Results for Heavy Flavor and Quarkonium production in high multiplicity p+p and p+A collisions in the CGC framework

Kazuhiro Watanabe

Old Dominion Univ / Jefferson Lab

April 19, 2018
DIS2018 at Kobe

with Y.-Q. Ma (Peking U), P. Tribedy (BNL), R. Venugopalan (BNL)
arXiv:1803.11093
High multiplicity events

Discovery of ridge like structure: the starting point.

- $p+p$ vs $p+A$ vs $A+A$: Initial state (fluctuation) or Final state (hydro) origins?
- Interplay of hard and soft collisions.
- Gluon saturation is a natural way to explain this phenomenon. cf. [Dumitru et al. (2010)]

### Motivation

Gluon saturation describes systematically heavy flavor and onium production in high multiplicity $p+p$ and $p+A$ collisions?
Gluon recombination at small-$x$ → Gluon Saturation

\[ Q_{s,A}^2 \propto \frac{\alpha_s}{S_{A\perp}} x G_A \sim A^{1/3} \left( \frac{1}{x} \right) \lambda \sim A^{1/3} Q_{s,p}^2 \]

- $k_\perp > Q_s$: Gluons are hard, pQCD is applicable.
- $k_\perp < Q_s$: Gluons are soft and high occupied in “Saturation region”.

High multiplicity events: Spacial and momentum structure of rare parton configurations are important.

⇒ Such rare parton configurations can be controlled by $Q_s(x)$. cf. [Dusling, Venugopalan (2012)]

Large $Q_s$ (hadron fluctuation) ↔ Soft gluon modes are enhanced ↔ High multiplicity
✓ Heavy flavor and Onium are complementary observables to light hadron, dijet production. → Event engineering studies.

✓ Provides unique playground to study gluon saturation or test the CGC framework. Remind $c\bar{c}$ is largely produced via initial gluon fusion at collider energies.

✓ Saturation scales are semihard at the energy frontier: $m_c$ vs $Q_{sp}(x_1)$ vs $Q_{SA}(x_2)$

✓ The CGC can be helpful in understanding of heavy flavor and onium production mechanisms at low-$p_\perp$.

$$ x_1 = \frac{1}{\sqrt{s}} \left( \sqrt{m_c^2 + p_{c\perp}^2} e^{yc} + \sqrt{m_c^2 + q_{\bar{c}\perp}^2} e^{\bar{y}\bar{c}} \right) $$

$$ x_2 = \frac{1}{\sqrt{s}} \left( \sqrt{m_c^2 + p_{c\perp}^2} e^{-yc} + \sqrt{m_c^2 + q_{\bar{c}\perp}^2} e^{-\bar{y}\bar{c}} \right) $$
The Color-Glass-Condensate (CGC) framework

- Projectile moving $x^+ = +\infty$, target moving $x^- = +\infty$.
- Solving classical Yang-Mills eq.:
  \[ [D^\mu, F_{\mu\nu}] = J^\nu \implies |T\rangle = \sum_i \prod g g \cdots g g \bigg\rangle \]

\[ d\sigma_{c\bar{c}} \frac{d^2 p_c \cdot d^2 q_{\perp} \cdot dy_c \cdot dy_{\bar{c}}}{2(2\pi)^6} = \frac{\alpha_s N_c^2 \pi R_A^2}{2(2\pi)^{10} d_A} \int_{k_{2\perp},k_{\perp}} \frac{d^2 \varphi_{p,Y_p}(k_{\perp})}{k_{1\perp}^2} N_Y(k_{\perp}) N_Y(k_{2\perp} - k_{\perp}) \Xi \]

- Unintegrated gluon distribution function: $\varphi_{p,Y_p}(k_{\perp}) = \frac{\pi R_p^2}{4\alpha_s} N_Y (k_{\perp})$
- Dipole amplitude: $N_{Y_p}(Y)(k_{\perp}) = \int d^2 r_{\perp} e^{-ik_{\perp} \cdot r_{\perp}} \frac{1}{N_c} \left\langle \text{Tr} \left[ V_F(r_{\perp}) V_F^\dagger(0_{\perp}) \right] \right\rangle_{Y_p}(Y)

- The rcBK equation describes $x$-evolution of the dipole amplitude. ($N_Y(k_{\perp}) = F.T. \ of \ D_Y(r_{\perp})$)

[Balitsky (2006)]
Minimum Bias events
- $D$ meson production
- $J/\psi$ production
- $\psi(2S)$ production
- $\Upsilon$ production

High multiplicity events
- $D$ meson production vs $N_{ch}$
- $J/\psi$ meson production vs $N_{ch}$
A quick guide to numerical calculations

- $m = 1.3$ GeV for $D$ meson and $J/\psi$. But $m = 1.5$ GeV $\approx m_{J/\psi}/2$ is used only when NRQCD factorization is employed.

- $\alpha_s$ is fixed.

- Initial saturation scale of proton: $Q^2_{sp,0} = Q^2_0 = 0.168$ GeV at $x = 0.01$. $\iff$ HERA-DIS global data fitting. [AAMQS (2010)]

$$D_{Y=Y_0,r_\perp} = \exp \left[ -\frac{\left( r_\perp Q^2_{sp,0} \right)^{\gamma}}{4} \ln \left( \frac{1}{r_\perp \Lambda} + e \right) \right],$$

- Initial saturation scale of nucleus: $Q^2_{sA,0} = 2Q^2_0$. $\iff$ A fit to the available NMC (New Muon Collab.) data (fixed target $eA$) on the nuclear structure functions $F_{2,A}(x, Q^2)$ at $x \sim 0.01$. [Dusling, Gelis, Lappi, Venugopalan (2009)]

- $\varphi$ at large-$x$: Matching between $\varphi$ and collinear PDF $xG$ with CTEQ6M set at $x = 0.01$.

$$N^A_Y(k_\perp) \overset{x>x_0}{=} \frac{xG_{CTEQ}(x, Q^2_0)}{xG_{Dipole}(x_0, Q^2_0)} N^A_{Y_0}(k_\perp)$$

with the identity $xG_{Dipole}(x, Q^2_0) = \frac{1}{4\pi^3} \int_0^{Q^2_0} dk_\perp^2 \varphi_Y(k_\perp)$. Switch from $\varphi$ to $xG$ at $x > x_0$.

- $R_p \sim 0.5$ fm, $Q_0 \sim 5$ GeV are obtained from the matching. $R_A$ is chosen to reproduce $R_{PA} = \frac{d\sigma_{pA}}{Ad\sigma_{pp}} = 1$ when $p_\perp \rightarrow \infty$. 

Kazuhiro Watanabe (ODU/JLab)  
HF production in high multiplicity pp and pA collisions  
April 19, 2018  7 / 20
**$D$ meson production**

[Fujii, KW (2013)][Ma, Tribedy, Venugopalan, KW (2018)]

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

- $D_{c \to D}(z)$: BCFY Fragmentation Function [Braaten, Cheung, Fleming, Yuan(1994)]
The CGC cross sections at short distance are matched to NRQCD LDMEs.

\[
\frac{d\sigma^{\psi}}{dy dp_{\perp}^2} = \sum_{\kappa} \frac{d\hat{\sigma}^{\kappa}_{c\bar{c}}}{dy dp_{\perp}^2} \times \left\langle O^\psi_{\kappa} \right\rangle_{\text{LDMEs}} (\kappa = 2S+1 L_{J}^{[c]})
\]

The LDMEs are extracted from high \( p_{\perp} \) data fitting at Tevatron. [Chao et al. (2012)]

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

\[
\left\langle O^{J/\psi \left[ ^3 P_0^{[8]} \right]} \right\rangle = 0.0056 \pm 0.0021 \text{GeV}^3
\]

The contribution of CS channel is relatively small. (10% in pp, 15% - 20% in pA at small-\( p_{\perp} \))
Color Evaporation Model (CEM) is consistent with NRQCD in the sense that color octet $c\bar{c}$ is mainly considered.

Improved CEM (ICEM) can reproduce different $p_\perp$ distributions of $J/\psi$ and $\psi(2S)$ correctly. [Ma, Vogt (2016)]

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

[Ma, Venugopalan, Zhang, KW (2017)]
Soft color exchanges between partonic comovers and the $c\bar{c}$ can affect greatly $\psi(2S)$ production. [Ma, Venugopalan, Zhang, KW (2017)]

In p+p collisions, $F_{q\bar{q} \rightarrow \psi}$ is fitted and should include the effect of soft color exchanges at final stage.

Important assumption: the role of soft color exchanges should be enhanced in p+A collisions. $\rightarrow \Lambda$ is responsible for the nuclear enhancement effect.

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

where $\Lambda$ denotes the average momentum kick given by additional nuclear parton comovers.
**$\Upsilon(1S)$ production**

- Large Mass scale $\rightarrow \#\alpha_s \ln^2 \frac{M^2}{P_{\perp}^2} \sim O(1)$. (Sudakov double logs)

- The soft gluon shower effect and the saturation effect can be described straightforwardly in the hybrid framework: [K.W., Xiao (2015)]

\[
\frac{d\sigma_{\text{resum}}}{dP_{\perp}dy} \propto \int \frac{d^2u \, d^2v}{(2\pi)^4} \, e^{-i p_{rel} \cdot u_{\perp}} \, e^{i p_{\perp} \cdot v_{\perp}} \, x_1 G(x_1, \frac{c_0}{v_{\perp}}) \, D_Y(x_{\perp}) \, D_Y(y_{\perp}) \, e^{-S_{\text{Sud}}(M,v_{\perp})} \, \hat{H}_{LO},
\]

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

- $S_{\text{Sud}}$ must be “Universal”. cf. [Sun, Yuan, Yuan (2012)]

- Sudakov effect is dominant for low-$p_{\perp}$ $\Upsilon$ production in p+p collisions. cf. [Qiu, K.W. (2017)]

- In p+A collisions, Saturation effect can be comparable to Sudakov effect.
Minimum Bias events
- $D$ meson production
- $J/\psi$ production
- $\psi(2S)$ production
- $\Upsilon$ production

High multiplicity events
- $D$ meson production vs $N_{ch}$
- $J/\psi$ meson production vs $N_{ch}$
Matching between $\varphi_p$ and $xG$ is no more justified. In lieu, the adopt the simple extrapolation ansatz for $\varphi$: [Gelis, Stasto, Venugopalan (2006)]

$$\varphi_{p, y}(k_\perp) = \varphi_{p, y_0}(k_\perp) \left( \frac{1 - x}{1 - x_0} \right)^4 \left( \frac{x_0}{x} \right)^{0.15}.$$ 

Hadronization of charm to $D$ meson, $J/\psi$ production models are the same as used in MB events.

All the input parameters are taken to be the same, except for $Q_s$. 

**Charged hadron multiplicity in the CGC framework**

- **$p + p/A \rightarrow g(\rightarrow h) + X$: [Kovchegov, Tuchin (2001)]**

\[
\frac{d\sigma_g}{d^2 p_\perp dy} = \frac{\alpha_s \hat{K}_b}{(2\pi)^3 \pi^3 C_F} \frac{1}{p_\perp^2} \int d^2 k_\perp \varphi_{p_p}(k_\perp) \varphi_{A,Y}(p_\perp - k_\perp)
\]

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

where $J_{\eta \rightarrow \eta} = p_\perp \cosh \eta \sqrt{p_\perp^2 \cosh^2 \eta + m_h^2}$ and $p_\perp \equiv z p_\perp$.

It is clear that the relative $N_{ch}$ grows almost linearly as $Q_{sp,0}^2$ increases when the KKP FF is used.
$D$ meson production vs $N_{ch}$

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

- Average $D^0$, $D^+$, $D^{*-}$

- $\langle dN_{ch}/d\eta \rangle$ vs $|\eta| < 1.0$

- $p+p$ collisions
  - Normalized in MB $p+p$ collisions.

  - $Q_{sp, proj}^2 > Q_0^2$ and $Q_{sp, targ}^2 = Q_0^2$.
  - $Q_{sp, targ}^2 > Q_0^2$ and $Q_{sp, proj}^2 = Q_0^2$.
  - $Q_{sp1}^2 = Q_{sp2}^2 > Q_0^2$.

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

- Average $D^0$, $D^+$, $D^*$

- $\langle dN_{ch}/d\eta \rangle$ vs $|\eta| < 1.0$

- $p+A$ collisions
  - Normalized in MB $p+A$ collisions.
  - Different colors: Different $Q_{sA,0}^2 \Rightarrow$ Fluctuation effect of proton is important to achieve high $N_{ch}$ when $Q_{sA,0}^2$ is being fixed.
  - The same qualitative trend in $p+p$ and $p+A$ collisions.
$J/\psi$ meson production vs $N_{ch}$ at mid rapidity

(a) $pp$, $|y| < 0.9$

- p+p collisions
  - The CGC+ICEM framework is used.
  - The ratios are $\sqrt{s}$-independent! In the CGC, events at different energies with the same $Q_s$ are identical.

(b) $pA$, $\sqrt{s} = 5.02$ TeV, $-1.365 < y < 0.435$

- p+A collisions
  - Different colors: Different $Q_{sA,0}$

The similar trends are seen for $D$ meson and $J/\psi$ production. → Hadronization dynamics is irrelevant, rather saturation effect at short distance plays a key role in describing data.
$J/\psi$ meson production vs $N_{ch}$ at forward rapidity

(a) $pp$, $\sqrt{s} = 7$ TeV, $2.5 < y < 4.0$

- p+p collisions
  - Different colors: Different $Q_{sp 1,0}^2$ and $Q_{sp 2,0}^2 \geq Q_{sp 1,0}^2$.
  - In contrast to mid rapidity, the symmetrical treatment; $Q_{sp 1,0}^2 = Q_{sp 2,0}^2$ 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; $Q_{sp 1,0}^2 < Q_{sp 2,0}^2$.

(b) $pA$, $\sqrt{s} = 5.02$ TeV, $2.035 < y < 3.535$

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

Kazuhiro Watanabe (ODU/JLab)
$N_{ch}$ dependence of $J/\psi$ production in the CGC+NRQCD

- The normalized $c\bar{c}$ differential cross section for the $^3S_1^{[8]}$ channel is close to that of the ICEM over the entire $p_\perp$ range at large $Q^2_{sp,0}$.

- With increasing event activity, the $^3S_1^{[8]}$ state dominates $J/\psi$ production.

- This is 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 (2009)]

- Note: the LDMEs used in the CGC+NRQCD previously violates this upper bound.
Event engineered Heavy flavor and Onium production in high multiplicity p+p and p+A collisions provide unique opportunity to study gluon saturation phenomenon.

Excellent agreement is found between the CGC computations and the LHC heavy flavor data on $D$ and $J/\psi$ production in high multiplicity events in p+p and p+A collisions.

Data comparisons using the CGC+NRQCD framework potentially can distinguish between intermediate states with differing quantum numbers that contribute to the hadronization of $J/\psi$ mesons.

Thank you!
\[
\frac{d\sigma^\kappa_{c\bar{c},\text{CS}}}{d^2p_\perp dy} = \frac{\alpha_s \pi R_A^2}{(2\pi)^9 d_A} \int_{k_2\perp, k_\perp, k'_\perp} \frac{\varphi_{p'y_p}(k_{1\perp})}{k_{1\perp}^2} N_Y(k_\perp) N_Y(k'_\perp) N_Y(k_{2\perp} - k_\perp - k'_\perp) \mathcal{G}_{1_{\kappa}}^\kappa
\]

\[
\frac{d\sigma^\kappa_{c\bar{c},\text{CO}}}{d^2p_\perp dy} = \frac{\alpha_s \pi R_A^2}{(2\pi)^7 d_A} \int_{k_2\perp, k_\perp} \frac{\varphi_{p'y_p}(k_{1\perp})}{k_{1\perp}^2} N_Y(k_\perp) N_Y(k_{2\perp} - k_\perp) \Gamma_{8_{\kappa}}^\kappa
\]
We follow [Cacciari et al. (2012)]:

\[ D_{c \rightarrow D^0}(z; r) = 0.168 D_{BCFY}^{(P)}(z; r) + 0.39 D_{BCFY}^{(V)}(z; r), \]

\[ D_{c \rightarrow D^+}(z; r) = 0.162 D_{BCFY}^{(P)}(z; r) + 0.07153 D_{BCFY}^{(V)}(z; r), \]

\[ D_{c \rightarrow D^*}(z; r) = 0.233 D_{BCFY}^{(V)}(z; r), \]

where the original BCFY FFs are given by

\[
D_{BCFY}^{(P)}(z; r) = N \frac{rz(1-z)^2}{[1-(1-r)z]^6} \left[ 6 - 18(1-2r)z + (21 - 74r + 68r^2)z^2 - 2(1-r)(6 - 19r + 18r^2)z^3 \\
+ 3(1-r)^2(1-2r+2r^2)z^4 \right],
\]

\[
D_{BCFY}^{(V)}(z; r) = 3N \frac{rz(1-z)^2}{[1-(1-r)z]^6} \left[ 2 - 2(3-2r)z + 3(3-2r+4r^2)z^2 - 2(1-r)(4-r+2r^2)z^3 \\
+ (1-r)^2(3-2r+2r^2)z^4 \right].
\]

\(N\) is determined analytically from \(\int_0^1 dz D_{BCFY}^{(P,V)}(z; r) = 1.\)

\[ D_{BCFY}^{(V)}(z; r) = \theta \left( \frac{m_D}{m_{D^*}} - z \right) D_{BCFY}^{(V)} \left( \frac{m_{D^*}}{m_D} z; r \right) \frac{m_{D^*}}{m_D}. \]

We fix \(m_D = (m_{D^0} + m_{D^\pm})/2 = 1.867\) GeV and \(m_{D^*} = (m_{D^{*0}} + m_{D^{*\pm}})/2 = 2.009\) GeV. \(r\) is a single nonperturbative parameter.