Transverse momentum distribution of charmonium production in lepton-hadron scattering at the EIC

- Single inclusive heavy quarkonium production in hadronic collisions
- Single inclusive heavy quarkonium production in lepton-hadron collisions at the EIC
- Nuclear modification to quarkonium production in e-A collisions
- Summary and outlook

Jianwei Qiu
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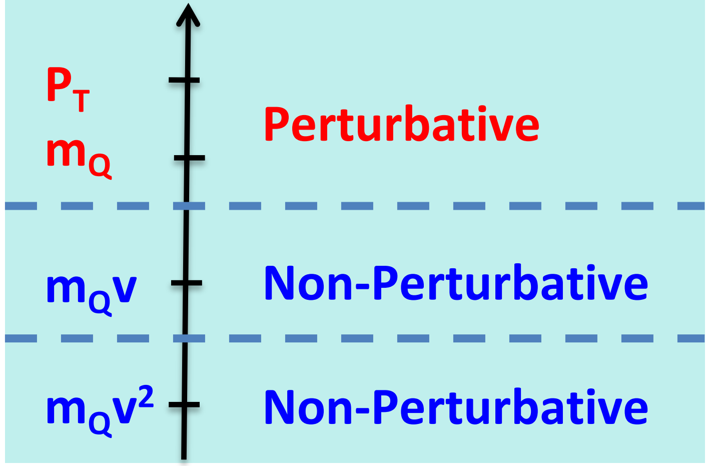
In collaboration with Kazuhiro Watanabe (Seikei University, Japan)

Scales for heavy quarkonium production at high P_T

- Well-separated momentum scales – effective theory:



Hard — Production of $Q\bar{Q}$ **[pQCD]**

To make this part as reliable as we can!

Soft — Relative Momentum **[NRQCD]**

Λ_{QCD}

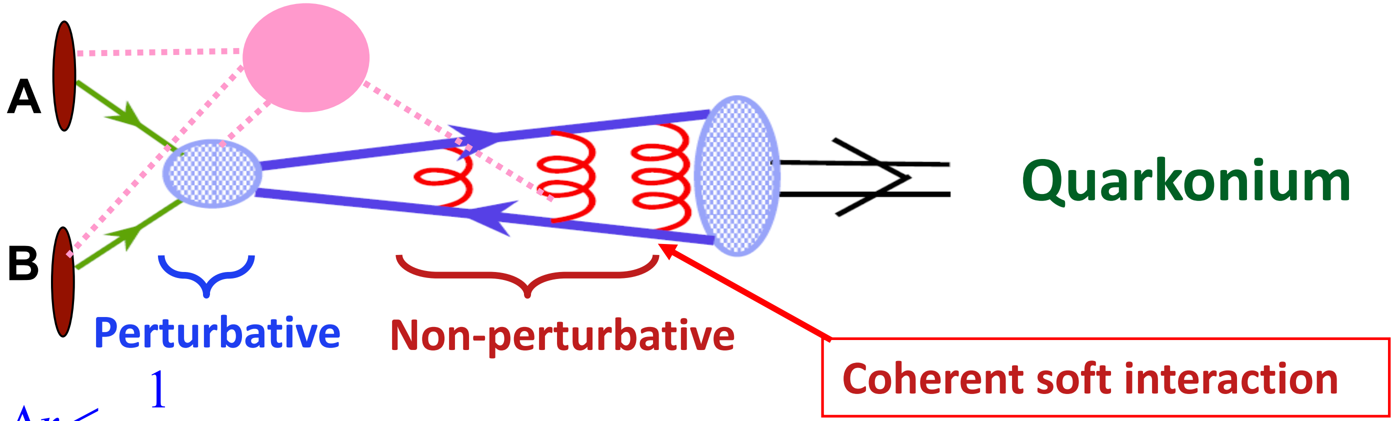
Ultrasoft — Binding Energy **[pNRQCD]**

Λ_{QCD}

Known quarks

Flavor	Mass
u	$1.5 - 4.5$ MeV
d	$5.0 - 8.5$ MeV
s	$80 - 155$ MeV
c	$1.0 - 1.4$ GeV
b	$4.0 - 4.5$ GeV
t	174.3 ± 5.1 GeV

- Basic production mechanism:



$$\Delta r \leq \frac{1}{2m_Q}$$

- QCD Factorization is "expected" to work for the production of heavy quark pair
- Difficulty: how the heavy quark pair becomes a quarkonium?
- Medium: filter/diagnose the emergence

QCD factorization for heavy quarkonium production at high P_T

Lee, Qiu, Sterman, Watanabe, 2022

❑ PQCD factorization:

$$E\frac{d\sigma_{hh'\to J/\psi(P)X}}{d^3P} = \sum_{c\bar{c}[n]} F_{c\bar{c}[n]\to J/\psi} \otimes \sum_{a,b} \int dx_a\, f_{a/h}(x_a,\mu_f^2) \int dx_b\, f_{b/h'}(x_b,\mu_f^2) \times \left[E\frac{d\tilde{\sigma}^{\text{Resum}}_{ab\to c\bar{c}[n](P)X}}{d^3P} + E\frac{d\tilde{\sigma}^{\text{NRQCD}}_{ab\to c\bar{c}[n](P)X}}{d^3P} - E\frac{d\tilde{\sigma}^{\text{Asym}}_{ab\to c\bar{c}[n](P)X}}{d^3P} \right]$$

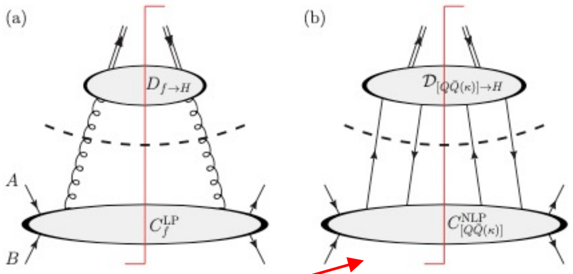
NRQCD:

$$F_{c\bar{c}[n]\to J/\psi} = \langle O^{J/\psi}_{c\bar{c}[n]}(0)\rangle$$

$$c\bar{c}[n] = c\bar{c}[^{2S+1}L_J^{[1,8]}]$$

- **PQCD factorization + FFs:** $\kappa = (v,a,t)^{[1,8]} = (\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma_\perp^i)^{[1,8]}$

$$E\frac{d\tilde{\sigma}^{\text{Resum}}_{ab\to c\bar{c}[n](P)X}}{d^3P} \approx \sum_f \int \frac{dz}{z^2} D_{f\to c\bar{c}[n]}(z,\mu_f^2) E_f \frac{d\hat{\sigma}_{ab\to f(p_f)X}}{d^3p_f}(z, p_f = P/z, \mu_f^2) + \sum_{[c\bar{c}(\kappa)]} \int \frac{dz}{z^2} D_{[c\bar{c}(\kappa)]\to c\bar{c}[n]}(z,\mu_f^2) E_c \frac{d\hat{\sigma}_{ab\to [c\bar{c}(\kappa)](p_c)X}}{d^3p_c}(z, p_c = P/z, \mu_f^2)$$



Kang, Ma, Qiu, Sterman, 2014

- **PQCD fixed-order:**

$$E\frac{d\tilde{\sigma}^{\text{NRQCD}}_{ab\to c\bar{c}[n](P)X}}{d^3P}$$

Known to NLO

- **PQCD Asymptotic contribution:**

$$E\frac{d\tilde{\sigma}^{\text{Asym}}_{ab\to c\bar{c}[n](P)X}}{d^3P} = E\frac{d\tilde{\sigma}^{\text{Resum}}_{ab\to c\bar{c}[n](P)X}}{d^3P}\bigg|_{\text{fixed order}}$$

QCD factorization for heavy quarkonium production at high P_T

❑ PQCD factorization:

Lee, Qiu, Sterman, Watanabe, 2022

$$E\frac{d\sigma_{hh'\to J/\psi(P)X}}{d^3P} = \sum_{c\bar{c}[n]} F_{c\bar{c}[n]\to J/\psi} \otimes \sum_{a,b} \int dx_a\, f_{a/h}(x_a,\mu_f^2) \int dx_b\, f_{b/h'}(x_b,\mu_f^2)$$

$$\times \left[E\frac{d\tilde{\sigma}^{\rm Resum}_{ab\to c\bar{c}[n](P)X}}{d^3P} + E\frac{d\tilde{\sigma}^{\rm NRQCD}_{ab\to c\bar{c}[n](P)X}}{d^3P} - E\frac{d\tilde{\sigma}^{\rm Asym}_{ab\to c\bar{c}[n](P)X}}{d^3P} \right]$$

NRQCD:

$$F_{c\bar{c}[n]\to J/\psi} = \langle O^{J/\psi}_{c\bar{c}[n]}(0)\rangle$$

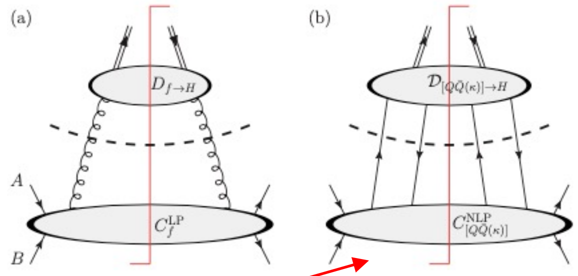
$$c\bar{c}[n] = c\bar{c}[{}^{2S+1}L_J^{[1,8]}]$$

- **PQCD factorization + FFs:**

$$\kappa = (v,a,t)^{[1,8]} = (\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma_\perp^i)^{[1,8]}$$

$$E\frac{d\tilde{\sigma}^{\rm Resum}_{ab\to c\bar{c}[n](P)X}}{d^3P} \approx \sum_f \int \frac{dz}{z^2} D_{f\to c\bar{c}[n]}(z,\mu_f^2) E_f \frac{d\hat{\sigma}_{ab\to f(p_f)X}}{d^3p_f}(z, p_f = P/z, \mu_f^2)$$

$$+ \sum_{[c\bar{c}(\kappa)]} \int \frac{dz}{z^2} D_{[c\bar{c}(\kappa)]\to c\bar{c}[n]}(z,\mu_f^2) E_c \frac{d\hat{\sigma}_{ab\to [c\bar{c}(\kappa)](p_c)X}}{d^3p_c}(z, p_c = P/z, \mu_f^2)$$



Kang, Ma, Qiu, Sterman, 2014

- **PQCD fixed-order:**

$$E\frac{d\tilde{\sigma}^{\rm NRQCD}_{ab\to c\bar{c}[n](P)X}}{d^3P}$$

Known to NLO

- **PQCD Asymptotic contribution:**

$$E\frac{d\tilde{\sigma}^{\rm Asym}_{ab\to c\bar{c}[n](P)X}}{d^3P} = E\frac{d\tilde{\sigma}^{\rm Resum}_{ab\to c\bar{c}[n](P)X}}{d^3P}\bigg|_{\rm fixed\ order}$$

When $P_T \gg m_c$, $E\frac{d\tilde{\sigma}^{\rm Asym}_{ab\to c\bar{c}[n](P)X}}{d^3P}$ **cancels** $E\frac{d\tilde{\sigma}^{\rm NRQCD}_{ab\to c\bar{c}[n](P)X}}{d^3P}$

When $P_T \gtrsim m_c$, $E\frac{d\tilde{\sigma}^{\rm Asym}_{ab\to c\bar{c}[n](P)X}}{d^3P}$ **cancels** $E\frac{d\tilde{\sigma}^{\rm Resum}_{ab\to c\bar{c}[n](P)X}}{d^3P}$

Renormalization group improvement

Kang, Ma, Qiu, Sterman, PRD 90, 034006 (2014)

❑ Renormalization group:

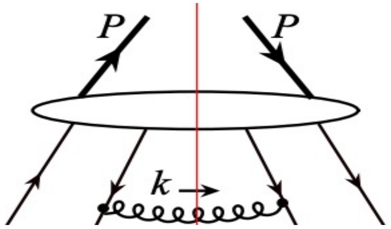
$$\frac{d}{d\ln\mu_f^2}\left[E\frac{d\tilde{\sigma}^{\mathrm{Resum}}_{ab\to c\bar{c}[n](P)X}}{d^3P}\right]=0$$

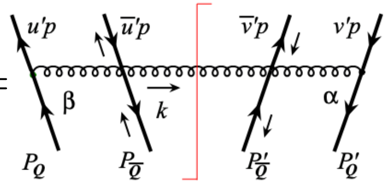
To be accurate up to the 1st power correction

❑ Modified evolution equations:

NRQCD: $H = c\bar{c}[^{2S+1}L_J^{[1,8]}]$

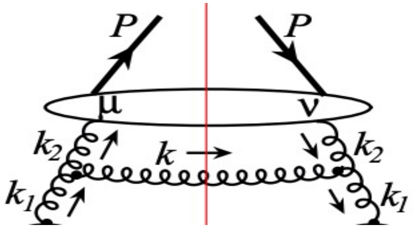
$$\frac{\partial \mathcal{D}_{[Q\bar{Q}(n)]\to H}}{\partial \ln \mu_f^2} = \Gamma_{[Q\bar{Q}(n)]\to[Q\bar{Q}(\kappa)]}\otimes \mathcal{D}_{[Q\bar{Q}(\kappa)]\to H}$$



$\Gamma =$ 

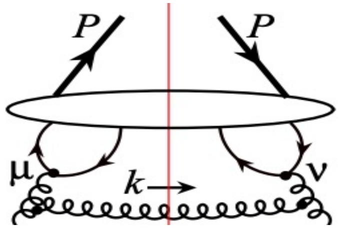
DGLAP-type: Heavy quark pair produced at the hard scale

$$\frac{\partial D_{[f]\to H}}{\partial \ln\mu_f^2} = \gamma_{[f]\to[f']}\otimes D_{[f']\to H}$$



Heavy quark pair produced at the input scale

$$+\frac{1}{\mu_f^2}\,\overline{\gamma}_{[f]\to[Q\bar{Q}(\kappa)]}\otimes\mathcal{D}_{[Q\bar{Q}(\kappa)]\to H}$$



$\longleftarrow \quad \overline{\gamma}_{g\to[Q\bar{Q}]}$

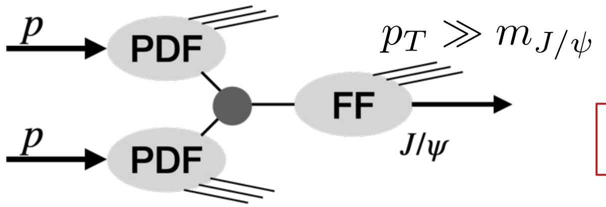
Heavy quark pair produced between the hard scale and the input scale

Modified DGLAP – inhomogeneous evolution

Single inclusive high P_T J/ψ-production in hadronic collisions

❑ Test the consistency:

$p + p \to J/\psi + X$



NLO

LO x K_{NLP}

$$\frac{d\sigma_{p+p\to J/\psi+X}}{dp_T} \approx f_{i/p} \otimes f_{j/p} \otimes \left[D_k^{J/\psi} \otimes C_{ij\to k} + D_{c\bar{c}}^{J/\psi} \otimes C_{ij\to c\bar{c}} \right]$$

❑ Input FFs from NRQCD:

Ma, Qiu, Zhang, PRD89 (2014) 094029; ibid. 94030

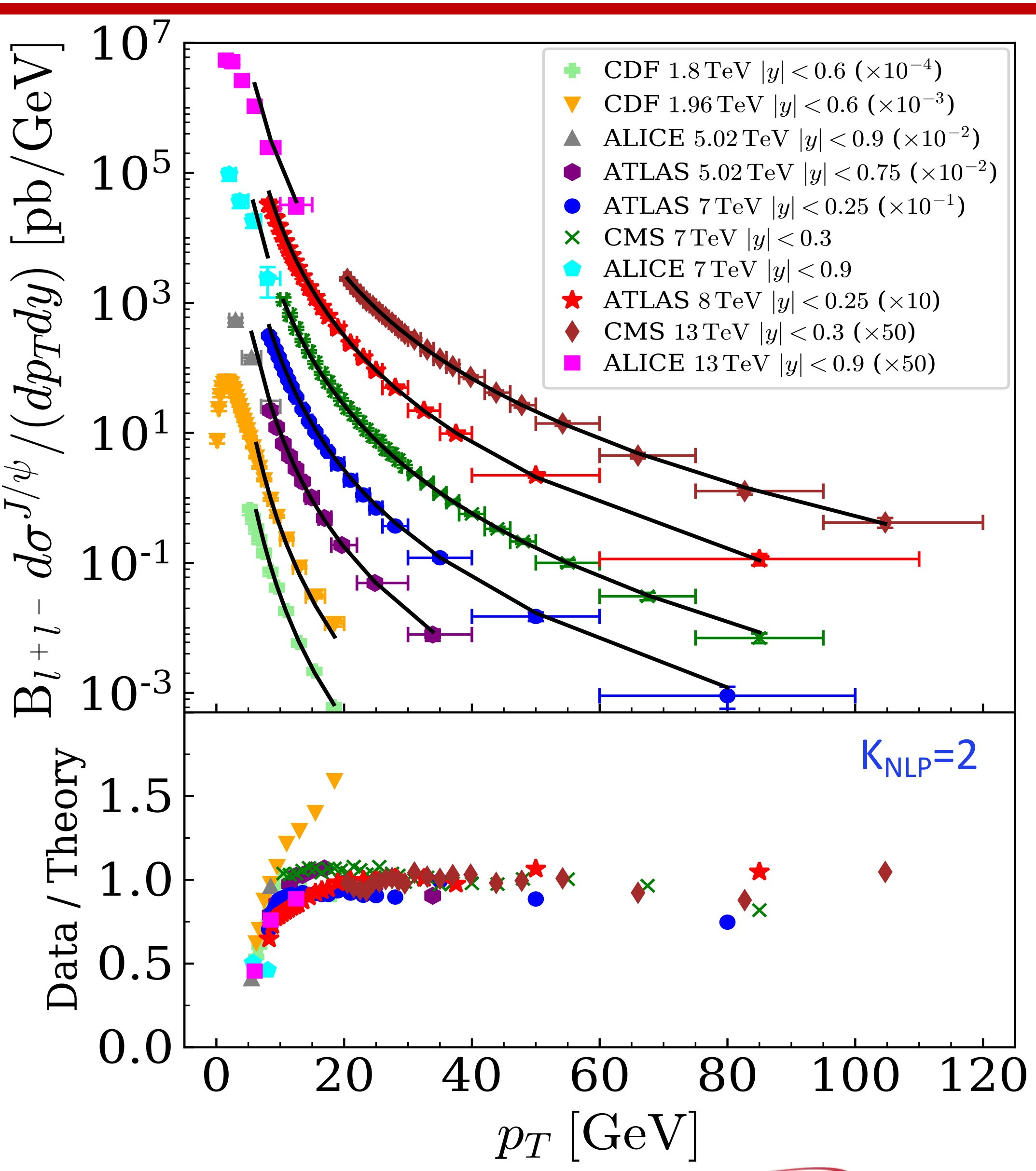
$$D_{f\to H}(z;m,\mu_0) = \sum_{[Q\bar{Q}(n)]} \pi\alpha_s \left\{ \hat{d}^{(1)}_{f\to[Q\bar{Q}(n)]}(z;m,\mu_0,\mu_\Lambda) + \frac{\alpha_s}{\pi}\hat{d}^{(2)}_{f\to[Q\bar{Q}(n)]}(z;m,\mu_0,\mu_\Lambda) + \mathcal{O}(\alpha_s^2) \right\} \frac{\langle \mathcal{O}^H_{[Q\bar{Q}(n)]}(\mu_\Lambda)\rangle}{m^{2L+3}}$$

$\kappa = v^{[c]}, a^{[c]}, t^{[c]}, \quad n = {}^{2S+1}L_J^{[c]}$

$$D_{[Q\bar{Q}(\kappa)]\to H}(z;m,\mu_0) = \sum_{[Q\bar{Q}(n)]} \left\{ \hat{d}^{(0)}_{[Q\bar{Q}(\kappa)]\to[Q\bar{Q}(n)]}(z;m,\mu_0,\mu_\Lambda) + \frac{\alpha_s}{\pi}\hat{d}^{(1)}_{[Q\bar{Q}(\kappa)]\to[Q\bar{Q}(n)]}(z;m,\mu_0,\mu_\Lambda) + \mathcal{O}(\alpha_s^2) \right\} \frac{\langle \mathcal{O}^H_{[Q\bar{Q}(n)]}(\mu_\Lambda)\rangle}{m^{2L+1}}$$

$\mu_0 = \mathcal{O}(2m)$: input scale, $\mu_\Lambda = \mathcal{O}(m)$: NRQCD factorization scale

➡ $$D_{f\to H}(z) = N_f \frac{z^{\alpha_f}(1-z)^{\beta_f}}{B(1+\alpha_f, 1+\beta_f)}$$

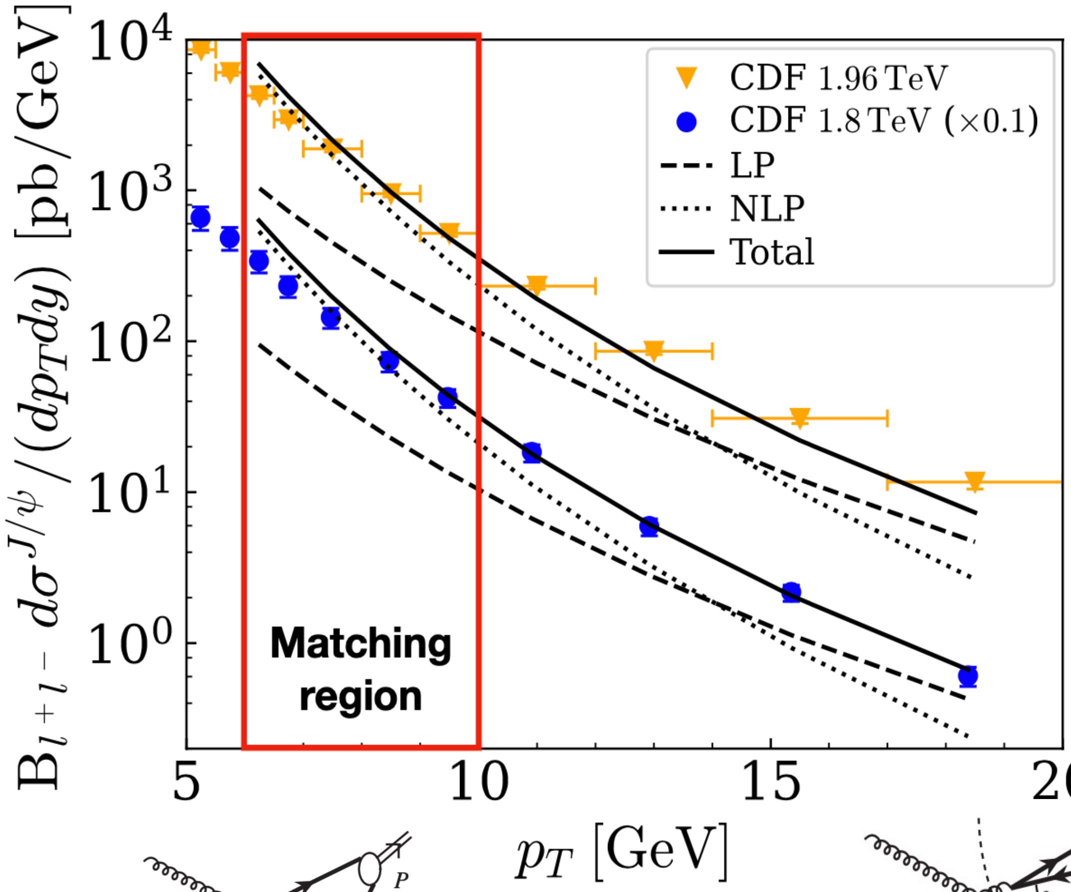


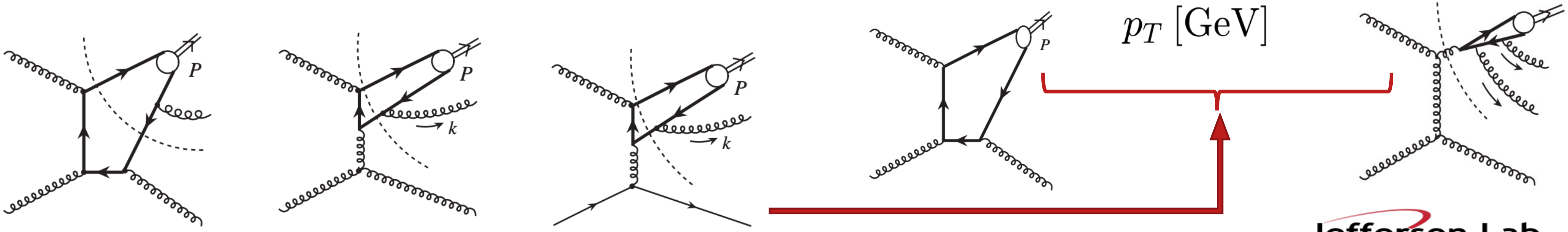
Lee, Qiu, Sterman, Watanabe, 2108.00305, 2211.12648

Matching to fixed-order PQCD calculation

- **Leading power logarithmically enhanced contributions start to dominate when**
  $P_T \gtrsim 5(2m_c) \sim 15$ GeV
- **Next-to-leading power is important for**
  $5(2m_c) \gtrsim P_T \gtrsim (2m_c)$
- **Matching to fixed-order NRQCD calculation**
  $P_T \sim (2m_c)$
  NLP term is necessary for the matching
- **Further improvement by exploring the FFs**
  Use the medium as a filter?

Lee, Qiu, Sterman, Watanabe, 2022





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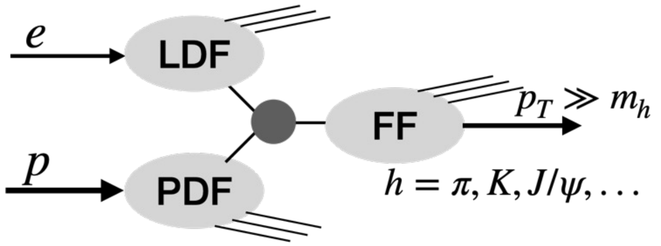
Single inclusive high P_T J/ψ-production in lepton-hadron collisions

❑ PQCD factorization:

$$e + p \to h(p_T) + X$$



PDFs, FFs are common blocks in and collisions.

Perturbatively calculable coefficients

$$\frac{d\sigma_{e+p\to J/\psi+X}}{dp_T} \approx f_{i/e} \otimes f_{j/p} \otimes \left[D_k^{J/\psi} \otimes C_{ij\to k} + D_{c\bar{c}}^{J/\psi} \otimes C_{ij\to c\bar{c}} \right]$$

Universal functions: LDFs, PDFs, FFs

NLO

LO x K_{NLP}

Kang, Metz, Qiu and Zhou, PRD84, 034046 (2011)
Hinderer, Schlegel, Vogelsang, PRD92, 014001 (2015)
Abelof, Boughezal, Liu, Petriello, PLB763, 52-59 (2016)

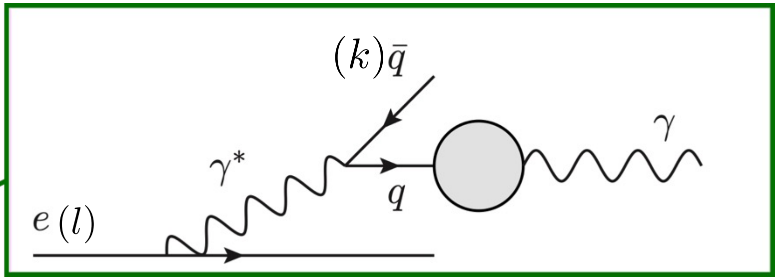
- The scattered lepton is not observed (cf. semi-inclusive DIS: $e + p \to e' + h + X$)
- Collision-induced QED and QCD radiations are consistently treated in terms of collinear factorization formalism [Liu, Melnitchouk, Qiu, Sato, PRD104, no.9, 094033 (2021), JHEP11, 157 (2021)]
- Leptons, photons, and partons in the beam lepton: Universal Lepton Distribution Functions (LDFs)

Remark: DESY-HERA introduced a cut on the transverse momentum of the scattered lepton to separate (electro-production) from (photo-production), leading to the “direct” vs “resolved” photon production

In our approach: we have a choice of the factorization scale, but, no need for such a cut!

Quantum evolution of LDFs

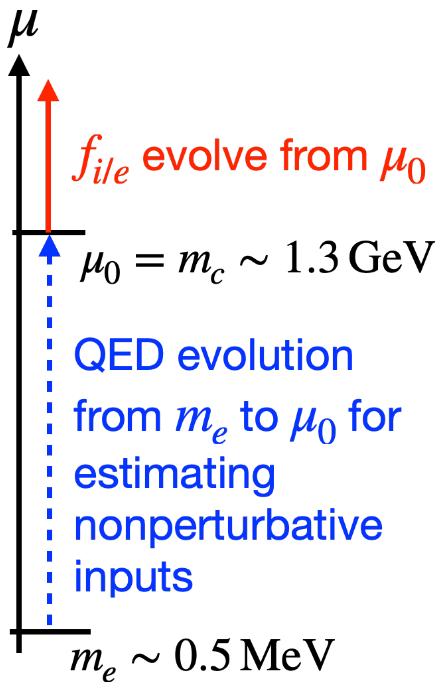
❑ DGLAP evolution: $\xi = \dfrac{k^+_{\text{activelepton(quark)}}}{l^+_{\text{lepton}}}$



QED part **Mixing part**

$$
\frac{\partial}{\partial \ln \mu^2}
\begin{pmatrix}
f_{e/e}(\xi,\mu^2) \\
f_{\bar{e}/e}(\xi,\mu^2) \\
f_{\gamma/e}(\xi,\mu^2) \\
f_{q/e}(\xi,\mu^2) \\
f_{\bar{q}/e}(\xi,\mu^2) \\
f_{g/e}(\xi,\mu^2)
\end{pmatrix}
=
\begin{pmatrix}
P^{(1,0)}_{ee} & P^{(2,0)}_{e\bar{e}} & P^{(1,0)}_{e\gamma} & P^{(2,0)}_{eq} & P^{(2,0)}_{e\bar{q}} & P^{(2,1)}_{eg} \\
P^{(2,0)}_{\bar{e}e} & P^{(1,0)}_{\bar{e}\bar{e}} & P^{(1,0)}_{\bar{e}\gamma} & P^{(2,0)}_{\bar{e}q} & P^{(2,0)}_{\bar{e}\bar{q}} & P^{(2,1)}_{\bar{e}g} \\
P^{(1,0)}_{\gamma e} & P^{(1,0)}_{\gamma\bar{e}} & P^{(1,0)}_{\gamma\gamma} & P^{(1,0)}_{\gamma q} & P^{(1,0)}_{\gamma\bar{q}} & P^{(1,1)}_{\gamma g} \\
P^{(2,0)}_{qe} & P^{(2,0)}_{q\bar{e}} & P^{(1,0)}_{q\gamma} & P^{(0,1)}_{qq} & P^{(0,2)}_{q\bar{q}} & P^{(0,1)}_{qg} \\
P^{(2,0)}_{\bar{q}e} & P^{(2,0)}_{\bar{q}\bar{e}} & P^{(1,0)}_{\bar{q}\gamma} & P^{(0,2)}_{\bar{q}q} & P^{(0,1)}_{\bar{q}\bar{q}} & P^{(0,1)}_{\bar{q}g} \\
P^{(2,1)}_{ge} & P^{(2,1)}_{g\bar{e}} & P^{(1,1)}_{g\gamma} & P^{(0,1)}_{gq} & P^{(0,1)}_{g\bar{q}} & P^{(0,1)}_{gg}
\end{pmatrix}
\otimes
\begin{pmatrix}
f_{e/e}(\xi,\mu^2) \\
f_{\bar{e}/e}(\xi,\mu^2) \\
f_{\gamma/e}(\xi,\mu^2) \\
f_{q/e}(\xi,\mu^2) \\
f_{\bar{q}/e}(\xi,\mu^2) \\
f_{g/e}(\xi,\mu^2)
\end{pmatrix}
$$

Mixing part **QCD part**



Splitting functions in QED+QCD:

$$
P_{ij}(\xi,\mu^2) = \sum_{n,m=0}^{\infty} \left(\frac{\alpha_{em}(\mu^2)}{2\pi}\right)^n \left(\frac{\alpha_s(\mu^2)}{2\pi}\right)^m \hat{P}^{(n,m)}_{ij}(\xi) \equiv \sum_{n,m=0}^{\infty} P^{(n,m)}_{ij}(\xi,\mu^2)
$$

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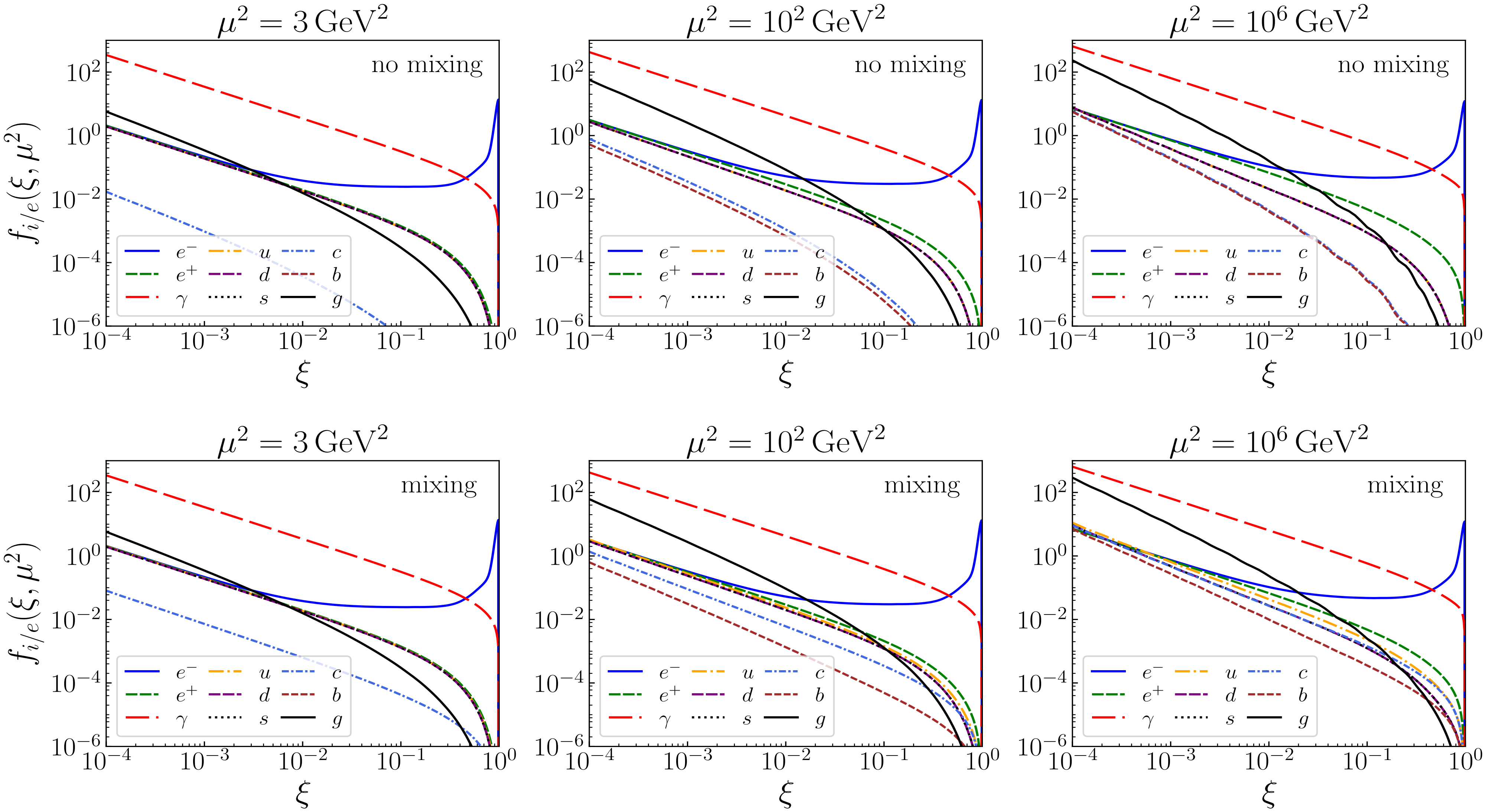
Lepton distribution functions (LDFs) after evolution

Qiu, Watanabe
in preparation



QED (QCD) evolution is slow (fast) due to the weak (strong) μ-dependence of $\alpha_{em}(\alpha_s)$

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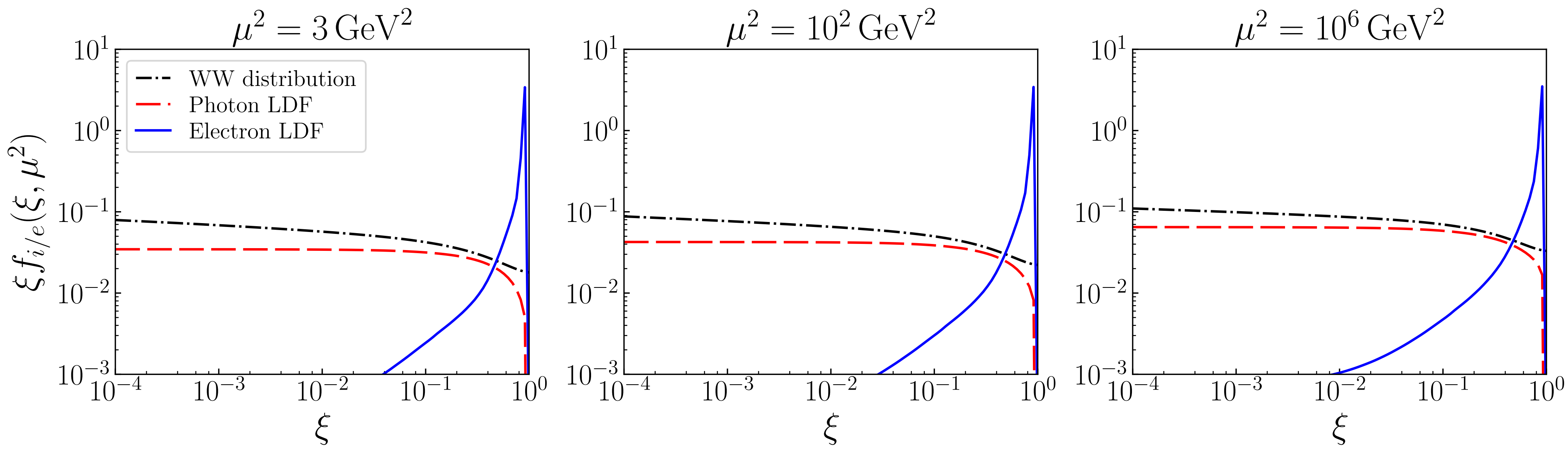
Photon LDF vs. Weizsäcker-Williams distribution

Qiu, Watanabe in preparation



Weizäcker-Williams (WW) distribution at LO with $\overline{\mathrm{MS}}$-scheme: Hinderer, Schlegel, Vogelsang, PRD92, no.1, 014001 (2015)

$$f^{WW}_{\gamma/l}(\xi, \mu^2) = \frac{\alpha_{\mathrm{em}}}{2\pi} P_{\gamma l}(\xi) \left[\ln\left(\frac{\mu^2}{\xi^2 m_l^2}\right) - 1 \right] + \mathcal{O}(\alpha_{\mathrm{em}}^2)$$

- Photon LDF is smaller to WW distribution, but different because of the resummation of large logs, and higher-order corrections, such as $\gamma \to e^+e^-, q^+\bar{q}, \ldots$.
- Photon LDF depends on our purely QED evolution from m_e to μ_0; a global fitting could systematically improve the "red" dashed line.

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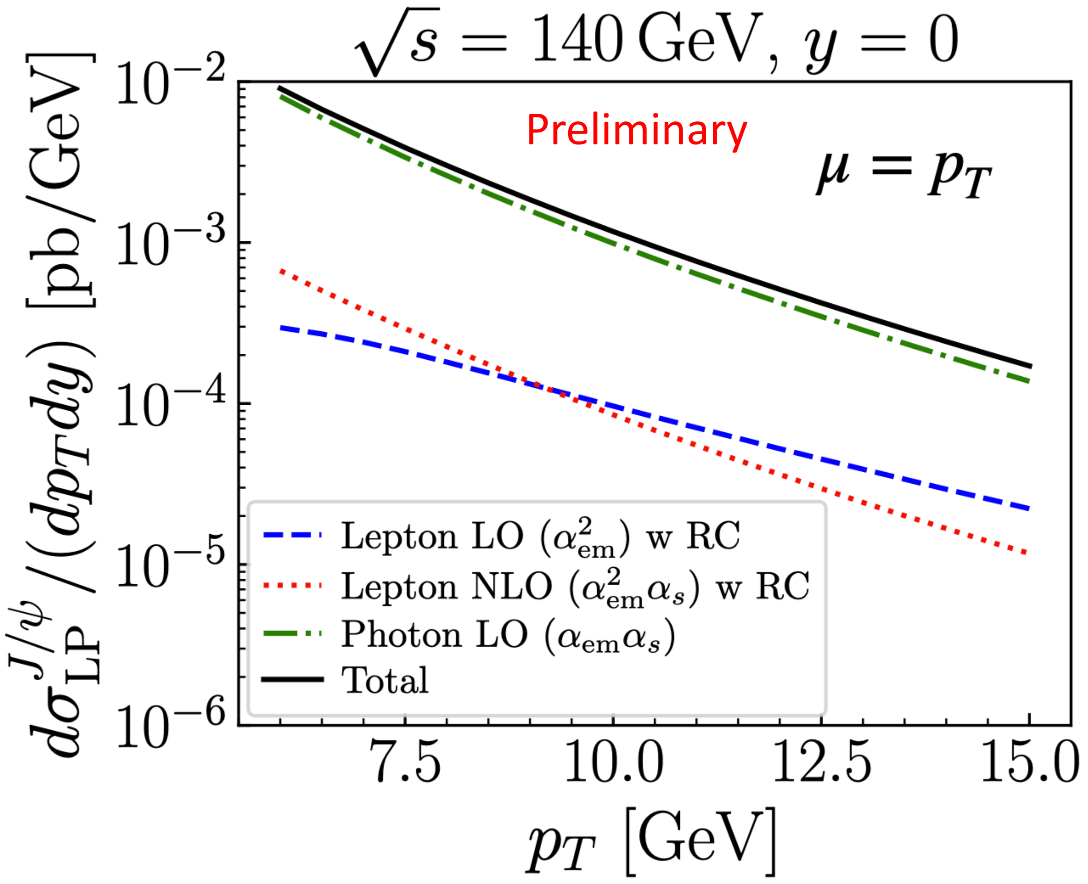
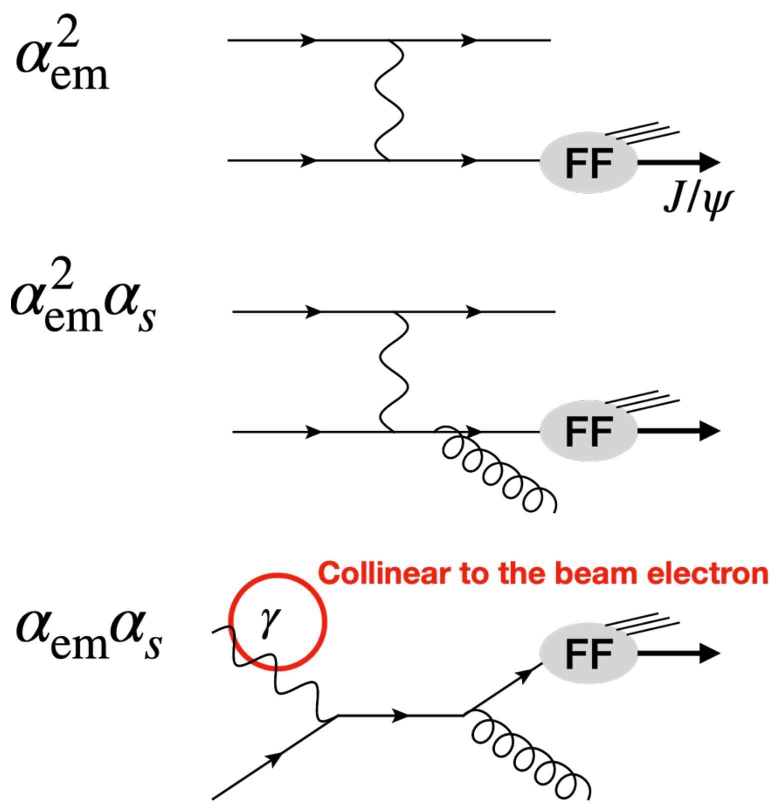
Lepto- and photo-production of J/ψ at leading power (LP)



Qiu, Watanabe
in preparation

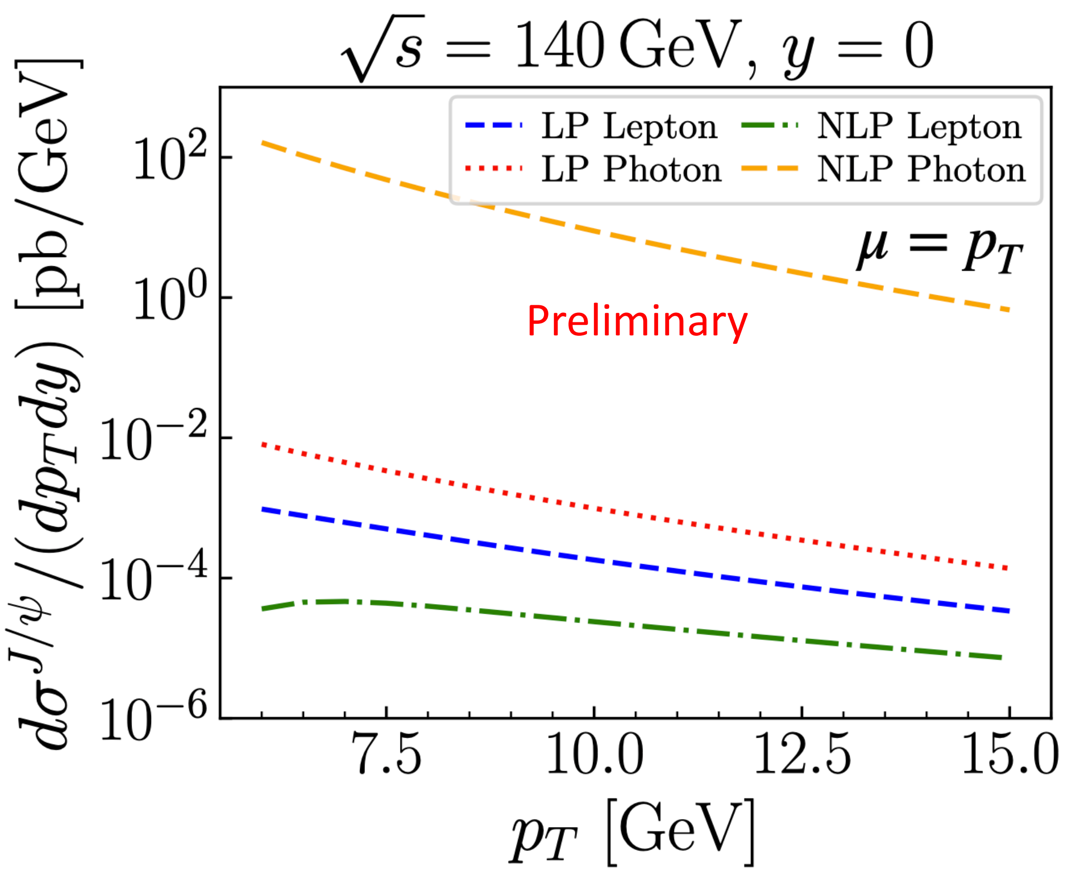
Leading-power in P_T:



- **No Q^2-cut in calculations.**
- **Input scale for the evolution of quarkonium FFs: $\mu_0 = 2m_{J/\psi} \sim 6$ GeV.**
- **The photoproduction overwhelms the leptoproduction at lower P_T.**

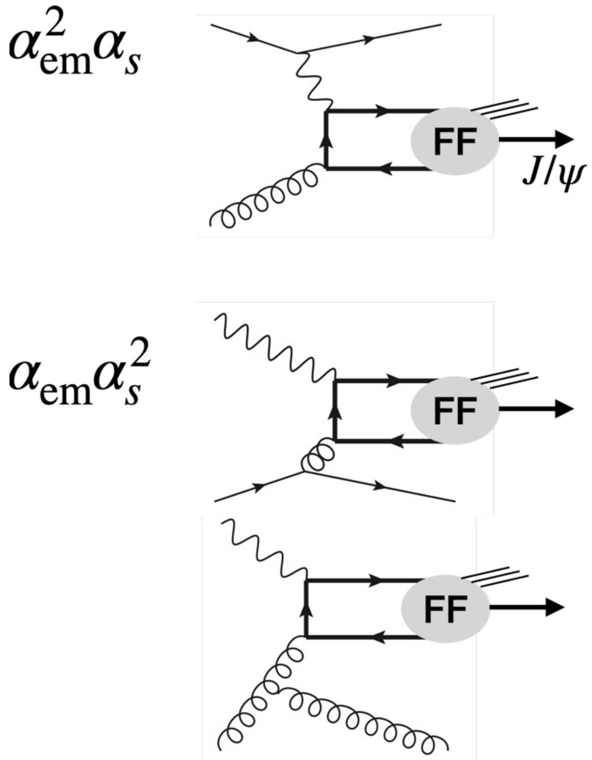
PDFs: CT18ANLO central set
FFs: LQSW set [Lee, Qiu, Sterman, KW, 2108.00305, 2211.12648, and 2023.xxxx]

Next-to-leading power (NLP) contributions



Qiu, Watanabe
in preparation

Next-to-Leading-power in P_T:



- **The photoproduction of J/ψ at NLP is predominant over the LP contribution.**
- **A pair produced at short-distance can easily form a bound state compared to a single parton that fragments into it.**

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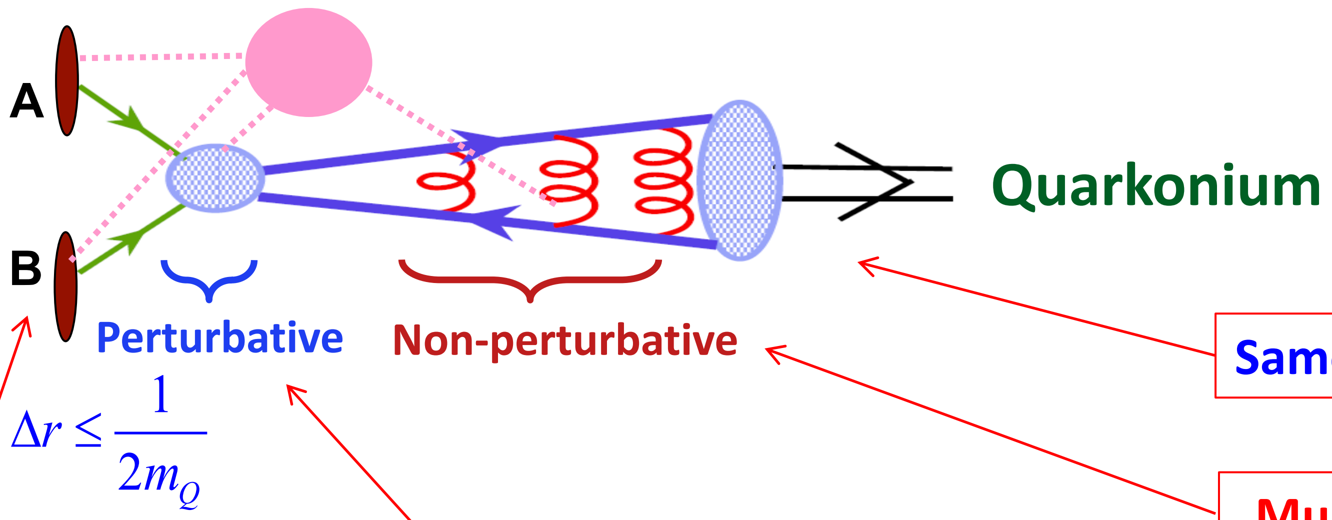
Heavy quarkonium production in a cold medium

Qiu, Watanabe, 2022

- **From ep to eA collision:**



- **QCD Factorization is "expected" to work for the production of heavy quark pair**
- **Hadronization can break the factorization**
- **Large y – time dilation – delay hadronization**

Same wave function

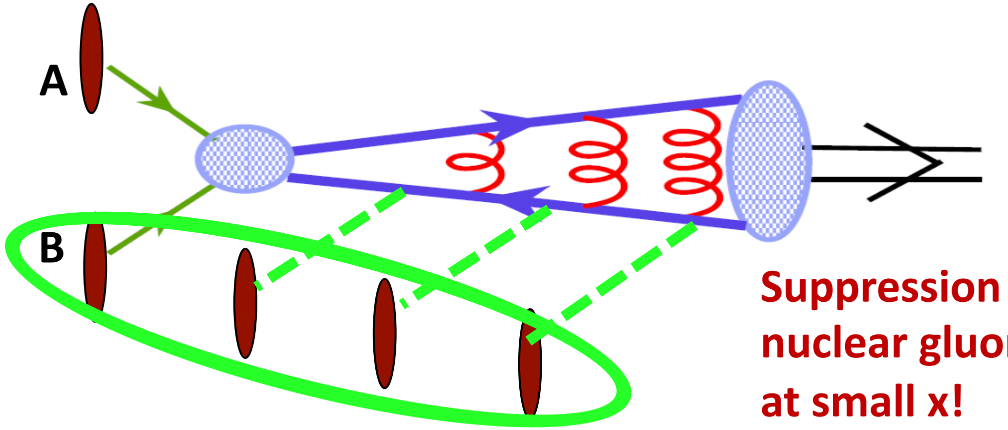
Multiple scattering

Nuclear PDFs

Almost Not affected

- **Multiple scattering of heavy quarks can change:**
  - **Distribution of total momentum of the pair – Cronin effect**

    Guo, Qiu, Zhang, PRL 2000
  - **Invariant mass of the pair (broadening) – Suppression of quarkonium** $R_{pA}(3\Upsilon) < R_{pA}(2\Upsilon) < R_{pA}(1\Upsilon)$



Suppression of nuclear gluons at small x!

Qiu, Vary, Zhang, PRL 2002

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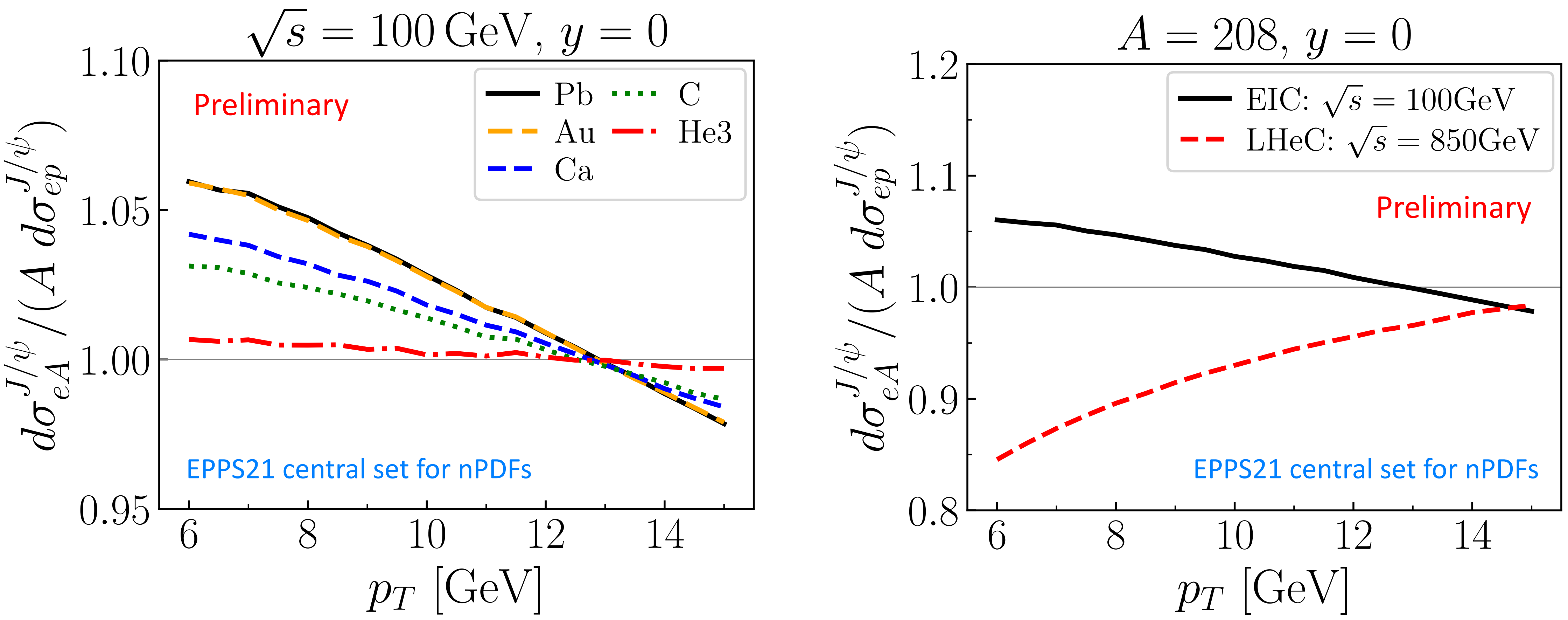
Nuclear modification from nuclear PDFs



- **The onset of nuclear anti-shadowing or EMC effects can be seen in J/ψ production at high P_T in eA collisions at the U.S.-EIC.**
- **LHeC experiments could allow us to explore nuclear shadowing effect.**

Summary and Outlook

- We studied the QCD factorization for single inclusive J/ψ production at high P_T
  - Our approach can consistently describe the full P_T distribution of J/ψ production at Tevatron and the LHC
  - The LP contribution dominates the high PT regime while NLP contribution is necessary for the low P_T shape
  - Theory predictions could be further improved with better determined FFs
  - The FFs at the input scale μ_0 can be extracted for testing NRQCD factorization
- We calculated single inclusive J/ψ production at high P_T in lepton-hadron collisions at the EIC
  - We do not need to introduce artificial cut to separate the lepto- and photo-production of J/ψ
  - Both are very naturally included in our factorization formalism with universal LDFs
  - We found NLP contribution from the production of charm-anticharm pair dominates the production rate
  - We introduced a systematic matching between the fixed-order NRQCD calculation and our factorized contributions
- We calculated nuclear dependence of J/ψ production in eA collisions
  - Soft interaction between colliding nuclei and the hadronization to J/ψ can potentially break the factorization
  - Nuclear dependence from nuclear PDFs, multiple scattering, and de-coherence of the charm-anticharm pair
- Heavy quarkonium production offers more opportunities and challenges

Thanks!

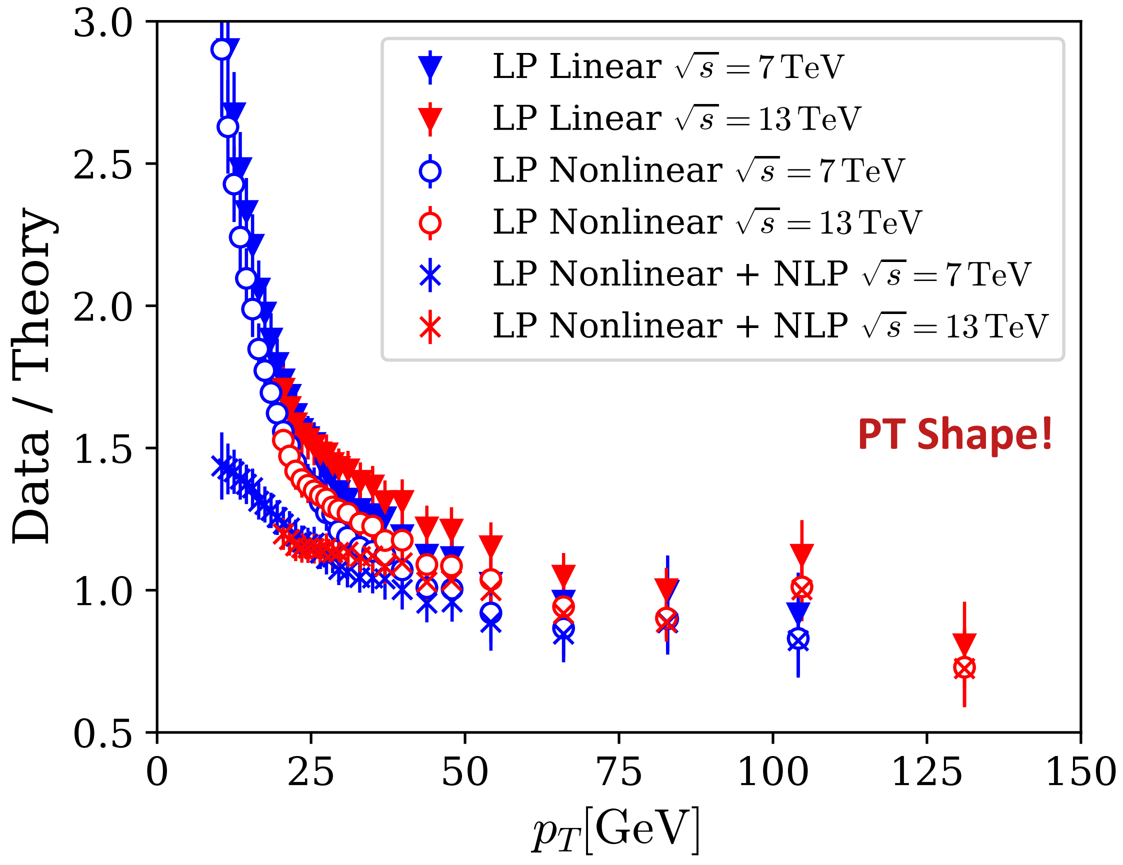
Backup slides

Single inclusive J/ψ-production in hadronic collisions

❑ Leading power contribution:

Lee, Qiu, Sterman, Watanabe, 2022

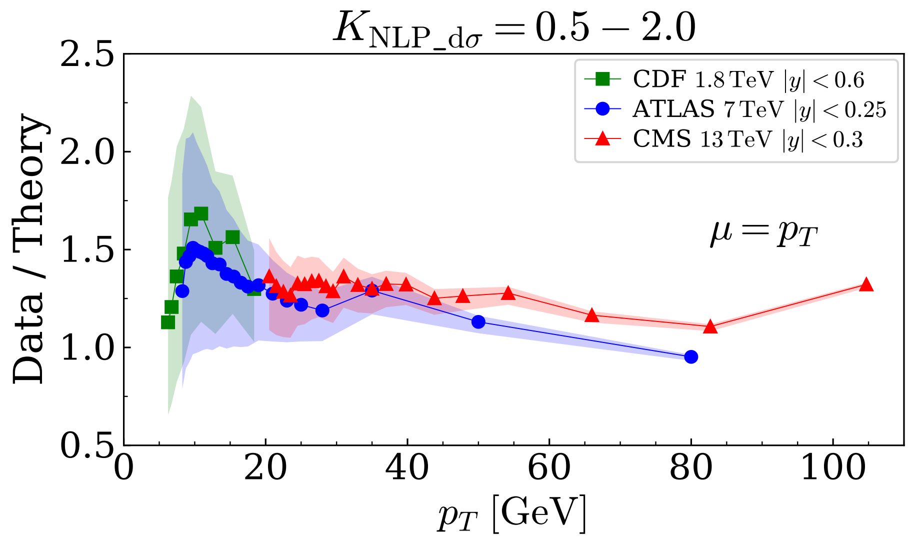
- Fitting the LP formalism with the linear evolution eq. to CMS data on high p_T prompt J/ψ at $\sqrt{s} = 7, 13\,\text{TeV}$ in the bin, $|y| < 1.2$.
- # of data points in a fit: 3@7TeV + 4@13TeV = 7 for $p_T \geq 60\,\text{GeV}$.
- Only the ${}^1S_0^{[8]}$ channel is considered, yielding unpolarized J/ψ. The other two color octet channels could overshoot data by combining LP and NLP.
- $\langle \mathcal{O}({}^1S_0^{[8]}) \rangle/\text{GeV}^3 = 0.1286 \pm 5.179 \cdot 10^{-3}$ fitted by high p_T data is similar to the one extracted using fixed order NRQCD at NLO. Chao, Ma, Shao, Wang, Zhang, PRL108, 242004 (2012)
- Global data fitting is useful to pin down LDMEs and the shape of input FFs.

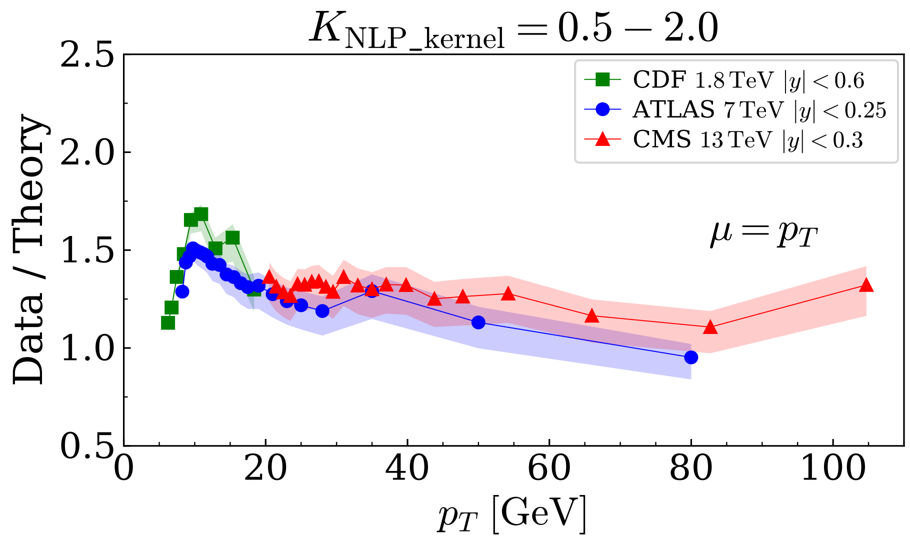


The "power corrections" do not vanish even at the highest p_T, giving 10-30% corrections.
At p_T = 30 GeV and below, the NLP corrections become significant.

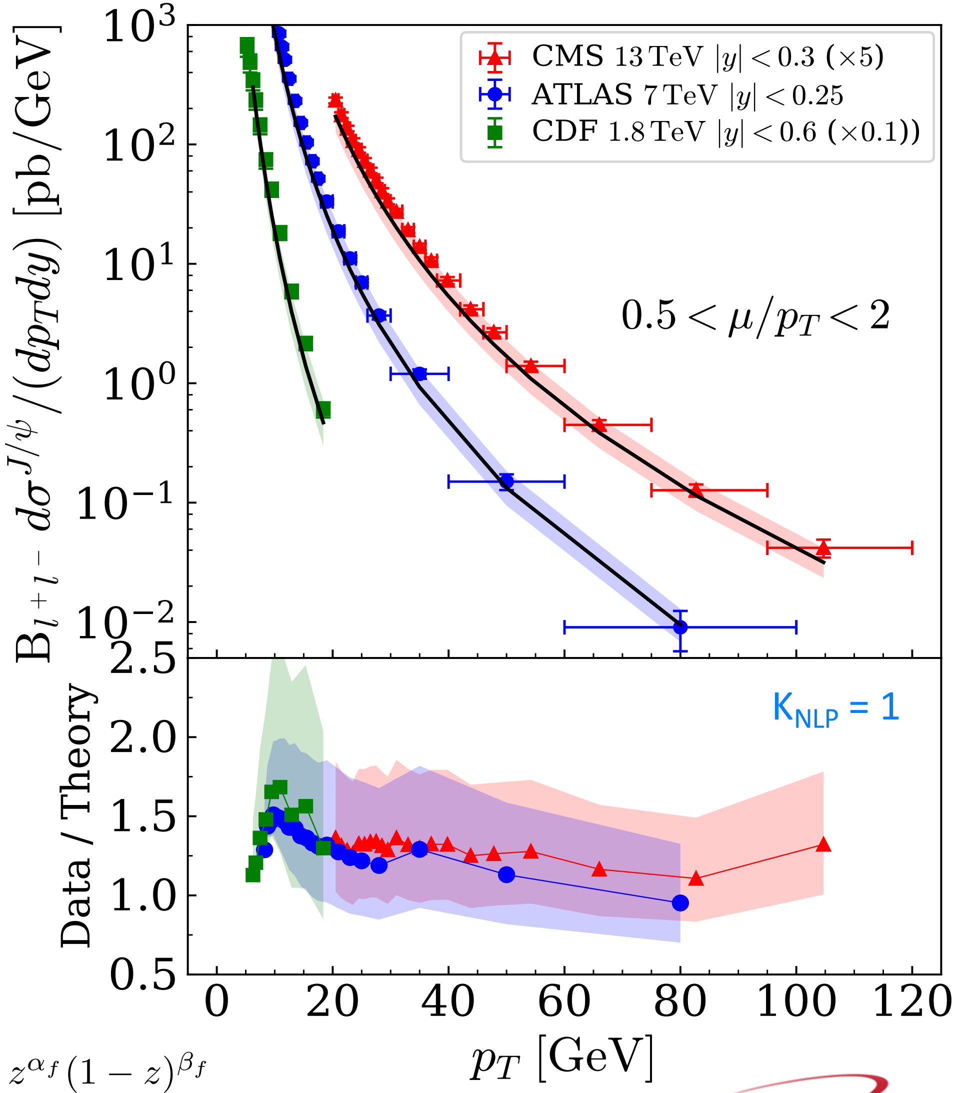
Uncertainty of theoretical calculations for hadronic collisions

❑ K-factor for NLP:





❑ Choice of factorization/renormalization scale:



Model III FFs:

$$D_{f\to H}(z) = N_f \frac{z^{\alpha_f}(1-z)^{\beta_f}}{B(1+\alpha_f, 1+\beta_f)}$$