Heavy quark production in pA collision with rcBK evolution

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Heavy Ion Collision

Aim of HIC exp.

- To create Quark-Gluon Plasma (QGP) in Lab.
- To study bulk properties of QGP

Observables

- EM probes; leptons & photons
- Soft probes; hadron distributions
- Hard probes; Jets, heavy flavor, Quarkonia

Toward comprehensive understanding
Heavy Quark System as Hard probe

Scale hierarchy in quarkonia:

\[ m \gg mv \gg mv^2 \]

\[ m : \text{mass} \]
\[ v \sim \alpha_s : \text{velocity} \]

• Heavy quarks \((m \gg \Lambda_{QCD})\) are produced in perturbative process.
• HQs in Quarkonia moves slowly \((mv)\) and their binding energy \((mv^2)\) can be \(\Lambda_{QCD}\) scale.
• Quarkonium formation in QGP is sensitive to Debye screening.
• Modification of Open HQ due to Energy-loss and hadronization are also very important.
Strategy for HQ production in HIC

pp : test of pQCD calculation
• Quarkonium production mechanism remains as an open question.

pA : nuclear pdf, multiple scattering
• These effects will modify HQs and Quarkonium production

AA : Hot medium effects
• HQs Energy-loss
• Quarkonium suppression and enhancement

Color Glass Condensate (CGC) describes multiple scattering and gluon distribution in Hadron. Typical saturation scale $Q_s^2$ reaches to a few GeV$^2$ at RHIC, LHC, and we expect that the saturation affects HQs and Quarkonium production.
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Color Glass Condensate (CGC)


McLerran-Venugopalan (MV) model
McLerran and Venugopalan, PRD49,50 (1994)

- Large Bjorken-\( x \) partons: random color sources (gaussian dist.)
- Small-\( x \) partons: classical fields produced from the sources

- multiple scattering
- no rapidity dependence

Quantum evolution of MV model: CGC

- Source dist. func. follows JIMWLK renormalization group eqn.

CGC provides us the framework to study the parton multiple scattering and quantum evolution effects.
Consider the proton and nucleus colliding at the speed of light.

**Color Current at leading order in the source**

\[
J^\mu_a = g\delta^\mu+\delta(x^-)\rho_{p,a}(x_\perp) + g\delta^\mu-\delta(x^+)\rho_{A,a}(x_\perp)
\]

**Yang-Mills Eqn ; background soft modes**

\[
[D_\mu, F^{\mu\nu}] = J^\nu
\]

HQ pair production amplitude is obtained by computing quark propagator in the background.
HQ pair production cross section

- A single QQbar pair production cross section at LO in gauge coupling.

\[
\frac{d\sigma_{q\bar{q}}}{d^2q_\perp d^2p_\perp dy_q dy_p} = \frac{\alpha_s^2}{(2\pi)^4 C_F} \int_{k_2\perp, k_\perp} \Xi(k_{1\perp}, k_{2\perp}, k_\perp) \frac{\phi_{p}^{g,g}(k_{1\perp}) \phi_{A}^{q\bar{q},g}(k_{2\perp}, k_\perp)}{k_{1\perp}^2 k_{2\perp}^2}
\]

Hard matrix element  \hspace{5cm} uGDs

- uGD is expressed with dipole amplitude \( S(k) \) in large-\( N_c \)

\[
\phi_{A}^{q\bar{q},g}(k_{2\perp}, k_\perp) = \frac{\pi R_A^2 k_{2\perp} N_c}{4\alpha_s} S(k_{2\perp} - k_\perp) S(k_\perp)
\]

\[
S(k) = \text{F.T.} \left[ 1 - \mathcal{N}(r, Y) \right] = \text{F.T.} \left[ \frac{1}{N_c} \text{tr} \left\langle \tilde{U}(r_\perp)\tilde{U}(0) \right\rangle \right]
\]
Quantum evolution in small-x region

- In large-Nc and large-A mean field approximation, JIMWLK eqn reduces non-linear Balitsky-Kovchegov (BK) eqn.
- We can obtain dipole amplitude by only solving BK eqn.

\[ \frac{\partial \mathcal{N}(r, Y)}{\partial Y} = \int dr_1 K_{LO} \left[ \mathcal{N}(r_1, Y) + \mathcal{N}(r_2, Y) - \mathcal{N}(r, Y) - \mathcal{N}(r_1, Y)\mathcal{N}(r_2, Y) \right] \]

**LO BK eqn**

Balitsky, NPB463 (1996), Kovchegov, PRD60 (1999)

- **Gluon recombination** effect becomes more important in forward rapidity region, which corresponds to smaller x.

\[ Y = \ln\left(\frac{x_0}{x}\right), \quad r = r_1 + r_2 \]
rcBK evolution

- Running coupling effect as LO correction is included, and evolution kernel becomes scale dependent one.


\[
\frac{\partial N(r, Y)}{\partial Y} = \int dr_1 K_{\text{run}} [N(r_1, Y) + N(r_2, Y) - N(r, Y) - N(r_1, Y)N(r_2, Y)]
\]

- Fixed coupling
  \[
  K_{\text{LO}} = \frac{N_c \alpha_s}{2\pi^2} \frac{r^2}{r_1^2 r_2^2}
  \]

- Balitsky’s prescription
  \[
  K_{\text{run}} = \frac{N_c \alpha_s (r^2)}{2\pi^2} \left[ \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_1^2} \left( \frac{\alpha_s (r_1^2)}{\alpha_s (r_2^2)} - 1 \right) + \frac{1}{r_2^2} \left( \frac{\alpha_s (r_2^2)}{\alpha_s (r_1^2)} - 1 \right) \right]
  \]

- 1-loop running coupling:
  \[
  \alpha_s (r^2) = \frac{1}{\beta_2 \ln \left( \frac{4C^2}{r^2 \Lambda_{\text{QCD}}^2} \right)}
  \]

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rcBK solutions ; uGDS

Evolution speed ; BK(\(\alpha_s=0.1\)) \sim rcBK
CGC phenomenology

Applications of rcBK eqn have been successful in describing some exp. data.

DIS @ HERA

AAMQS, EPJC71(2011)

\[ \text{dN/dy @ LHC} \]

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Setup

MV model for Initial condition of dipole.
McLerran and Venugopalan, PLB424 (1998)

\[ N^{MV}(r, x = x_0 = 0.01) = 1 - \exp \left[ -\frac{r^2 Q_{s0}^2}{4} \ln \left( \frac{1}{r\Lambda} + e \right) \right] \]

Initial saturation scale at \( x_0 = 0.01 \)

\[ Q_{s0}^p = 0.2 \text{ GeV}^2, \quad Q_{s0}^A = A^{1/3} Q_{s0}^p = 1.2 \text{ GeV}^2 \]

\[ \sim 6 \text{ for Au / Pb} \]

Here we only discuss the Nuclear Modification Factor ;

\[ R_{pA} = \frac{d\sigma_{pA}}{N_{coll}d\sigma_{pp}} = \frac{d\sigma_{pA}}{6 \times d\sigma_{pp}} \]

to study the running coupling effect by computing LO cross section + LO BK or rcBK eqns.
Charm-pair : vs $P_T$ @RHIC

Charm mass $m=1.5$ GeV, Invariant mass $M=4$ GeV

\[ \sqrt{s} = 200 \text{GeV} \]

$y = 0$ ; Cronin peak, fixed by initial model at $x_0=0.01$

$y = 2$ ; Evolution effects are seen.

rcBK vs BK eqns ; some quantitative difference
Charm-pair : vs $P_T$ @LHC

Charm mass $m=1.5$ GeV, Invariant mass $M=4$ GeV

- $y=0$ ; $x_2$ is already very small.
- $y=0, 4$ ; strong suppression due to $x$-evolution
- rcBK vs BK ; difference becomes larger than at RHIC
- In large-$P_T$ region, rcBK result approaches BK one with $\alpha_s=0.1$. 

\[ y = \ln \left( \frac{M_T}{\sqrt{s} x_2} \right) \]
Fragmentation function

Open Heavy Flavor: **Peterson’s fragmentation function.**

\[ D_Q(z) = \frac{N}{z[1 - (1/z) - \epsilon_Q/(1 - z)]^2} \]
\[ \epsilon_Q \sim \frac{m_q^2}{m_Q^2} \]

Quarkonium: We suppose that the bound states are produced via soft color interaction (**Color Evaporation Model**) both in the pp and pA collision.

\[ d\sigma_{(Q\bar{Q})} = F_{(Q\bar{Q})} \int_{2m_Q}^{2m_{Q\bar{Q}}} dM \frac{d\sigma}{dM} \]

Spin polarization → Future study
D-meson : vs $P_T$

Charm mass $m=1.5$ GeV

- $\sqrt{s} = 200$ GeV
- $\sqrt{s} = 5$ TeV

- $y=0$ at RHIC energy; Cronin peak is small
- Qualitative results of Open Heavy flavor production are similar to results of HQ pair production.
\( J/\psi : \text{vs } y \) (Integrating over \( P_T \))

- Good agreement with exp. data “at RHIC”
- Other parameters set → Future study
- \( \text{rcBK result is close to BK result with } \alpha_s = 0.2 \)
From uGDs

- $P_T$ dependence of $R_{pA}$ cannot be explained only from a ratio of uGDs.
  - Future study
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Summary

• CGC provides the framework to study the multiple scattering and saturation effects on HQs and Quarkonium production in pA collision.

• We found that the saturation effects manifest even in the HQ and Quarkonium production in the forward rapidity region at the RHIC energy as well as in wider rapidity region at the LHC energy.

• rcBK and LO BK eqns result in quantitatively different $P_T$ dependences of $R_{pA}$ of HQs and Quarkonium.

Outlook

We will elaborate the model toward unified description of nuclear effects from DIS to pA with rcBK eqn.