Probing small-x gluons in hadrons and nuclei

Kazuhiro Watanabe

Old Dominion University

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Jefferson Lab

Biography

Educational Background

- 2009, B.S. at Tokyo University of Science
  - ✓ Charmonium spectroscopy
- 2014, Ph.D at University of Tokyo (supervisors: T. Matsui and H. Fujii)
  - ✓ Color Singlet Model for quarkonium production in hadronic collisions
  - ✓ Study of heavy quark pair production in high energy pA collisions in the Color Glass Condensate framework

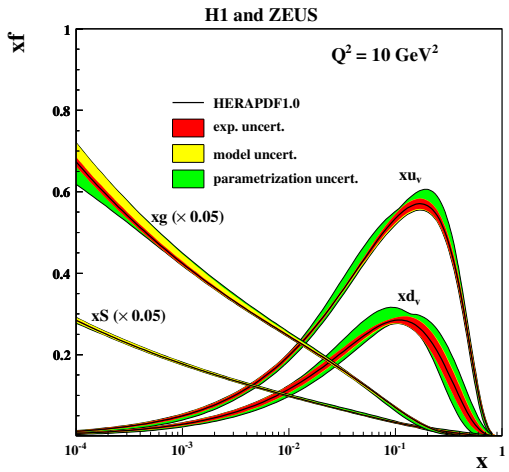
Professional background

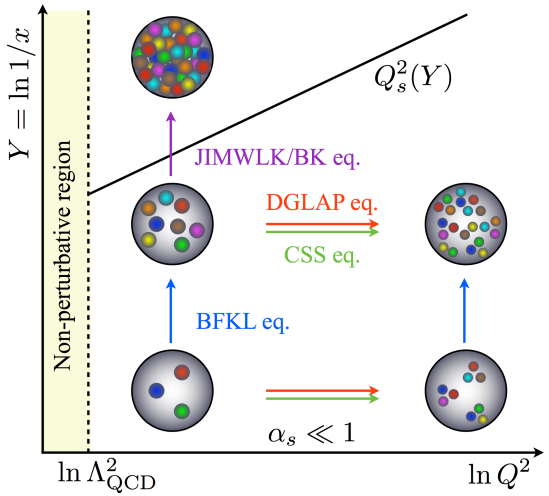
- 2014 – 2016: Postdoc researcher in Nuclear Theory Group at Central China Normal University.
  - ✓ Small-x factorization, saturation physics, TMD physics
- 2016 – Present: Postdoctoral researcher in ODU Nuclear Theory Group.
  - ✓ Small-x and TMD physics

My work

Research interests

- ✓ Gluon saturation dynamics at small value of Bjorken variable x.
- ✓ Transverse momentum dependent gluon distribution in hadron/nucleus





- One large scale Q and dilute : collinear factorization.
- (At least) Two large scales $Q \gg Q' \gg \Lambda_{\rm QCD}$ and dilute : TMD factorization.
- Small-x and dense : Small-x saturation/Color-glass-condensate (CGC).

$\Rightarrow$ **Unintegrated (Transverse momentum dependent) PDFs are important.**

My work

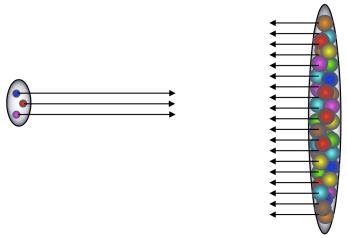
Q. Is there any clear evidence of the gluon saturation?

⇒ Not clear.

Q. How to find out a smoking gun evidence of the gluon saturation?

⇒ High energy eA collision provides clean tests. Future EIC and LHeC are promising, although we need to wait and prepare a lot of things.

⇒ High energy pA collision is more or less complicated. However, we should learn invaluable lessons from pA and also pp collisions.



Q. What kinds of measurements should we consider?

⇒ Inclusive hadron

$$p + p/A \to h + X$$

⇒ Heavy quark pair ($c\bar{c}$, $b\bar{b}$)

$$p + p/A \to J/\psi, \Upsilon, D, D\bar{D}, etc. + X$$

Talk Plan

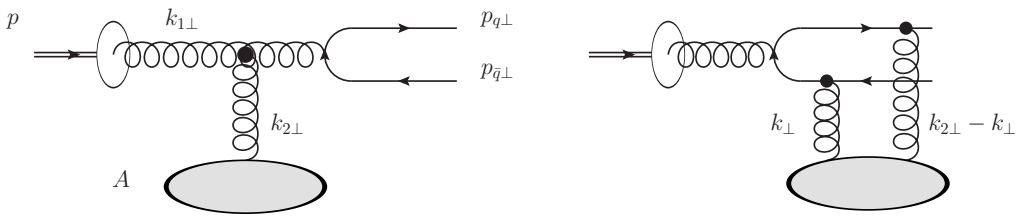
1. Introduction

2. Highlights
   - J/ψ and Open charm productions : Phenomenology
   - One loop factorization in the small-x formalism
   - Sudakov effect in the small-x formalism

3. Future research plans

J/ψ and Open charm productions : Phenomenology

KW, arXiv:1611.00700 [hep-ph]; H. Fujii and KW, Nucl. Phys. A **951**, 45 (2016); Nucl. Phys. A **920**, 78 (2013); Nucl. Phys. A **915**, 1 (2013).



- LO k_t-factorization framework [Blaizot,Gelis,Venugopalan (2004)] [Kovchegov,Tuchin (2005)]$\cdots$

$$d\sigma_{q\bar{q}} = \Xi^{\rm LO}_{\rm Hard} \otimes \varphi_{{\rm p},x_1}(k_{1\perp}) \otimes \phi_{A,x_2}(k_{2\perp}, k_\perp)$$

- Unintegrated dipole gluon distribution function and multipoint Wilson line correlator (Large-N_c):

$$\varphi_{{\rm p},x_1}(k_{1\perp}) = S_{p\perp} \frac{N_c k_{1\perp}^2}{4\alpha_s} F^A_{x_1}(k_{1\perp}).$$

$$\phi_{A,x_2}(k_{2\perp}, k_\perp) = S_{A\perp} \frac{N_c k_{2\perp}^2}{4\alpha_s} F^F_{x_2}(k_{2\perp} - k_\perp) F^F_{x_2}(k_\perp)$$

- Small-x evolution for $F_x \Rightarrow$ rcBK evolution equation. [Balitsky (2007)]

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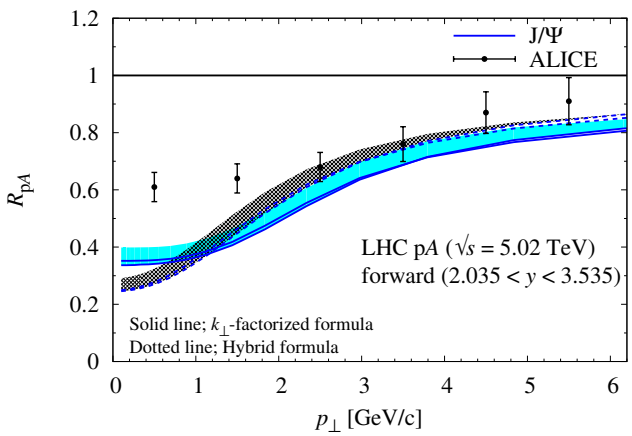
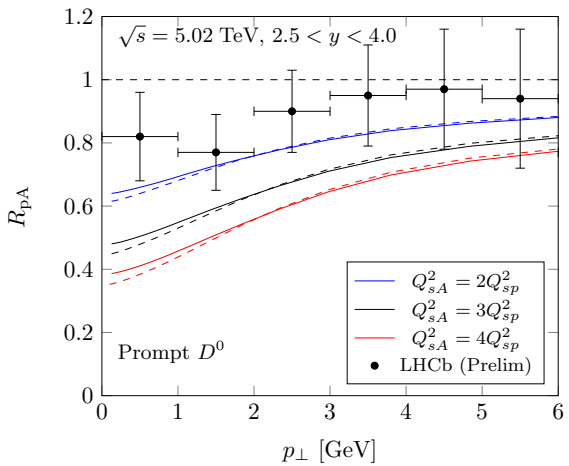
- **Selected Results**

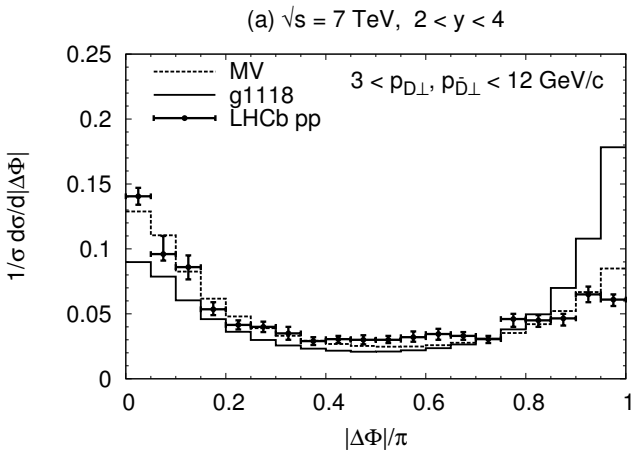
✓ J/ψ: Color Evaporation Model

✓ Open charm: Functional form Fragmentation Function

⇒ Key measurements: $R_{pA} = \frac{d\sigma_{pA}}{A d\sigma_{pp}}$, Two particle correlation





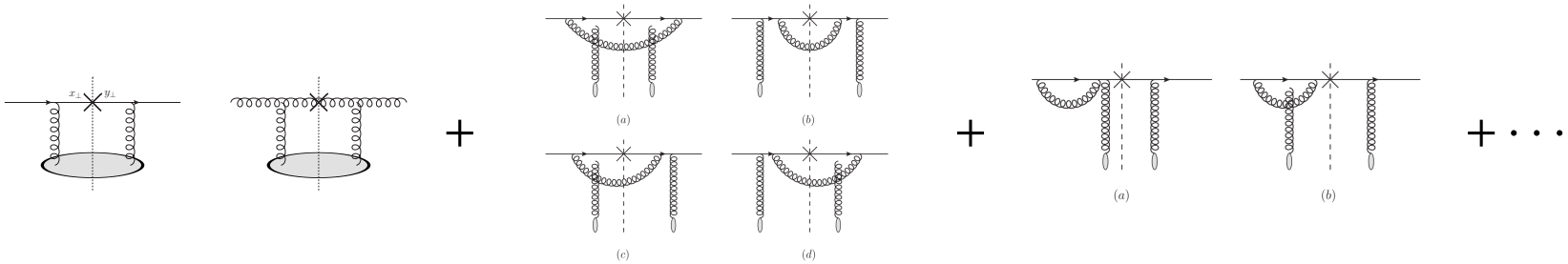


- These results are first numerical implementations. Cold Nuclear Matter effect is a hot issue. Many things to do!
- NLO calculation is strongly desired.

One loop factorization in the small-x formalism

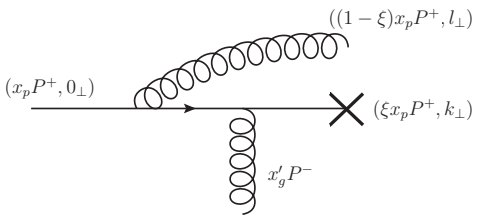
KW and B.-W. Xiao, Phys. Rev. D **92**, no. 11, 111502 (2015): KW, B.-W. Xiao, F. Yuan and D. Zaslavsky, Phys. Rev. D **92**, no. 3, 034026 (2015)

- Inclusive hadron production: $p + p/A \to h + X$
- First NLO calculations in pA are done by [Chirilli, Xiao, Yuan (2011)]



- Full NLO calculations in pA [KW, Yuan, Xiao, Zaslavsky (2015)], in pp [KW, Xiao (2016)]:

  Exact light cone energy conservation: $x'P^- = \frac{l_\perp^2}{2(1-\xi)xP^+} + \frac{k_\perp^2}{2\xi x P^+} \leq P^-$ leads to the constraint $\xi \leq 1 - \frac{l_\perp^2}{xs}$. $\frac{l_\perp^2}{xs}$ provides double logarithmic power corrections in coordinate space. (Similar to Sudakov double logs.)



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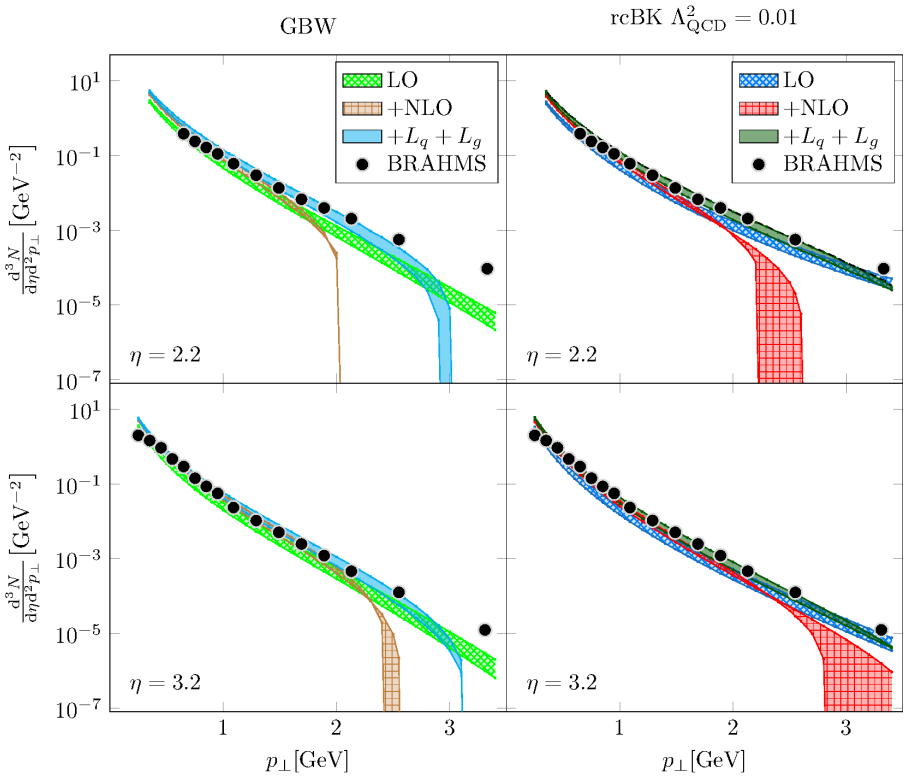
- **Numerical Results: LO+NLO+Double logs in Hybrid formalism**



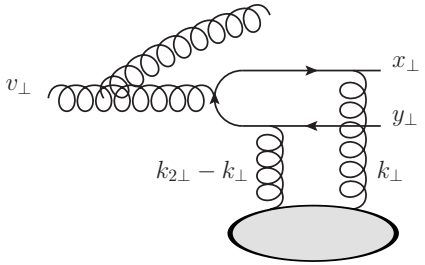
- Beyond Hybrid formalism $\Rightarrow$ $k_\perp$-factorization for projectile proton.

Sudakov effect in the small-x formalism

KW and B.-W. Xiao, Phys. Rev. D **92**, no. 11, 111502 (2015)

- Indeed, for heavy quarkonium production, two kinds of resummation parameters involve in the small-x formalism: [Mueller, Xiao, Yuan (2013)] [Qiu, Sun, Xiao, Yuan (2013)]
  - ✓ $\alpha_s N_c \ln \frac{1}{x} = \mathcal{O}(1) \Rightarrow$ BK equation
  - ✓ $\alpha_s N_c \ln^2 \frac{M^2}{p_\perp^2} = \mathcal{O}(1) \Rightarrow$ CSS equation
- We improved heavy quark pair production cross section in the $b_\perp$-space to include both the saturation effect and the Sudakov effect. [KW, Xiao (2015)]

$$d\sigma_{q\bar{q}} \propto \int \frac{d^2x_\perp d^2y_\perp}{(2\pi)^4} e^{ik_\perp\cdot x_\perp} e^{i(k_{2\perp}-k_\perp)\cdot y_\perp} \underbrace{S_Y(x_\perp)S_Y(y_\perp)x_1 G\left(\mu = \frac{c_0}{v_\perp}\right) e^{-S_{\rm Sud}(M,v_\perp)}}_{\text{“W−term”}}$$

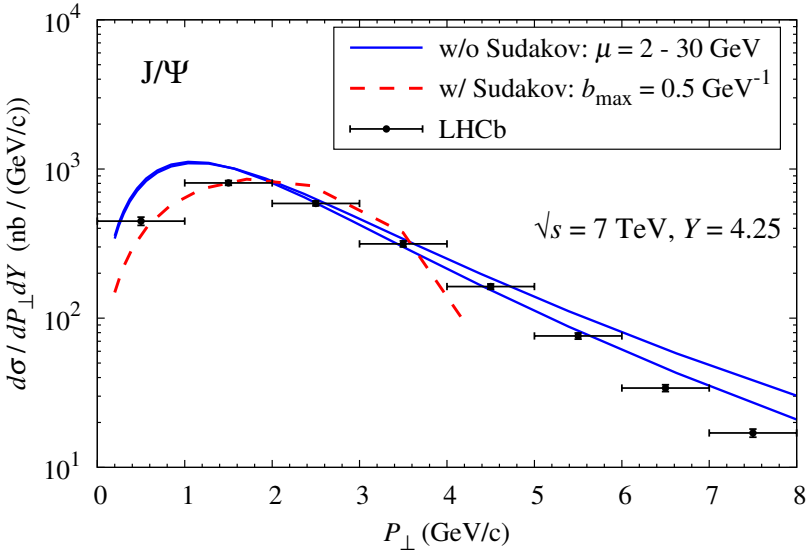


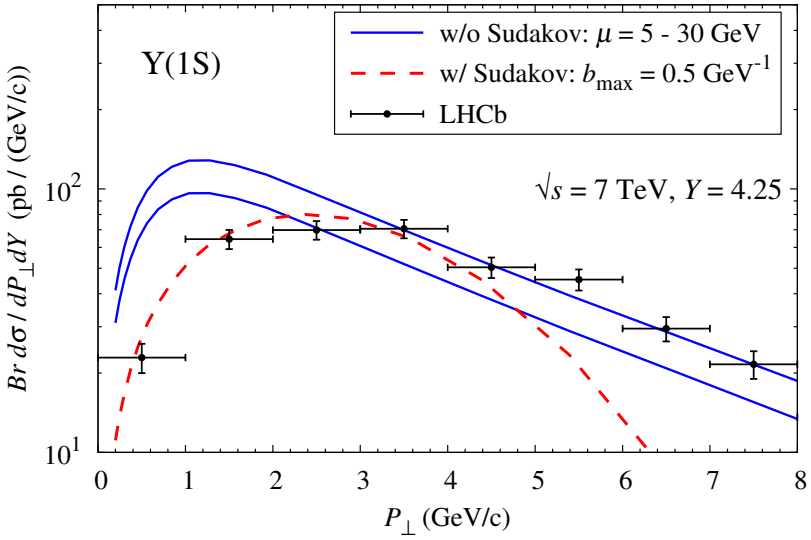
$+ \cdots$

Sudakov effect in the small-x formalism

KW and B.-W. Xiao, Phys. Rev. D **92**, no. 11, 111502 (2015)

- **Numerical Results: Sudakov + Saturation effects**





  - Sudakov factor is essential to interpret the data (large $P_\perp$ broadening).
  - This framework breaks down around $P_\perp \sim M$. We need to add "Y-term".

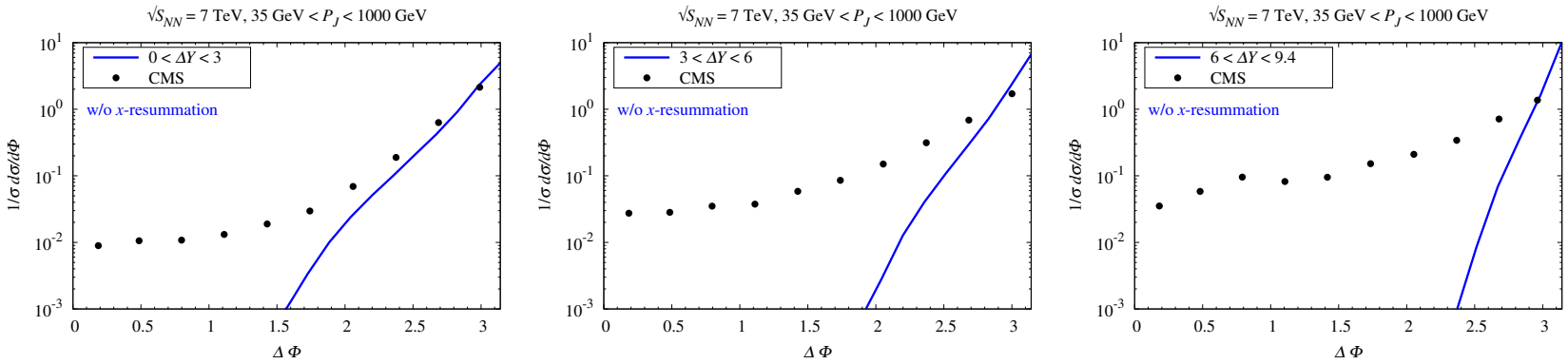
- We must obtain the Sudakov factor in the NLO saturation formalism.
- We need to investigate other observables for which both Sudakov & Saturation effects are important.

One more thing: CSS evolution & Small-x evolution

- Mueller-Navelet jets (forward-backward dijets) production in pp collisions $a(p_1) + b(p_2) \to c(k_1) + d(k_2)$.

$$\frac{d\sigma}{d^2k_{1\perp}d^2k_{2\perp}dy_1dy_2} = \sum_{ab}\sigma_0 \int \frac{d^2b_\perp}{(2\pi)^2} e^{-iq_\perp\cdot b_\perp} W(b_\perp)$$

with $W_{ab\to cd}(b_\perp) = x_1 f_a(x_1,\mu) x_1 f_b(x_2,\mu) h_{ab\to cd}(\hat{s},\hat{t}) e^{-\widetilde{S}_{ab\to cd}(P_J,b_\perp)}$



- Clearly, BFKL evolution is required on top of CSS evolution to interpret data.
- Sudakov + BFKL is underway with Mueller, Szymanowski, Wallon, Xiao, Yuan.

Talk Plan

1. Introduction
2. Highlights
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   - Sudakov effect in the small-x formalism
3. Future research plans

Future research plans (I)

Saturation effect as a CNM effect for quarkonium, open flavor productions

- ✓ Calculate NLO contributions to quarkonium production with use of various models of bound state formation (CEM, NRQCD).
- ✓ Verify that Sudakov double logarithms appeared systematically in the small-x formalism.

$\Rightarrow$ Reduce uncertainties of higher order corrections.

More clean process than pA collision

- ✓ DIS, SIDIS, Dijet, Quarkonium, $D\bar{D}$ productions in ep/eA scatterings.
- ✓ Various hard scales: Q, $p_\perp$, M_{dijet}, Q_s, $\cdots$

$\Rightarrow$ Verify that Sudakov double logs and Small-x logs are involved.

$\Rightarrow$ Powerful tools: Operator Product Expansion and Lightcone Perturbation Theory.

Future research plans (II)

Saturation effect in Spin physics

Q. Saturation effect is important for quarkonium production in $p^{\uparrow}p$ and $p^{\uparrow}A$ collisions?

$\Rightarrow$ Yes, it should be important. It is possible to examine so-called Sivers effect at intermediate or small-x in $p^{\uparrow}p$ or $p^{\uparrow}A$ collisions by employing polarized TMDs.

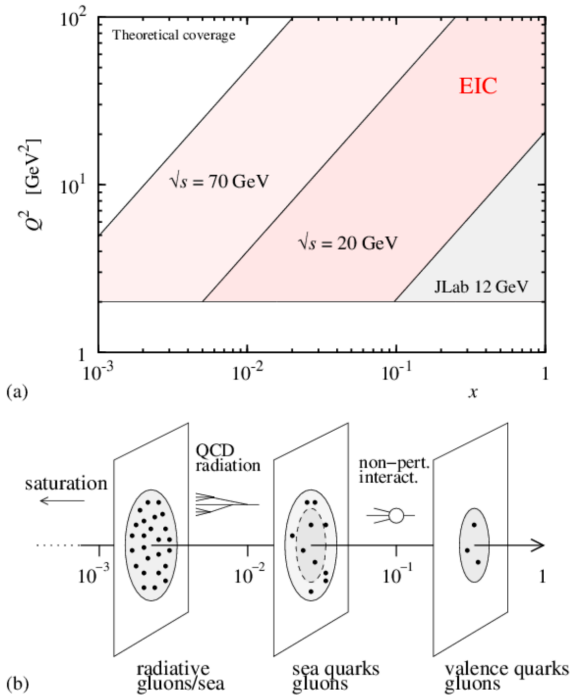
Q. How about $ep^{\uparrow}$ and $eA^{\uparrow}$ collisions?

$\Rightarrow$ It is possible. Direct probe to access gluon TMD in hadron or nuleus.

- ✓ Model dependence : CEM, NRQCD [see, Yuan (2008)]

My potential contributions to physics at JLab

- TMD PDFs are the key issues at Theory group.
  - ✓ Polarized& Unpolarized TMDs are process dependent and x-evolution of TMD PDFs are not understood well.
  - ⇒ I can study TMDs from small-x viewpoint by considering SIDIS & Dijet in DIS in terms of Lightcone Perturbation Theory or Operator Product Expansion.
- Exploring the onset of the gluon saturation in nucleus is the important issue in future Medium energy EIC at JLab.
  - ✓ The initial condition for BK equation for nucleus is poorly understood due to lack of precise data of Nuclear DIS.
  - ⇒ Data analysis of dihadron or dijet production at MEIC could solve this problem.



Backup slides

4 Backup slides

Conventional TMD framework

One loop calculations in NRQCD factorization framework [Sun, Yuan, Yuan (2012)]

$$\left.\frac{d\sigma}{d^2P_\perp dy}\right|_{|P_\perp|\ll M} = \int \frac{d^2b_\perp}{(2\pi)^2} e^{iP_\perp\cdot b_\perp} W(M, b_\perp, x_1, x_2) + (\mathrm{Y}-\mathrm{term})$$

with

$$W(M, b_\perp, x_1, x_2) = e^{-S_{sud}(M,b_\perp)} W(M, b_\perp, C_1, C_2)$$

$$W(M, b_\perp, C_1, C_2) = \sigma_0 \frac{M^2}{s} \int \frac{dx}{x}\frac{dx'}{x'} C_{gg}\left(\frac{x_1}{x}\right) C_{gg}\left(\frac{x_2}{x'}\right) G(x_1,\mu) G(x_2,\mu)$$

- TMD factorization [Collins-Soper-Sterman (1985)] [Collins (2011)]
- Y-term is power suppressed by $P_\perp/M$ at low $P_\perp$
- $\mu = \frac{c_0}{b_\perp}$ with $c_0 = 2e^{-\gamma_E} \simeq 1$

Collins-Soper-Sterman (CSS) formalism

Split the Sudakov factor into two parts

$$\boxed{S_{\mathrm{Sud}}(M,b) = S_{\mathrm{perp}}(M,b_\star) + S_{\mathrm{NP}}(M,b)} \quad \text{with } b_\star = \frac{b}{\sqrt{1+(b/b_{\mathrm{max}})^2}}$$

- Perturbative : $b_\star \sim b \ll b_{max}$

$$S_{\mathrm{perp}}(M,b) = \int_{c_0/b^2}^{M^2} \frac{d\mu^2}{\mu^2}\left[A\ln\left(\frac{M^2}{\mu^2}\right) + B\right]$$

$A = \sum_{i=1} A^{(i)}\left(\frac{\alpha_s}{\pi}\right)^i$, $B = \sum_{i=1} B^{(i)}\left(\frac{\alpha_s}{\pi}\right)^i$. $A^{(1)} = C_A$ and $B^{(1)} = -(b_0 + \delta_{8c}/2)N_c$ with $b_0 = \left(\frac{11}{6}N_c - \frac{n_f}{3}\right)\frac{1}{N_c}$.

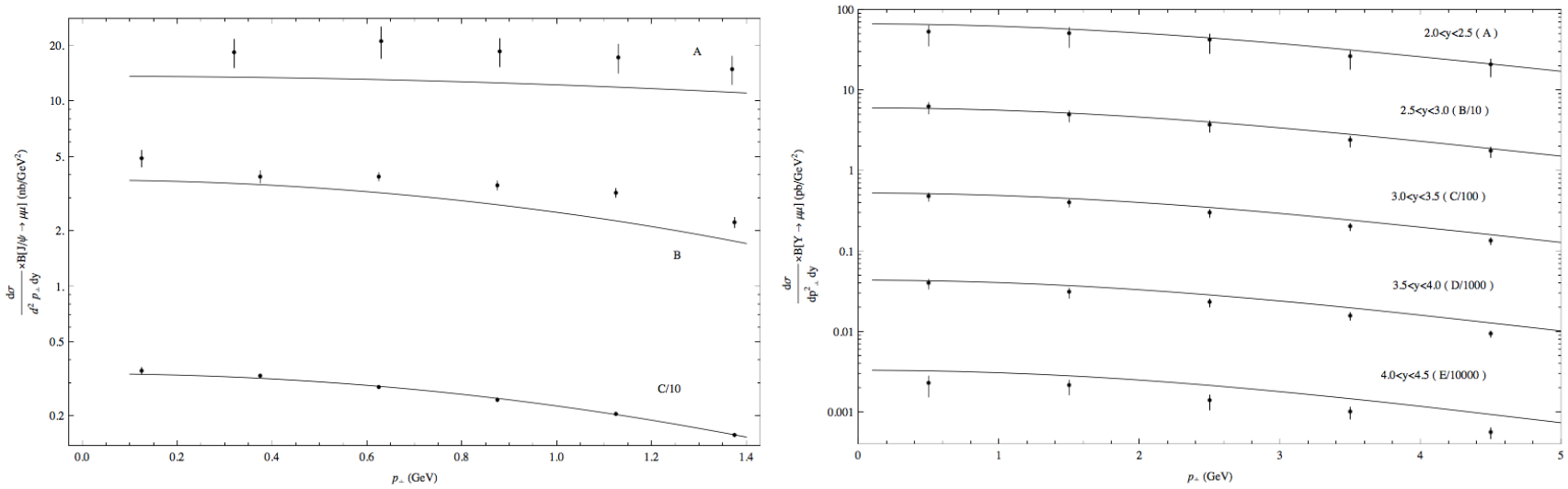
- Non-perturbative : $b > b_{max}$ [Sun, Yuan, Yuan (2012)]

$$S_{\mathrm{NP}}(M,b) = \exp\left[b^2\left(-g_1 - g_2\ln\left(\frac{M}{2Q_0}\right) - g_1 g_3 \ln(100x_1x_2)\right)\right]$$

$g_1 = 0.03$, $g_2 = 0.87$, $g_1 g_3 = -0.17$ with $Q_0 = 1.6$ GeV, $b_{\mathrm{max}} = 0.5$ GeV.

Lesson from conventional TMD calculation

[Sun, Yuan, Yuan (2012)]



- Left fig: J/ψ at LHC forward, RHIC mid and forward. Right fig: Υ at LHC forward.
- The agreement between theoretical results and experimental data for J/ψ production is not as good as that for Υ production