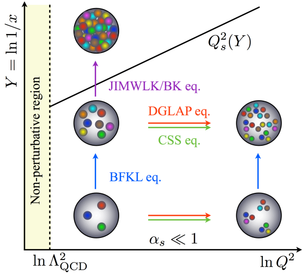
Quarkonium production in hadronic collisions: Small-x saturation and TMD evolution

Kazuhiro Watanabe

Old Dominion Univ

May 23, 2017
QCD evolution 2017

Gluon saturation in hadron/nucleus



- Gluon bremsstrahlung + recombination at small Bjorken $x \Rightarrow$ "Saturation" : Small-x saturation/Color-Glass-Condensate framework.
- Probes : single hadron, dijet, heavy flavor/quarkonium productions in forward pp and pA collisions.

Overview

Motivation

Naively, we anticipate that the saturation scale Q_s should characterize $P_\perp$ spectra of quarkonia production in pA and pp at forward rapidity. We need a test on the CGC framework.

- J/ψ production
  - The CGC framework with CEM/NRQCD can reproduce the data of low $P_\perp$ spectra in pp/pA at LHC.
- Υ production
  - The saturation effect cannot provide enough $P_\perp$ broadening $\Longrightarrow$ Additional parton shower effect (Sudakov) is required to interpret data.

✓ We will discuss implementations of Sudakov factor in the improved CGC model.

✓ Check the dominant effect: Saturation? or Suakov? or Both?

Talk Plan

1. CGC
2. TMD
3. Implementation of Sudakov factor in the CGC framework
4. Summary

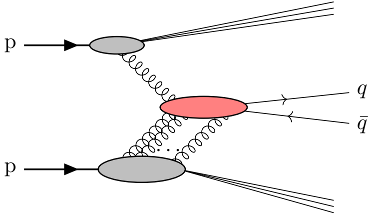
Talk Plan

1. CGC
2. TMD
3. Implementation of Sudakov factor in the CGC framework
4. Summary

The CGC picture of pA/pp

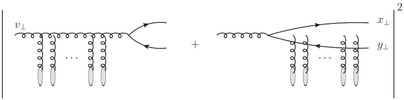
[Blaizot, Gelis, Venugopalan (2004)][Kovchegov, Tuchin (2006)] · · ·

- p moving $\to x^+ = +\infty$, A moving $\to x^- = +\infty$.
- Regard pA as a dilute-dense system : Dense classical fields are essential for target side. Solving classical Yang-Mills eq. : $[D^\mu, F_{\mu\nu}] = J^\nu \Longrightarrow |\mathcal{T}\rangle = \sum_i^\infty |\underbrace{gg\cdots gg}_{i}\rangle$
- Boost classical fields $\Longrightarrow$ JIMWLK equation
- Assume that the CGC picture is applicable to pp collision at forward rapidity.
- Let us consider p + p $\to c\bar{c},\ b\bar{b}[\Rightarrow J/\psi,\ \psi(2S),\ \Upsilon] + X$



The CGC-Hybrid formula

- Forward rapidity $\Longrightarrow$ collinear pdf+dense wave function is robust.
- Differential xsection for $q\bar{q}$ production:



$$\frac{d\sigma^{\mathrm{pp}\to q\bar{q}+X}}{d^3p_1d^3p_2} = \frac{\alpha_S T_R}{p^+} xG(x) \int \frac{d^2x_\perp d^2y_\perp d^2x'_\perp d^2y'_\perp}{(2\pi)^8} e^{-ip_{1\perp}\cdot(x_\perp - x'_\perp)} e^{-ip_{2\perp}\cdot(y_\perp - y'_\perp)}$$
$$\times \sum_{\lambda,\alpha,\beta} \psi^{\lambda *}_{q\bar{q}\alpha\beta}(u'_\perp)\psi^{\lambda}_{q\bar{q}\alpha\beta}(u_\perp)\left[S^{(4)}_{q\bar{q}q\bar{q}}(x,y,y',x') - S^{(3)}_{q\bar{q}g}(y',x',v) - S^{(3)}_{q\bar{q}g}(x,y,v') - S_{gg}(v,v')\right]$$

- Complicated multipoint Wilson line correlators:

$$S^{(4)}_{q\bar{q}q\bar{q}}(x,y,y',x') \equiv \frac{1}{N_c C_F}\left\langle \mathrm{Tr}\left[U(x_\perp)t^aU^\dagger(y_\perp)U(y'_\perp)t^aU^\dagger(x'_\perp)\right]\right\rangle_{x_g}$$
$$S^{(3)}_{q\bar{q}g}(x,y,v') \equiv \frac{1}{N_c C_F}\left\langle \mathrm{Tr}\left[U(x_\perp)t^aU^\dagger(y_\perp)t^b\right]W^{ba}(v'_\perp)\right\rangle_{x_g}$$
$$S_{gg}(v,v') \equiv \frac{1}{N_c^2-1}\left\langle \mathrm{Tr}\left[W(v_\perp)W^\dagger(v'_\perp)\right]\right\rangle_{x_g}$$

- U and W : Fundamental and adjoint Wilson line.
- $\langle\cdots\rangle_{x_g}$: the CGC expectation

The CGC-Hybrid formula in large-N_c limit

- All of the correlators can be cast into

$$\begin{aligned} S^{(4)}_{q\bar{q}q\bar{q}}(x,y,y',x') &\approx S^{(2)}_{x_g}(x_\perp,x'_\perp)S^{(2)}_{x_g}(y_\perp,y'_\perp), \\ S^{(3)}_{q\bar{q}g}(x,y,v') &\approx S^{(2)}_{x_g}(x_\perp,v'_\perp)S^{(2)}_{x_g}(v'_\perp,y_\perp), \\ S_{gg}(v,v') &\approx S^{(2)}_{x_g}(v_\perp,v'_\perp)S^{(2)}_{x_g}(v'_\perp,v_\perp) \end{aligned}$$

- The differential xsection in momentum space:

$$\frac{d\sigma^{pp\to q\bar{q}X}_{\mathrm{LO}}}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2} = \frac{\alpha_S S_\perp}{(2\pi)^2} xG(x) \int d^2q_{1\perp}d^2q_{2\perp} F_{x_g}(q_{1\perp})F_{x_g}(q_{2\perp})\delta^{(2)}(P_{\mathrm{tot}}-q_{1\perp}-q_{2\perp})\hat{H}_{\mathrm{LO}}$$

with $F_{x_g}(k_\perp) = \int \frac{d^2r_\perp}{(2\pi)^2} e^{-ik_\perp\cdot r_\perp} S^{(2)}_{x_g}(r_\perp)$ the dipole amplitude.

- All of the color and spin in final state are summed up. $\Longrightarrow$ Dipole type Unintegrated Gluon Distribution Function (UGDF) is essential.
- $k_\perp$-factorization is violated.

Rapidity evolution

- Rapidity dependence of the dipole amplitude ($S = 1 - T$) $\Longleftarrow$ Balitsky-Kovchegov equation
  [Balitsky (1995)][Kovchegov (1996)]

$$\frac{dT_{x_g}(r)}{d\ln 1/x_g} = \mathcal{K} \otimes \left[\underbrace{T_{x_g}(r_1) + T_{x_g}(r - r_1) - T_{x_g}(r)}_{\text{BFKL}} \underbrace{- T_{x_g}(r_1) T_{x_g}(r - r_1)}_{\text{Recombination}} \right]$$

- The running coupling kernel in Balitsky's prescription is well controllable numerically.
  [Balitsky (2006)]

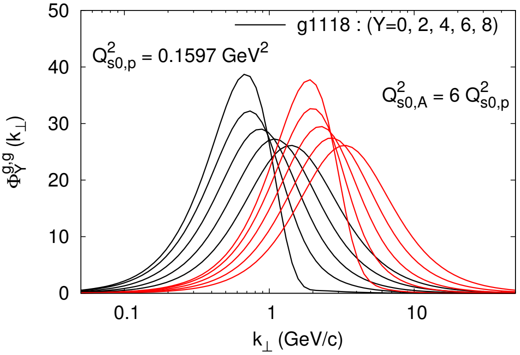
$$\mathcal{K}(r_\perp, r_{1\perp}) = \frac{\alpha_s(r^2) N_c}{2\pi^2} \left[\frac{1}{r_1^2} \left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_2^2} \left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right]$$

- Set Initial condition to be McLerran-Venugopalan model like functional form:

$$S_{x=0.01}(r_\perp) = \exp\left[- \frac{\left(r_\perp^2 Q_{s0,\mathrm{p}}^2 \right)^\gamma}{4} \ln\left(\frac{1}{r_\perp \Lambda} + e \right) \right]$$

✓ Input parameters γ, $Q_{s0,\mathrm{p}}^2$ are precisely constrained from HERA-DIS global data fitting.
[AAMQS (2010)]

The dipole gluon distribution function at small-x



- $x_{1,2} = M/\sqrt{s}e^{\pm y}$ reads $x_2 = 8.1 \times 10^{-6}$ for J/ψ production at $\sqrt{s} = 7$ TeV, $y = 4 \Longrightarrow$ $Y \approx 7$ when $x_0 = 0.01 \longleftrightarrow Q_{s,\mathrm{p}} = 1 \sim 2$ GeV for proton
- For nucleus, $Q_{s,A} = (2 \sim 3)Q_{s,\mathrm{p}}$

Hadronization from $q\bar{q}$ to ψ

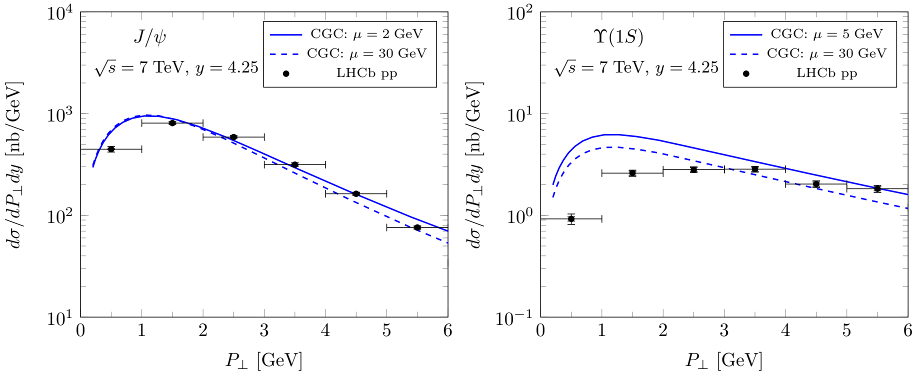
✓ From now on in this talk, **Color Evaporation Model (CEM)** is employed:

$$\frac{d\sigma_\psi}{d^2P_\perp dy} = F_{q\bar{q}\to\psi} \int_{2m_q}^{2M_Q} dM \frac{d\sigma_{q\bar{q}}}{dM d^2P_\perp dy}$$

- $q\bar{q}$ converts into ψ with the probability $F_{q\bar{q}\to\psi}$.
- We disregard complicated bound state formation dynamics, but our discussion would be simplified.
- As long as low $P_\perp$ production, CEM is reasonable in accordance with the large-N_c approximation.
- CGC+NRQCD $\Longrightarrow$ See [Kang, Ma, Venugopalan (2013)][Ma, Venugopalan (2014)]

Numerical results

[Fujii, K.W. (2013)][K.W., Xiao (2015)]



- The CGC can describe J/ψ production, since the saturation scale is "Hard" $\rightarrow$ $m_c \lesssim Q_s \approx \langle P_\perp \rangle$.
- For Υ production, the saturation scale is "Soft" $\rightarrow m_b > Q_s \approx \langle P_\perp \rangle$. More $P_\perp$ broadening effect is required.

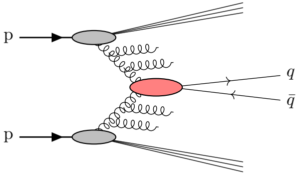
Let us consider Υ production further!

Talk Plan

1. CGC
2. TMD
3. Implementation of Sudakov factor in the CGC framework
4. Summary

CSS formalism

[Collins-Soper-Sterman (1985)][Berger, Qiu, Wang (2005)][Sun, Yuan, Yuan (2012)]



Heavy quark pair production with soft gluon emissions:

$$\frac{d\sigma^{pp\to q\bar{q}+X}}{d^2P_\perp dy}=\int\frac{d^2b_\perp}{(2\pi)^2}e^{iP_\perp\cdot b_\perp}\underbrace{W(M,b_\perp,x_1,x_2)}_{\text{resum}}+\underbrace{(d\sigma_{\text{perp}}-d\sigma_{\text{asy}})}_{\text{Y-term}}$$

where W satisfies $\frac{\partial}{\partial \ln Q^2}W=[K+G]W$: resummation of the large logs. It can be written as $W(M,b_\perp,x_1,x_2)=\sum_{ij}d\hat{\sigma}_{\text{LO}}^{ij\to q\bar{q}}W_{ij}(M,b_\perp)e^{-S_{ij}(M,b_\perp)}$ with

$$\begin{cases} W_{ij}(M,b_\perp)=\sum_{a,b}\int\frac{d\xi}{\xi}\frac{d\xi'}{\xi'}C_{a\to i}\left(\frac{x_A}{\xi}\right)C_{b\to j}\left(\frac{x_B}{\xi'}\right)\underbrace{\phi_{a/A}(\xi,\mu)\phi_{b/B}(\xi',\mu)}_{\text{collinear-pdfs}} \\ S_{ij}(M,b)=\int_{c_0/b^2}^{M^2}\frac{d\mu^2}{\mu^2}\left[A_{ij}\ln\left(\frac{M^2}{\mu^2}\right)+B_{ij}\right] \end{cases}$$

A, B, C are calculated perturbatively.

Nonperturbative form factor

- CSS type extrapolation

$$W(M, b_\perp) = W^{\text{perp}}(M, b_\star) F^{\text{NP}}(M, b_\perp)$$

with $b_\star = \frac{b}{\sqrt{1+(b/b_{\text{max}})^2}} < b_{\text{max}} = 0.5\ \text{GeV}^{-1}$.

✓ NP form factor at $b > b_{max}$:for example, [Sun, Yuan, Yuan (2012)]

$$F^{\text{NP}}(M, b_\perp) = \exp\left[b_\perp^2\left(-g_1 - g_2 \ln\left(\frac{M}{2Q_0}\right) - g_1 g_3 \ln(100 x_1 x_2)\right)\right]$$

g_1, g_2, g_3 are obtained by data fitting.

- Matching type extrapolation [Qiu, Zhang (2001)]

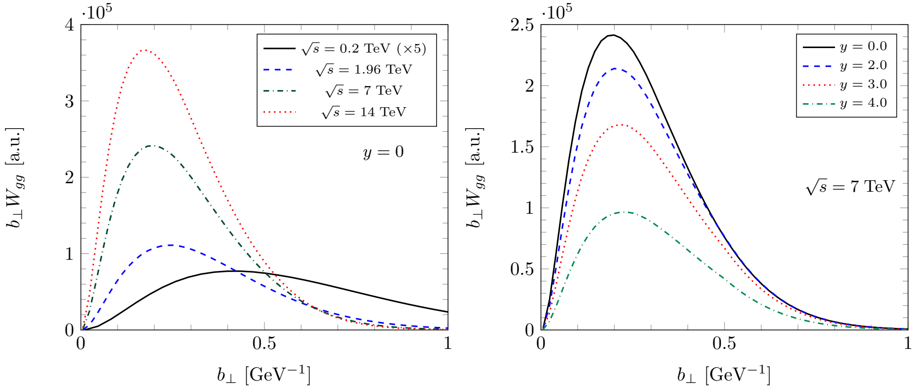
$$W(M, b_\perp) = \begin{cases} W^{\text{perp}}(M, b_\perp) & b_\perp \leq b_{\text{max}} \\ W^{\text{perp}}(M, b_{\text{max}}) F^{\text{NP}}(M, b_\perp; b_{\text{max}}) & b_\perp > b_{\text{max}} \end{cases}$$

✓ NP form factor at $b_\perp > b_{\text{max}}$

$$F^{\text{NP}}(b_\perp, M) = \exp\left[-\ln\left(\frac{M^2 b_{\text{max}}^2}{c^2}\right)\left[g_1((b_\perp^2)^\alpha - (b_{\text{max}}^2)^\alpha) + g_2(b_\perp^2 - b_{\text{max}}^2)\right] - \bar{g}_2(b_\perp^2 - b_{\text{max}}^2)\right]$$

g_1, α are obtained by connecting W^{perp} and F^{NP} smoothly at $b_\perp = b_{\text{max}}$. g_2, $\bar{g}_2$ are obtained from data fitting.

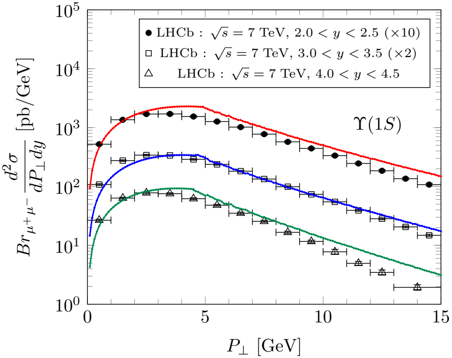
$b_\perp$-distributions for $b\bar{b}$ production



- $s \uparrow \Longrightarrow b_{sp}$ shifts toward small $b_\perp$: Perturbative domains ($b < b_{max} = 0.5[\mathrm{GeV}^{-1}]$) are essential. F^{NP} is not crucial for $b\bar{b}$ production at Tevatron & LHC.
- $y \uparrow \Longrightarrow b_{sp}$ shifts toward large $b_\perp$ but $b_{sp} < b_{max}$.

Differential xsection for Υ production in CSS

[Berger, Qiu, Wang (2005)][Qiu, K.W. (2017)]



- CEM is used with resummation scheme : $\mu = c/b_\perp$.
- $P_\perp \lesssim M_\Upsilon/2 : d\sigma_{\rm resum}$, $P_\perp \gtrsim M_\Upsilon/2 : d\sigma_{\rm perp}$

Next $\Longrightarrow$ How about pA? Consider the saturation effect and the Sudakov effect together!

Talk Plan

1 CGC

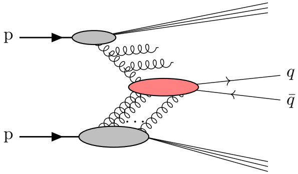
2 TMD

3 Implementation of Sudakov factor in the CGC framework

4 Summary

Improved CGC-Hybrid framework

[K.W., Xiao (2015)]



- Indeed, NLO calculations for $q\bar{q}$ production have not completed in the CGC framework. But assume that large logarithms concerning soft gluon emission can be resummed over.
- The soft gluon shower effect and the saturation effect can be described straightforwardly in the dipole model based approach:

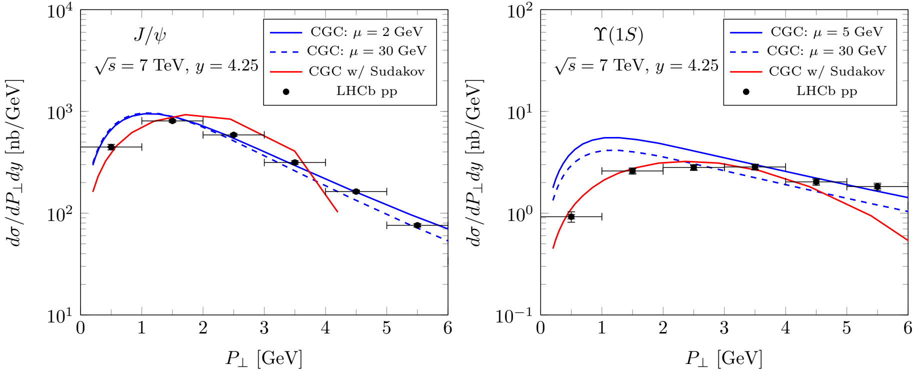
$$d\sigma_{\rm resum}^{pp\to q\bar{q}+X} \propto \int \frac{d^2u_\perp d^2v_\perp}{(2\pi)^4}\, e^{-iP_{\rm rel}\cdot u_\perp} e^{iP_\perp\cdot v_\perp} x_1 G\Big(x_1, \frac{c_0}{v_\perp}\Big) S_{x_g}(x_\perp) S_{x_g}(y_\perp) e^{-S_{\rm Sud}(M,v_\perp)} \hat{H}_{\rm LO},$$

with $x_\perp = v_\perp + (1-z)u_\perp$ and $y_\perp = v_\perp - zu_\perp$.

- $e^{-S_{\rm Sud}(M,v_\perp)}$ must be “Universal”.
- $P_{\rm rel}$ is integrated over in the CEM.

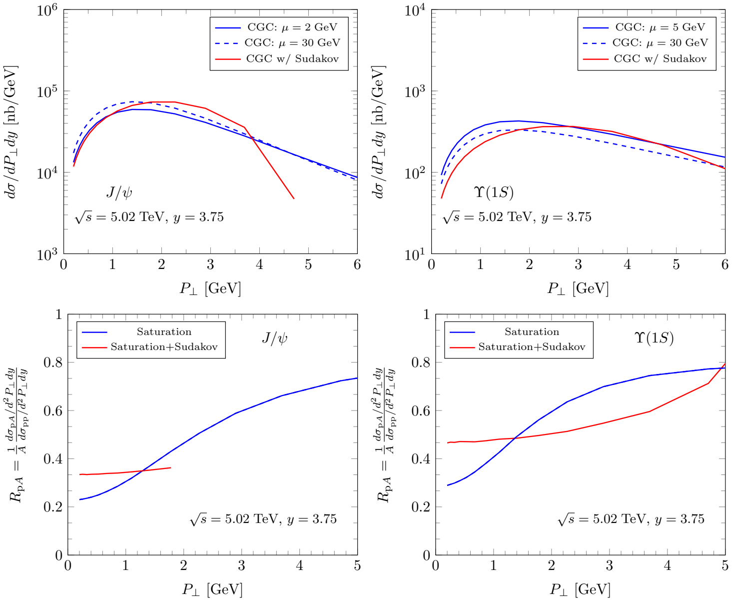
Υ production in pp collisions with Parton shower effect

[KW and Xiao (2015)]



- Resummation scheme : $\mu = c/b_\perp$.
- Parton shower (Sudakov) effect is dominant for low-$P_\perp$ Υ production in pp collisions.
- For J/ψ production, NP Sudakov form factor is crucial.

Predictions at pA collision



Talk Plan

1 CGC

2 TMD

3 Implementation of Sudakov factor in the CGC framework

4 Summary

Summary

- Motivation: we want to study whether quarkonium production is a promising probe into the gluon saturation in hadron/nucleus.
- What we have done is computing $P_\perp$ spectra of J/ψ and $\Upsilon(1S)$ in pp and pA collisions by using two different framework: CGC and TMD framework.

✓ pp collision

- J/ψ is better, since $m_c \lesssim Q_s$. Soft gluon emission effect can be not large but the nonperturbative form factor is essential.
- The results in the CGC and TMD frameworks show clearly that soft gluon emissions effect is predominant over the saturation effect for Υ production.

✓ pA collision

- $m_c < Q_{s,A}$ and $m_b \sim Q_{s,A}$. $P_\perp$ distribution of Nuclear modification factor is sensitive to a combination of the small-x effect and parton shower effect.

Thank you!

Talk Plan

5 Appendix

Soft gluons emission on top of the BK resummation modifies $p_\perp$-dependence.

$$\frac{d\sigma_{Q\bar{Q}}}{d^2q_{Q\perp}d^2q_{\bar{Q}\perp}dy_q dy_{\bar{Q}}} = \frac{\alpha_s^2\overline{S}_\perp}{16\pi^2 C_F}\int d^2l_\perp d^2k_\perp \frac{\Xi_{\rm coll}(k_{2\perp}, k_\perp - zl_\perp)}{k_{2\perp}^2} \times F_{\rm TMD}(l_\perp) F_{Y_g}(k_\perp) F_{Y_g}(k_{2\perp} - k_\perp + l_\perp)$$

where the TMD gluon distribution is given by

$$F_{\rm TMD}(M, l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2} e^{-ib_\perp\cdot l_\perp} e^{-S_{\rm Sud}(M,b_\perp)} x_1 G\left(x_1, \mu = \frac{c_0}{b_\perp}\right).$$