NLO Corrections to $J/\psi + c\bar{c}$ Photoproduction and Hadroproduction

冯麒铭

UCAS

Based on 2405.05683, 2507.20654,
collaborating with Cong-Feng Qiao

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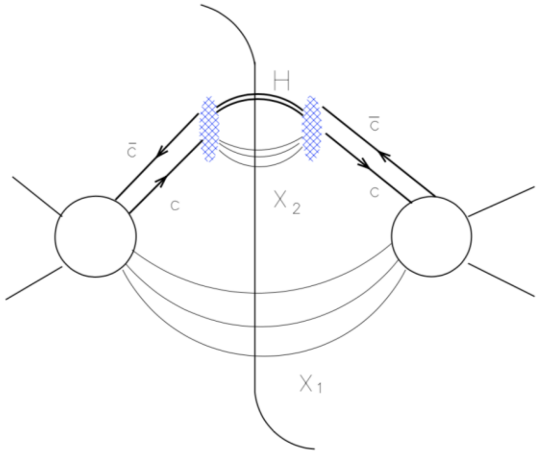
Why Heavy Quarkonium?



- Heavy quarkonia provide a **unique window** into strong interactions
- As typical quark-antiquark bound states, they probe both **perturbative** and **nonperturbative** regions of QCD
- Ideal laboratory for understanding **color confinement** and **hadronic structure**

Challenges

1. Perturbative & nonperturbative in production: **factorization hypothesis:**
   $$d\sigma(H+X)=\sum_n d\hat{\sigma}(Q\bar{Q}[n]+X)\langle\mathcal{O}^H(n)\rangle$$
2. Color singlet or color octet?
   Velocity scaling rule within Nonrelativistic QCD
3. In Long-distance matrix elements (**LDMEs**) extraction:
   Polarization puzzle and **universality** of LDMEs
4. …

Onium	Order	States
$J/\psi,\psi',\Upsilon$	1	${}^3S_1^{[1]}$
	v^4	${}^1S_0^{[8]}$ ${}^3S_1^{[8]}$ ${}^3P_J^{[8]}$
η_c,η_b	1	${}^1S_0^{[1]}$
	v^4	${}^1S_0^{[8]}$ ${}^3S_1^{[8]}$ ${}^1P_1^{[8]}$
χ_{cJ},χ_{bJ}	v^2	${}^3P_J^{[1]}$
	v^2	${}^3S_1^{[8]}$
h_c,h_b	v^2	${}^1P_1^{[1]}$
	v^2	${}^1S_0^{[8]}$

Motivation

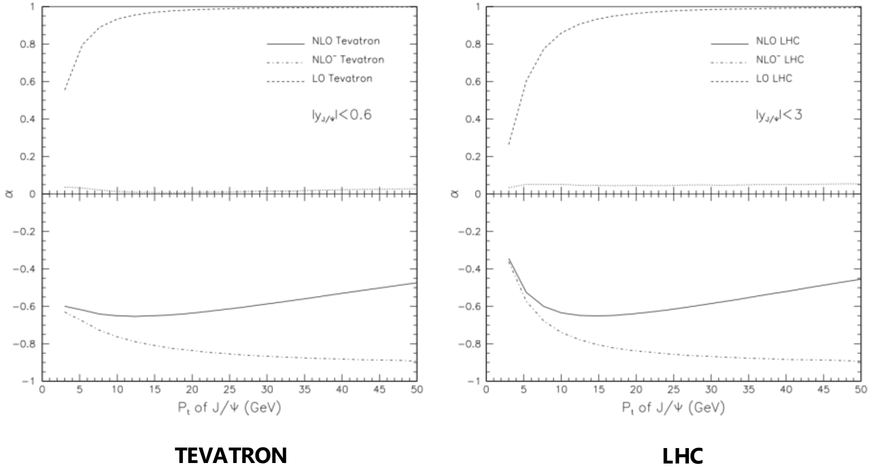
The CS contribution may have been underestimated.

- $J/\psi + c\bar{c}$ production at LO is among the most significant CS channels.

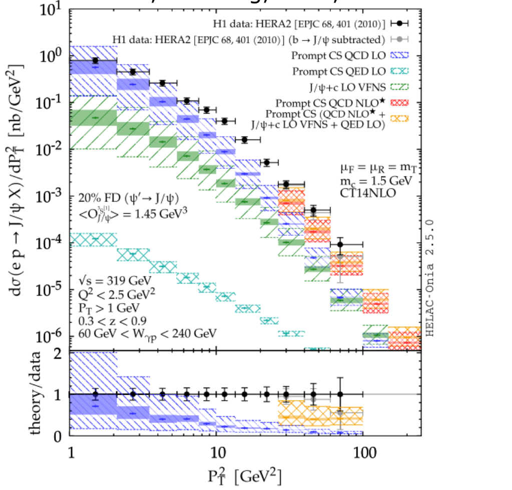
Left: polarization of **hadroproduction** process

Right: transverse momentum distribution of **photoproduction** process

B. Gong and J.X. Wang

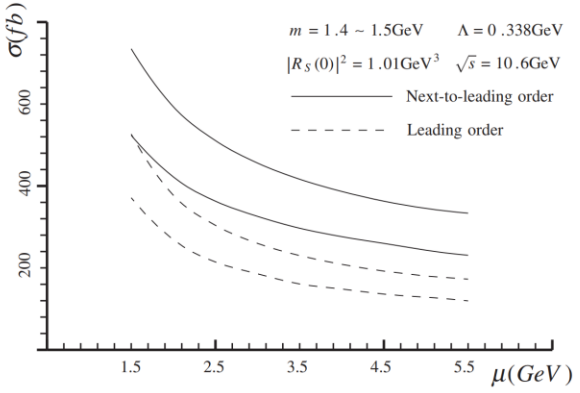


Flore, Lansberg, Shao, and Yedelkina



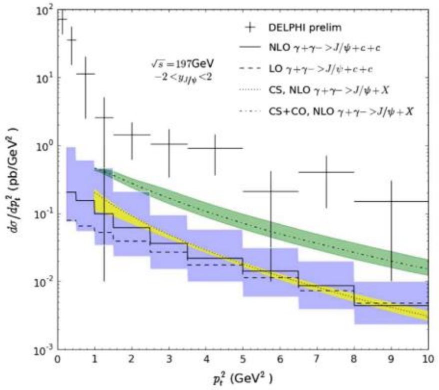
- NLO corrections of $J/\psi + c\bar{c}$ processes are prominent.

$e^+e^- \to J/\psi + c\bar{c}$



Y.J. Zhang and K.T. Chao

$\gamma\gamma \to J/\psi + c\bar{c}$



Chen, Chen, and Qiao

Methodology

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1. Amplitude:

Spinor-helicity formalism

and

conventional squared-amplitude

2. Loop reduction:

Integrand reduction

and

integration-by-parts (IBP)

Specifically for loop diagrams with Coulomb divergences

3. Infrared poles in real corrections:

Phase space slicing *and* **subtraction**

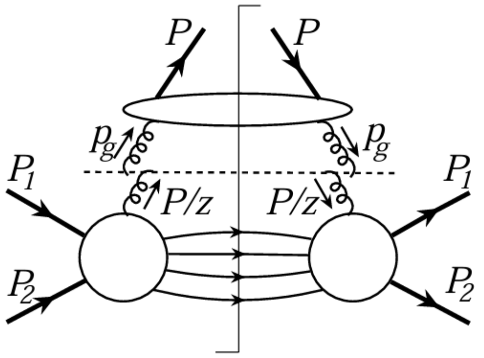
$$\sigma_{\text{tot}} = \int_{3-\text{body}} \left(d\sigma^{\text{LO}} + d\sigma^{\text{Virtual}} + d\sigma_{\text{S}}^{\text{Real}} + d\sigma_{\text{HC}}^{\text{Real}}\right) + \int_{4-\text{body}} d\sigma_{\overline{\text{HC}}}^{\text{Real}}$$

$$\sigma_{\text{tot}} = \int_{3-\text{body}} (d\sigma_{\text{LO}} + d\sigma_{\text{Virtual}} + d\sigma_{C} + d\sigma_{\hat{A}}) + \int_{4-\text{body}} (d\sigma_{\text{Real}} - d\sigma_{A})$$

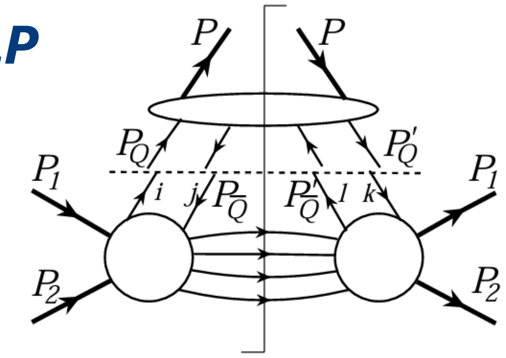
Methodology

Fragmentation processes

LP



NLP



Z.B. Kang, J.W. Qiu et al.

Factorization :

$$
\begin{aligned}
d\sigma_{A+B\to H+X}(p_T) &= \sum_f d\hat{\sigma}_{A+B\to f+X}(p_T/z,\mu_F)\otimes D_{f\to H}(z,m_Q,\mu_F)\\
&+\sum_\kappa d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(P_{[Q\bar{Q}(\kappa)]}=p_T/z,\mu_F)\otimes\mathcal{D}_{[Q\bar{Q}(\kappa)]\to H}(z,m_Q,\mu_F)\\
&+\mathcal{O}(m_Q^4/p_T^4)\,,
\end{aligned}
$$

Fragmentation functions :

$$
D_{f\to H}(z,m_Q,\mu_0)=\sum_n \hat{d}_{f\to Q\bar{Q}[n]}(z,m_Q,\mu_0,\mu_\Lambda)\langle\mathcal{O}_n^H(\mu_\Lambda)\rangle\,,
$$

$$
\mathcal{D}_{[Q\bar{Q}(\kappa)]\to H}(z,m_Q,\mu_0)=\sum_n \hat{d}_{[Q\bar{Q}(\kappa)]\to Q\bar{Q}[n]}(z,m_Q,\mu_0,\mu_\Lambda)\langle\mathcal{O}_n^H(\mu_\Lambda)\rangle\,.
$$

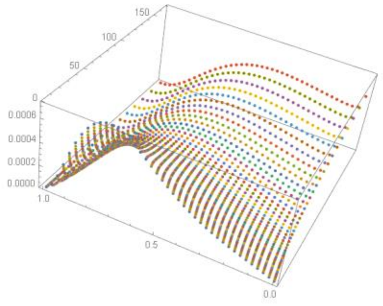
CS $c\to J/\psi$ *fragmentation contribution at NLO:*

$$
d\sigma_{LP}^{NLO}=d\hat{\sigma}_{A+B\to c+X}^{NLO}\otimes D_{c\to J/\psi}^{LO}+d\hat{\sigma}_{A+B\to c+X}^{LO}\otimes D_{c\to J/\psi}^{NLO}
$$

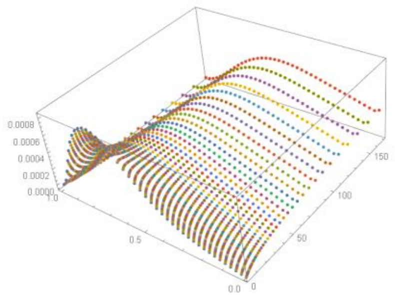
DGLAP evaluation:

$$
\mu^2\frac{d}{d\mu^2}D_{c\to J/\psi}(z,\mu_f)=\frac{\alpha_s(\mu)}{2\pi}P_{cc}(z)\otimes D_{c\to J/\psi}(z,\mu_f)
$$

Evaluated FFs:



LO



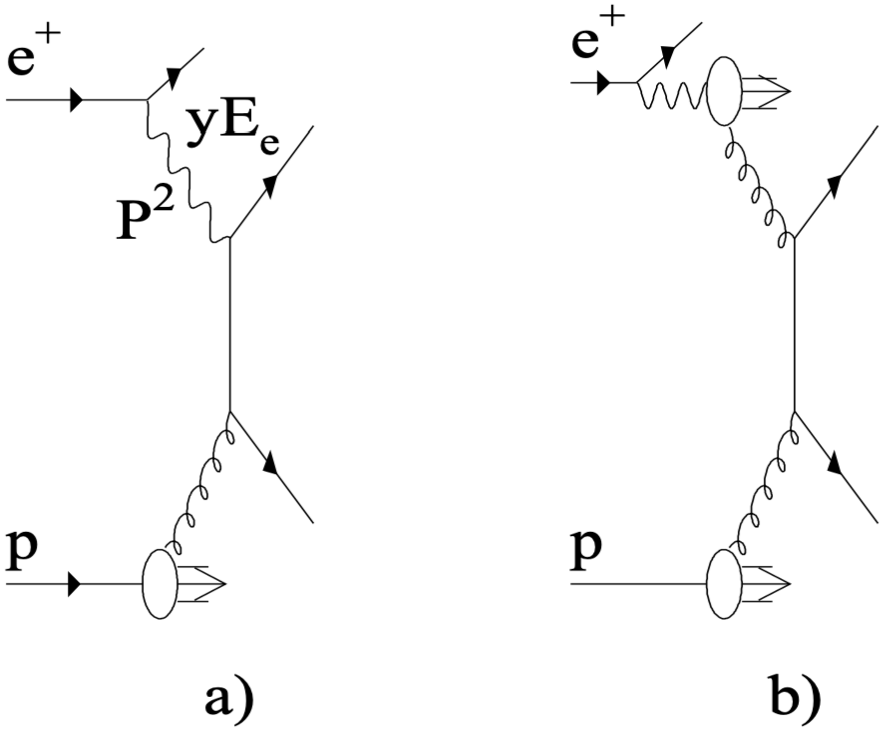
NLO

Typical J/ψ production mechanisms at ep colliders

Inelastic process:

1. direct:

2. resolved:

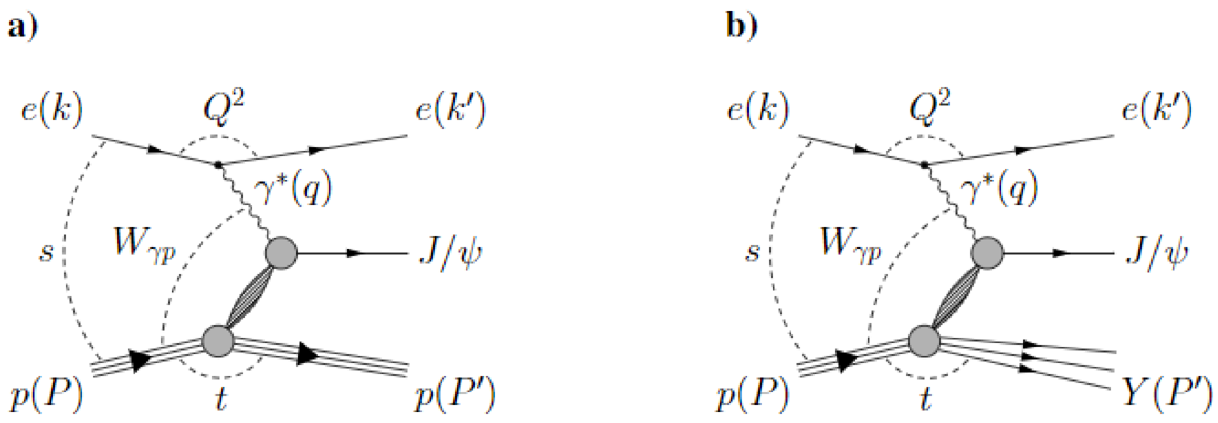


M.L. Utley, ZEUS Collab.
Brussels, 1995, eds. J. Lemonne et al.

Diffractive process:

1. elastic:

2. proton dissociative:

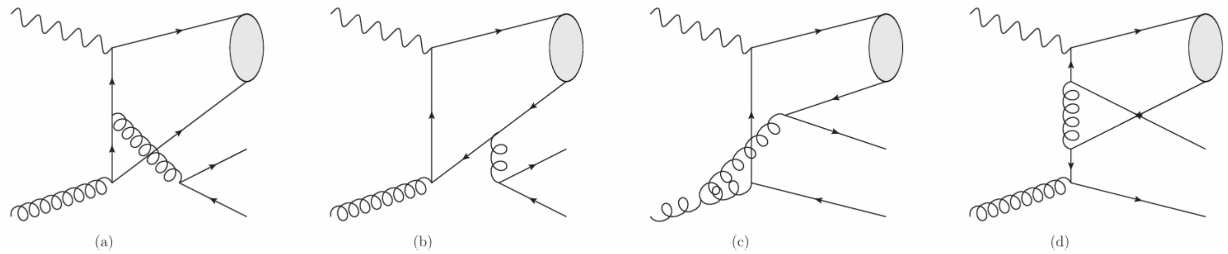


Regge Theory

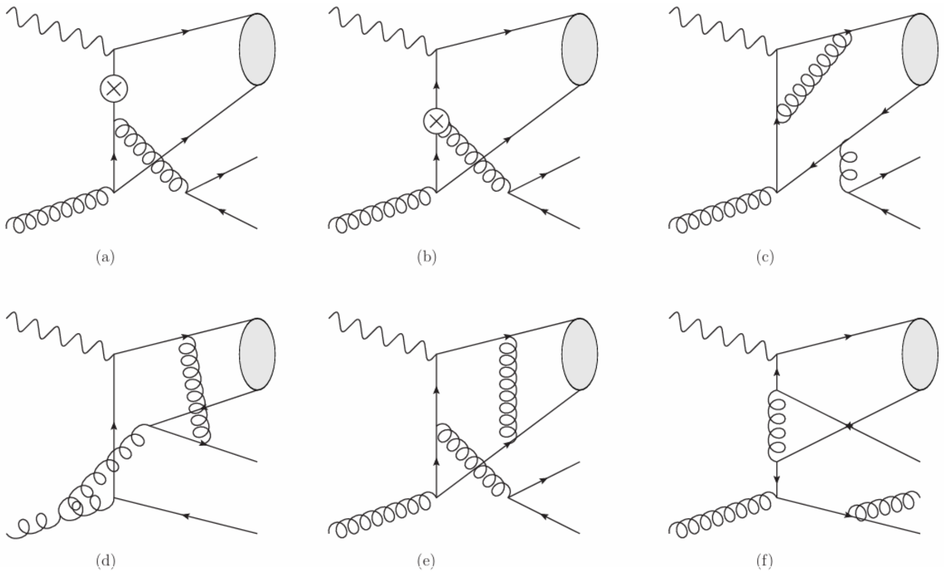
Photoproduction process

Process: $\gamma(k_1) + g(k_2) \to J/\psi(p_0) + c(p_1) + \bar{c}(p_2)$

Typical Feynman diagrams



- ***LO***: *30*



- ***NLO***

  CTs: *210*

  Loops: *837+30*

  Real corr.: *274*

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Total cross sections:

HERA: $\boldsymbol{\sigma_{NLO(LO)}} = \mathbf{0.118^{+0.141}_{-0.056}}\ (\mathbf{0.074^{+0.087}_{-0.039}})$ nb, K-factor: $\sim \mathbf{1.60}$

EIC: $\boldsymbol{\sigma_{NLO(LO)}} = \mathbf{0.046^{+0.069}_{-0.026}}\ (\mathbf{0.027^{+0.063}_{-0.017}})$ nb, K-factor: $\sim \mathbf{1.67}$

Theoretical uncertainties (charm quark mass and scales, in nb):

- The cross sections show strong sensitivity to both charm quark mass and scales, particularly to scales.
- NLO results show reduced dependence on scales compared to LO results.

$m_c \backslash \mu$ (GeV)	$\frac{1}{2}m_T$	m_T	$2m_T$
1.4	0.258(0.161)	0.164(0.097)	0.114(0.061)
1.5	0.189(0.123)	0.118(0.074)	0.081(0.046)
1.6	0.136(0.095)	0.086(0.056)	0.061(0.035)

Transverse momentum distributions:

- $J/\psi + c\bar{c}$ process shows milder falloff than inclusive $J/\psi + X$ in CSM.

W distribution:

- consistent in shape but smaller in normalization.

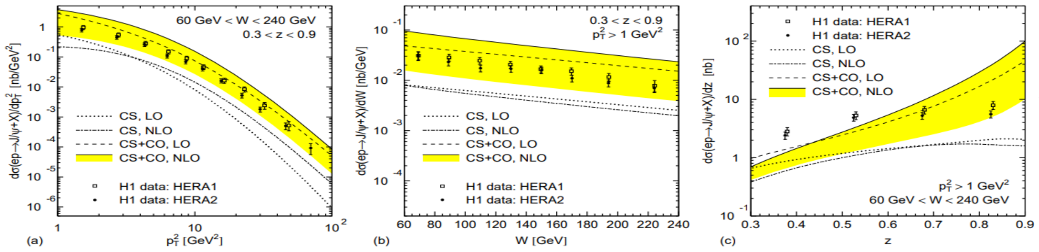
z distribution:

- steep decrease—distinct from inclusive channel.

PhysRevLett.104.072001

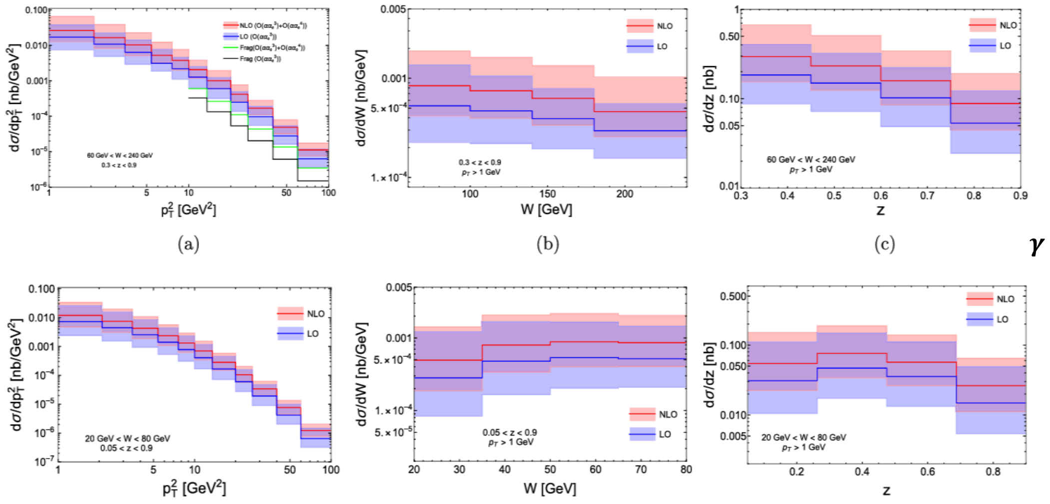
HERA

$\gamma + g \to J/\psi + X$



$\gamma + g \to J/\psi + c\bar{c}$

EIC



(a) (b) (c) (d) (e) (f)

QMF and C.F. Qiao, 2405.05683

HERA cut: $p_T > 1\text{GeV}, \quad 60\text{GeV} < W < 240\text{GeV}, \quad 0.3 < z < 0.9.$

EIC cut: $p_T > 1\text{GeV}, \quad 20\text{GeV} < W < 80\text{GeV}, \quad 0.05 < z < 0.9.$

Result

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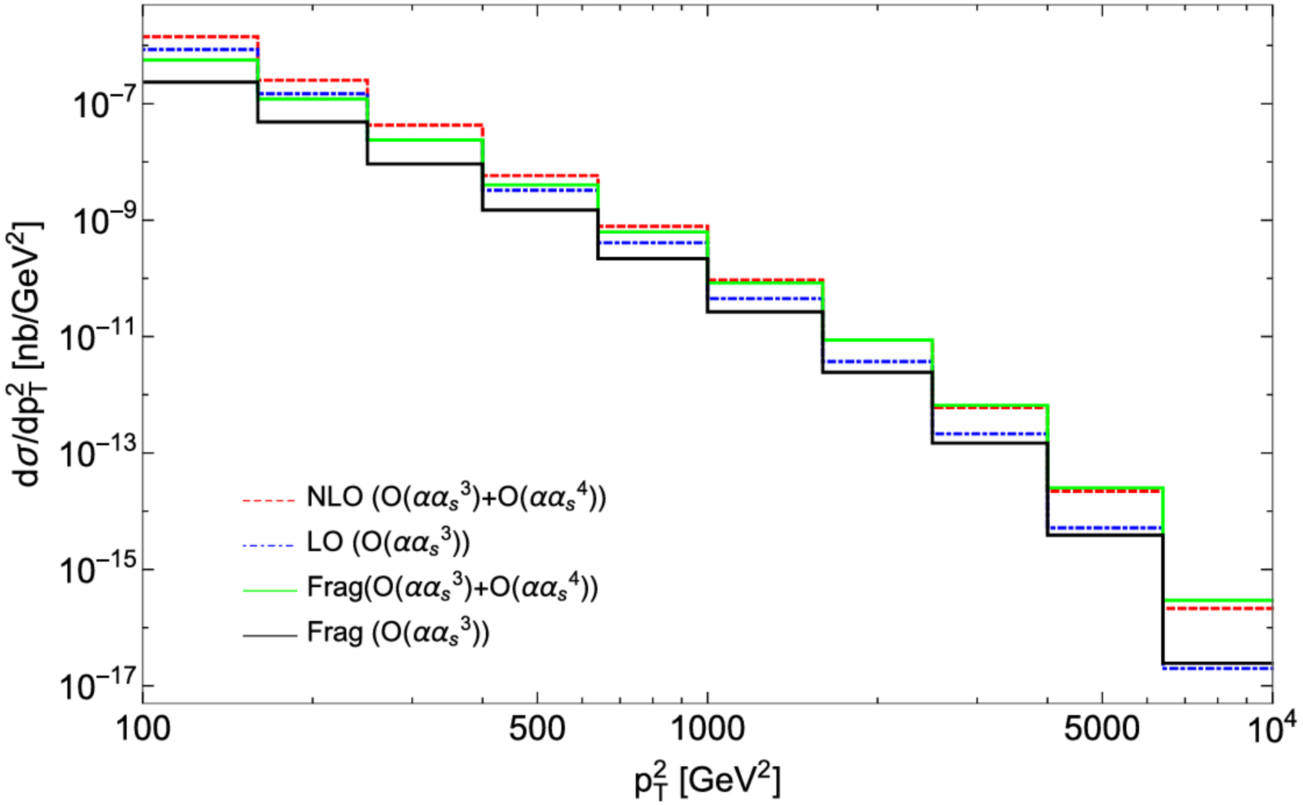
Transverse momentum distribution at high p_T:

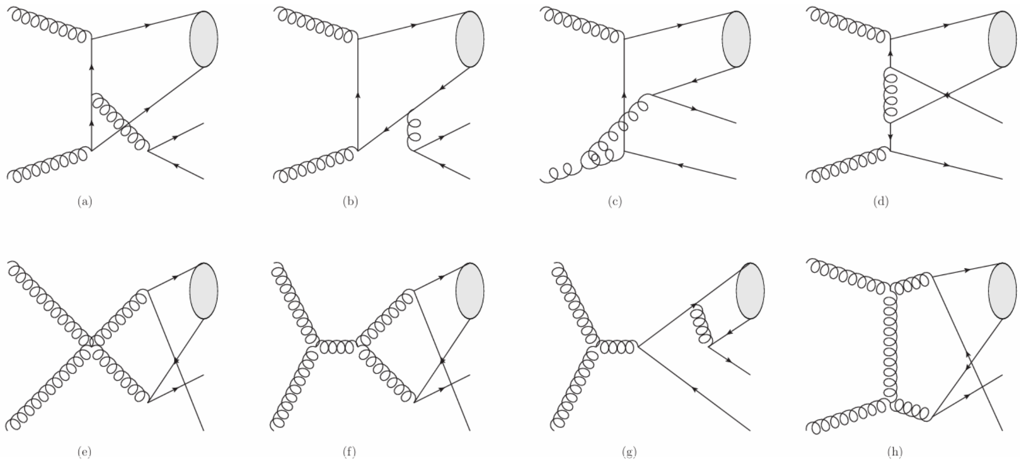
- the fragmentation contribution approaches and eventually exceeds the corresponding fixed-order direct production results.



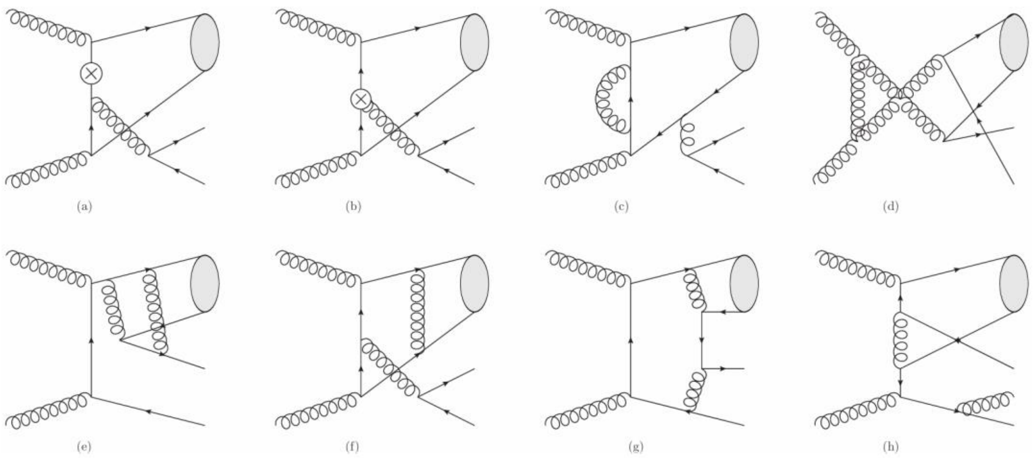
Hadroproduction process

Process: $g(k_1) + g(k_2) \to J/\psi(p_0) + c(p_1) + \bar{c}(p_2)$

Typical Feynman diagrams



- ***LO***: *42*



- ***NLO***
  - ***CTs***: *292*
  - ***Loops***: *1627+42*
  - ***Real corr.***: *437*

Hadroproduction process

- The polarization of the J/ψ is determined by its dilepton decay angular distribution in the J/ψ rest frame:

$$\frac{d\sigma(J/\psi \to \ell^+\ell^-)}{d\cos\theta} \propto 1 + \lambda_\theta \cos^2\theta$$

- λ_θ characterizes the reconstructed J/ψ polarization:

$\lambda_\theta \to 1$: Transverse
$\lambda_\theta \to -1$: Longitudinal

- Expression of λ_θ:

$$\lambda_\theta = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}$$

- The spin density matrix is built from helicity amplitudes:

$$d\hat{\sigma}_{s_z s_z'} \propto \sum_{s_i, s_j, s_c, s_{\bar{c}}} \mathcal{A}^{s_i s_j s_z s_c s_{\bar{c}}} \left(\mathcal{A}^{s_i s_j s_z' s_c s_{\bar{c}}}\right)^*$$

Polarized cross section calculation:

- Spinor helicity formalism:
  - separate s_z component
- Conventional squared-amplitude:
  - Longitudinal polarization squaring:

$$\Pi_L^{\mu\nu} = \varepsilon_L^{\mu}(p_0)\varepsilon_L^{*;\nu}(p_0) = \frac{1}{M^2}\left(p_0^\mu - \frac{M^2}{k_1 \cdot p_0} k_1^\mu\right)\left(p_0^\nu - \frac{M^2}{k_1 \cdot p_0} k_1^\nu\right)$$

  - Transverse cross section:

$$d\sigma_T = d\sigma_{11} + d\sigma_{-1,-1} = d\sigma - d\sigma_0$$

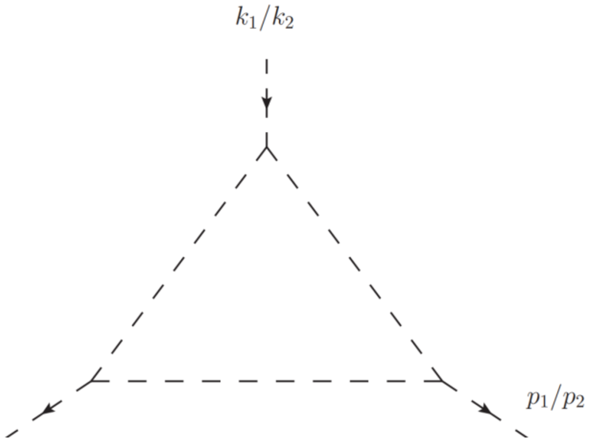
Simplification in the calculation

- For loop diagrams, the calculation can be greatly simplified by removing the contributions that are related by symmetric permutations of the initial gluons and the final (anti-)charm quarks.

$$k_1 \leftrightarrow k_2, \quad p_1 \leftrightarrow p_2$$

For example, diagrams with the following triangle loops yield identical cross sections.

$$\frac{1}{q^2(q-k_1)^2(q-k_1-p_1)^2} \leftrightarrow \frac{1}{q^2(q-k_2)^2(q-k_2-p_1)^2}$$
$$\leftrightarrow \frac{1}{q^2(q-k_1)^2(q-k_1-p_2)^2} \leftrightarrow \frac{1}{q^2(q-k_2)^2(q-k_2-p_2)^2}$$



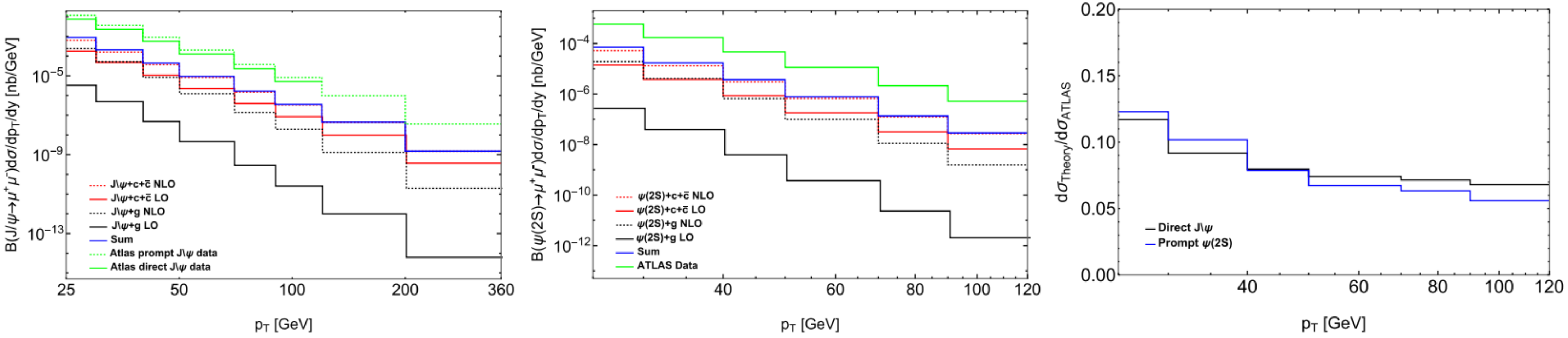
Result

Feed-down contributions:

- $\psi(2S) \to J/\psi$: fitted using distribution data from ATLAS, 2023
- $\chi_{cJ} \to J/\psi$: ~26% (from ATLAS, 2014)

Transverse momentum distribution (at $\sqrt{S} = 13\ \mathrm{TeV}$ LHC):

1. The NLO QCD corrections are substantial and may enhance the LO contribution by several times.
2. Despite being higher order in α_s, the associated $J/\psi + c\bar{c}$ production dominates over $J/\psi + g$.
3. The shape of the $J/\psi + c\bar{c}$ process matches the direct J/ψ data well, though a normalization gap remains.
4. $\psi(2S)$ provides a clean probe of short distance dynamics. The similar p_T dependence of J/ψ and $\psi(2S)$ ratios suggests analogous behavior in the CS channel.

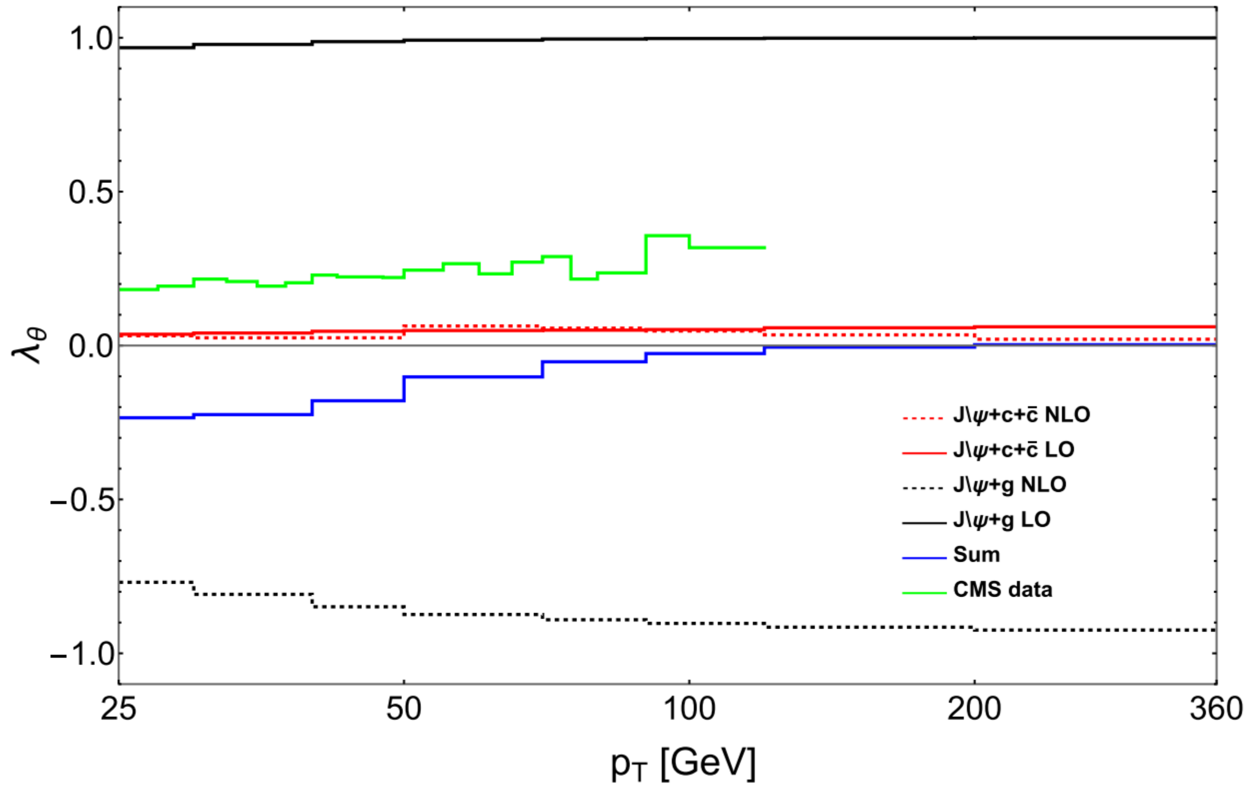


(a) (b) (c)

Result

Polarization distribution (at $\sqrt{S} = 13\ \mathrm{TeV}$ LHC):

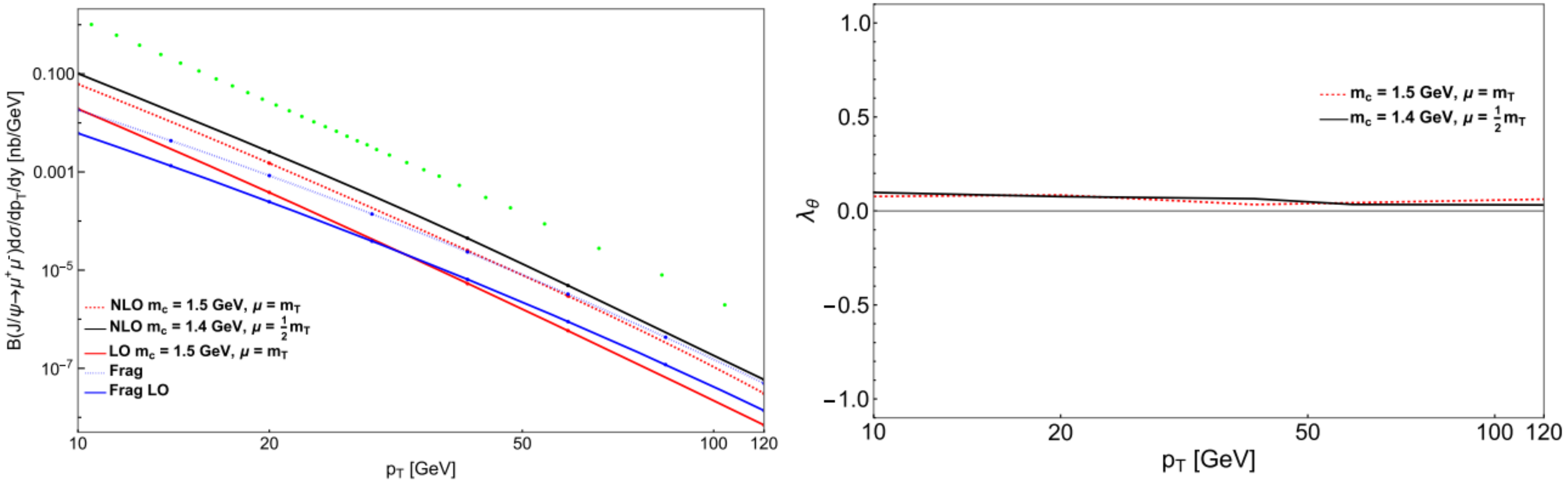
➢ The $J/\psi + c\bar{c}$ channel yields nearly unpolarized J/ψ at both LO and NLO, improving agreement with experimental measurements. The polarization tends toward unpolarized as p_T increases.



Result

$J/\psi + c\bar{c}$ vs **fragmentation contribution** vs **the CMS measurement** (at $\sqrt{S} = 7\ \mathrm{TeV}$ LHC):

- The fragmentation contribution cannot adequately describe the associated process at fixed order in QCD, and the discrepancy is expected to be mitigated by re-summation of higher-order logarithmic terms.
- Considering mass and scale uncertainties, the cross section increases roughly twofold, yet a gap with experimental data persists.
- The polarization parameter shows little sensitivity with varied charm mass and scale.



(a) (b)

Summary

$J/\psi + c\bar{c}$ photoproduction:

1. The NLO QCD corrections are **prominent.**

2. **Not negligible** in the evaluation of photoproduction processes in ep colliders, **particularly at high-p_T.**

$J/\psi + c\bar{c}$ hadroproduction:

1. The NLO QCD corrections enhance the LO contribution by **several times.**

2. **Dominant** among CS production schemes.

3. The p_T spectrum exhibits a **similar shape** to the experimental data , though an obvious **discrepancy in magnitude** remains.

4. **Nearly unpolarized**, consistent with the recent CMS measurement.

Thanks.

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