Heavy quarkonium production and suppression in a dense medium and the impact of threshold effect

- Scales for heavy quarkonium production
- Heavy quarkonium production in terms of QCD factorization
- Quarkonium suppression in a medium as a reduction in production
- Summary and outlook

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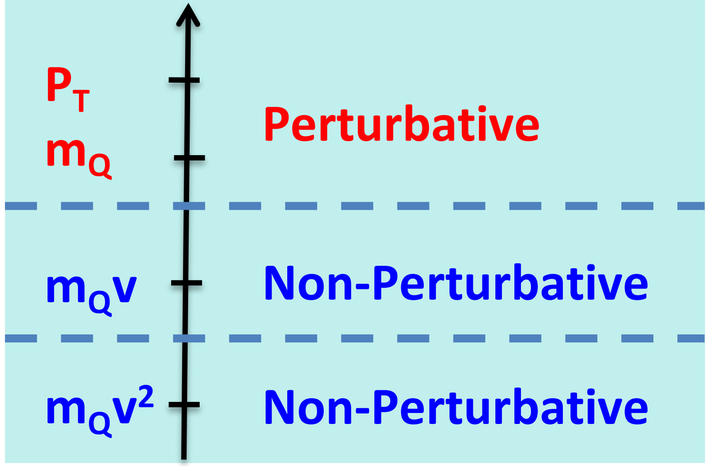
Collaboration with Z.B. Kang, K. Lee, Y.Q. Ma, G. Sterman, K. Watanabe, …

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}

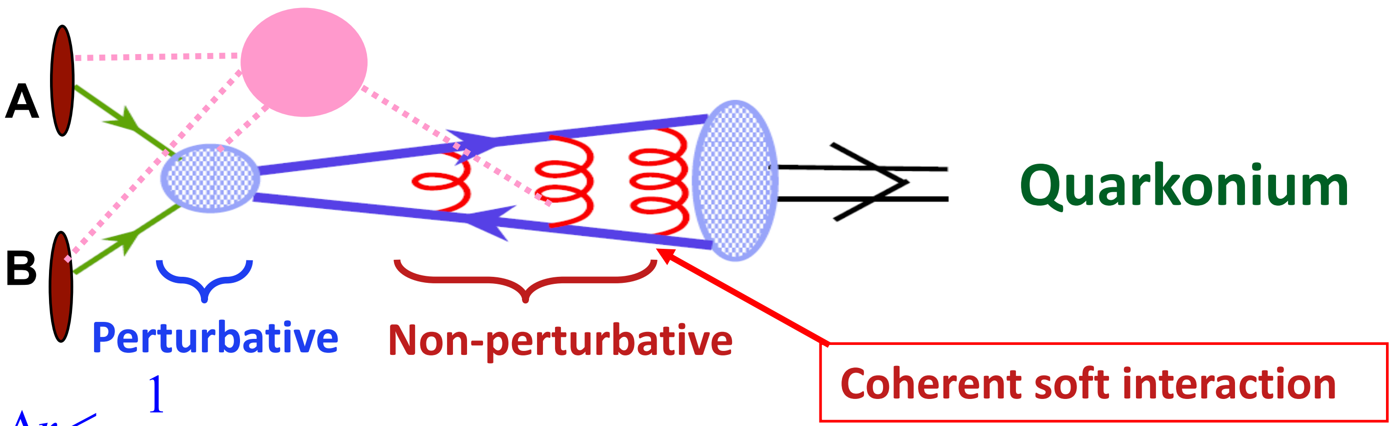
Ultrasoft — Binding Energy [pNRQCD]

Known quarks

Λ_{QCD}

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?
- But, most sensitive to medium effect

Medium effect to learn the emergence of quarkonium from a heavy quark pair

NRQCD factorization and the "lack" of universality of LDMEs

Bodwin, Braaten, Lepage, PRD, 1995

❑ NRQCD factorization:

Expansion in powers of both α_s and v !

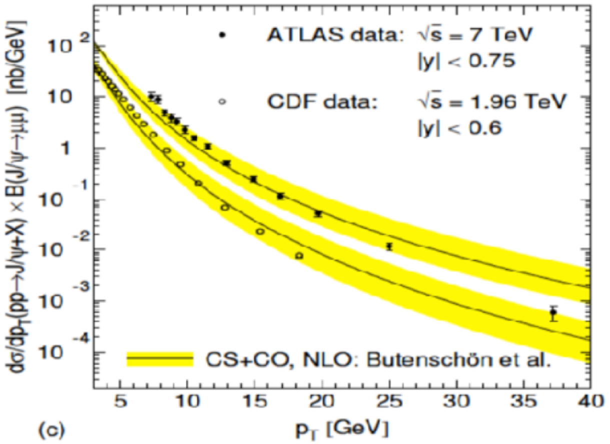
$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \langle \mathcal{O}^H(n) \rangle$$

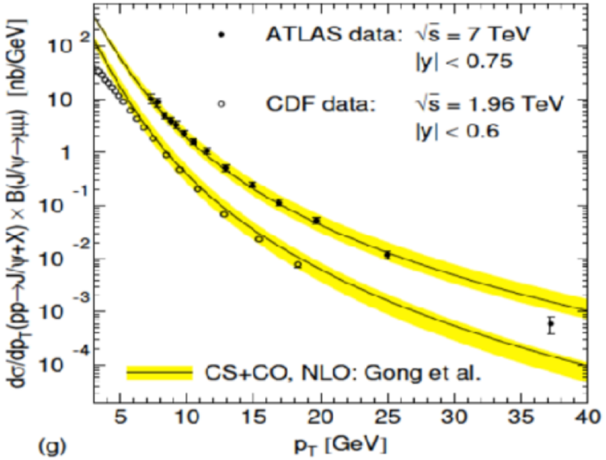
Hadronization

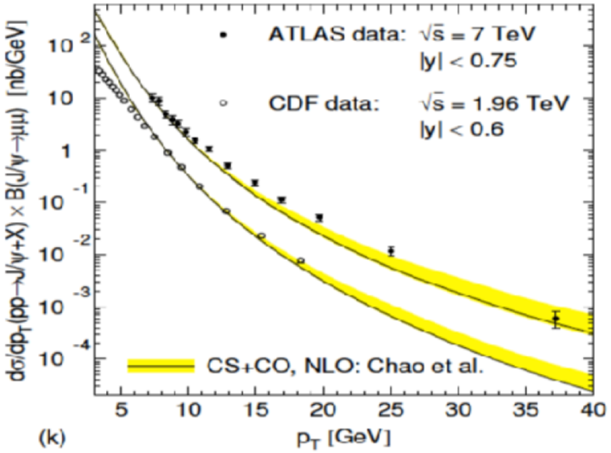
- **4 leading channels in v:**

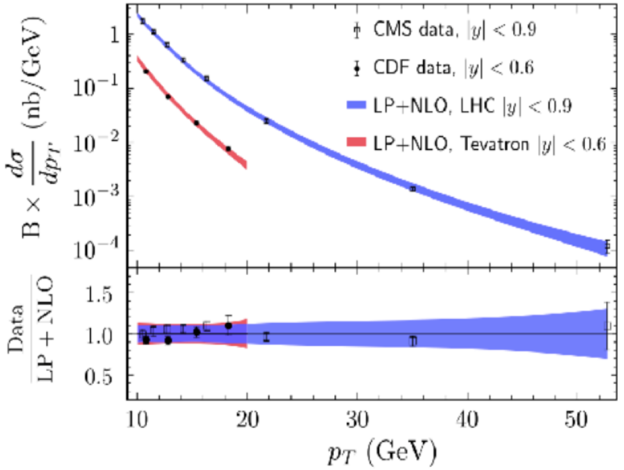
$${}^3S_1^{[1]},\ {}^1S_0^{[8]},\ {}^3S_1^{[8]},\ {}^3P_J^{[8]}$$

❑ Phenomenology – full NLO in α_s:









	$\langle\mathcal{O}({}^3S_1^{[1]})\rangle$ 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
Set I (Butenschoen *et al.*)	1.32	3.04	0.16	−0.91
Set II (Chao *et al.*)	1.16	8.9	0.30	1.26
Set III (Gong *et al.*)	1.16	9.7	−0.46	−2.14
Set IV (Bodwin *et al.*)	-	9.9	1.1	1.1

LDMEs should be universal, however:

- **Numbers are not the same.**
- **Not even the sign.**

More work is needed!

Fits in NRQCD
Butenschoen, Kniehl, PRD84, 051501 (2011).
Chao, Ma, Shao, Wang, Zhang, PRL108, 242004 (2012).
Gong, Wan, Wang, Zhang, PRL110, 042002 (2013).
Bodwin, Chung, Kim, Lee, PRL113, 022001 (2014).
…
Fits in pNRQCD
Brambilla, Chung, Vairo, Wang, PRD105, no.11, L111503 (2022).

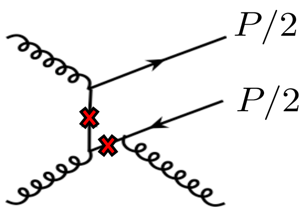
Heavy quarkonium production at high p_T

Kang, Qiu and Sterman, 2011

- $O(\alpha_s)$ **expansion vs. $1/p_T$ expansion:**

CS channel as a case study

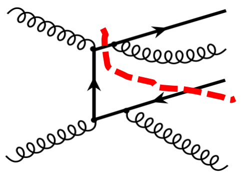
LO in α_s:

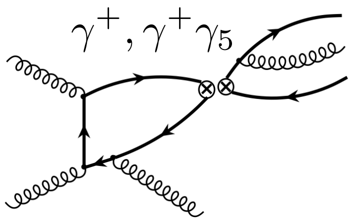


$$\hat{\sigma}^{\rm LO} \propto \frac{\alpha_s^3(p_T)}{p_T^8}$$

P_T Power!

NLO in α_s:

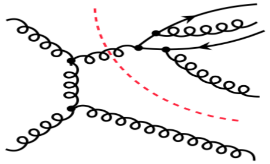




$$\hat{\sigma}^{\rm NLO} \to \frac{\alpha_s^3(p_T)}{p_T^6} \otimes \alpha_s(\mu) \log(\mu^2/\mu_0^2)$$

$$\mu_0 \gtrsim 2m_Q$$

NNLO in α_s:



$$\hat{\sigma}^{\rm NNLP} \to \frac{\alpha_s^2(p_T)}{p_T^4} \otimes \alpha_s^3(\mu) \log^m(\mu^2/\mu_0^2)$$

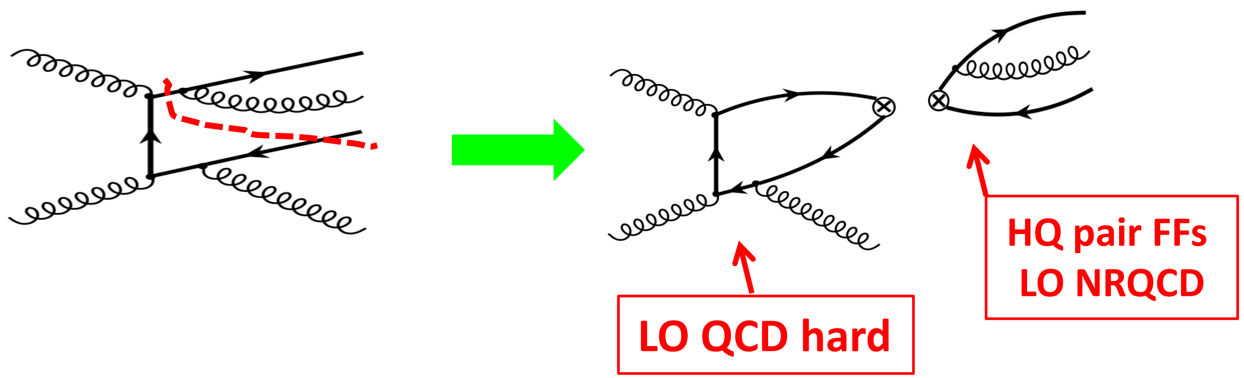
- **When p_T >> m_Q, the expansion in powers of α_s is not reliable!**
- **Leading order in α_s-expansion =\= leading power in $1/p_T$-expansion!**

- **PQCD factorization:**
  - $1/p_T$ expansion first: leading power (LP) & next-to-leading power (NLP) are factorizable!
  - $O(\alpha_s)$-expansion: leading order (LO) & next-to-leading order (NLO) are calculated

QCD factorization + NRQCD factorization

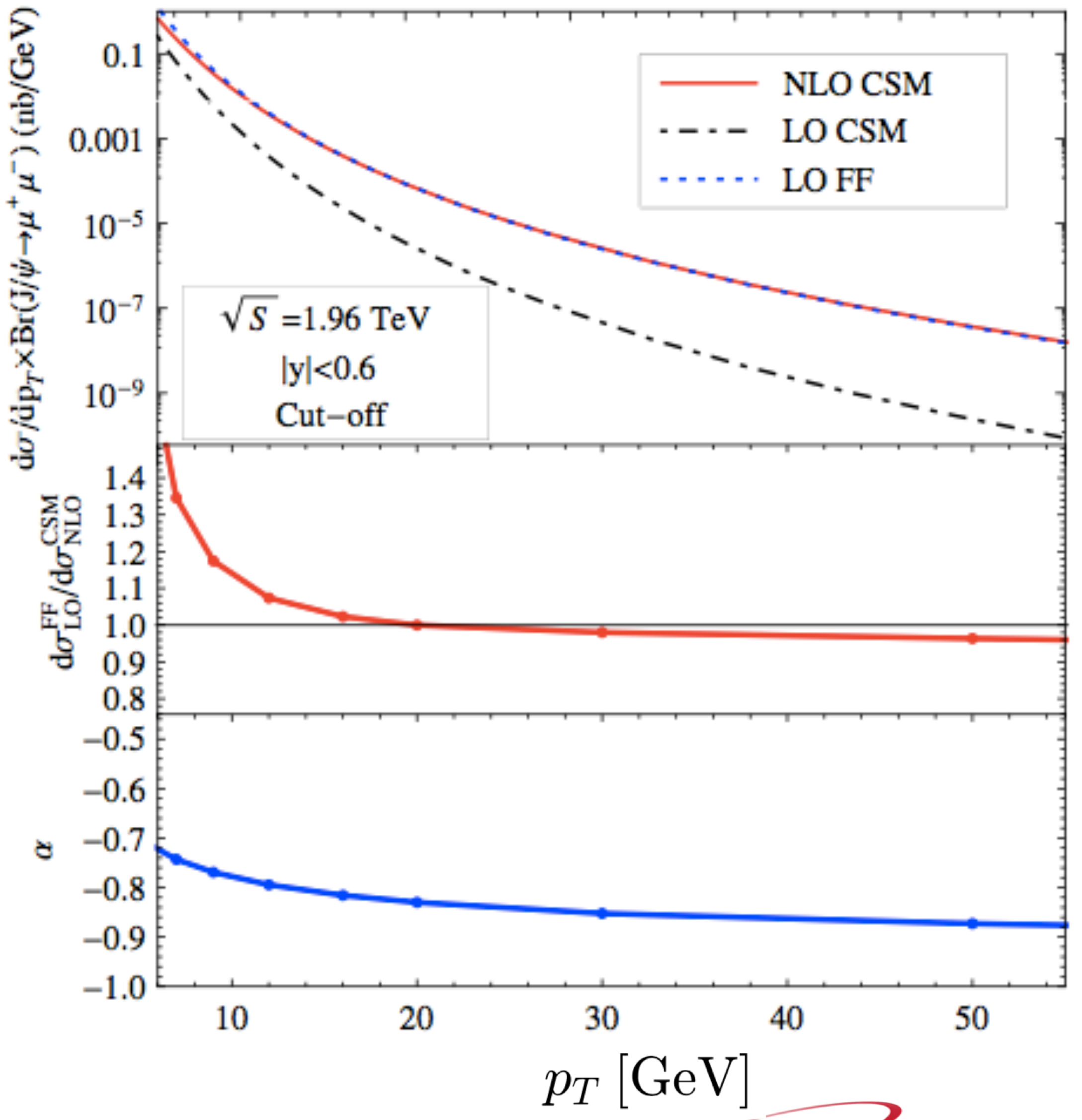
Kang, Qiu and Sterman, 2011

❑ **Color singlet as an example:**



$$\sigma^{(\mathrm{NLO})}_{\mathrm{NRQCD}} \propto \Big[d\hat{\sigma}^{A(\mathrm{LO})}_{ab\to[Q\bar{Q}(v8)]} \otimes \mathcal{D}^{(\mathrm{LO})}_{[Q\bar{Q}(v8)]\to J/\psi} + d\hat{\sigma}^{S(\mathrm{LO})}_{ab\to[Q\bar{Q}(a8)]} \otimes \mathcal{D}^{(\mathrm{LO})}_{[Q\bar{Q}(a8)]\to J/\psi} \Big]$$

$$v8 = [\gamma^+]^{[8]}$$
$$a8 = [\gamma^+\gamma_5]^{[8]}$$



Reproduce NLO CSM for p_T > 10 GeV!

Cross section + polarization

Different kinematics, different approximation,
Dominance of different production channels!

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:

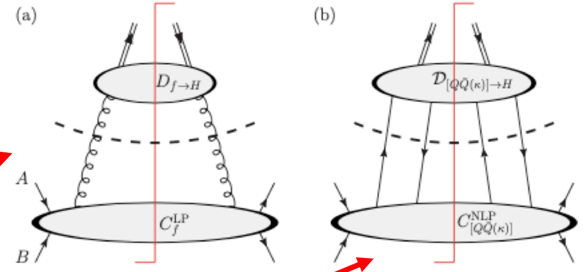
$$F_{c\bar{c}[n]\to J/\psi} = \langle O^{J/\psi}_{c\bar{c}[n]}(0)\rangle$$

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

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

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

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



Kang, Ma, Qiu, Sterman, 2014

- **PQCD fixed-order:**

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

- **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

- **Renormalization group:**

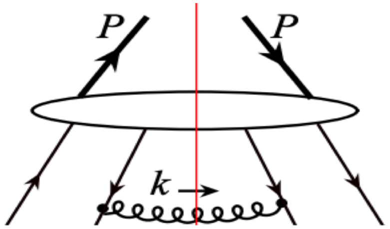
Kang, Ma, Qiu, Sterman, PRD 90, 034006 (2014)

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

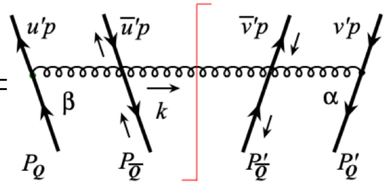
To be accurate up to the 1st power correction

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

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

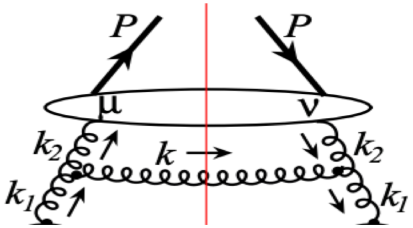


$\Gamma =$



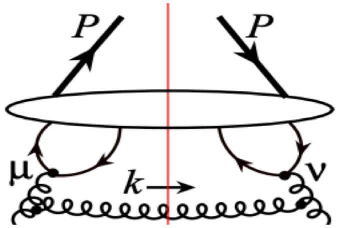
DGLAP-type: Heavy quark pair produced at the hard scale

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



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

Evolution of $c\bar{c}$-fragmentation function in μ, ν space

Lee, Qiu, Sterman, Watanabe, in preparation

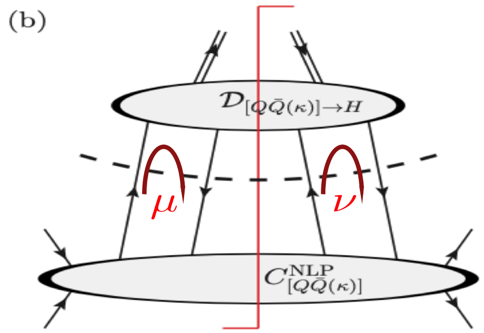
- To justify an approximation at $\mu = \nu = 1/2$:

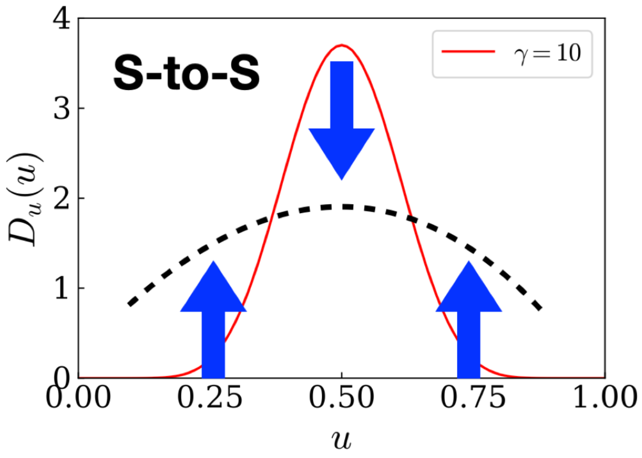
$$D'_{\kappa\to n}(z,u,v) \equiv \frac{2\pi}{\alpha_s}\frac{dD_{\kappa\to n}(z,u,v)}{d\ln\mu^2},$$

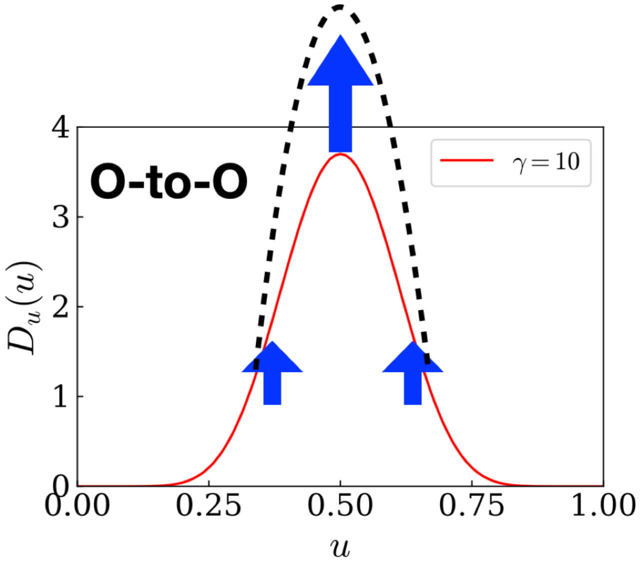
$$D(z,u,v) \to D_z(z)D_u(u)D_v(v),$$

$$D_z(z,\alpha) = \frac{z^\alpha(1-z)^\beta}{B[1+\alpha,1+\beta]},$$

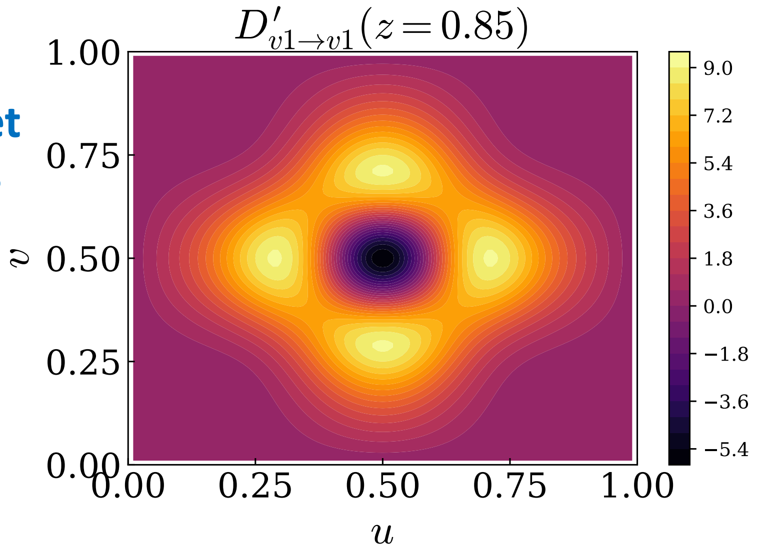
$$D_{u,v}(x,\gamma) = \frac{x^\gamma(1-x)^\gamma}{B[1+\gamma,1+\gamma]},$$



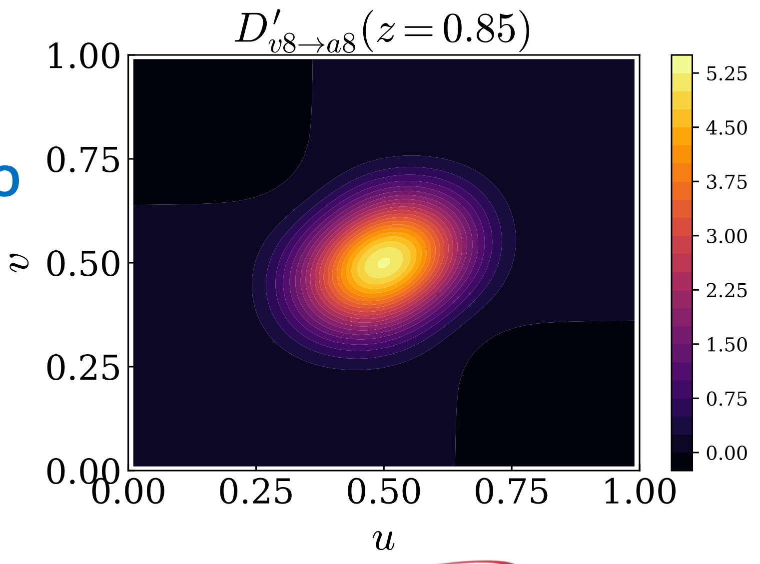




Diagonal singlet channel: S-to-S



Diagonal octet channel: O-to-O



- S-to-S DP FFs get broader in -space after evolution.
- O-to-O DP FFs become narrower with a large peak around .
- Off-diagonal channels: similar to O-to-O.

Input fragmentation functions at $\mu_0 \sim \# \, m_c$

❑ Input FFs from NRQCD:

Ma, Qiu, Zhang, PRD89 (2014) 094029; ibid. 94030
Lee, Qiu, Sterman, Watanabe, SciPost Phys. Proc. 8, 143 (2022)

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

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

$\mu_0 = \mathcal{O}(2m)$: input scale, $\mu_\Lambda = \mathcal{O}(m)$: NRQCD factorization scale $\quad \kappa = v^{[c]}, a^{[c]}, t^{[c]}, \quad n = {}^{2S+1}L_J^{[c]}$

Perturbative SDCs $\hat{d}^{(n)}(z)$ of input FFs in α_s and v expansion in the NRQCD are reliable only when SDCs << O(1).
SDCs $\hat{d}^{(n)}(z)$ calculated in NRQCD factorization is not reliable as $z \to 1$ for the following terms:

1. $\delta(1-z)$ at LO in α_s expansion
2. $f(z)\ln(1-z)$ with $f(z)$ being a regular function
3. $\dfrac{f(z)}{[1-z]_+}$, $f(z)\left[\dfrac{\ln(1-z)}{1-z}\right]_+$ due to the perturbative cancelation of IR divergences

In our current analysis, we use analytic results if those vanish as $z \to 1$; and for singular or negative input FFs, we model them with proper normalization:

$C_{[Q\bar{Q}(n)]}(\alpha_s)$: abs. value of the first moment

$$D_{[Q\bar{Q}(n)]}(z) = C_{[Q\bar{Q}(n)]}(\alpha_s)\frac{z^\alpha(1-z)^\beta}{B[1+\alpha, 1+\beta]} \qquad (\alpha \gg 1,\ 1 > \beta > 0)$$

→ to be tuned, imitating δ-function at LO

NLP contribution to single parton fragmentation functions

Lee, Qiu, Sterman, Watanabe, 2022

❑ Impact of inhomogeneous term:

$$\frac{\partial D_{f\to H}}{\partial \ln \mu^2} = \gamma_{f\to f'} \otimes D_{f'\to H} + \frac{1}{\mu^2}\gamma_{f\to[Q\bar{Q}(\kappa)]} \otimes \mathcal{D}_{[Q\bar{Q}(\kappa)]\to H}$$

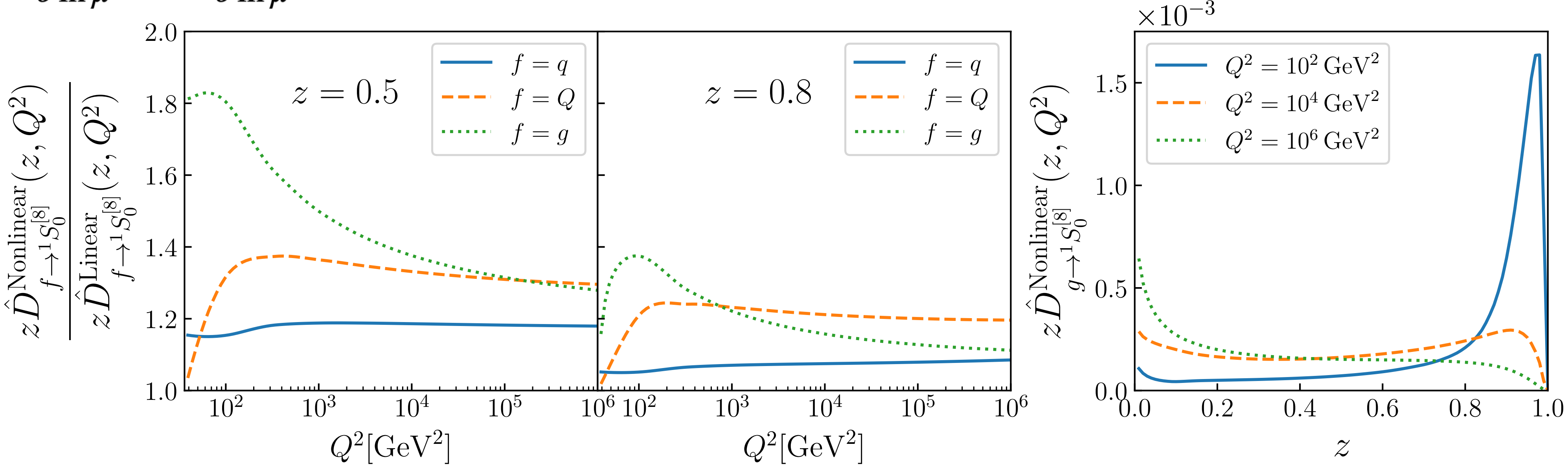
$$\frac{\partial D^{\text{Nonlinear}}_{f\to H}}{\partial \ln \mu^2} \sim \frac{\partial D^{\text{Linear}}_{f\to H}}{\partial \ln \mu^2}$$

$\mu^2 \to \infty$: the slope of $D_{f\to H}$ is the same as LP DGLAP.

$\alpha = 30, \beta = 0.5$

$\mu_0 = 4m_c = 6\,\text{GeV}$

$\mu_\Lambda = m_c = 1.5\,\text{GeV}$



The inhomogeneous quark pair corrections remain significant even at high $Q^2 \sim \mu^2 \sim pT^2$

The power corrections effect at low μ^2 does not go away fast: analogous to nonlinear gluon recombination effects to gluon PDF at small-x and large μ^2.

Mueller and Qiu, NPB268, 427 (1986)
Qiu, NPB291, 746 (1987)
Eskola, Honkanen, Kolhinen, Qiu and Salgado, NPB660, 211 (2003)

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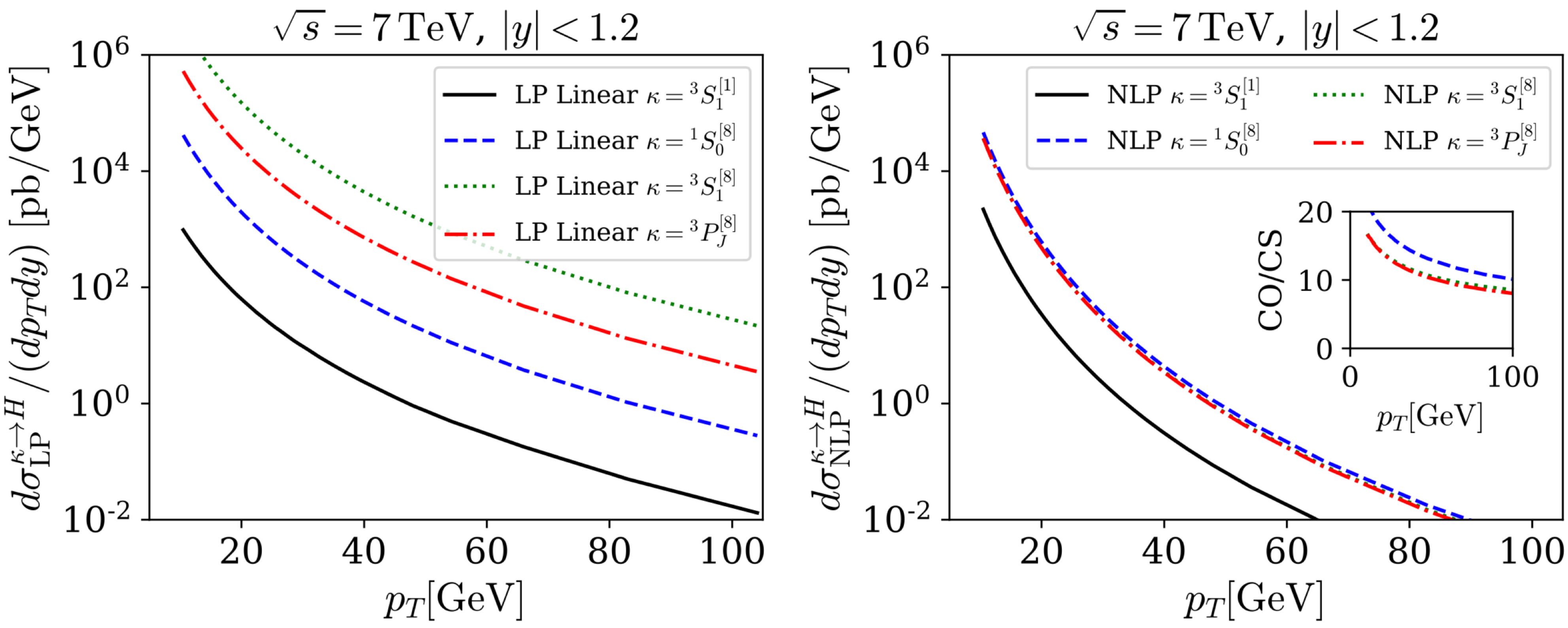
J/ψ-production in hadronic collisions

❑ Separate LDMEs from pQCD effects:

Lee, Qiu, Sterman, Watanabe, 2022



- Unweighted results: $\langle \mathcal{O}(^3S_1^{[1]})\rangle/\mathrm{GeV}^3 = \langle \mathcal{O}(^1S_0^{[8]})\rangle/\mathrm{GeV}^3 = \langle \mathcal{O}(^3S_1^{[8]})\rangle/\mathrm{GeV}^3 = \langle \mathcal{O}(^3P_0^{[8]})\rangle/\mathrm{GeV}^5 = 1.$
- $\alpha = 30, \beta = 0.5$ are fixed for both SP and DP FFs.
- $^1S_0^{[8]}$ is two orders of magnitude smaller than $^3S_1^{[8]}$ at LP.
- Three color octet channels at NLP provide similar contributions, steeply falling with p_T.

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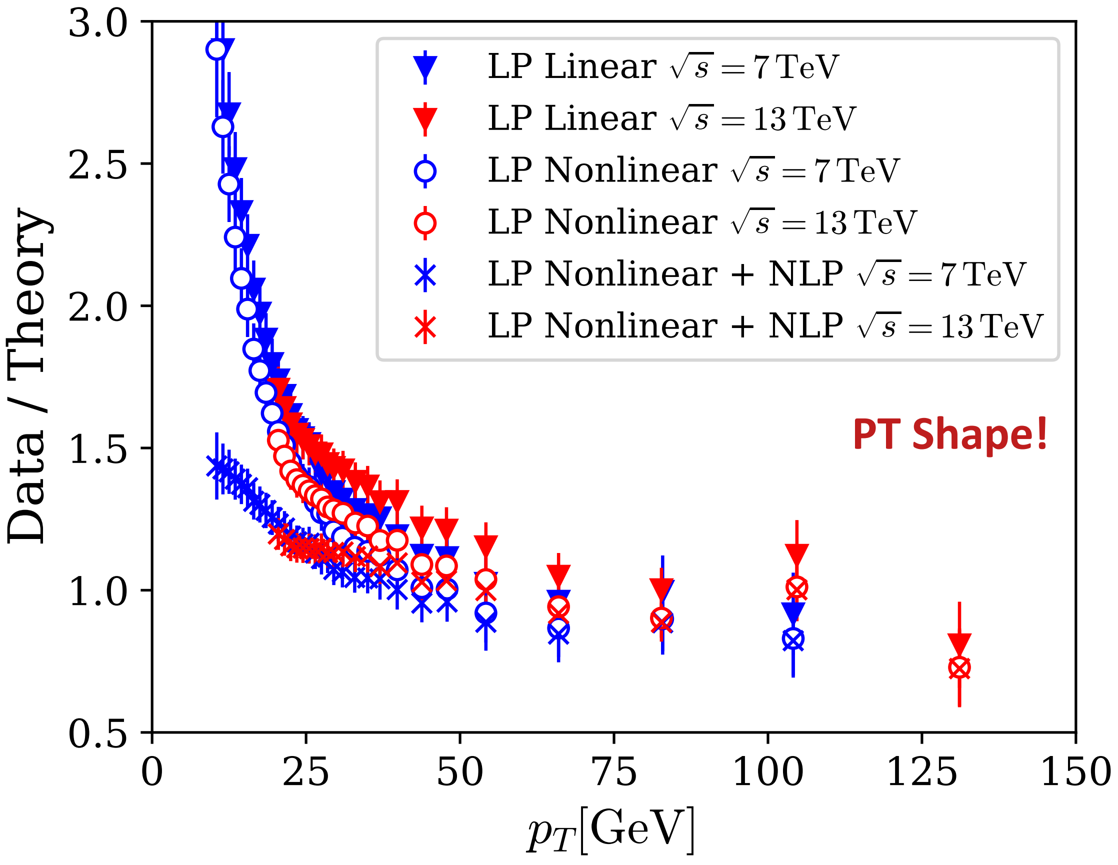
J/ψ-production in hadronic collisions

❑ 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 $\sqrt{s} = 7, 13$ 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.

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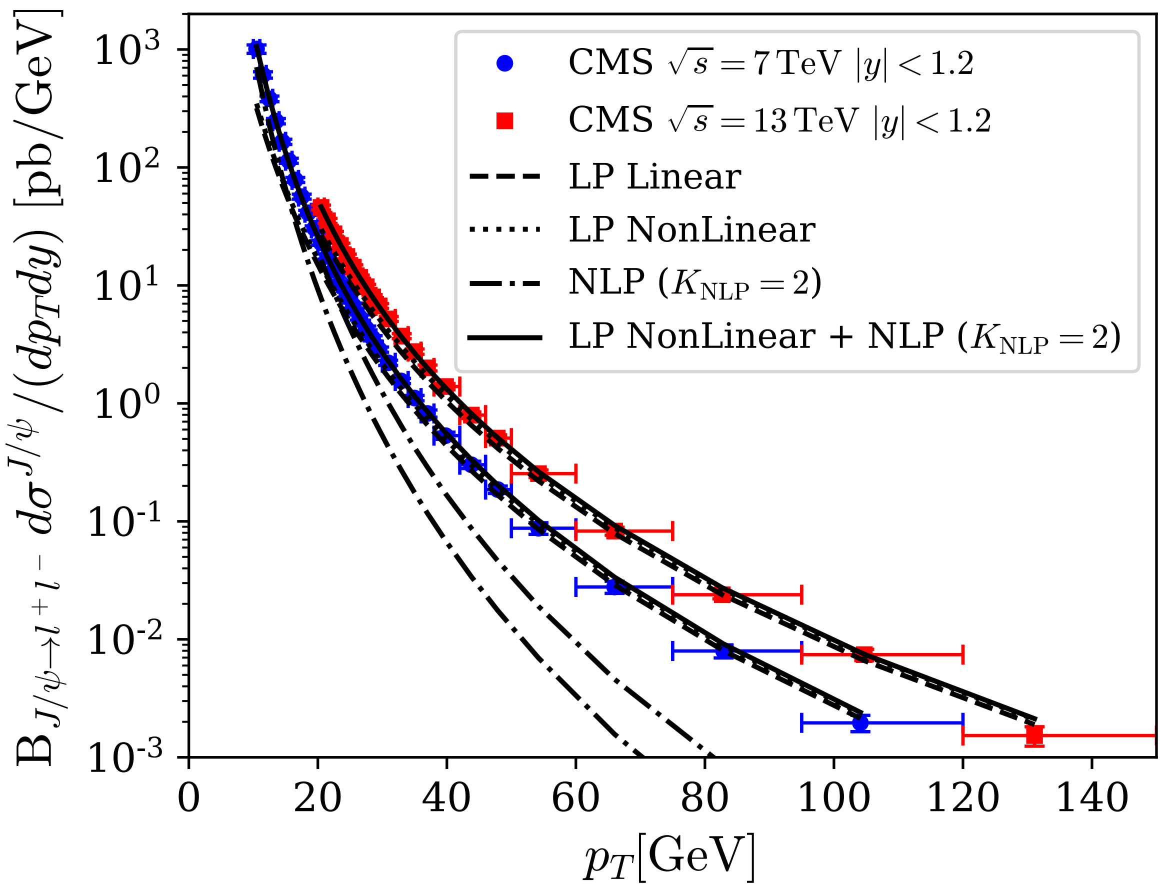
J/ψ-production in hadronic collisions

Lee, Qiu, Sterman, Watanabe, 2022

❑ LP + NLP contributions:

- Putting $\alpha = 30, \beta = 0.5$ at $\mu_0 = 4m_c$ and $\mu_\Lambda = m_c$, $\langle \mathcal{O}(^1S_0^{[8]})\rangle/\text{GeV}^3 = 0.1286 \pm 5.179 \cdot 10^{-3}$ is obtained.
- K-factor is included to account for higher order corrections of the NLP partonic cross section. We simply fix $K_{\text{NLP}} = 2$.

Choose two numbers with a smaller set of data



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J/ψ-production in hadronic collisions

❑ **Test the consistency:**

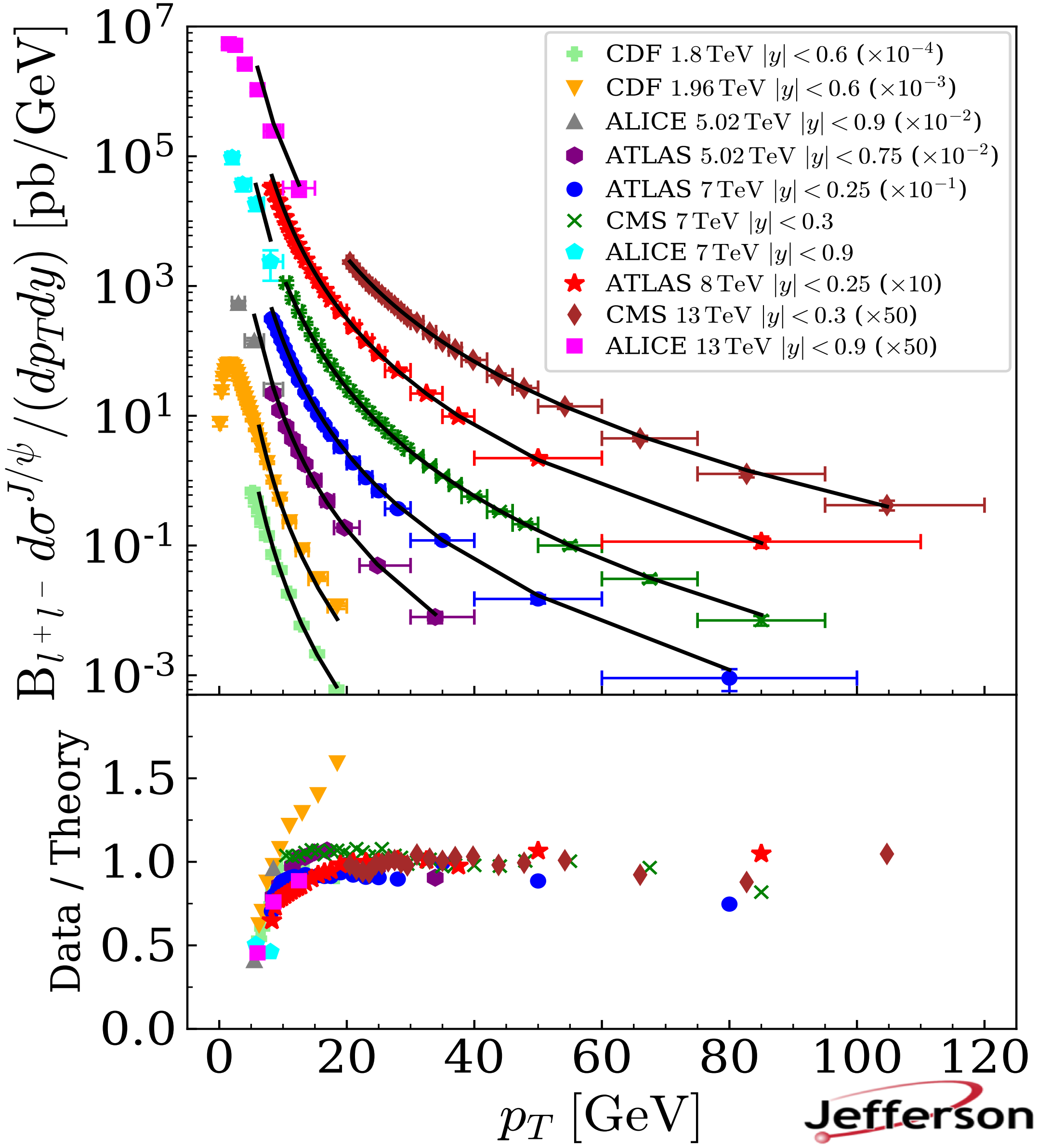
- Given that the overall normalization factor is fixed, QCD factorization approach describes LHC data on prompt J/ψ production in hadronic collisions.

→ **QCD global data analysis is possible.**

- We could modify K_{NLP} at Tevatron energies, but $K_{\text{NLP}} = 2$ is fixed here.

Compare with both the LHC and Tevatron data without changing parameters!

Lee, Qiu, Sterman, Watanabe, 2022



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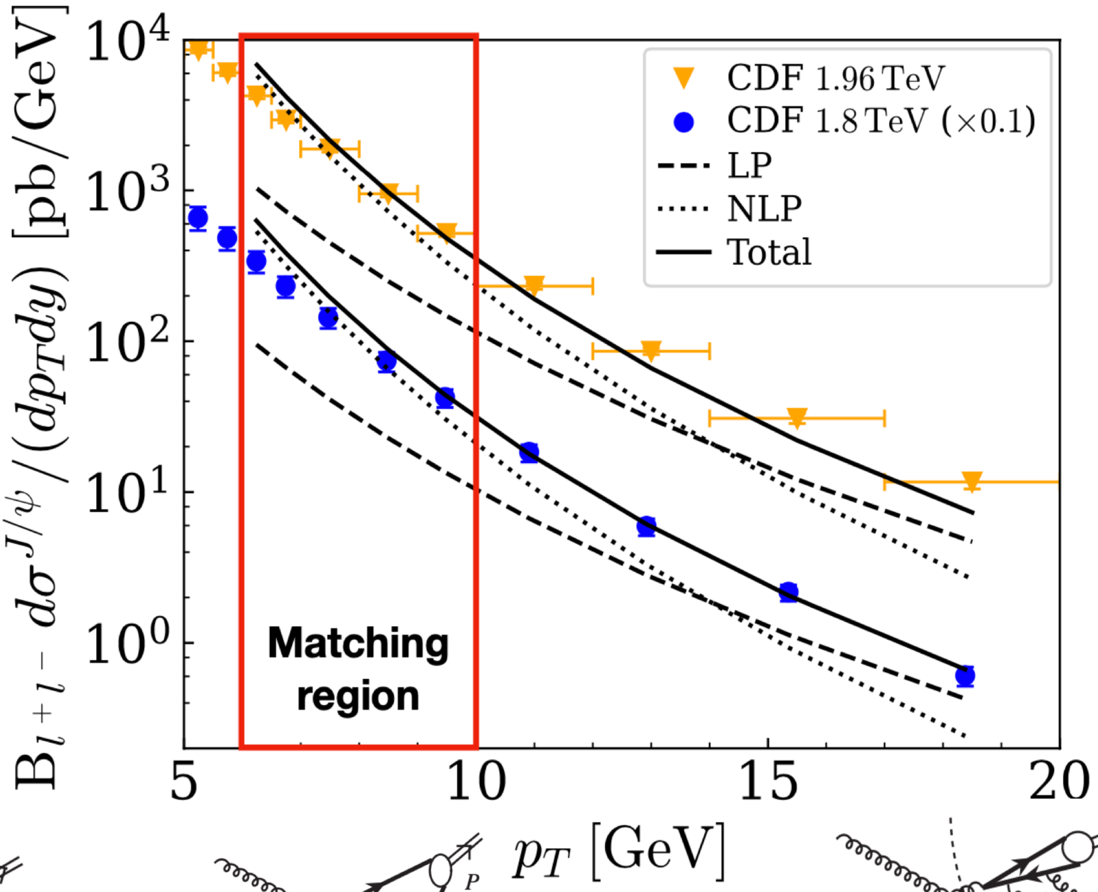
Matching to fixed-order PQCD calculation

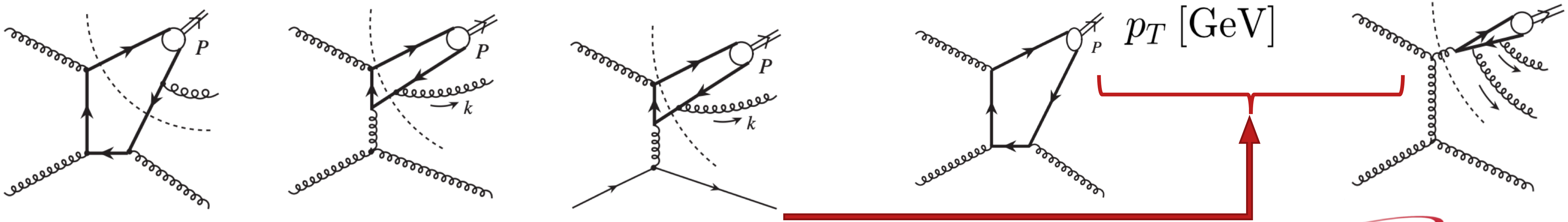
1. $\ln(p_T^2/m^2)$-type logarithmically enhanced contributions start to dominate when $p_T \gtrsim 5\,(\text{or } 7)\,(2m_c) \sim 15 - 20\,\text{GeV}$, where the LP is significant, power corrections are small.

2. The NLP contribution is important at $p_T = \mathcal{O}(2m_c) \lesssim 10\,\text{GeV}$, where matching between QCD factorization and NRQCD factorization can be made.

3. Further exploration of the shape of the FFs at large-z would help us understand the quarkonium production mechanism.

Lee, Qiu, Sterman, Watanabe, 2022





Or use the medium as a filter or detector?

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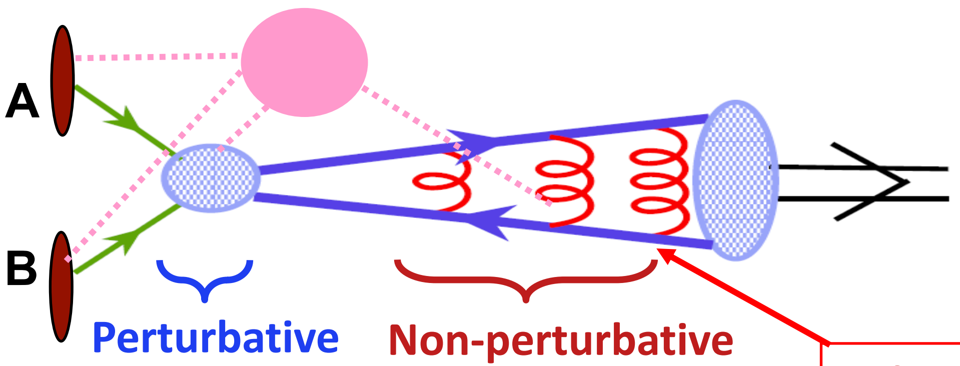
Emergence of a heavy quarkonium from a heavy quark pair

Qiu, Watanabe, 2022

❑ Basic production mechanism:

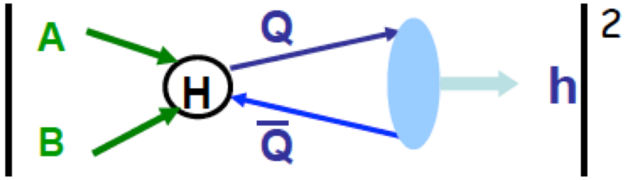


$\Delta r \le \frac{1}{2m_Q}$

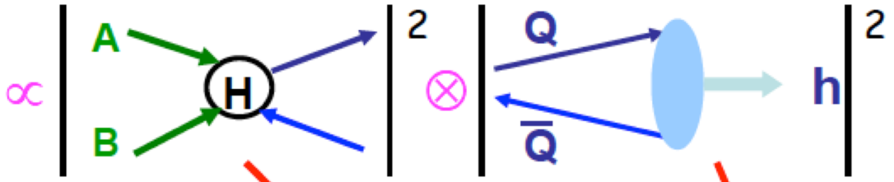
- QCD Factorization is "expected" to work for the production of heavy quark pair
- Difficulty: how the heavy quark pair becomes a quarkonium?
- But, most sensitive to medium effect

❑ Approximation:

$\sigma_{AB\to h} \propto$



$\propto$



$+ \frac{\langle M_H^2 - 4m_Q^2 \rangle}{M_H^2}$

Transition Distribution

$$\sigma_{AB\to h} = \int dq^2\ \hat{\sigma}_{AB\to[Q\bar{Q}]}(m_Q^2, q^2)\ F_{[Q\bar{Q}]\to h}(q^2) + \ldots = \sum_{[Q\bar{Q}]} F_{[Q\bar{Q}]\to H} \otimes \hat{\sigma}_{AB\to[Q\bar{Q}]} + \ldots$$

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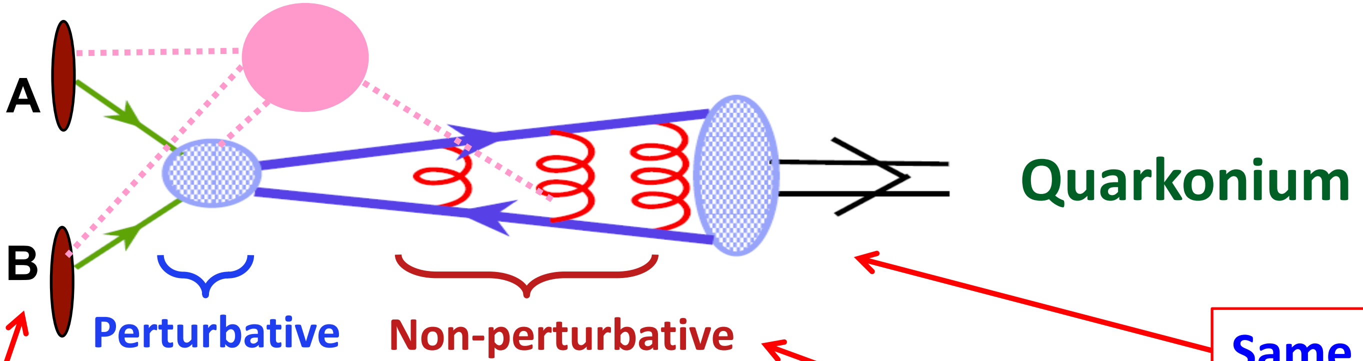
Emergence of a heavy quarkonium from a heavy quark pair

Qiu, Watanabe, 2022

- **From pp to pA collision:**



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

- **QCD Factorization is "expected" to work for the production of heavy quark pair**

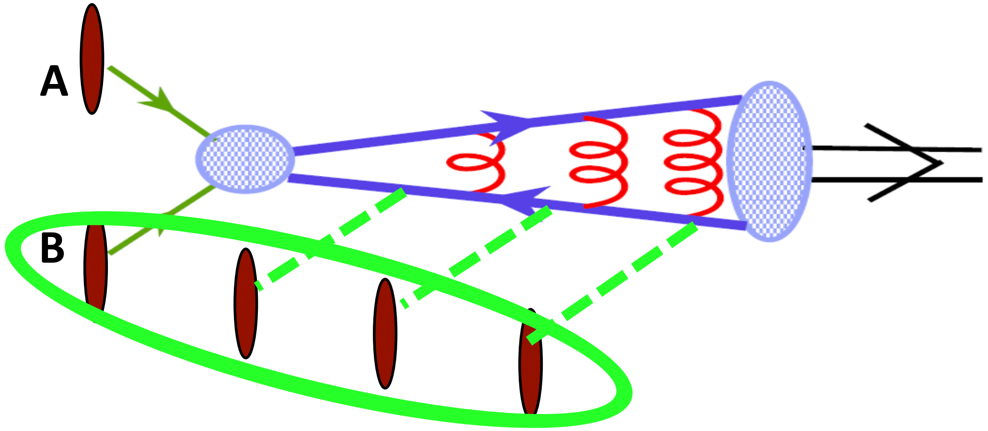
Same wave function

Multiple scattering

Nuclear PDFs

Almost Not affected

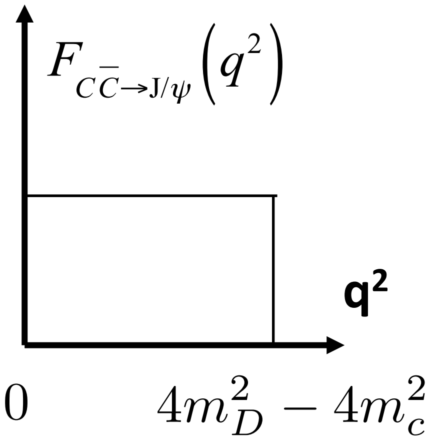
- **Multiple scattering of heavy quarks can change:**
  - **Distribution of total momentum of the pair – Cronin effect**
  - **Invariant mass of the pair (broadening) – Suppression of quarkonium**



Production model = approximation to the transition distribution

❑ Color evaporation model (and the improved one):

Fritsch (1977), Halzen (1977), …



Transition distribution:

- Vanishes above the open charm threshold
- Independent of pair's mass and color, and
- Is a constant

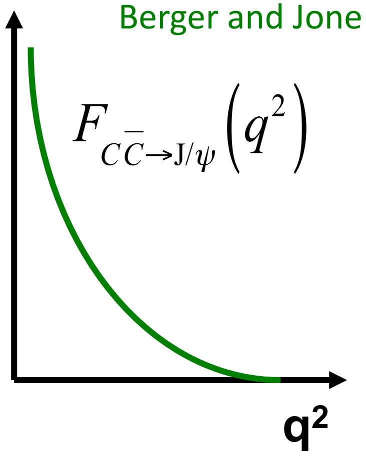
$$\sigma_{AB\to J/\psi}(P_{J/\psi}) \approx \sum_n \int dq^2 \left[\sigma_{AB\to[Q\bar{Q}](n)}(q^2)\right] F_{[Q\bar{Q}(n)]\to J/\psi}(P_{J/\psi}, q^2)$$

$$\sigma^{\rm CEM}_{AB\to J/\psi}(P_{J/\psi}) \approx F_{c\bar{c}\to J/\psi} \int_0^{4m_D^2 - 4m_c^2} dq^2 \left[\sigma_{AB\to c\bar{c}}(q^2)\right]$$

One parameter per quarkonium state

❑ Color singlet model:

Einhorn, Ellis (1975),
Chang (1980),
Berger and Jone (1981), …



Transition distribution:

- Narrowly peaked at q^2=0
- Only color singlet pair with "right" quantum #
- Moment = square of wave function at origin

$$\sigma_{AB\to J/\psi}(P_{J/\psi}) \approx \sigma_{AB\to[Q\bar{Q}]}(q^2=0) \int dq^2 F_{[Q\bar{Q}]\to H}(P_{J/\psi}, q^2)$$

$$\propto \sigma_{AB\to[Q\bar{Q}]}(q^2=0) |\widetilde{\Psi}_{J/\psi}(0)|^2$$

Effectively No free parameter!

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Production model = approximation to the transition distribution

❑ Non-Relativistic QCD (NRQCD) model:

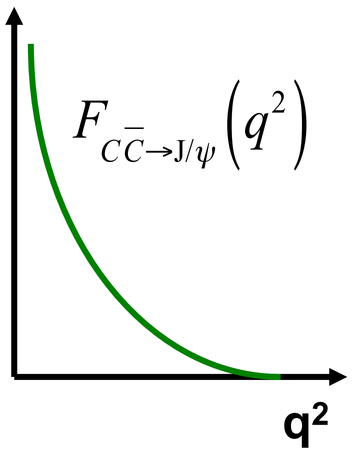
Caswell, Lapage (1986)
Bodwin, Braaten, Lepage (1995)
QWG review: 2004, 2010

Transition distribution:
- Narrowly peaked distribution at $q^2 \ll m_c^2$
- Velocity expansion is a good approximation $v \sim |q|/m_c$
- Perturbatively defined color singlet and octet states $m_c \gg \Lambda_{\rm QCD}$

$$\sigma_{AB\to[Q\bar{Q}](n)}(q^2) \approx \sum_m \frac{[q^2]^m}{m!}\left[\frac{d}{dq^2}\right]^m \sigma_{AB\to[Q\bar{Q}](n)}(q^2=0)$$

$$\Rightarrow \quad \sigma_{AB\to J/\psi}(P_{J/\psi}) \approx \sum_{n,m}\left[\frac{d}{dq^2}\right]^m \sigma_{AB\to[Q\bar{Q}](n)}(q^2=0) \times \int dq^2 \frac{[q^2]^m}{m!} F_{[Q\bar{Q}(n)]\to J/\psi}(q^2)$$

$$\approx \sum_{\mathcal{O}} \sigma_{AB\to\mathcal{O}}(q^2=0)\langle \mathcal{O}^{J/\psi}\rangle$$



Infinite parameters
– organized in powers of v and α_s

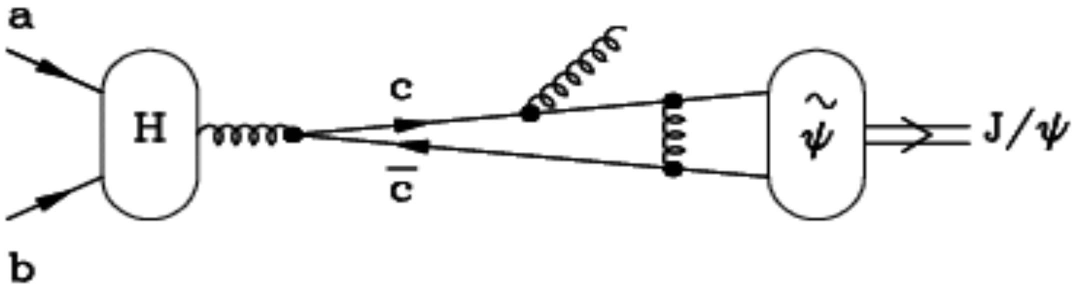
- Both NRQCD and CEM (or ICEM) can describe the production data reasonably well
- Inclusive production rate is not very sensitive to the details of hadronization

⇒ ***Need another observed "scale"!*** ***Polarization, medium effect,…***

Production model = approximation to the transition distribution

Qiu, Vary, Zhang, PRL 2002

❑ Transition distribution:

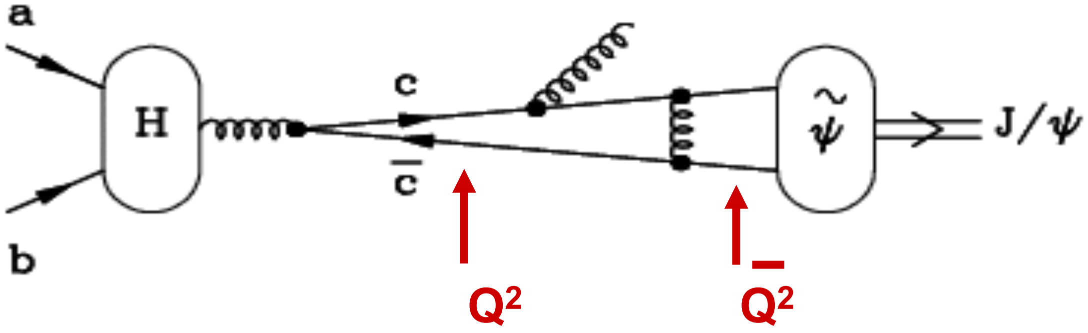


- **Large phase space available for gluon radiation:**

$$Q^2 - 4M_C^2 \Rightarrow 4M_D^2 - 4M_C^2 \approx 6\ \text{GeV}^2$$

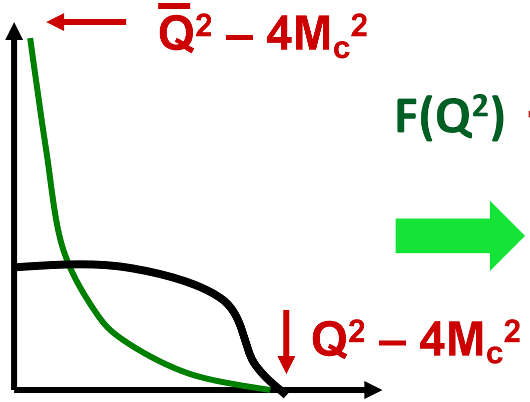
- **Larger heavy quark velocity in production than decay:**

$$v_{\text{decay}} \sim \sqrt{\frac{M_{J/\psi}^2 - m_c^2}{4m_c^2}} \sim 0.48 \qquad v_{\text{prod}} \sim \frac{|q_c|}{m_c} \sim \sqrt{\frac{4m_D^2 - 4m_c^2}{4m_c^2}} \sim 0.88 > v_{\text{decay}}$$



- **Radiation pays a penalty in coupling,
But, gains a lot on wave function**

- **Over 6 GeV² phase space for gluon radiation**
- **Pair with large q^2 has a vanishing chance to become J/ψ in NRQCD Model**

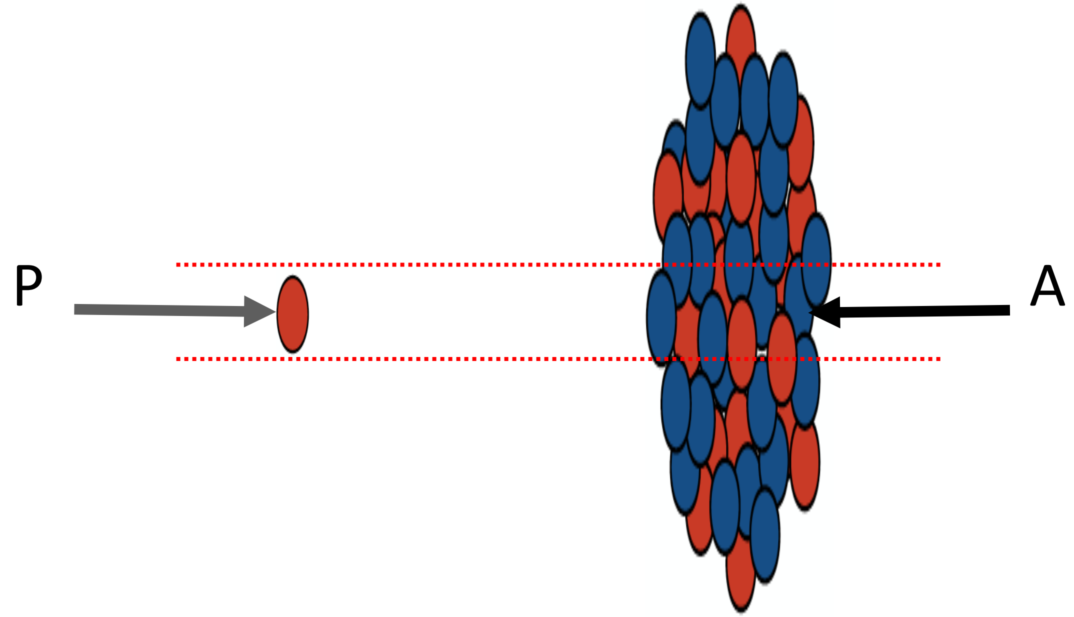


$F(Q^2) \rightarrow \alpha_s(Q^2)\ln(Q^2/4M_c^2)\, F(4M_c^2)$

Threshold behavior for the transition distribution!

Heavy quarkonium production in pA collision

- **Nucleus as a "detector":**
  - **Hard probe (m_Q >> 1/fm)**
    - → **quark-gluon structure of nucleus!**
  - **Necessary calibration for AA collisions**

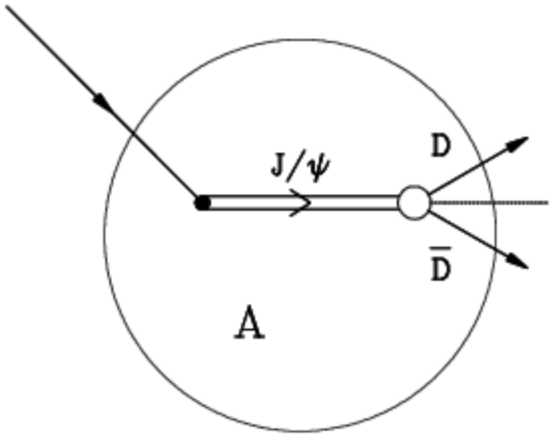


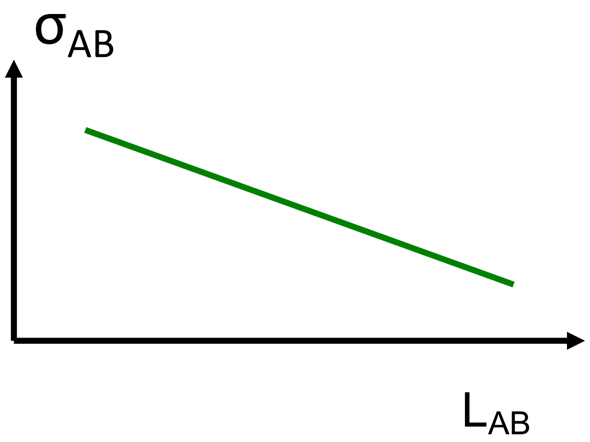
- **If J/ψ were produced at the collision point:**
  - **Nuclear effect in PDFs**
  - **Medium dependence from J/ψ-nucleon absorption**
  - **Glauber model:**

$$\sigma_{AB} \approx AB\sigma_{NN} e^{-\rho_0 \sigma_{\text{abs}}^{J/\psi} L_{AB}}$$

With a J/ψ absorption cross section σ_{abs}

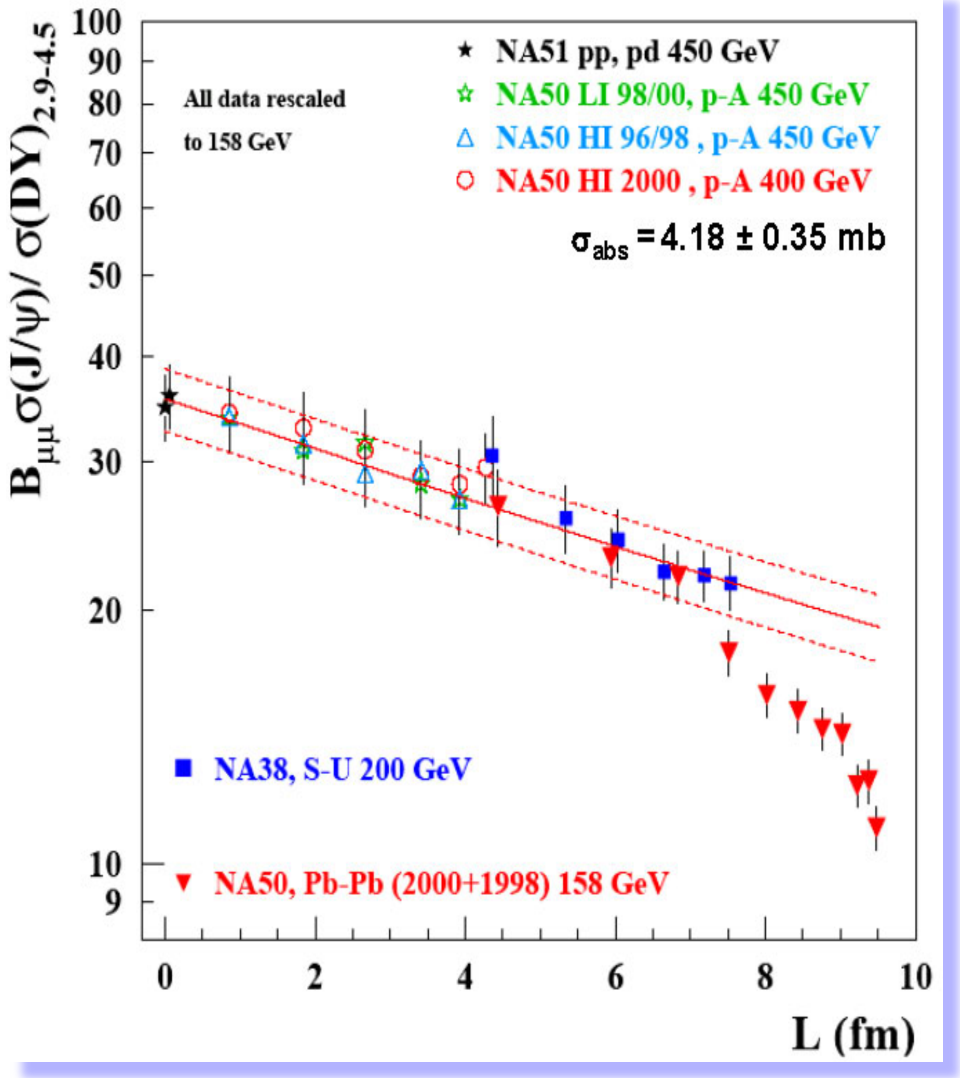
  - **Expect a straight line on a semi-log plot**

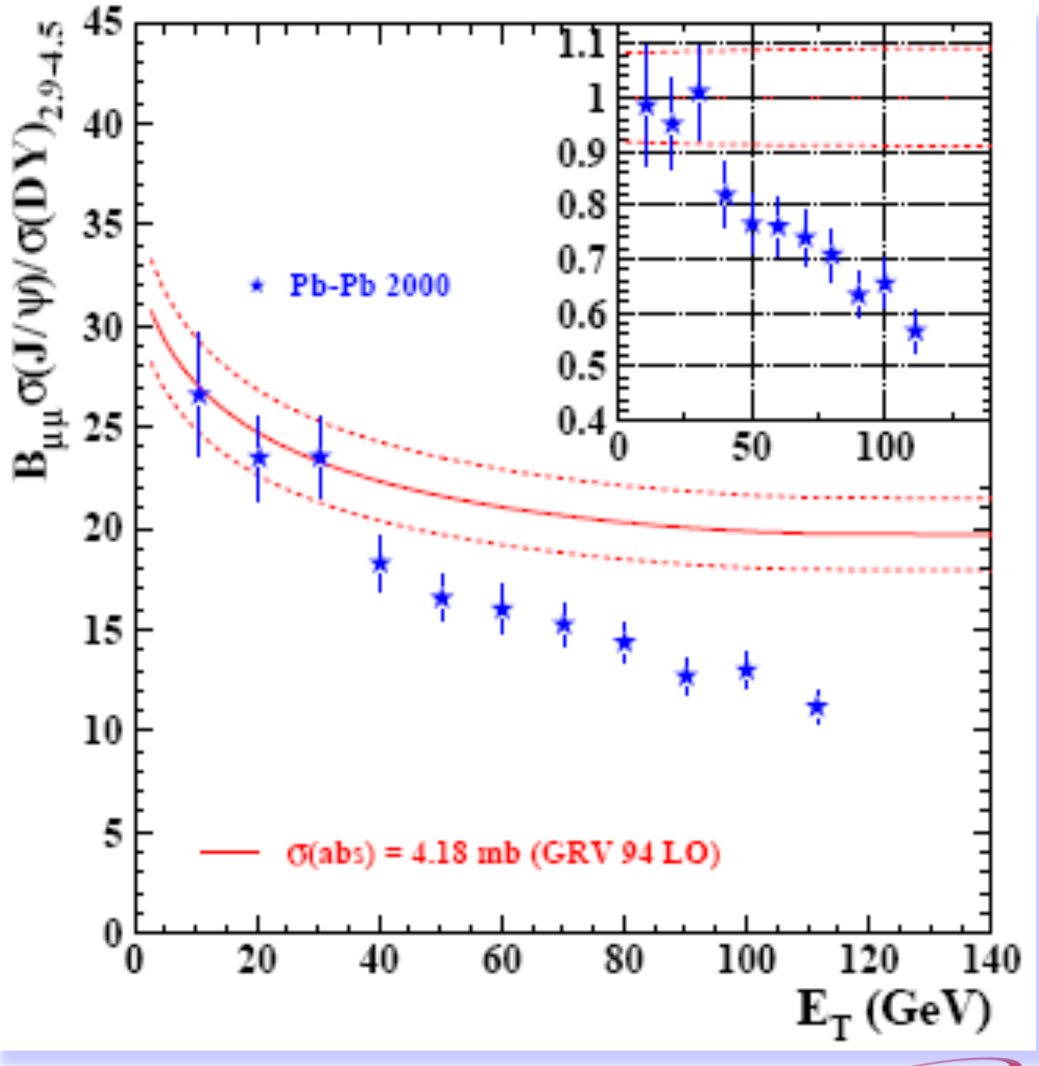




Heavy quarkonium production in pA collision

- Anomalous suppression:





Heavy quarkonium production in pA collision – impact of threshold effect

Guo, Qiu, Zhang, PRL, PRD 2002

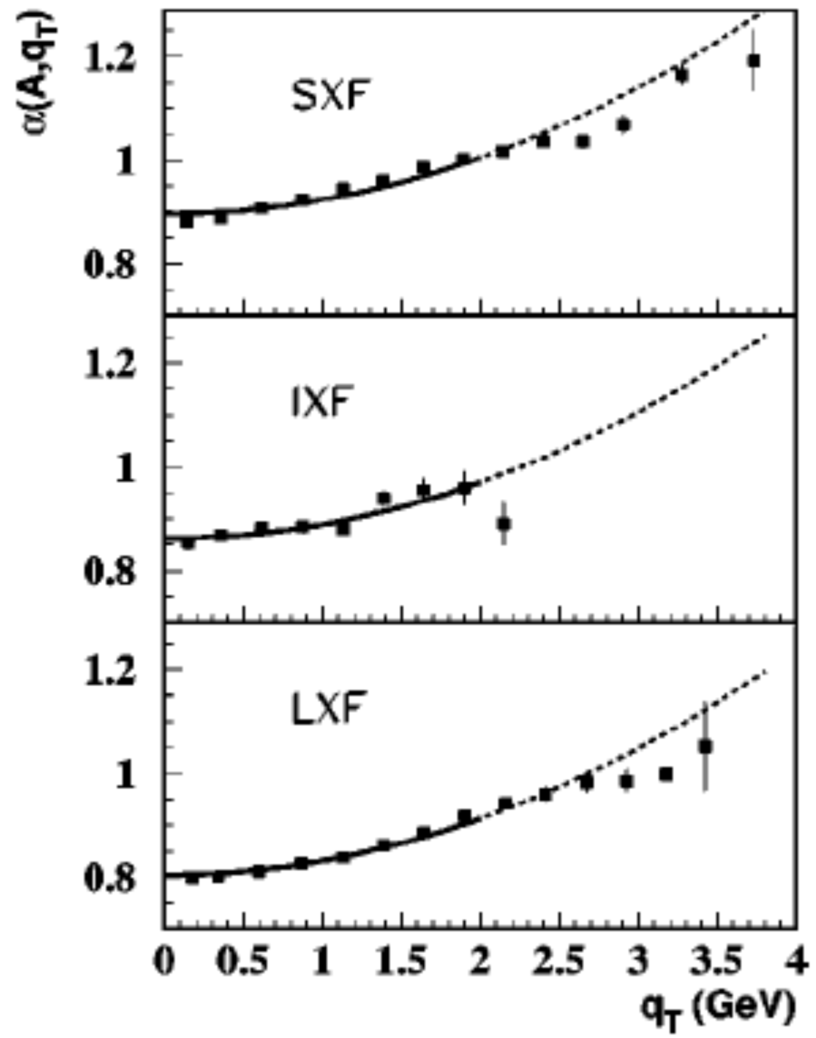
- **Multiple scattering in A:**
  - **Modify momentum distribution of the pair – Cronin effect**
  - **Each scattering is too soft to calculate perturbatively**
    - **Resummation of multiple scattering (small-x limit)**
    - **Moment of P_T-distribution – calculable**
      - based on observed particles only
      - less sensitive to hadronization

$$\langle (q_T^2)^n \rangle = \frac{\int dq_T^2 (q_T^2)^n \, d\sigma/dq_T^2}{\int dq_T^2 \, d\sigma/dq_T^2} \qquad \Delta\langle q_T^2 \rangle = \langle q_T^2 \rangle_{AB} - \langle q_T^2 \rangle_{NN}$$

- **Ratio of pT-distribution – Cronin type:**

$$R(A,q_T) \equiv \frac{1}{A} \frac{d\sigma^{hA}}{dQ^2\, dq_T^2} \Big/ \frac{d\sigma^{hN}}{dQ^2\, dq_T^2} \equiv A^{\alpha(A,q_T)-1}$$

$$\approx 1 + \frac{\Delta\langle q_T^2 \rangle}{A^{1/3} \langle q_T^2 \rangle_{J/\psi}^{hN}} \left[-1 + \frac{q_T^2}{\langle q_T^2 \rangle_{J/\psi}^{hN}} \right]$$



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Heavy quarkonium production in pA collision – impact of threshold effect

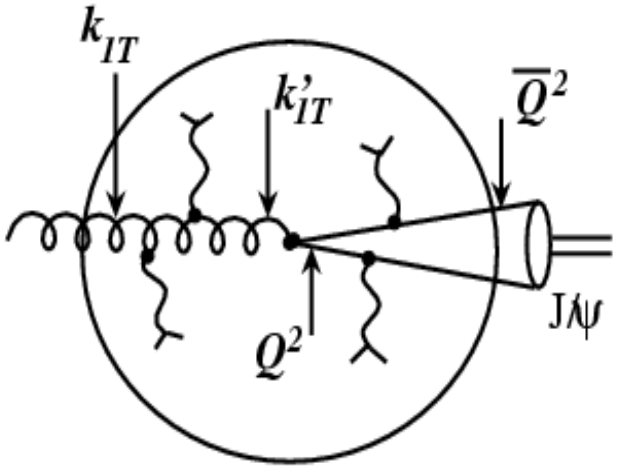
Qiu, Vary, Zhang, PRL 2002

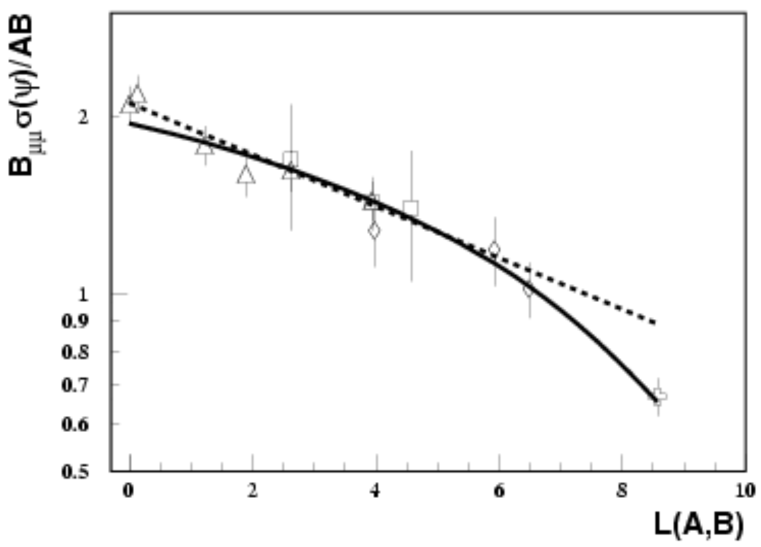
❑ Multiple scattering in A:

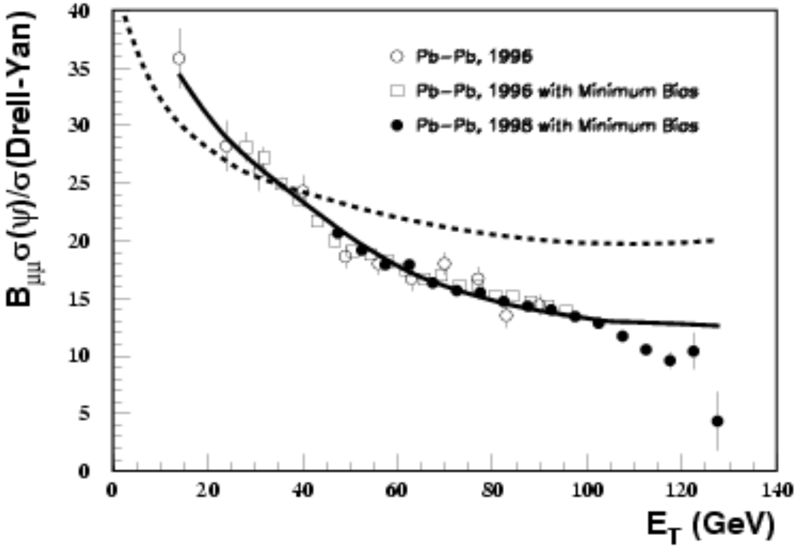
- **Enhance the invariant mass of the pair – "Suppression" of quarkonium**
- **Multiple scattering of the pair broads the relative momentum of the pair**
  - **Increases the relative momentum of the pair: $\overline{Q}^2 > Q^2$**

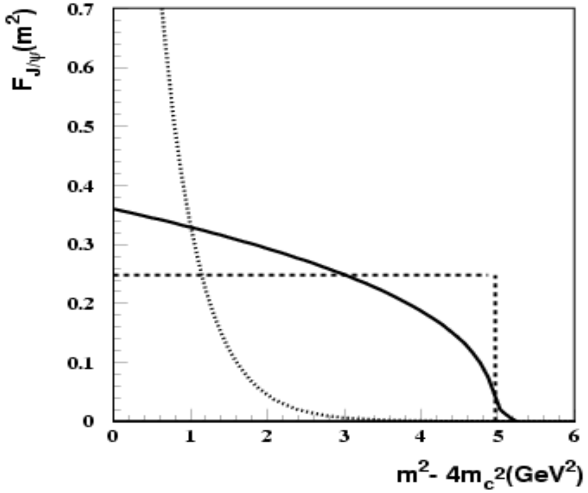
$$q^2 \Rightarrow q^2 + \varepsilon L_{AB} \qquad \varepsilon \sim \hat{q} \sim \langle \Delta q_T^2 \rangle$$

  - **Threshold effect leads to different effective σ_{abs} - Curved line for R_{pA}**









Single parameter: $\varepsilon \propto \hat{q}$

Heavy quarkonium production in pA collision – impact of threshold effect

Qiu, Watanabe, 2022

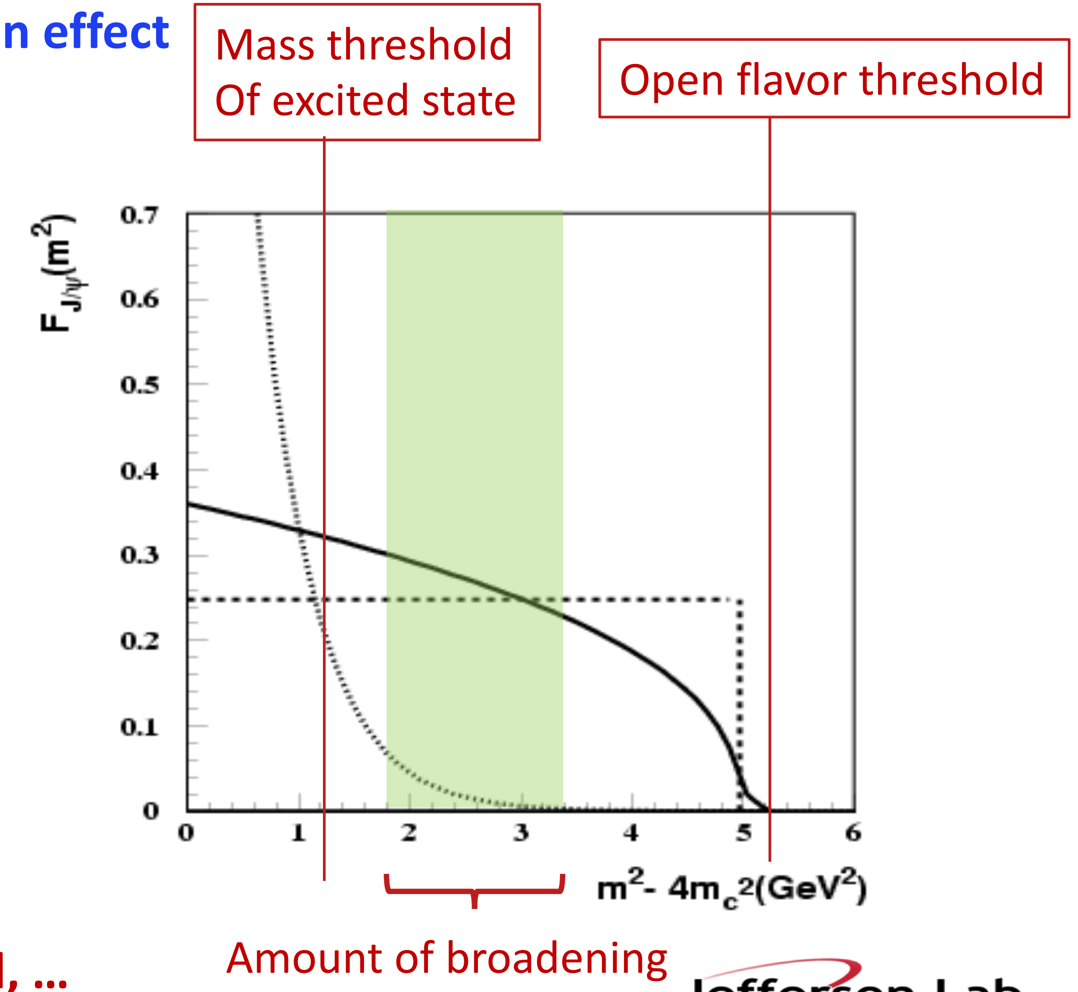
- **Multiple scattering in A:**
  - **"Suppression" of quarkonium = less production, not produced and absorbed by the medium**
  - **Also modify momentum distribution of the pair – Cronin effect**
- **Consequence:**
  - **Different suppression for different quarkonium states:**
    J/ψ, ψ', … Υ(1s), Υ2s), Υ(3s), …
  - **The difference is a consequence of the difference in the transition distribution**
- **Predictions for ratio of pT-distributions:**

$$R_{pA}(3\Upsilon) < R_{pA}(2\Upsilon) < R_{pA}(1\Upsilon)$$

Similarly for R_{AA}

  - **More profound in low pT than high pT**
  - **Difference goes away at very high pT**

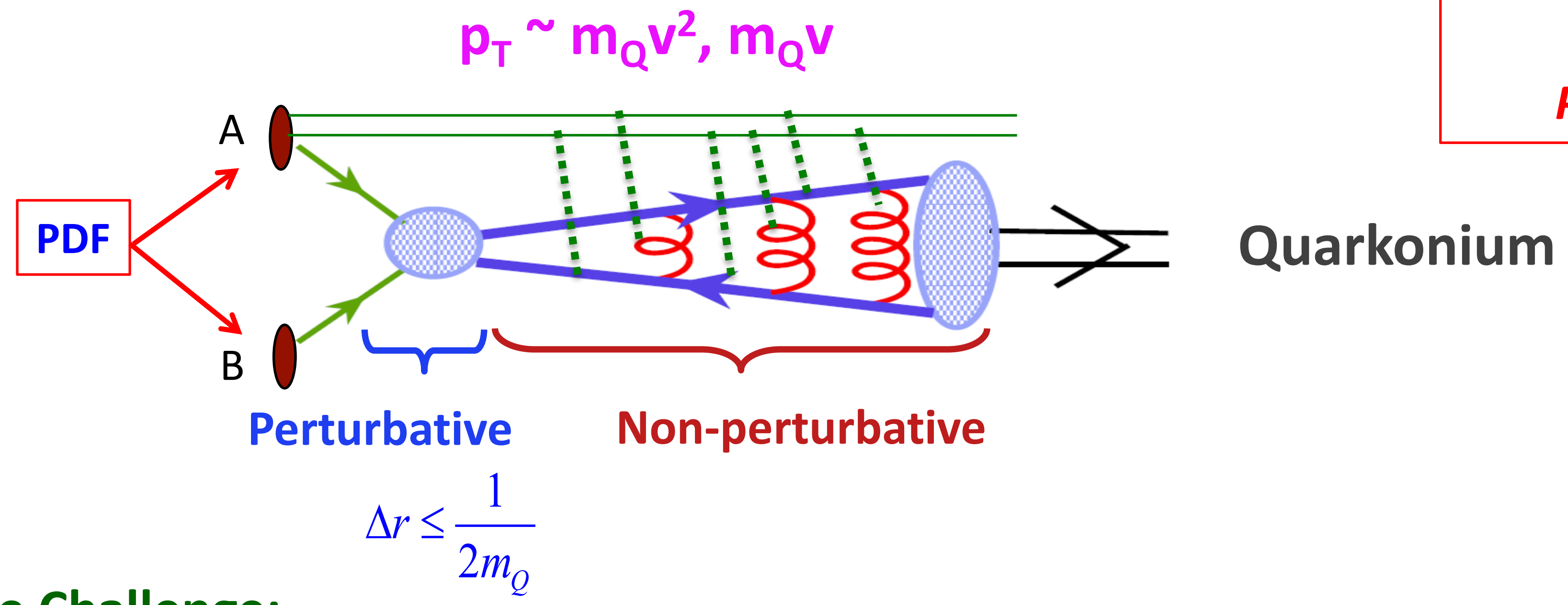
Similar conclusion for charm system, but, less profound, …



Breaking of factorization in hadronic collisions

- Spectator interaction – always there:

Interfere with the formation of the quarkonium
Process dependence



- The Challenge:

  Process dependence – Break of factorization – No predictive power

- The need:

  Controllable calculation of medium effect, extract medium properties, …

- The Opportunities:

  Medium as a “detector” or “filter” to probe “color neutralization”, …

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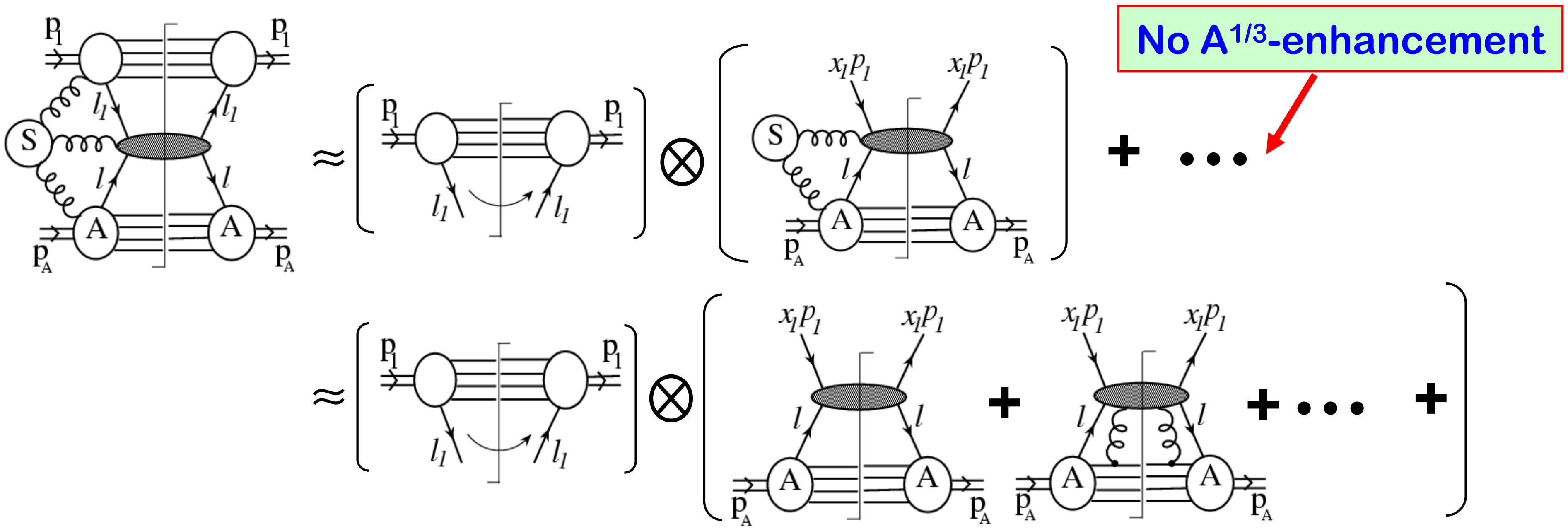
Breaking of factorization in hadronic collisions

❑ A-enhanced power corrections, $A^{1/3}/Q^2$, may be factorizable:

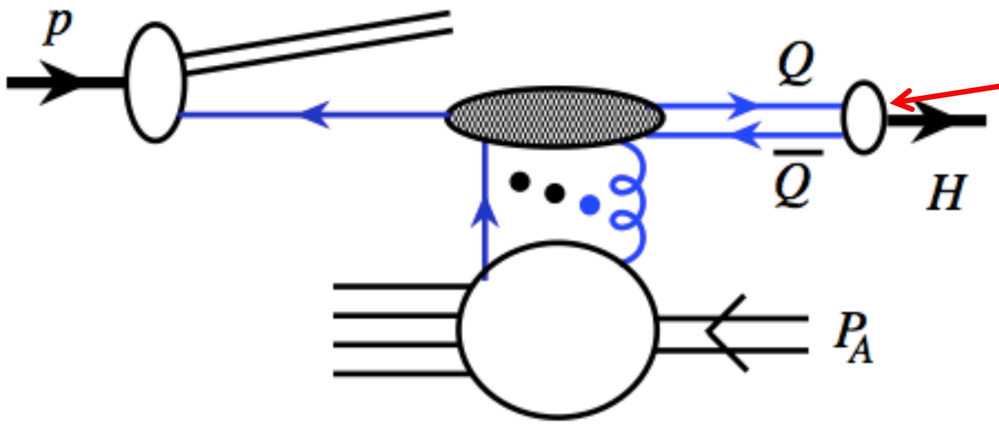


- **Total x-section:** **Factorization argument similar to DIS**
  - **Collinear power expansion – single scale**
- **P_T spectrum:** **Factorization argument similar to SIDIS**
  - **TMD or collinear – low P_T to high P_T**

Breaking of factorization in hadronic collisions

- ***Backward*** **production in p(d)+A collisions:**

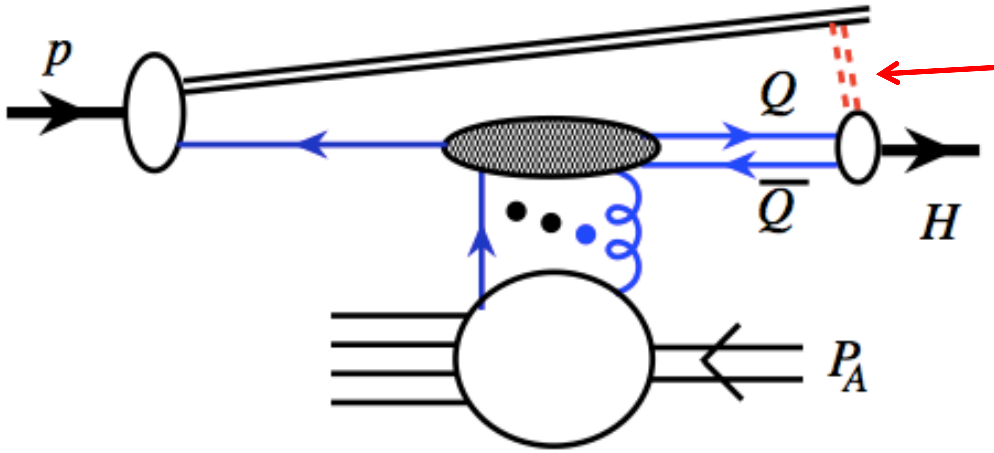
Brodsky and Mueller, PLB 1988



J/Ψ could be formed Inside nucleus

Multiple scattering interfere with the non-perturbative hadronization – no factorization!!

- **Production at low P_T (➔0) in p(d)+A collisions:**



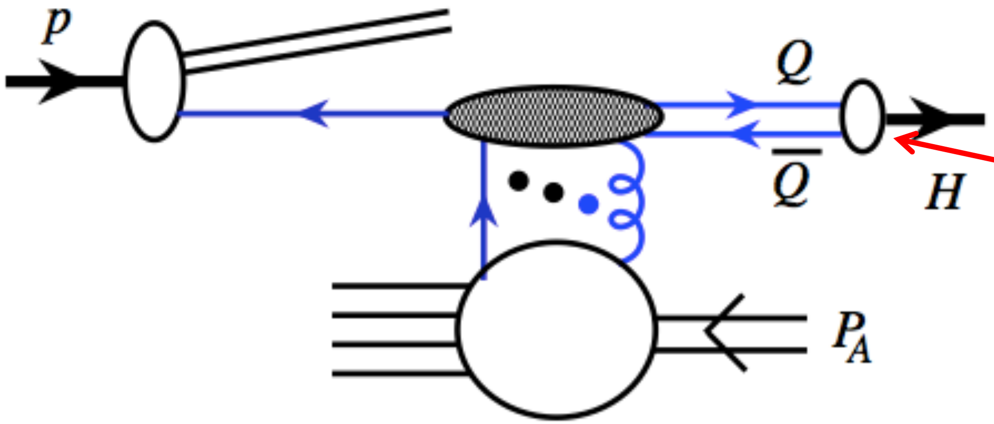
Co-mover interaction

to interfere with quarkonium formation - Break of factorization!!

Breaking of factorization in hadronic collisions

- ❑ ***Forward* production in p(d)+A collisions:**

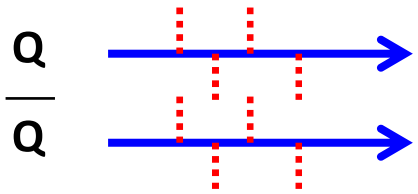
Brodsky and Mueller, PLB 1988



✧ **Time dilation**

Non-perturbative formation of J/Ψ is far outside of nucleus

- **Multiple scattering with incoming parton & heavy quarks, not J/Ψ**
  - **Induced gluon radiation – energy loss – suppression at large y**
  - **Modified P_T spectrum – transverse momentum broadening**
  - **De-coherence of the pair – different $Q\bar{Q}$ state to hadronize – lower rate**



Soft multiple scattering – "random walk"

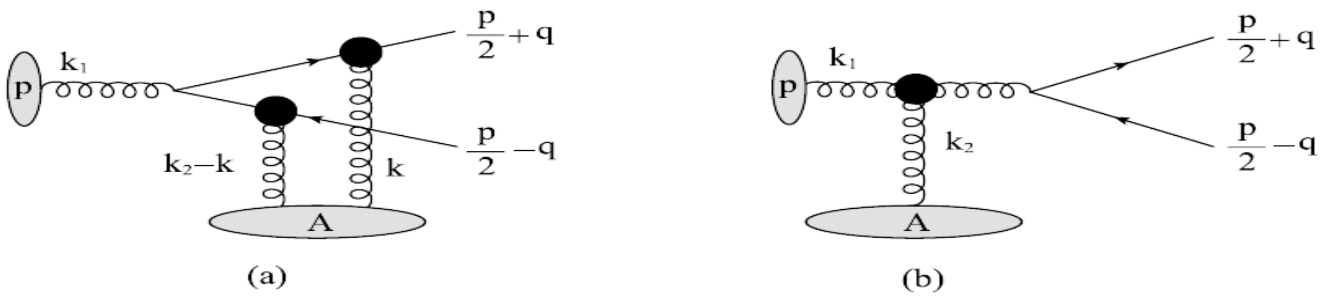
➡ **Momentum imbalance – larger invariant mass**

➡ **Match to the tail of wave function - ``suppression"**

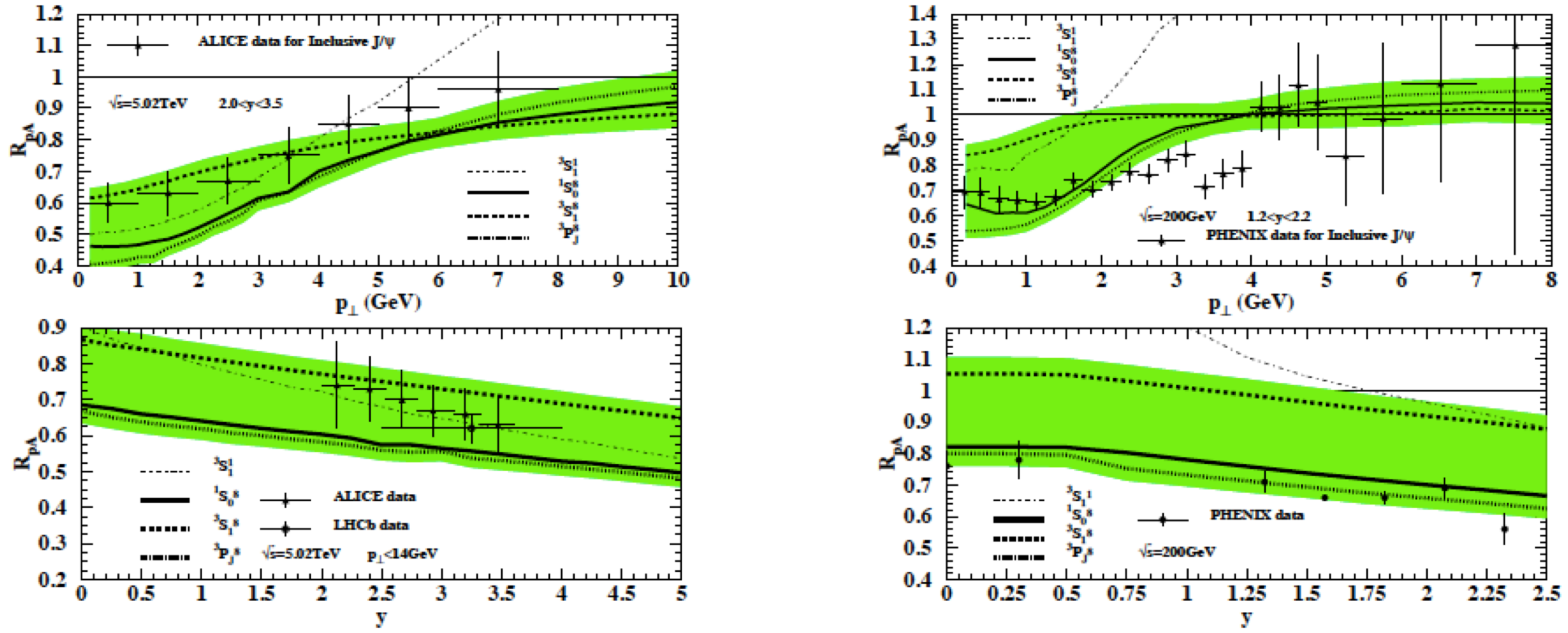
Forward quarkonium production in p(d)+A

- **Calculation of multiple scattering:**

Kang, Ma, Venugopalan, JHEP (2014)
Qiu, Sun, Xiao, Yuan PRD89 (2014)



Coherent multiple scattering → **suppression at large y**



Ma, Venugopalan, Zhang, PRD92, 071901 (2015)

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Summary and Outlook

- It has been almost 50 years since the discovery of J/Ψ, but, we are still not completely sure about its production mechanism
- We have studied the QCD factorization for hadronic quarkonium production at high pT
- We demonstrated that the LP contributions are significant for hadronic quarkonium production at high pT while the NLP contributions are sizable at lower pT but different in shape, and both are needed, leading to a smooth matching to fixed-order calculations
- The initial success of QCD factorization formalism should encourage a global data analysis. There is sufficient room to improve the input FFs
- Inclusive heavy quarkonium production is not very sensitive to the details of formation of a quarkonium from a pair of heavy quarks
- Controllable medium dependence should provide a better probe for how a heavy quarkonium could be emerged from a pair of heavy quarks

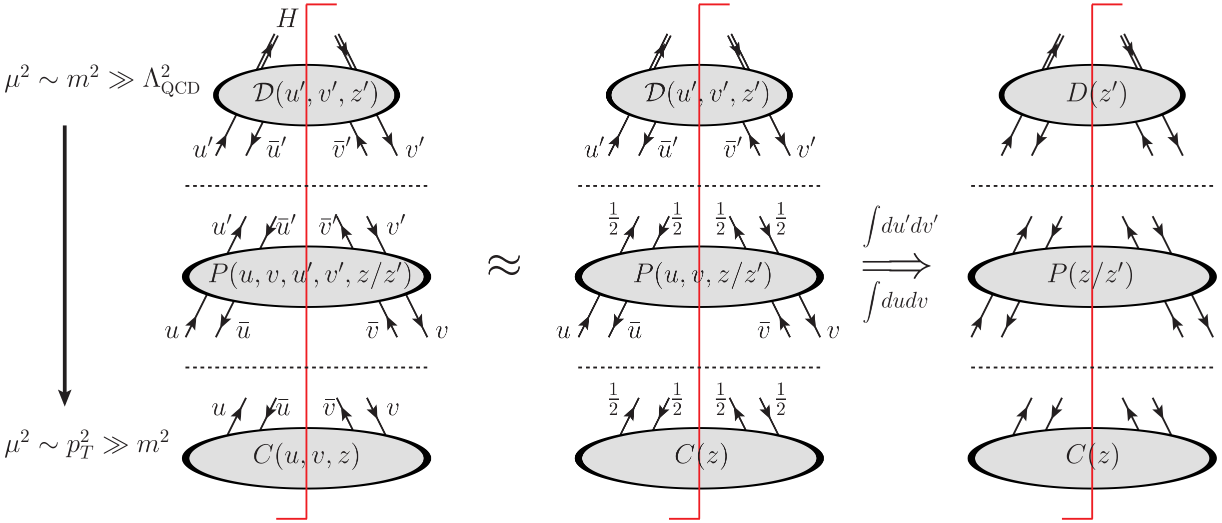
Thanks!

Evolution equations in a simplified situation

Lee, Qiu, Sterman, Watanabe, in preparation

❑ Simplified evolution equations:

- The produced heavy quark pair is dominated by its on-shell state at high .
- We may expand the SDCs and evolution kernels on lower virtuality sides at each evolution step around .
- This can be a reasonable approximation suggested by the evolution of DP FFs in μ,ν-space. S-to-S channels are not dominant at high .



$$\frac{d\sigma^H_{\rm NLP}}{dyd^2p_T} = \int dzdudv\, C_{[Q\bar{Q}]}(p_Q, p_{\bar{Q}}, \mu)\, \mathcal{D}_{[Q\bar{Q}]\to H}(u,v,z,\mu) \approx \int dz\, C_{[Q\bar{Q}]}\left(\hat{p}^+_Q = \frac{1}{2}p^+_c, \hat{p}^+_{\bar{Q}} = \frac{1}{2}p^+_c, \mu\right) \underbrace{\int dudv\, \mathcal{D}_{[Q\bar{Q}]\to H}(u,v,z,\mu)}_{\equiv D_{[Q\bar{Q}]\to H}(z,\mu)}$$

$$\frac{\partial D_{[Q\bar{Q}(\kappa)]\to H}(z,\mu)}{\partial \ln \mu^2} \approx \sum_n \int_z^1 \frac{dz'}{z'} \int_0^1 du \int_0^1 dv\, \Gamma_{[Q\bar{Q}(n)]\to[Q\bar{Q}(\kappa)]}\left(u, v, u' = \frac{1}{2}, v' = \frac{1}{2}, \frac{z}{z'}\right) D_{[Q\bar{Q}(\kappa)]\to H}(z',\mu),$$

$$\frac{\partial D_{f\to H}(z,\mu)}{\partial \ln \mu^2} \approx \frac{\alpha_s}{2\pi} \sum_{f'} \int_z^1 \frac{dz'}{z'} P_{f\to f'}(z/z') D_{f'\to H}(z') + \frac{\alpha_s^2(\mu)}{\mu^2} \sum_{[Q\bar{Q}(\kappa)]} \int_z^1 \frac{dz'}{z'} P_{f\to[Q\bar{Q}(\kappa)]}\left(u' = \frac{1}{2}, v' = \frac{1}{2}, \frac{z}{z'}\right) D_{[Q\bar{Q}(\kappa)]\to H}(z',\mu)$$

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