Heavy Flavor and Quarkonium Production in the Color Glass Condensate framework: From p+p to p+A collisions

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PRC97 (2018) 014909 with Y.-Q. Ma, R. Venugopalan, H. F. Zhang
arXiv:1803.11093 with Y.-Q. Ma, P. Tribedy, R. Venugopalan
Highly occupied small-$x$ gluons are at the core in the Color-Glass-Condensate (CGC).

Nonlinear gluon recombination leads to “Gluon Saturation”.

Semihard saturation scale in nucleus:

\[ Q_s^2 A(x) \sim A^{1/3} \left( \frac{1}{x} \right)^{0.3} \gg \Lambda_{QCD}^2 \]

How to probe into the CGC in HICs? What are we able to expect from the CGC in HICs? ⇒ Heavy quarks in p+p and p+A collisions.
Why Heavy Quarks?

- Heavy quark pair ($Q\bar{Q}$) is mainly produced in a hard gluon scattering at high energy. $Q\bar{Q}$ probes into gluons inside hadron or nucleus.

- $m \gg \Lambda_{QCD}$ allows weak coupling calculations. If $m \lesssim Q_s$, heavy quark pair can probe a dense gluon regime inside hadron/nucleus even at low-$p_{\perp}$ of order $O(\Lambda_{QCD})$.

The Role of p+p Collision

- Elementary process for understanding HF and Onium production mechanisms at low $p_{\perp}$. The CGC framework is complementary to pQCD approach which works well at high $Q^2$.

- p+p is an important reference against p+A and A+A collisions.

The Role of p+A Collision

- Large $Q_s$ should modify $p_{\perp}$ distribution of $Q\bar{Q}$ production compared to p+p collisions. ⇒ This is a Cold Nuclear Matter (CNM) effect which must be distinguished from hot medium effect in A+A collisions.
FRAMEWORK

MINIMUM BIAS EVENTS

HIGH MULTIPLICITY EVENTS

SUMMARY
**Q̅Q production in the CGC framework**

[Blaizot, Gelis and Venugopalan, NPA743, 57 (2004)]

- **Large-\(x\):**
  
  \[ J^\nu = g \delta^{\nu+} \delta(x^-) \rho_p (x_\perp) + g \delta^{\nu-} \delta(x^+) \rho_A (x_\perp). \]

- **Small-\(x\):**
  
  Classical fields satisfy CYM equation,
  
  \[ [D_\mu, F^{\mu\nu}] = J^\nu. \]

- **\(Q\bar{Q}\) is produced coherently as a whole in the background fields.**

- In **Large-\(N_C\) limit,**
  
  \[
  \frac{d\sigma_{Q\bar{Q}}}{d^2p_{Q\perp} d^2q_{\bar{Q}\perp} dy_Q dy_{\bar{Q}}} = \frac{\alpha_s N_C^2 \pi R_A^2}{2(2\pi)^{10} d_A} \int \frac{\varphi_{p,y_p}(k_{1\perp})}{k_{1\perp}^2} N_Y (k_{\perp}) N_Y (k_{2\perp} - k_{\perp}) \Xi \]

  \(\varphi_{p,y_p}\): Unintegrated gluon distribution function. \(N_Y\): Dipole amplitude. \(\Xi\): Hard part.

- **Wilson lines represents Multiple scattering of fast partons in background fields (Higher twist).**

- **Energy/Rapidity dependence:** Running coupling BK equation. [Balitsky, PRD75, 014001 (2007)]

- **Caveat:** The CGC framework is essentially applicable to a dilute-dense system at forward rapidity. Backward rapidity is unfavorable.
Open Heavy Flavor

(*Suppose charm production)

Single Open Heavy Flavor production:

\[
\frac{d\sigma_D}{d^2 p_{D\perp} dy} = \int_{z_{min}}^{1} dz \frac{D_{c \rightarrow D}(z)}{z^2} \int dy \bar{c} \int_{q_{\perp}} d^2 p_{c\perp} \frac{d\sigma_{c \bar{c}}}{d^2 q_{\perp} dy dy \bar{c}}
\]

- Heavy quark fragmentation function \( D_{c \rightarrow D}(z) \) modifies \( p_\perp \) spectrum of charm: \( \langle p_\perp^D \rangle < \langle p_\perp^c \rangle \).
- Large theoretical uncertainties may be indispensable at \( p_\perp \lesssim m \).
- cf. [Cacciari, Frixione, Houdeau, Mangano, Nason and Ridolfi, JHEP1210, 137 (2012)]

Heavy Flavor Decay Lepton production:

\[
\frac{d\sigma_l}{d^2 p_{l\perp} dy} = \int d^2 p_{D\perp} d^2 p_D dy_D \mathcal{F}(p_L, p_D) \frac{d\sigma_D}{d^2 p_{D\perp} dy}
\]

- Decay distribution function involved.
- \( \mathcal{F} \) is calculable analytically or obtained by fitting CLEO data.
- Decay from heavy flavor meson at high \( p_\perp \) into low \( p_\perp \) lepton is actually unfavorable in the CGC framework.
Improved CEM (ICEM): [Ma, Vogt, PRD 94, 114029(2016)]

\[
\frac{d\sigma_\psi}{d^2p_\perp dy} = F_{c \bar{c} \rightarrow \psi} \int_{m_\psi}^{2m_D} dM \left( \frac{M}{m_\psi} \right)^2 \frac{d\sigma_{c \bar{c}}}{dM d^2p'_\perp} dy \bigg|_{p'_\perp = \frac{M}{m_\psi} p_\perp}
\]

Soft gluons emission takes some momentum away from \(c\bar{c}\) in final state: \(\langle p^{\psi}_\perp \rangle > \langle p^{c\bar{c}}_\perp \rangle\).

NRQCD: [Kang, Ma, Venugopalan, JHEP 1401, 056(2014)]

\[
\frac{d\sigma_\psi}{dy dp_\perp^2} = \sum_\kappa \frac{d\hat{\sigma}_\kappa^{c\bar{c}}}{dy dp_\perp^2} \times \left\langle O_\kappa^\psi \right\rangle \quad (\kappa = 2S+1 L^{[c]}_J)
\]

\[
\frac{d\sigma^{c\bar{c},\text{CS}}}{d^2p_\perp dy} = \frac{\alpha_s \pi R_A^2}{(2\pi)^9 d_A} \int_{k_{2\perp},k_\perp,k'_\perp} \frac{\varphi_{p,y_p}(k_{1\perp})}{k_{1\perp}^2} N_Y(k_{\perp}) N_Y(k'_{\perp}) N_Y(k_{2\perp} - k_\perp - k'_\perp) G_1^\kappa
\]

\[
\frac{d\sigma^{c\bar{c},\text{CO}}}{d^2p_\perp dy} = \frac{\alpha_s \pi R_A^2}{(2\pi)^7 d_A} \int_{k_{2\perp},k_\perp} \frac{\varphi_{p,y_p}(k_{1\perp})}{k_{1\perp}^2} N_Y(k_{\perp}) N_Y(k_{2\perp} - k_\perp) \Gamma_8^\kappa
\]

CS channel probes the quadrupole amplitude \(Q_Y \rightarrow \text{Cubic in } N_Y\) in a quasi-classical approximation in the large-\(N_C\) limit. cf. [Dominguez, Kharzeev, Levin, Mueller and Tuchin, PLB 710, 182(2012)]
1 Framework

2 Minimum Bias events

3 High Multiplicity events

4 Summary
**Initial condition at Large-χ**

### Proton

Saturation scale is embedded in the initial condition:

$$S_Y(r_{\perp}) = \exp\left[\frac{\left(x_{\perp}^2 Q_{s,0}^2\right)^{\gamma}}{4} \ln\left(\frac{1}{|r_{\perp}| \Lambda + e}\right)\right]$$

$$Q_{sp,0}^2 = Q_0^2 \sim 0.168 \text{ GeV}^2 \text{ with } \gamma \sim 1.1 \text{ at } x = 0.01 \text{ by DIS global data fitting for total cross section at HERA.}$$

[Albacete, Armesto, Milhano, Quiroga-Arias and Salgado, EPJC71, 1705 (2011)]

### Nucleus

$$Q_{sA,0}^2(b_{\perp}) \propto A \hat{T}_A(b_{\perp}) S_{\perp} Q_{sp,0}^2,$$

$$Q_{sA,0}^2 \sim (0.25 - 0.5) A^{1/3} Q_{sp,0}^2 \sim 2Q_0^2 \text{ at } x \sim 0.01 \text{ for heavy nuclei by fitting the New Muon Collaboration data on } F_{2,A}. $$

[Dusling, Gelis, Lappi and Venugopalan, NPA836, 159 (2010)]
**Selected Results of Open Heavy Flavors**

**D mesons** [Ma, Triedy, Venugopalan, KW, 1803.11093]

(a) $pp$, $\sqrt{s} = 7$ TeV, $|y| < 0.5$

(b) $pA$, $\sqrt{s} = 5.02$ TeV, $-0.965 < y < 0.035$

**Charm decay leptons** [Fujii, KW, NPA951 (2016) 45]
**Nuclear Modification Factor**

**D meson [Fujii, KW, 1706.06728]**

- **Nice agreement between the CGC calculation and D mesons’ data.**
- **The choice of** $Q^2_{sA,0} = 2Q^2_{sp,0}$ (blue curves) **works.**
- **Charm decay lepton is less suppressed:** $R^l_{pA} > R^D_{pA}$. 

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**Charm decay electron**

- **$\sqrt{s} = 5.02$ TeV, $-0.965 < y < 0.035$**
- **$\sqrt{s} = 5.02$ TeV, $2.5 < y < 4.0$**
Both the NRQCD and ICEM reproduce nicely $J/\psi$ data. The LDMEs are extracted from high $p_\perp$ data fitting at Tevatron. [Chao, Ma, Shao, Wang and Zhang, PRL\textbf{108},242004(2012)]

$$\langle O_{J/\psi}^{1S_0^{[8]}} \rangle = 0.089 \pm 0.0098 \text{GeV}^3, \langle O_{J/\psi}^{3S_1^{[8]}} \rangle = 0.0030 \pm 0.0012 \text{GeV}^3,$$

$$\langle O_{J/\psi}^{3P_0^{[8]}} \rangle = 0.0056 \pm 0.0021 \text{GeV}^3 \quad (1S_0^{[8]} \text{ has a large weight.})$$

The contribution of CS channel is relatively small. (10% in p+p, 15% – 20% in p+A at small-$p_\perp$)

CO states are going to be $J/\psi$ in the ICEM.
Description of $\psi(2S)$ in the CGC+NRQCD is unclear: Large systematic uncertainties w.r.t quark mass and LDMEs.

The ICEM explains the $p_\perp$ dependence of data on the ratio of the $\psi(2S)$ to $J/\psi$ yields. In CEM, the ratio of the $\psi(2S)$ to $J/\psi$ yields is always constant.
Evidence of Final State Effect in p+A collisions

- $c\bar{c}$ produced at short distance $t_c \gtrsim 1/2m \sim 0.07$ fm does not know yet long distance information.

- The saturation effect is short distance physics at $t_c$ and $M_{J/\psi} \sim M_{\psi(2S)} \Rightarrow$ The CGC predicts $R_{pA}^{J/\psi} \sim R_{pA}^{\psi(2S)}$.

- The large suppression of $\psi(2S)$ production in p+A at both RHIC and the LHC has widely been interpreted as arising from final state interactions with comovers.

  cf. [Ferreiro, PLB749, 98 (2015)]
Soft color exchange (SCE) between $c\bar{c}$ and comover spectators can happen at later stage.

The role of SCEs should be enhanced in p+A collisions so that momentum kick given by additional nuclear parton comovers breaks bound state:

$$2m_\psi \leq M_{c\bar{c}} \leq 2m_D - \Lambda.$$

$\Lambda$: the average momentum kick given by additional nuclear parton comovers. $\Lambda = 0$ in p+p collisions.

$J/\psi$

$\psi(2S)$

$$Q_{s0,A}^2 = 2Q_{s0,p}^2$$
Nuclear suppression: $J/\psi$ vs $\psi(2S)$

[Ma, Venugopalan, Zhang, KW, PRC97,014909(2018)]

RHIC

(a) $\sqrt{s} = 0.2$ TeV

$|y| < 0.5$

Light: $Q_{s0,A}^2 = (1.5 - 2)Q_{s0,p}^2$, $\Lambda = (5 - 10)$ MeV

Dark: $Q_{s0,A}^2 = (1.5 - 2)Q_{s0,p}^2$, $\Lambda = 7.5$ MeV

$J/\psi$

$\psi(2S)$

$P_{\perp}$ [GeV]

0 1 2 3 4 5

1.4

1.2

1.0

0.8

0.6

0.4

0.2

RHIC

PHENIX dAu : $J/\psi$

STAR pAu : $J/\psi$

LHC

(a) $\sqrt{s} = 5.02$ TeV

$2.035 < y < 3.535$

Light: $Q_{s0,A}^2 = (1.5 - 2)Q_{s0,p}^2$, $\Lambda = (10 - 20)$ MeV

Dark: $Q_{s0,A}^2 = (1.5 - 2)Q_{s0,p}^2$, $\Lambda = 15$ MeV

$J/\psi$

$\psi(2S)$

$P_{\perp}$ [GeV]

0 1 2 3 4 5

1.2

1.0

0.8

0.6

0.4

0.2

LHC

ALICE : $J/\psi$

ALICE : $\psi(2S)$

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HF and Onium Production in the CGC

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**Remarks on γ production**

[KW, Xiao, PRD92,111502(2015)]

![Diagram](image)

- \( m_\gamma \gg p_\perp \gg \Lambda_{\text{QCD}} \) allows more phase space for gluons shower. \( \Rightarrow \) Sudakov double logs:

\[
\frac{d\sigma_{c\bar{c}}}{d^2p_\perp dy} \propto F.T. \left[ x_1 G \left( x_1, \frac{c_0}{v_\perp} \right) S_Y (x_\perp) S_Y (y_\perp) e^{-S_{\text{Sud}}(M, v_\perp)} \hat{H}_{\text{LO}} \right]
\]

where \( v_\perp = zx_\perp + (1 - z)y_\perp \sim (x_\perp + y_\perp)/2 \).

- Parton shower effect is dominant for low-\( p_\perp \) \( \gamma \) production in p+p collisions, however, can be comparable to Saturation effect in p+A collisions.
1 Framework

2 Minimum Bias events

3 High Multiplicity events

4 Summary
**High Multiplicity events and Gluon Saturation**

- Discovery of ridge like structure: The starting point.
- p+p vs p+A vs A+A: Initial state (fluctuation) or Final state (hydro) origins?

Gluon saturation/CGC is a natural way to explain this phenomenon.

Classical gluon fields have $A \sim 1/g$:

$$\frac{dN_{ch}}{d^2 b \, d^2 k_\perp \, dy} \sim \langle AA \rangle \sim \frac{f(k_\perp/Q_s)}{\alpha_s} \Rightarrow \frac{dN_{ch}}{dy} \sim \frac{S Q_s^2}{\alpha_s}$$

Large fluctuation in $Q_s(x) \leftrightarrow$ Rare partons configuration.
Charged hadron multiplicity

\[ \frac{d\sigma_g}{d^2 p_g \perp dy} = \frac{\alpha_s \hat{K}_B}{(2\pi)^3 \pi^3 C_F} \int \frac{d^2 k \perp}{p_g \perp^2} \varphi_{p, p}(k \perp) \varphi_{A,Y}(p_g \perp - k \perp) \]

\[ \frac{dN_{ch}}{d\eta} = \frac{\hat{K}_{ch}}{\sigma_{\text{inel}}} \int d^2 p \perp \int_{z_{\text{min}}}^1 dz \frac{D_h(z)}{z^2} J_{y \rightarrow \eta} \frac{d\sigma_g}{d^2 p_g \perp dy} \]

- \( b \perp \) dependence \( \leftrightarrow Q_{s,0}^2 \) dependence with \( S \perp \) fixed.
- MB: \( dN_{ch}/\langle dN_{ch} \rangle = 1 \) at \( Q_{s,0}^2 = Q_0^2 \) in p+p and \( 2Q_0^2 \) in p+A.
- Large \( Q_{s,0}^2 \) gives High Multiplicity events: \( dN_{ch}/\langle dN_{ch} \rangle \gg 1 \).
- W/o the FF, larger \( Q_{s,0}^2 \) is required to obtain large event activity. Use of the FF mitigates this.

\[ \text{MB:} \frac{dN_{ch}}{d\eta} = \frac{\hat{K}_{ch}}{\sigma_{\text{inel}}} \int d^2 p \perp \int_{z_{\text{min}}}^1 dz \frac{D_h(z)}{z^2} J_{y \rightarrow \eta} \frac{d\sigma_g}{d^2 p_g \perp dy} \]

\[ \frac{d\sigma_g}{d^2 p_g \perp dy} = \frac{\alpha_s \hat{K}_B}{(2\pi)^3 \pi^3 C_F} \int \frac{d^2 k \perp}{p_g \perp^2} \varphi_{p, p}(k \perp) \varphi_{A,Y}(p_g \perp - k \perp) \]

\[ \frac{dN_{ch}}{d\eta} = \frac{\hat{K}_{ch}}{\sigma_{\text{inel}}} \int d^2 p \perp \int_{z_{\text{min}}}^1 dz \frac{D_h(z)}{z^2} J_{y \rightarrow \eta} \frac{d\sigma_g}{d^2 p_g \perp dy} \]
**$N_{ch}$ Dependence of $D$ Production using the BCFY FF**

[Ma, Tribedy, Venugopalan, KW, 1803.11093]

**p+p**

(a) $pp, \sqrt{s} = 7$ TeV, $|y| < 0.5$

- Average $D^0, D^+, D^{\ast\pm}$
  - ALICE 1 $< p_{\perp} < 2$ GeV
  - ALICE 2 $< p_{\perp} < 4$ GeV

\[ Q_{sp1}^2 \sim Q_{sp2}^2 > Q_0^2 \]

→ $\phi_p \times \phi_A$ has a large probability at

\[ Q_{sp1}^2 \sim Q_{sp2}^2. \]

**p+A**

(b) $pA, \sqrt{s} = 5.02$ TeV, $-0.965 < y < 0.035$

- Average $D^0, D^+, D^*$
  - ALICE 2 $< p_{\perp} < 4$ GeV

\[ Q_{sp,0}^2 = (1 - 3)Q_0^2 \]

Different colors: Different $Q_{sA,0}^2$
$N_{ch}$ DEPENDENCE OF $J/\psi$ PRODUCTION IN THE CGC + ICEM

[Ma, Tribedy, Venugopalan, KW, 1803.11093]

**p+p**

\[ \frac{dN_{J/\psi}/dy}{dN_{ch}/dy} \mid |\eta| < 1.0 \]

- $\sqrt{s}$-dependence of the ratios are weak.

**p+A**

\[ \frac{dN_{J/\psi}/dy}{dN_{ch}/dy} \mid |\eta| < 1.0 \]

- $Q_{sp,0}^2 = (1 - 3)Q_0^2$
- Different colors: Different $Q_{sA,0}^2$

The similar trends are seen for $D$ and $J/\psi$ production. → Hadronization dynamics is irrelevant, rather saturation effect at short distance plays a key role in describing data.
The $^3S_1^{[8]}$ state dominates $J/\psi$ production with increasing event activity.

Remarkably consistent with the universality requirement from BELLE $e^+e^-$ data:

$$\langle O^{J/\psi}[^1S_0^{[8]}] \rangle + 4.0 \langle O^{J/\psi}[^3P_0^{[8]}] \rangle / m^2 < 2.0 \pm 0.6 \times 10^{-2} \text{GeV}^3$$

[Zhang, Ma, Wang, Chao, PRD81,034015(2010)]

Caveat: The $^1S_0^{[8]}$ is likely to be dominant by comparison with $p_\perp$ spectrum of $J/\psi$ production in p+p and p+A collisions in the CGC+NRQCD.
“Event engineered” Heavy Flavor mesons and Quarkonia production in p+p and p+A collisions have been studied extensively in the CGC framework.

Nice agreement is found between the CGC computations and the LHC data on $D$ and $J/\psi$ production in minimum bias and rare high multiplicity events in p+p and p+A collisions.

The factorization breaking effect at last stage causes strong $\psi(2S)$ nuclear suppression.

Quantitative evaluation of $R_{pA}$ of $\Upsilon$ in the CGC + Parton Shower effect is needed.

$1S_0^{[8]}$ vs $3S_1^{[8]}$: New constrains on the NRQCD LDMEs for $J/\psi$ production are found.

$N_{ch}$ dependence of $\psi(2S)$, $\Upsilon$, and Heavy flavor decay lepton are in progress.
Backup

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HF and Onium Production in the CGC
$J/\psi$ vs $N_{ch}$ at Forward Rapidity

- **p+p collisions**
  - Different colors: Different $Q_{sp1,0}^2$ and $Q_{sp2,0}^2 \geq Q_{sp1,0}^2$.
  - In contrast to mid rapidity, the symmetrical treatment; $Q_{sp1,0}^2 = Q_{sp2,0}^2$ overshoots the data slightly in $p+p$ collisions (Dashed line). Data point at $dN_{ch}/\langle dN_{ch} \rangle \sim 4$ seems to favor the asymmetrical treatment; $Q_{sp1,0}^2 < Q_{sp2,0}^2$.

- **p+A collisions**
  - Different colors: Different $Q_{sA,0}^2$.
  - Lower points: $Q_{sp,0}^2 = Q_0^2$, Upper points: $Q_{sp,0}^2 = 2Q_0^2$. 

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