Second conference on heavy ion collisions in the LHC era and beyond

Heavy quark pair production in pA collisions at the LHC within the CGC framework

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Talk Plan
Heavy quark pair production in HIC

- The goals of ultrarelativistic heavy ion collisions (HICs) physics are to create quark-gluon plasma (QGP) and to understand its properties.

- Heavy quark pair is produced in initial hard process $\rightarrow$ Subsequent interactions reflect medium properties.

- Initial cold nuclear matter (CNM) effects, such as nPDF, energy loss, parton saturation, should be studied in pA collisions $\rightarrow$ A controlled baseline against AA.
At the LHC, HQ productions can be reflected of small-x information of dense gluon for the target hadron.

Their typical transverse momentum is around the saturation momentum:

\[ Q_{sA}^2(x_2) \sim A^{1/3} \left( \frac{0.01}{x_2} \right)^{0.3} \Lambda_{QCD}^2 \]

→ a test of CGC
The CGC formula


- **kt-factorized formula**

\[
\frac{d\sigma_{q\bar{q}}}{d^2 q_{\perp} d^2 q_{\perp} dy_d y_{\bar{q}}} = \frac{\alpha_s^2}{(2\pi)^6 C_F} \int d^2 k_{2\perp} d^2 k_{\perp} \frac{\Xi(k_{1\perp}, k_{2\perp}, k_{\perp})}{k_{1\perp}^2 k_{2\perp}^2} \varphi_{p,x_1}(k_{1\perp}) \phi_{A,x_2}(k_{2\perp}, k_{\perp})
\]

- **Hybrid (DHJ) formula : collinear/CGC (Forward regions)**

\[
\frac{d\sigma_{q\bar{q}}}{d^2 q_{\perp} d^2 q_{\perp} dy_d y_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F} \int d^2 k_{\perp} \frac{\Xi_{\text{coll}}(k_{2\perp}, k_{\perp})}{k_{2\perp}^2} x_1 G(x_1, \mu) \phi_{A,x_2}(k_{2\perp}, k_{\perp})
\]

**High energy limit :** \(s \to \infty\)
The multipoint function

\[ \phi_{A,Y_g}^{q\bar{q},g}(k_{2\perp}, k_{\perp}) \propto \int \frac{d^2 x_\perp d^2 y_\perp}{(2\pi)^4} e^{-i k_{\perp} \cdot x_\perp} e^{i(k_{2\perp} - k_{\perp}) \cdot y_\perp} S_{Y_g}(x_\perp) S_{Y_g}(y_\perp) \]

\[ = F_{Y_g}(k_{\perp}) F_{Y_g}(k_{2\perp} - k_{\perp}) \]

\[ Y_g = \ln \frac{1}{x^2} \]

The multipoint function is the same in both CEM and color octet channel of NRQCD in large-Nc.

Nuclear dependence is expected to be universal for quarkonium production.

Qiu, Sun, Xiao and Yuan, PRD89(2014)
Balitsky-Kovchegov equation


- BK equation: Quantum evolution of dipole

\[
\frac{d}{dY} N_Y(\vec{r}_\perp) = \int d\vec{r}_1^\perp \mathcal{K}(\vec{r}_\perp, \vec{r}_1^\perp) \left[ N_Y(\vec{r}_1^\perp) + N_Y(\vec{r}_2^\perp) - N_Y(\vec{r}_\perp) - N_Y(\vec{r}_1^\perp)N_Y(\vec{r}_2^\perp) \right]
\]

BFKL cascade
Recombination

- The running coupling evolution kernel (rcBK)

\[
\mathcal{K}_{\text{run}}(\vec{r}_\perp, \vec{r}_1^\perp) = \frac{\alpha_s(r^2) N_c}{2\pi^2} \left[ \frac{1}{r_1^2} \left( \frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_2^2} \left( \frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right]
\]

rcBK is the state-of-the-art technology for phenomenologies

I. Balistky (2007)
Initial condition of the rcBK

- Parametrized initial condition at $x=0.01$: $MV^\gamma$ model

$$N_{Y=0}(r_\perp) = 1 - \exp \left[-\frac{(r^2 Q_{s0,p}^2)^\gamma}{4} \ln \left(\frac{1}{\Lambda r} + e\right)\right] \quad (*\Lambda = 0.241\text{GeV})$$

$$\alpha_s(r^2) = \left[b_0 \ln \left(\frac{4C^2}{r^2 \Lambda^2} + a\right)\right]^{-1}$$

$$\alpha_s(r \to \infty) = \alpha_{fr}$$

Global analysis of DIS data

<table>
<thead>
<tr>
<th>$Q_{s0,p}^2/\text{GeV}^2$</th>
<th>$\gamma$</th>
<th>$\alpha_{fr}$</th>
<th>$C$</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV$^\gamma$</td>
<td>0.1597</td>
<td>1.118</td>
<td>1.0</td>
<td>2.47</td>
</tr>
</tbody>
</table>

$\gamma$ controls the steepness of the gluon distribution at higher momentum $k_\perp > Q_{s0,p}$

cf. for rcBK:
Fujii, Itakura, Kitadono, Nara, JPG38(2011),
Albacete, Dumitru, Fujii, Nara, NPA897 (2013)
Dipole gluon distribution function

\[ \Phi^g_{Y} (k_{\perp}) \propto \int \frac{d^2x_{\perp}}{(2\pi)^2} e^{-ik_{\perp} \cdot x_{\perp}} S_Y(x_{\perp}) S_Y(x_{\perp}) \]

Forward rapidity at RHIC

\[ x_2 = 10^{-2} \sim 10^{-3} \]

\[ Q_{sp} < 1\text{GeV} \]

\[ Q_{sA} \sim 2\text{GeV} \]

Forward rapidity at the LHC

\[ x_2 = 10^{-4} \sim 10^{-5} \]

\[ Q_{sp} \sim 1\text{GeV} \]

\[ Q_{sA} \sim 3\text{GeV} \]
Early CGC results 1

Quarkonium
Fujii, KW, NPA915(2013)

Color evaporation model (CEM)
Open heavy flavor seems in good agreement with the data compared to quarkonium.
Early results

$Q_{s0,A}^2 = (4 \sim 6)Q_{s0}^2$

Another choice

$Q_{s0,A}^2 = (2 \sim 3)Q_{s0}^2$

cf. Ma, Venugopalan, and Zhang, arXiv:1503.07772,
Ducloue, Lappi, and Mantysaari, arXiv:1503.02789

Fig. 14. Nuclear modification factor $R_{pA}$ for $J/\psi$ as a function of $Q_{s0,A}^2$ at $y = 0, 1, 2$ and 3 for $\sqrt{s} = 200$ GeV (left) and at $y = 0, 1, 2$ and 4 for $\sqrt{s} = 5.02$ TeV (right). Fitted curves are also shown.

$R_{pA} = \frac{a}{(b + Q_{s0,A}^2)^\alpha}$

Fig. 15. Nuclear modification factor $R_{pA}$ for $\Upsilon(1S)$ as a function of $Q_N^2$ at $y = 0, 1, 2$ and 4 at $\sqrt{s} = 5.02$ TeV.
"LHCb puzzle"

- The saturation scale at the LHC is about 1GeV.
- What is the LHC data telling?

These results are computed in hybrid formula.
Two kinds of correction

- **Small-x**
  \[ \alpha_s N_c \ln \frac{1}{x_2} \sim \mathcal{O}(1) \]
  
  BK eq.

- **Low-pt**
  \[ \alpha_s N_c \ln^2 \frac{M^2}{p_{\perp}^2} \sim \mathcal{O}(1) \]
  
  Sudakov factor

  cf. Higgs boson production

“Heavy” quarkonium production at low-pt is expected to be sensitive to the Sudakov factor: \( p_t < M \).

KW and Xiao, arXiv:1507.06564
The CGC formula with the Sudakov factor

\[ \frac{d\sigma_{q\bar{q}}}{d^2q_{\perp} d^2\bar{q}_{\perp} dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F} \int d^2l_{\perp} d^2k_{\perp} \frac{\Xi_{\text{coll}}(k_{2\perp}, k_{\perp} - zl_{\perp})}{k_{2\perp}^2} \phi_{x_1,x_2}(k_{2\perp}, k_{\perp}, l_{\perp}) \]

\[ \phi_{x_1,x_2}(k_{2\perp}, k_{\perp}, l_{\perp}) \propto F_{Y_g}(k_{\perp}) F_{Y_g}(k_{2\perp} - k_{\perp} + l_{\perp}) F_{\text{Sud}}(l_{\perp}) \]

\[ F_{\text{Sud}}(M,l_{\perp}) = \int \frac{d^2b_{\perp}}{(2\pi)^2} e^{-ib_{\perp} \cdot l_{\perp}} e^{-S_{\text{Sud}}(M,b_{\perp})} x_1 G \left( x_1, \frac{c_0}{b_{\perp}} \right) \]
The CGC formula with the Sudakov factor

\[
\frac{d\sigma_{q\bar{q}}}{d^2 q_{\perp} d^2 \bar{q}_{\perp} dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F} \int d^2 l_{\perp} d^2 k_{\perp} \frac{\Xi_{\text{coll}}(k_{2\perp}, k_{\perp} - z l_{\perp})}{k_{2\perp}^2} \phi_{x_1, x_2}(k_{2\perp}, k_{\perp}, l_{\perp})
\]

**Improved Hybrid formula**

\[
\phi_{x_1, x_2}(k_{2\perp}, k_{\perp}, l_{\perp}) \propto F_{Yg}(k_{\perp}) F_{Yg}(k_{2\perp} - k_{\perp} + l_{\perp}) F_{\text{Sud}}(l_{\perp})
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F_{\text{Sud}}(M, l_{\perp}) = \int \frac{d^2 b_{\perp}}{(2\pi)^2} e^{-i b_{\perp} \cdot l_{\perp}} e^{-S_{\text{Sud}}(M, b_{\perp})} x_1 G \left( x_1, \frac{c_0}{b_{\perp}} \right)
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The CGC formula with the Sudakov factor

\[ d \sigma_{q\bar{q}} \frac{d^2 q_{\perp}}{d^2 q_{\perp}d^2 q_{\perp} dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F} \int d^2 l_{\perp} d^2 k_{\perp} \frac{\Xi_{\text{coll}}(k_{\perp}, k_{\perp} - zl_{\perp})}{k_{\perp}^2} \phi_{x_1,x_2}(k_{2\perp}, k_{\perp}, l_{\perp}) \]

**Improved** Hybrid formula

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**Sudakov**

\[ F_{\text{Sud}}(M, l_{\perp}) = \int \frac{d^2 b_{\perp}}{(2\pi)^2} e^{-ib_{\perp} \cdot l_{\perp}} e^{-S_{\text{Sud}}(M, b_{\perp})} x_1 G \left( x_1, \frac{c_0}{b_{\perp}} \right) \]
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\frac{d\sigma_{q\bar{q}}}{d^2q_\perp d^2\bar{q}_\perp dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F} \int d^2l_\perp d^2k_\perp \frac{\Xi_{\text{coll}}(k_\perp, k_\perp - zl_\perp)}{k_\perp^2} \phi_{x_1,x_2}(k_\perp, k_\perp, l_\perp)
\]

**Improved Hybrid formula**

\[
\phi_{x_1,x_2}(k_\perp, k_\perp, l_\perp) \propto F_{Yg}(k_\perp) F_{Yg}(k_\perp - k_\perp + l_\perp) F_{\text{Sud}}(l_\perp)
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\[
F_{\text{Sud}}(M, l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2} e^{-ib_\perp \cdot l_\perp} e^{-S_{\text{Sud}}(M, b_\perp)} x_1 G \left( x_1, \frac{c_0}{b_\perp} \right)
\]

**BK**

DGLAP (CTEQ6M)
Collins-Soper-Sterman (CSS) formalism

\[ S_{\text{Sud}}(M, b) = S_{\text{perp}}(M, b_\star) + S_{\text{NP}}(M, b) \]  

CSS, NPB250(1985)

\[ b_\star = b / \sqrt{1 + (b/b_{\text{max}})^2} \]

small-b: \( b_\star \sim b \)

large-b: \( b_\star \sim b_{\text{max}} = 0.5 \text{ GeV}^{-1} \)

- Perturbative form factor (small-b)  
  \[ S_{\text{perp}}(M, b) = \int_{c_0/b^2}^{M^2} \frac{d\mu^2}{\mu^2} \left[ A \ln \left( \frac{M^2}{\mu^2} \right) + B \right] \]

\[ A = \sum_{i=1}^{\infty} A^{(i)} \left( \frac{\alpha_s}{\pi} \right)^i \]

At 1-loop calculation in NRQCD

\[ B = \sum_{i=1}^{\infty} B^{(i)} \left( \frac{\alpha_s}{\pi} \right)^i \]

\[ A^{(1)} = C_A \quad B^{(1)} = -\left( b_0 + \frac{1}{2} \delta_{8c} \right) N_c \quad b_0 = \left( \frac{11}{6} N_c - \frac{n_f}{3} \right) \frac{1}{N_c} \]

- Non-Perturbative form factor (large-b) ← Determined by the data fitting

\[ S_{\text{NP}}(M, b) = \exp \left[ \frac{b^2}{2} \left( -g_1 - g_2 \ln \left( \frac{M}{2Q_0} \right) - g_1 g_3 \ln(100x_1x_2) \right) \right] \]
The spectrum of soft gluons emission

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

- Upsilon production: a large broadening of the distribution is expected.
- Soft gluon emissions carry away $pt$ of the quarkonium about 1–2GeV.
The results are roughly in agreement with the data.

The Sudakov resummation is not applicable at \( p_T > 4,5 \) GeV.

When \( p_T \sim M \), we should switch to the fixed order CGC calculation, which is responsible for the large \( p_T \) region of the spectrum.
We can reproduce the data points very well due to the gluon cascade.

The peak is located at $p_t = 1 \text{ GeV} \rightarrow 3 \text{ GeV}$ (w/ Sudakov).

The Sudakov factor in association with large $M$ gives additional strong broadening of the $p_t$ distributions for Upsilon production.
Predictions of Y(1S) in pPb

The initial condition \( Q_{sA,0}^2 = 3 Q_{s,0}^2 \)

- The Sudakov effect in pA collisions is less pronounced as compared to pp.
- Nuclear modification factor can be modest at low pt.
Summary

- Heavy quark pair production in pA can probe the dense gluon structure.

- We have demonstrated both the small-x resummation and low-pt resummation are essential to understand the LHC data → NLO corrections are not small.

- The effect of the Sudakov factor

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<tr>
<th>J/ψ in pp</th>
<th>Y in pp</th>
<th>Y in pPb</th>
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<tbody>
<tr>
<td>△</td>
<td>⚫</td>
<td>△</td>
</tr>
</tbody>
</table>

- The large-pt broadening of quarkonium due to initial soft gluon emission could be seen in the other model such as CGC+NRQCD.