Exploring J/ψ production mechanism at the future Electron-Ion Collider

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Virtual Quarkonium As Tools 2021

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Outlines

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Factorization formula & NLO calculations

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Summary & conclusion

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Motivations:

- Quarkonium serves as an ideal laboratory to study QCD both in perturbative and non-perturbative region because of its large mass and non-relativistic nature
- It's fair to say that the J/ψ production mechanism is still not clear since its discovery in 1974
- Although the non-relativistic QCD (NRQCD) factorization approach has achieved tremendous successes in describing quarkonium production and decay, there are still some long standing problems such as the polarization of the produced J/ψ in hadron colliders
- Resolve the differences among the various sets of non-perturbative long distance matrix elements (LDMEs) extracted from the world data
- J/ψ can be used as an excellent probe to QCD matter.

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Factorization for $e + h \to J/\psi(p) + X$

Factorization formula:

$$\frac{d\sigma_{eh\to J/\psi(p)}}{dp_T d\eta} = \sum_{a,b,n} \int \frac{dx_a}{x_a}\frac{dx_b}{x_b} f_{a/e}(x_a,\mu_f^2) f_{b/h}(x_b,\mu_f^2) \times \hat{\sigma}_{ab\to c\bar{c}[n]}(x_a,x_b,p_T,\eta,m_c,\mu_f^2)\langle \mathcal{O}_{[n]}^{J/\psi}\rangle. \quad (1)$$

- QCD ($f_{b/h}$) and QED ($f_{a/h}$) collinear factorization are applied to colliding hadron and electron, respectively;
- $\langle \mathcal{O}_{[n]}^{J/\psi}\rangle$ – NRQCD factorization is used to describe the hadronization of produced $c\bar{c}[n]$ pair to a physical J/ψ ;
- The inclusiveness from not measuring the final state electron helps us to eliminate a major uncertainty of QED rediative corrections in SIDIS [Liu, Melnitchouk, Qiu & Sato, arXiv:2008.02895].

Leading order

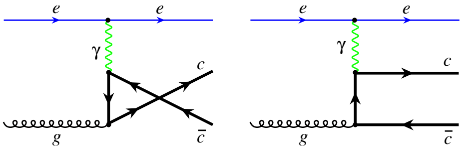

Figure: Leading order Feynman diagrams for J/ψ production in eh collisions.

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

Only color octet ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ channels can contribute to high p_T J/ψ production in eh collisions at leading order!(Get better information on $\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle$ and $\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]}) \rangle$.)

Next-to-leading order

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

$$f_{e/e}(x,\mu_f^2) = \delta(1-x_a),\ f_{\gamma/e}(x,\mu_f^2) = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\left[\ln\frac{\mu_f^2}{x^2 m_e^2} - 1\right]. \tag{4}$$

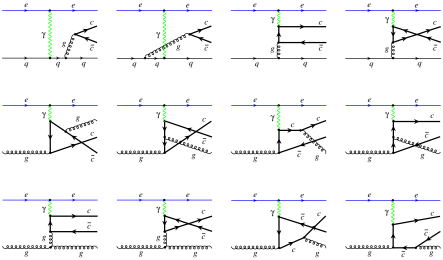

Figure: NLO Feynman diagrams for real contribution.

Next-to-leading order

We adopt the dipole subtraction method, recently developed specifically for heavy quarkonium production to extract the soft, collinear divergences in real corrections. [M. Butenschoen & B. A. Kniehl, Nucl. Phys. **B950**, 114843 (2020)]

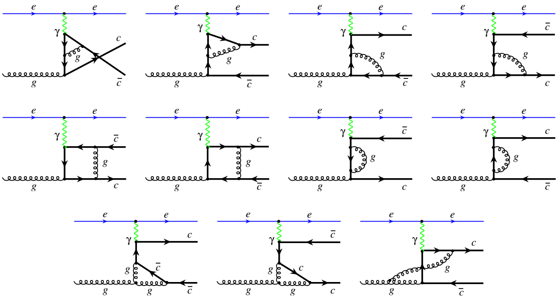

Figure: Virtual corrections to ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ channels.

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Parameter settings

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

	$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ $10^{-2}\ \mathrm{GeV}^3$	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ $10^{-2}\ \mathrm{GeV}^3$	$\langle\mathcal{O}(^3P_0^{[8]})\rangle$ $10^{-2}\ \mathrm{GeV}^5$
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

We use CT14-nlo for unpolarized proton PDFs [S. Dulat *et al.*, Phys. Rev. D **93**, 033006 (2016)].

$$\sqrt{s} = 141.4\,\mathrm{Gev},\ \mu_r = \mu_f = \sqrt{p_T^2 + M_{J/\psi}^2},\ M_{J/\psi} = 2m_c = 3.1\,\mathrm{Gev}, \tag{5}$$

$$n_f = 3,\ |\eta| < 4, , 3\,\mathrm{Gev} < p_T < 15\,\mathrm{Gev}. \tag{6}$$

p_T distribution at NLO

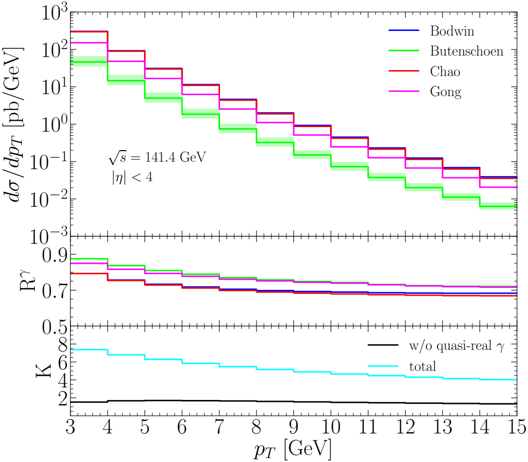

Figure: The green band shows the uncertainty from scale variation $\sqrt{p_T^2 + M^2}/2 < \mu_f < 2\sqrt{p_T^2 + M^2}$. .

Remarks and comments

- The cross section is large enough for producing sufficient (>1000) J/ψ events at the future EIC;
- There is almost an order of magnitude difference in production rate between Bodwin/Chao and Butenschoen, which clearly demonstrates the discriminative power of this new observable on J/ψ production mechanism;
- We used leading logarithmic approximation for the photon distribution in an electron ($f_{\gamma/e}$), the 70% contribution from quasi-real photon channel should be reduced once we consider the resummed photon distribution, but not in a significant way;
- The large K-factor at NLO comes from the dominated quasi-real photon channel as it first appear at NLO, such large K-factor is expected to be reduced when NNLO contribution is included.

Without quasi-real photon contribution ($Q^2 > 1$ Gev)

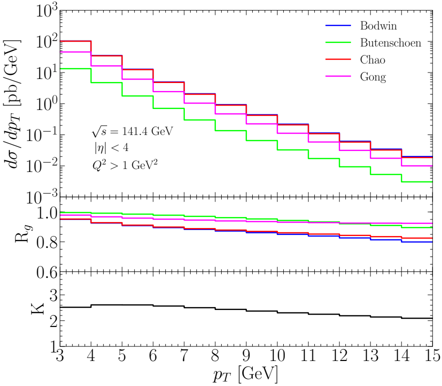

Figure: The middle panel shows the fraction from initial gluon channel.

- Initial gluon channel dominates, which makes J/ψ production in eh collisions a good observable to probe the initial gluon distribution.

Contributions from different channels

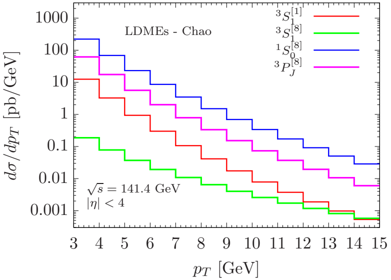

Figure: Contributions from four different $c\bar{c}$ states, respectively.

- $^1S_0^{[8]}$ channel dominates, which indicates J/ψ produce in eh collision will likely be unpolarized;
- Extending this study to electron-nucleus collisions at the EIC, $^1S_0^{[8]}$ dominance 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.

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- We 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;
- Without tagging the outgoing electron, this observable will not be sensitive to the major uncertainty from QED radiative corrections in the traditional SIDIS;
- We performed explicit calculations up to NLO in α_s and found that the existing four sets of NRQCD LDMEs give very different predictions for this new proposed observable, which clearly demonstrates the discriminative power of this new observable on J/ψ production mechanism;
- Initial gluon dominance could provide even more opportunities to probe initial-state gluon distribution in nucleon or nucleus;
- The ${}^1S_0^{[8]}$ channel dominance not only provides a solid prediction that J/ψ produced in eh collisions will likely be unpolarized, but also serves a good channel to study how a color-octet $c\bar{c}$ state propagates through the nuclear medium.