)}}{dp_{\rm T}d\eta} = \sum_{a,b,n} \int \frac{dx_a}{x_a}\frac{dx_b}{x_b} f_{a/e}(x_a,\mu_{\rm f}^2) f_{b/h}(x_b,\mu_{\rm f}^2) \times \frac{d\hat{\sigma}_{ab\to c\bar{c}[n]}(x_a,x_b,p_{\rm T},\eta,m_{\rm c},\mu_{\rm f}^2)}{dp_{\rm T}d\eta}\langle\mathcal{O}^{J/\psi}_{[n]}\rangle, \quad (1)$$

with J/ψ pseudorapidity η and factorization scale $\mu_{\rm f}$. In Eq. (1), $a = e, \gamma$ in our calculations and could include all parton flavors at higher orders; $b = q, \bar{q}, g$; n sums over all color-spin states of the $c\bar{c}$ pair; $f_{a/e}$ is a collinear distribution to find an electron, a photon or a parton from the colliding electron; $f_{b/h}$ is the parton distribution function (PDF) of the colliding hadron; $\hat{\sigma}$ is the perturbatively calculable short distance hard part; and $\langle\mathcal{O}^{J/\psi}_{[n]}\rangle$ is the local LDME representing the probability for the state $c\bar{c}[n]$ to become a J/ψ. With the available collision energies at the EIC, we did not include the fragmentation contribution from resummation of $\log(p_{\rm T}/m_{\rm c})$-type logarithmic contributions.[38–41]

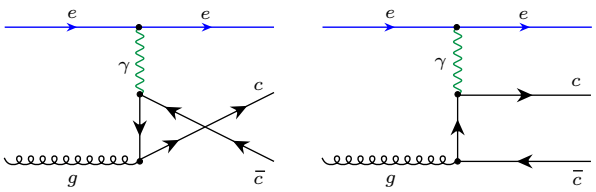

Fig. 1. Leading order Feynman diagrams for J/ψ production in eh collisions.

We calculate the $\hat{\sigma}$ in Eq. (1) at both LO and NLO in strong coupling $\alpha_{\rm s}$, together with leading contributions in electromagnetic coupling α, such that $d\sigma_{eh\to J/\psi(p)} \approx d\sigma^{\rm LO} + d\sigma^{\rm NLO}$. At the LO, as shown in Fig. 1, only gluon channel contributes,

$$\frac{d\sigma^{\rm LO}}{dp_{\rm T}d\eta} = \sum_{n={}^1S_0^{[8]},{}^3P_J^{[8]}} \int \frac{dx_b}{x_b} f_{g/h}(x_b,\mu_{\rm f}^2) \times \frac{d\hat{\sigma}^{(2,1)}_{e+g\to c\bar{c}[n]}}{dp_{\rm T}d\eta}\langle\mathcal{O}^{J/\psi}_{[n]}\rangle, \quad (2)$$

where leading order $f_{e/e} = \delta(1 - x_a)$ was used, $\hat{\sigma}^{(2,1)}$ denotes partonic cross section evaluated at $\mathcal{O}(\alpha^2\alpha_{\rm s})$. At this order, only color octet ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}c\bar{c}$ pair can contribute to high $p_{\rm T}$ J/ψ production in eh collisions. On the other hand, all four leading $c\bar{c}$ states (${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$) contribute at the LO in hh collisions. That is, it is advantageous for eh collisions to get better information on $\langle\mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle$ and $\langle\mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle$ [For ${}^3P_J^{[8]}$ channel, we converted all P-wave LDMEs according to $\langle\mathcal{O}^{J/\psi}({}^3P_J^{[8]})\rangle \approx (2J+1)\langle\mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle$].

At the NLO, one has to include both real and virtual contributions. For real contribution, new light-flavor quark (antiquark) channels open up, in addition to the gluon channel, as shown in Fig. 2. Since we do not measure the outgoing electron, the real contribution has QED collinear (CO) divergence (if the electron mass $m_e \to 0$) when the outgoing electron is collinear to the incoming one. Like QCD factorization, this QED CO divergence should be absorbed into $f_{\gamma/e}$. We adopt the method presented in Ref. [42] for QED divergence. In addition, there are QCD divergences. The outgoing light parton in Fig. 2 could be either soft or collinear to the incoming parton. The CO divergence should be absorbed into the PDFs of colliding hadron and the infrared (IR) divergence should

be either canceled by the virtual diagrams in Fig. 3 or by soft one-loop correction to LDMEs. In practice, we use the dipole subtraction method, recently developed specifically for heavy quarkonium production.[32] This method is based on the standard dipole subtraction techniques for light and heavy flavors[43,44] and has been successfully implemented into calculations for hh collisions.[45]

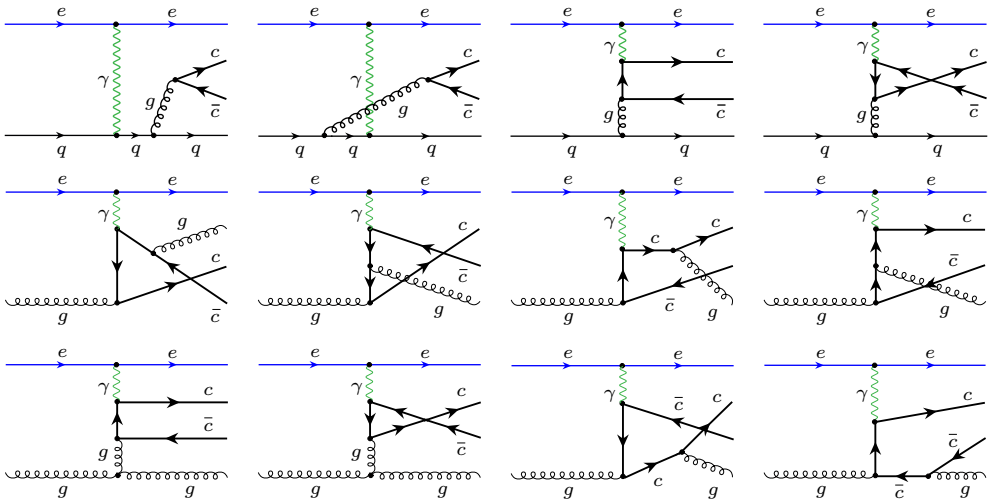

Fig. 2. NLO Feynman diagrams for real contribution to J/ψ production in eh collisions.

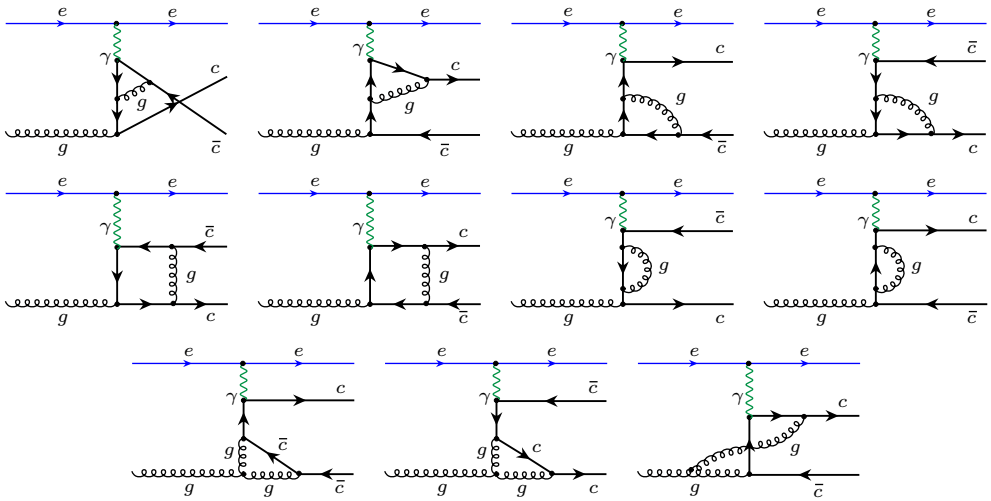

Fig. 3. NLO Feynman diagrams for virtual contribution to J/ψ production in eh collisions.

For the virtual contribution, shown in Fig. 3, the ultraviolet (UV) and IR divergences can be extracted through evaluation of some standard one-loop scalar integrals. Combining real and virtual contributions together, we obtain the finite partonic hard parts at NLO,

$$\frac{d\sigma^{\rm NLO}}{dp_{\rm T}d\eta} = \sum_{b,n}\int \frac{dx_a}{x_a}\frac{dx_a}{x_a}\Big[f_{e/e}(x_a)\frac{d\hat{\sigma}^{(2,2)}_{eb\to c\bar{c}[n]}}{dp_{\rm T}d\eta} + f_{\gamma/e}(x_a)\frac{d\hat{\sigma}^{(1,2)}_{\gamma b\to c\bar{c}[n]}}{dp_{\rm T}d\eta}\Big] f_{b/h}(x_b)\langle\mathcal{O}^{J/\psi}_{[n]}\rangle, \quad (3)$$

where $\sum_n$ runs over four $c\bar{c}$ states: ${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, and ${}^3P_J^{[8]}$. The $\hat{\sigma}^{(2,2)}$, $\hat{\sigma}^{(1,2)}$ represent the finite contributions at $\mathcal{O}(\alpha^2\alpha_{\rm s}^2)$ and $\mathcal{O}(\alpha\alpha_{\rm s}^2)$, respectively. Notice that the QED CO divergence has been removed in $\hat{\sigma}^{(2,2)}$ and thus no quasi-real photon contribution in this term, the $\hat{\sigma}^{(1,2)}$ in Eq. (3) corresponds to the region where the exchanged photon is quasi-real. In the leading logarithmic approximation, the leading order electron and photon distributions in an electron are given by

$$f_{e/e}(x,\mu_{\rm f}^2) = \delta(1-x_a), \quad (4)$$

$$f_{\gamma/e}(x,\mu_{\rm f}^2) = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\Big[\ln\frac{\mu_{\rm f}^2}{x^2m_e^2}-1\Big], \quad (5)$$

with factorization scale $\mu_{\rm f}$. An all order resummation of the logarithms could be carried out by solving a QED version of DGLAP evolution.[31] In this Letter,

we skip all details of standard NLO calculation. Our partonic hard parts, $\hat{\sigma}^{(2,1)}$, $\hat{\sigma}^{(2,2)}$ and $\hat{\sigma}^{(1,2)}$ are used for the following numerical results. Notice that we neglect the resolved contributions as they begin to show up at NNLO in this factorization approach, which is beyond the scope of the present study.

Phenomenology for EIC. We perform following numerical analysis for the EIC kinematics, and our evaluated cross section is fully differential, which gives us the flexibility to implement any kinematic cuts for final state particles including the outgoing electron. We choose a center-of-mass energy at $\sqrt{s} = 141.4\,\text{GeV}$, J/ψ pseudo-rapidity cut $|\eta| < 4$, and J/ψ transverse momentum cut $3 < p_\text{T} < 15\,\text{GeV}$ to be comfortable with QCD factorization and enough J/ψ events. We use CT14-nlo[46] for unpolarized proton PDFs and consider three quark flavors. We choose the factorization and renormalization scales $\mu_\text{r} = \mu_\text{f} = \sqrt{p_\text{T}^2 + M^2}$ with the J/ψ mass $M = 2m_\text{c} = 3.1\,\text{GeV}$ and m_c is the charm quark mass. We include four leading $c\bar{c}$ states for J/ψ production with corresponding LDMEs from four groups: Bodwin *et al.*,[6] Butenschoen *et al.*,[7] Chao *et al.*,[8] and Gong *et al.*,[9] which are referred as Bodwin, Butenschoen, Chao and Gong, respectively, and presented in Table 1. The numerical values for these LDMEs are very different, even different in sign in some cases, which is mainly due to the different choice of data sets in their global fittings. Notice that a large part of the data used for Butenschoen fit is HERA data, which leads to distinct results comparing to the others as will be shown below.

Table 1. J/ψ NRQCD LDMEs from four different groups.

	$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3P_0^{[8]})\rangle$ 10^{-2} GeV^5
Bodwin	0	9.9	1.1	1.1
Butenschoen	1.32	3.04	0.16	−0.91
Chao	1.16	8.9	0.30	1.26
Gong	1.16	9.7	−0.46	−2.14

In order to illustrate the sensitivity to the nonperturbative NRQCD LDMEs, we show in Fig. 4 the differential cross section of inclusive J/ψ production, without tagging the outgoing electron, as a function of p_T. It is clear that the production rate, evaluated with all four sets of LDMEs in Table 1, is large enough for producing sufficient J/ψ events at the future EIC. It is important to notice that predictions using LDMEs from Bodwin and Chao are very similar, but significantly different from those using other two sets of LDMEs. In addition, there is almost an order of magnitude difference in production rate between Bodwin/Chao and Butenschoen. Such drastic differences between predictions using the four different sets of LDMEs clearly demonstrates the discriminative power of this new observable on J/ψ production mechanism. The middle panel in Fig. 4 shows the fractional contribution from the channel with a quasi-real photon, R^γ, defined as a ratio of contribution from the quasi-real photon channel [$\hat{\sigma}^{(1,2)}$ term in Eq. (3)] and the total contribution. Clearly, the quasi-real photon channel is dominant for all four sets of LDMEs, especially at lower p_T due to the $1/x$-dependence of $f_{\gamma/e}$ in Eq. (5). Notice that we used the leading logarithmic approximation for the photon distribution in an electron as shown in Eq. (5), the 70% contribution from quasi-real photon channel should be reduced once we consider the resummed photon distribution in an electron, but not in a significant way. Detailed analysis considering QED evolution of photon distribution in an electron will be presented in a future publication. We also show in the lowest panel the K-factors, defined as the ratios of the NLO over LO cross sections, for the processes with (cyan) and without (black) the quasi-real photon contribution. The large K-factor at NLO comes from the dominated quasi-real photon channel as it first appears at NLO, such a large K-factor is expected to be reduced when NNLO contribution is included.[37]

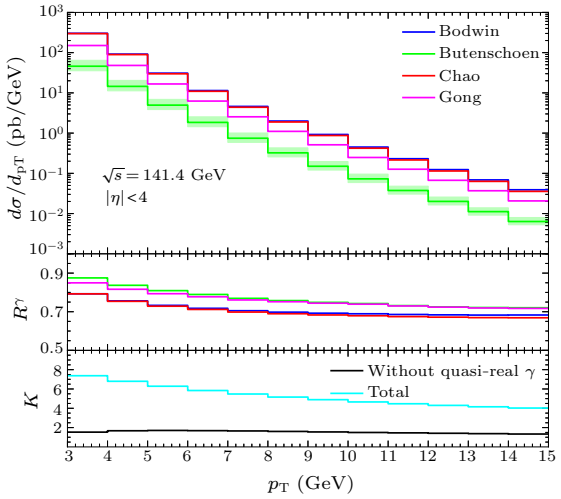

Fig. 4. The NLO differential cross section as a function of p_T. Four histograms correspond to four different sets of LDMEs, the green band shows the uncertainty from scale variation $\sqrt{p_\text{T}^2 + M^2}/2 < \mu_\text{f} < 2\sqrt{p_\text{T}^2 + M^2}$. The middle panel shows the fraction from the quasi-real photon channel, while the lowest panel shows the K-factors for the processes with (cyan) and without (black) the quasi-real photon contribution.

To further explore the sensitivity to each particular $\langle\mathcal{O}_{[n]}^{J/\psi}\rangle$, we studied the cross section more differentially in terms of four different $c\bar{c}$ states. In Fig. 5, we used the LDMEs from Chao as an example, and found that contribution to the J/ψ production is dominated by the production of $^1S_0^{[8]}$ state for whole p_T region. We checked that this feature also holds true for the other three sets of LDMEs. The fact that the $^1S_0^{[8]}$ channel clearly dominates the production rate and Bodwin and Chao have a very close value for corresponding $\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$ should be the

reason for the very similar predictions from Bodwin and Chao as shown in Fig. 4. Notice that the extracted $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$ from Gong has even closer value comparing to Bodwin, however, the opposite sign for $\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$ in these two sets eventually lead to big difference between the blue and purple histograms in Fig. 4. The detailed analysis shown in Fig. 5 indicates that J/ψ production in eh collisions can be served as a very sensitive observable to constrain the LDME $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$. Since $^1S_0^{[8]}$ has no polarization preference, we predict that high-p_T J/ψ produced in inclusive eh collisions will be likely unpolarized. The measurement of J/ψ polarization at the future EIC will be a stringent test of NRQCD factorization.

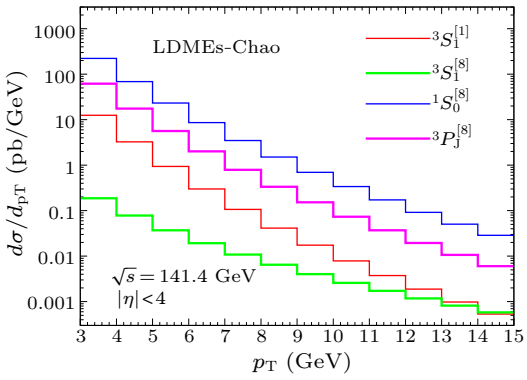

Fig. 5. The NLO differential cross section as a function of p_T for J/ψ production in eh collisions. The four histograms correspond to the contributions from four different $c\bar{c}$ states, respectively.

If we extend this study to electron-nucleus collisions at the EIC, the dominance of production rate for the $^1S_0^{[8]}c\bar{c}$ state in initial hard production will provide us a unique channel to study how a color octet $c\bar{c}$ state interacts with nuclear medium when it propagates through a large nucleus.

Since our result on J/ψ production is fully differential in phase space for final state electron, this allows us to study the production of J/ψ by exchanging a virtual photon. We impose a constraint on the momentum transfer $Q^2 > 1\,\mathrm{GeV}^2$ for the exchanged photon, so that we could neglect the contribution from quasi-real photon channel. In this case, the QED CO divergence will be regularized by Q^2 cut, and the QED dipole subtraction in $\hat{\sigma}^{(2,2)}$ has to be removed. In Fig. 6, we show the J/ψ cross section with Q^2 cut. As expected, the production rate becomes smaller compared to the result without constraint on Q^2, but still different sets of LDMEs lead to very different production rate. This feature has also been realized in the photoproduction process.[47] Our proposed approach of leptoproduction process will provide a complementary channel and new opportunity at future EIC to help resolve the long standing problem of heavy quarkonium production mechanism.

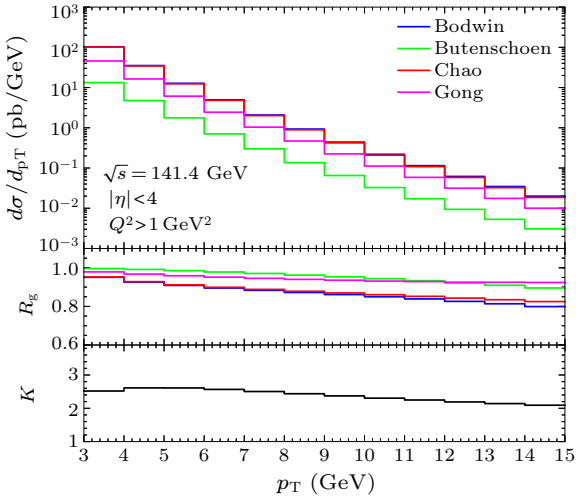

Fig. 6. Same as Fig. 4, but with $Q^2 > 1\,\mathrm{GeV}^2$. The middle panel shows the fraction from initial gluon channel, while the lowest panel shows the K-factor.

We further isolate the contributions from initial quark and gluon channels. In the middle panel of Fig. 6, we plot R_g as the gluon initiated fraction of total differential cross section. The large value of R_g in a wide p_T region indicates that J/ψ production in eh collisions is dominated by initial gluon channel. This feature makes J/ψ production in eh collisions a good observable to probe the initial gluon distribution, not only in the small-x region as pointed out in Ref. [48], but also in a wide x range in colliding proton or nucleus at the EIC. Understanding the glue is one of the main science goals for future EIC. We show in the lowest panel of Fig. 6 the K-factor for the process with Q^2 cut. As expected, the absence of quasi-real photon contribution significantly reduces the K-factor comparing to that without Q^2 cut as shown in the cyan histogram in Fig. 4.

In summary, we have proposed to measure the p_T distribution of inclusive J/ψ production in the electron-hadron frame at the future EIC without tagging the outgoing electron. We apply QCD and QED collinear factorization to the production of a $c\bar{c}$ pair at high p_T, and non-relativistic QCD factorization to the hadronization of the pair to a J/ψ, and argue that such factorization should be consistent with the factorization formalism used for hadron-hadron collisions. Using the dipole subtraction method within the framework of NRQCD, we have performed explicit calculations at both LO and NLO in α_s. It is found that the existing four sets of NRQCD LDMEs give very different predictions for this new proposed observable, which clearly demonstrates the uniqueness of future EIC in studying the J/ψ production mechanism. We also find that the dominance of producing the $^1S_0^{[8]}c\bar{c}$ state in the total contribution provides a solid prediction that J/ψ produced in eh collisions will likely be unpolarized. This prediction can provide a stringent test of NRQCD factorization and shed a

new light on the J/ψ production mechanism. Without tagging the outgoing electron, this observable will not be sensitive to the major uncertainty from QED radiative corrections in the traditional SIDIS. In addition, this new observable at the EIC could provide even more opportunities from its sensitivity to initial-state gluon distribution in nucleon or nucleus and its dominance to produce a color octet $c\bar{c}$ state propagating through the nuclear medium in eA collisions. All these unique features of this new observable will make the $p_{\rm T}$ distribution of single inclusive J/ψ production in eh collisions a new and very important channel to study at the future EIC.

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