Quarkonium production in proton-nucleus collisions at collider energies

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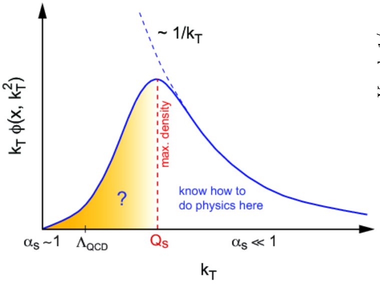
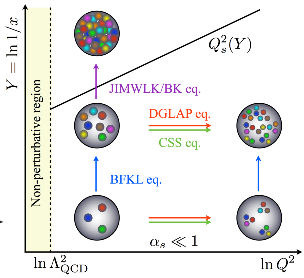
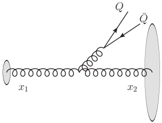
Gluon saturation in hadron/nucleus





- At small value of Bjorken x, Small-x/Color Glass Condensate (CGC) framework is essential.
- Semihard Saturation scale : $Q_{sA}^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{0.3} \gg \Lambda_{\rm QCD}^2$
- $k_\perp < Q_s$: "Saturation regime" in Gluon TMD ϕ.
- Energy/rapidity dep. of $\phi \Rightarrow$ NONLINEAR BK eq. or JIMWLK eq.

Forward Quarkonium production in pA collisions



- Consider Forward Quarkonium productions in pA collisions;

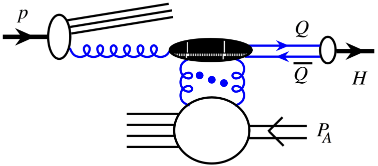
$$\mathrm{p} + A \rightarrow c\bar{c},\ b\bar{b}[\Rightarrow J/\psi,\ \psi(2S),\ \Upsilon] + X$$

LO kinematics: $x_{1,2} = \frac{m_\perp}{\sqrt{s}} e^{\pm y}$ $(p_\perp = 1,\ y = +2)$

$\sqrt{s}$	200 GeV	5.02 TeV	8 TeV
$J/\psi : x_2$	2.20×10^{-3}	8.78×10^{-5}	5.51×10^{-5}
$\psi(2S) : x_2$	2.58×10^{-3}	1.03×10^{-4}	6.46×10^{-5}
$\Upsilon : x_2$	6.44×10^{-3}	2.56×10^{-4}	1.61×10^{-4}

- Forward Qarkoniums production in pA collisions can probe Small-x gluons!$\Rightarrow$ $P_\perp$ distribution should reflect the saturation effect.

Effective Factorization : Short dist. and Long dist.



- Target nucleus ⇒ Multiple scattering effect.
- If $Q_{sA} \sim mv \sim Mv/2$ in $Q\bar{Q}$ rest frame → v-expansion is not ensured.
- In the very forward rapidity region, owing to Lorentz time dilation,

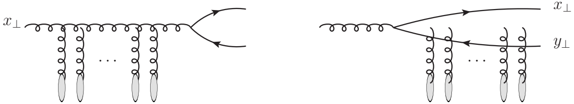
$$\frac{1}{mv}\frac{M\cosh y}{M} \gg \frac{1}{p_\perp} \sim \frac{1}{Q_{sA}}$$

The hadronization is effectively frozen when the $Q\bar{Q}$ passes through the nucleus. [Qiu,Sun,Xiao,Yuan (2013)]

- Yes, in principle. ✓CEM, ✓NRQCD

$Q\bar{Q}$ production in CGC framework

[Blaizot, Gelis, Venugopalan (2004)][Kovchegov, Tuchin (2006).] $\cdots$



- The scattering contributions are coherent as a whole.

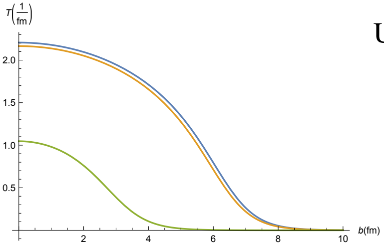
$$M_{s_1 s_2;ij}(q,p) = \frac{g^2}{(2\pi)^4}\int d^2k_\perp d^2k_{1\perp}\frac{\rho_p(k_{1\perp})}{k_{1\perp}^2}\int d^2x_\perp d^2y_\perp e^{ik_\perp\cdot x_\perp}e^{i(P_\perp - k_\perp - k_{1\perp})\cdot y_\perp}$$
$$\times \bar{u}_{s_1,i}(q)\left[T_g(k_{1\perp})t^b W^{ba}(x_\perp) + T_{q\bar{q}}(k_{1\perp},k_\perp)U(x_\perp)t^a U^\dagger(y_\perp)\right]v_{s_2,j}(p)$$

- Wilson lines $\Rightarrow$ Multiple gluon scatterings in Eikonal approximation
- In xsection, the nuclear wave function can be expressed by $S_{x_g}(r_\perp) = \frac{1}{N_c}\left\langle \mathrm{Tr}\left[U(x_\perp)U^\dagger(y_\perp)\right]\right\rangle_{x_g}$

Energy and nuclear dependence

- Energy/Rapidity dependence ⇒ rc-BK eq. [Balitsky (2006)]
  $$S_{Y=0}(r_\perp) = \exp\left[-\frac{\left(r_\perp^2 Q_{s,0}^2\right)^\gamma}{4}\ln\left(\frac{1}{|r_\perp|\Lambda} + e_c \cdot e\right)\right]$$
- Its IC is fixed by HERA-DIS global data analysis. [AAMQS][Lappi,Mantysaari (2013)]
- For Nucleus, change the saturation scale as

$$\boxed{Q_{sA,0}^2(b) = A\hat{T}_A(b) S_\perp Q_{sp,0}^2 \equiv N Q_{sp,0}^2}$$



Using Glauber Model with

1. $S_\perp = \sigma_{inel}^{NN} \Longrightarrow N_{\mathrm{MB}} \approx 4-8.$
2. $S_\perp = \int_p d^2b \Longrightarrow N_{\mathrm{MB}} \approx 1.6-1.9$
   [Lappi, Mantysaari (2013)]

Note : N_{MB} is model dependent.

Hadronization from $Q\bar{Q}$ to ψ

✓**Color Evaporation Model (CEM)** [Fujii, Gelis, Venugopalan (2006)]

$$\frac{d\sigma_\psi}{d^2P_\perp dy} = F_\psi \int_{2m_c}^{2M_D} dM \frac{d\sigma_{Q\bar{Q}}}{dM d^2P_\perp dy}$$

- **Sum over all possible quantum states of $Q\bar{Q}$.**
- $Q\bar{Q}$ converts into ψ with the probability $F_{Q\bar{Q}\to\psi}$.

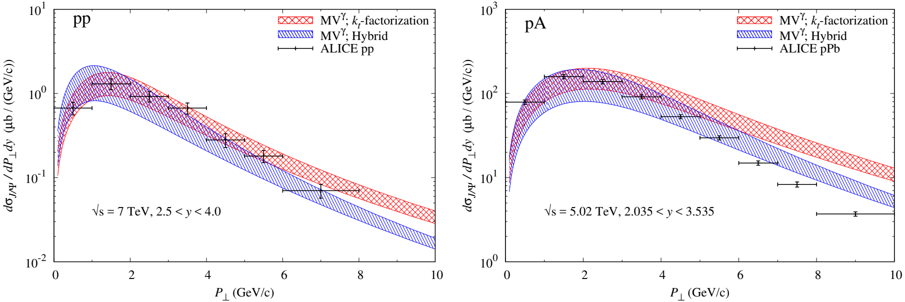
✓**Non-Relativistic QCD (NRQCD)** [Kang, Ma, Venugopalan (2013)]

$$\frac{d\sigma_\psi}{d^2P_\perp dy} = \sum_\kappa \frac{d\sigma^\kappa_{Q\bar{Q}}}{d^2P_\perp dy} \times \underbrace{\left\langle O^\psi_\kappa \right\rangle}_{\text{LDMEs}}$$

- Important LDMEs : ${}^3S_1^{[1]}$, $\underbrace{{}^1S_0^{[8]},\quad {}^3S_1^{[8]},\quad {}^3P_0^{[8]}}_{O(v^4)}$

J/ψ production in CGC + CEM

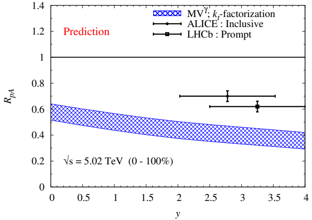
[Fujii and KW (2013)]

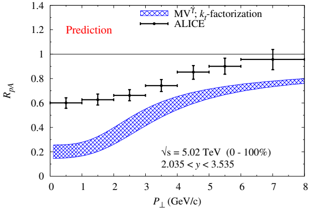


- The $P_\perp$ broadening at low $P_\perp$ can be described in CGC+CEM.

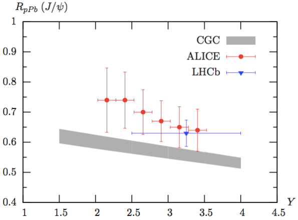
J/ψ suppression in CGC + CEM

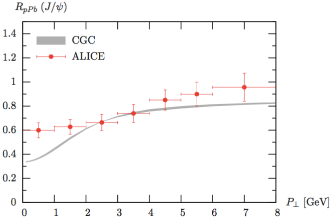
- $Q_{sA}^2 = (4-6)Q_{sp}^2$ [Fujii, KW (2013)]





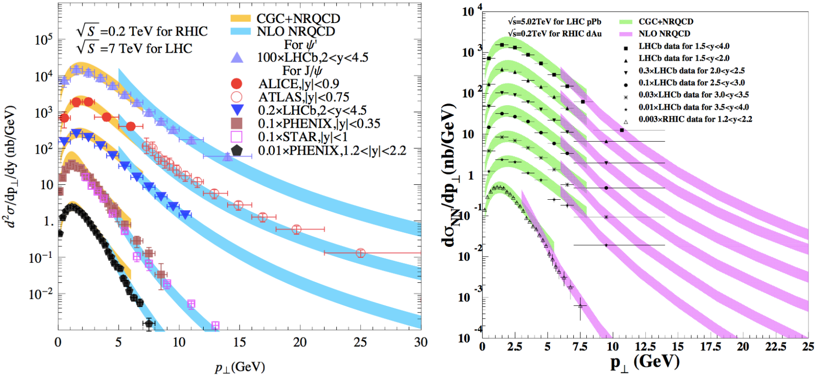
- Optical Glauber approach [Ducloue, Lappi, Mantysaari (2015)]





J/ψ production in CGC + NRQCD

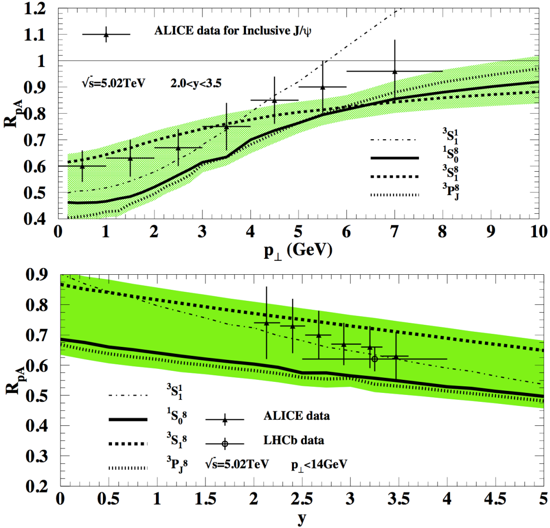
[Ma, Venugopalan (2014)] [Ma, Venugopalan, Zhang (2015)]



- Factorization assumed.
- The contribution of CS channel is enhanced in pA but relatively small contribution. (10% in pp, 15% – 20% in pA at small-$p_\perp$)

J/ψ suppression in CGC + NRQCD

[Ma, Venugopalan, Zhang (2015)]

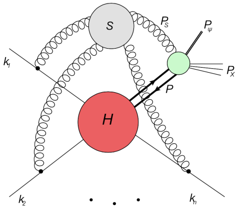


$\psi(2S)$ production

$\psi(2S)$ suppression in pA collisions is an interesting issue. Initial state interaction (saturation effect) is the same for J/ψ and $\psi(2S)$ due to similar kinematics and physical parameters. $\Rightarrow$ Final state interaction is required.

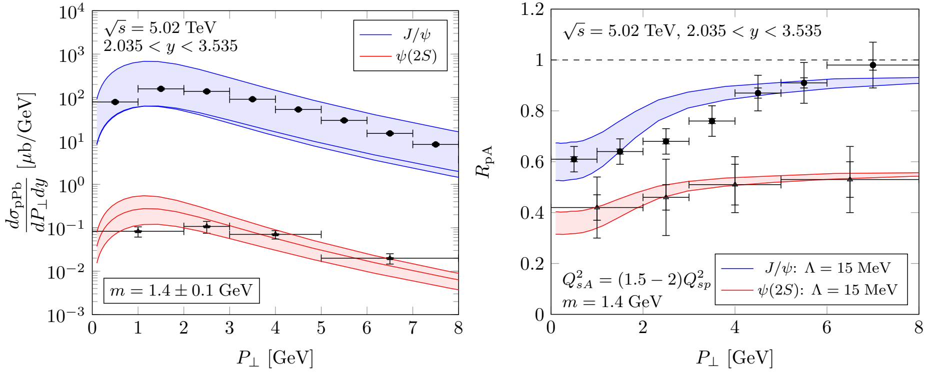
- ✓ Comovers produced in pA collisions [Ferreiro (2015)]
- ✓ Soft color clouds induced by $c\bar{c}$ traversing the nucleus $\Leftarrow$ Improved CEM. [Ma, Vogt (2016)]

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



$\psi(2S)$ production

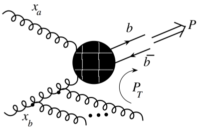
[Ma, Venugopalan, KW, Zhang in preparation]



- $Q^2_{sA} = 2Q^2_{sp}$ fixed for MB events.
- Local "temperature" in $Q\bar{Q}$ rest frame : $\Lambda \sim \mathcal{O}(\Delta E_{\psi(2S)})$

Υ production

Large mass scale $M \Rightarrow$ Large phase space $s \gg M^2 \gg p_\perp^2 \Rightarrow$ Parton shower (Sudakov resummation) effect is important. see [Berger, Qiu, Wang (2004)][[Sun, Yuan, Yuan (2012)]]



Small-x vs Sudakov

- $s \gg p_\perp^2$: Small-x resummation

$$\frac{\alpha_s N_c}{2\pi^2} \ln \frac{1}{x_g} \sim \mathcal{O}(1) \Longrightarrow \text{BFKL or BK/JIMWLK evolution}$$

- $M^2 \gg p_\perp^2$: Sudakov resummation

$$\frac{\alpha_s N_c}{2\pi} \ln^2 \frac{M^2}{p_\perp^2} \sim \mathcal{O}(1) \Longrightarrow \text{CSS evolution}$$

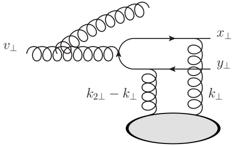
Sudakov implementation in CGC + CEM

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

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

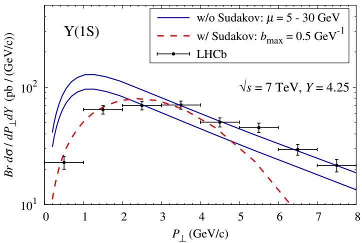
where the TMD gluon distribution is given by

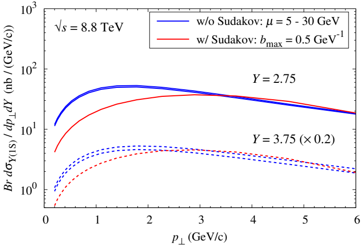
$$F_{\rm TMD}(M,l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2} e^{-ib_\perp\cdot l_\perp} e^{-S_{\rm Sud}(M,b_\perp)} x_1 G\left(x_1, \mu = \frac{c_0}{b_\perp}\right).$$



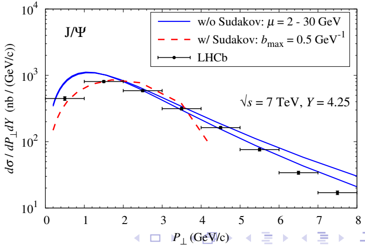
Υ production with Parton shower effect

[KW and Xiao (2015)]





- Parton shower (Sudakov) effect is dominant for low-$P_\perp$ Υ production in pp collisions, while it is less pronounced in pA collisions.

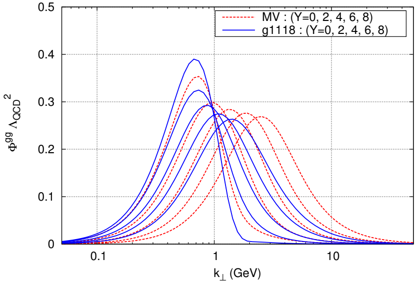


Summary

- J/ψ production can be described by CGC + CEM /NRQCD although the model dependence is a little bit messy.
- $\psi(2S)$ production in pA should be very sensitive to the color medium surrounding $Q\bar{Q}$. This color interaction enables us to interpret $\psi(2S)$ suppression easily in CGC + ICEM.
- Parton shower effect (Sudakov double logs) is essential to interpret data of Υ production.
- More importantly, full NLO calculations for quarkonium production are desired to complete.

Talk Plan

Energy dependence of UGDF



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

$$\frac{dT_Y(r)}{dY} = \mathcal{K} \otimes \left[\underbrace{T_Y(r_1) + T_Y(r - r_1) - T_Y(r)}_{\text{BFKL}} \underbrace{- T_Y(r_1) T_Y(r - r_1)}_{\text{Recombination}} \right]$$

Initial condition of Dipole amplitude

- GBW model [Golec-Biernat, Wusthoff (1998)]

$$S_Y(r_\perp) = 1 - T_Y(r_\perp) = \exp\left[-\frac{Q_s^2 r_\perp^2}{4}\right]$$

Not realistic model: high $k_\perp$ contribution is strongly suppressed.

- MV model [McLerran, Venugopalan (1994)]

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

- MV^γ and MV^e models [AAMQS(2010)][Lappi-Mäntysaari(2013)]

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

rcBK

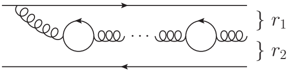
- Balitsky-Kovchegov equation

$$\frac{dT_Y(r)}{dY} = \mathcal{K} \otimes \left[\underbrace{T_Y(r_1) + T_Y(r - r_1) - T_Y(r)}_{\text{BFKL}} - T_Y(r_1) T_Y(r - r_1) \right]$$

- The running coupling kernel in Balitsky's prescription:

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

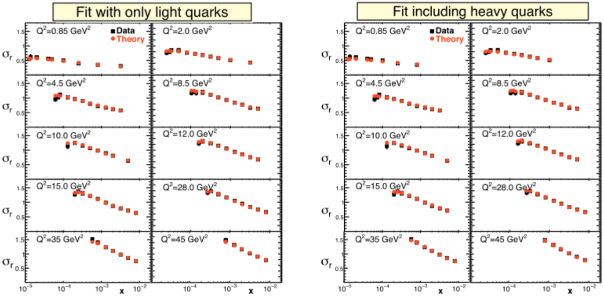
with $\alpha_s(r^2) = \left[\frac{9}{4\pi} \ln \left(\frac{4C^2}{r^2 \Lambda^2} + a_{\text{cutoff}} \right) \right]^{-1}$



- NLO BK equation can be used. See [Lappi, Mäntysaari (2015,2016)]

Constraint from DIS at HERA

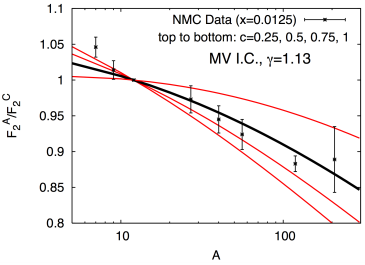
[AAMQS(2010)][Lappi-Mäntysaari(2013)]



set	$Q^2_{s0,\mathrm{p}}/\mathrm{GeV}^2$	γ	$\alpha_s(r \to \infty)$	e_c	$\chi^2/\mathrm{d.o.f.}$
MV	0.2	1	0.5	1	–
MV$^\gamma$	0.1597	1.118	1.0	1	1.12
MV^e	0.06	1	0.7	18.9	1.15

IC for the rcBK for nuclei

The initial condition of the rcBK equation for heavy nuclei is poorly understood due to lack of numerous data of eA scattering. A fit to the available NMC (New Muon Collab.) data (fixed target eA) on the nuclear structure functions $F_{2,A}(x, Q^2)$ gives valuable information in this respect.



- Set the initial saturation at $x = 0.01$ as $Q^2_{s,A}(x_2) = cA^{1/3}Q^2_{s0}$
- For MV$^\gamma$ model, $c = 0.5$ is favored from the fit of data. [Dusling, Gelis, Lappi, Venugopalan (2009)]

Extrapolation at $x \geq 0.01$

- From QCD scaling low, [Fujii, Gelis, Venugopalan][Fujii, KW]

$$\phi_{p,Y}(k_\perp) = \phi_{p,Y_0}(k_\perp) \left(\frac{1-x}{1-x_0}\right)^4 \left(\frac{x_0}{x}\right)^{0.15}$$

- Fitting from collinear PDF [Ma, Venugopalan (2014)]

$$F_Y(k_\perp) \overset{x \geq x_0}{=} a(x) F_{Y_0}(k_\perp)$$

where (e.g.)

$$a(x) = \frac{xG_{\text{CTEQ}}(x, Q_0^2)}{xG^{\text{Dipole}}(x_0, Q_0^2)}$$

with the identity

$$xG^{\text{Dipole}}(x, Q_0^2) = \frac{1}{4\pi^3} \int_0^{Q_0^2} dk_\perp^2 \phi_{Y,p}^{g,g}(k_\perp)$$

R_p is determined by fitting of collinear gluon PDF.

These extrapolations cause systematic uncertainty.

$Q\bar{Q}$ production in the CGC framework

The $q\bar{q}$ production amplitude from the background gauge fields of $\mathcal{O}(\rho_p^1 \rho_A^\infty)$ can be described as

$$M_{s_1 s_2;ij}(q,p) = \frac{g^2}{(2\pi)^4} \int d^2k_\perp d^2k_{1\perp} \frac{\rho_p(k_{1\perp})}{k_{1\perp}^2} \int d^2x_\perp d^2y_\perp e^{ik_\perp \cdot x_\perp} e^{i(P_\perp - k_\perp - k_{1\perp})\cdot y_\perp}$$
$$\times \bar{u}_{s_1,i}(q) \left[T_g(k_{1\perp}) t^b W^{ba}(x_\perp) + T_{q\bar{q}}(k_{1\perp}, k_\perp) U(x_\perp) t^a U^\dagger(y_\perp)\right] v_{s_2,j}(p)$$

At high scattering energies, Eikonal approximation is valid. The interaction between incident quark (gluon) and the dense gluons in the target nucleus can be expressed as the Wilson line in the fundamental (adjoint) representation:

$$U(x_\perp) = \mathcal{P}_+ \exp\left[ig \int_{-\infty}^{+\infty} dz^+ A_A^-(z^+, x_\perp)\cdot t\right],$$
$$W(x_\perp) = \mathcal{P}_+ \exp\left[ig \int_{-\infty}^{+\infty} dz^+ A_A^-(z^+, x_\perp)\cdot T\right]$$

$Q\bar{Q}$ production cross section from the CGC

At classical level, it is required to average the squared amplitude over the distributions of the classical color sources ρ_p and ρ_A

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d^2q_\perp d^2p_\perp dy_q dy_p} = \int \frac{d^2b_\perp}{[2(2\pi)^3]^2} \int \mathcal{D}\rho_p \mathcal{D}\rho_A W_p[\rho_p] W_A[\rho_A] \times |M_{s_1 s_2;ij}(q,p)|^2$$

with W_p and W_A are the weight functionals of ρ_p and ρ_A.

- Rapidity dependence of operator $\langle \mathcal{O} \rangle = \int \mathcal{D}\rho_p \mathcal{O} W_p[\rho_p]$ is embodied in the weight functionals which obey the JIMWLK equation

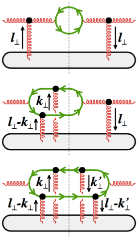
$Q\bar{Q}$ production in CGC framework at LO

[Blaizot, Gelis and Venugopalan (2004)][Fujii, Gelis and Venugopalan (2006)]

$$\phi_A^{g,g}(\boldsymbol{l}_\perp) =$$

$$\phi_A^{q\bar{q},g}(\boldsymbol{l}_\perp;\boldsymbol{k}_\perp) =$$

$$\phi_A^{q\bar{q},q\bar{q}}(\boldsymbol{l}_\perp;\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp) =$$



$$\frac{d\sigma_{Q\bar{Q}}}{d^2q_\perp d^2p_\perp dy_q dy_p} = \frac{\alpha_s}{(2\pi)^6 C_F}\int\frac{d^2k_{1\perp}}{(2\pi)^2}\frac{\varphi_{p,Y_p}(k_{1\perp})}{k_{1\perp}^2 k_{2\perp}^2}$$

$$\times\underbrace{\left[\Xi^{g,g}\phi^{g,g}_{A,Y_A} + \int\frac{d^2k_\perp}{(2\pi)^2}\Xi^{q\bar{q},g}\phi^{q\bar{q},g}_{A,Y_A} + \int\frac{d^2k_\perp d^2k'_\perp}{(2\pi)^4}\Xi^{q\bar{q},q\bar{q}}\phi^{q\bar{q},q\bar{q}}_{A,Y_A}\right]}_{\Longrightarrow\int\frac{d^2k_\perp}{(2\pi)^2}\Xi(k_{1\perp},k_{2\perp},k_\perp)\phi^{q\bar{q},g}_{A,Y_A}(k_{2\perp},k_\perp)}$$

Multipoint function

The unintegrated gluon distribution function

$$\varphi_{p,Y_p}(k_\perp) = \frac{(2\pi)^2 \alpha_s S_\perp}{k_\perp^2} \int d^2x_\perp e^{ik_\perp \cdot x_\perp} \langle \rho_p(0) \rho_p(x_\perp) \rangle_{Y_p} .$$

and the higher multi-point Wilson line correlator in large-N_c limit

$$\phi_{A,Y_A}^{q\bar{q},g}(k_{2\perp}, k_\perp) \approx S_\perp \frac{N_c k_{2\perp}^2}{4} F_{Y_A}(k_{2\perp} - k_\perp) F_{Y_A}(k_\perp)$$

Fourier transform of the fundamental dipole amplitude is defined as

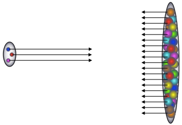
$$F_Y(k_\perp) = \int d^2x_\perp e^{-ik_\perp \cdot x_\perp} \underbrace{\frac{1}{N_c} \left\langle \mathrm{Tr} \left[U(x_\perp) U^\dagger(0_\perp) \right] \right\rangle_Y}_{\text{Dipole amplitude}} .$$

Forward production : Hybrid formalism

At forward rapidity where $x_1 \sim 1$, the phase space of the gluon distribution in projectile proton shrinks. By taking the limit $k_{1\perp} \to 0$ in the hard scattering parts and replacing the unintegrated gluon distribution function of proton with the collinear gluon distribution function (PDF), Hybrid-formula ($x_1 \sim 1$ and $x_2 \ll 1$) can be written as

$$\frac{d\sigma_{q\bar{q}}}{d^2p_{q\perp}d^2p_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{N_c\alpha_s S_\perp^A}{64\pi^2 C_F}\int_{k_\perp} \Xi_{\rm coll}(k_{2\perp}, k_\perp)x_1 G(x_1,\mu) \times F_{x_2}(k_{2\perp}-k_\perp)F_{x_2}(k_\perp)$$

with $p_{q\perp} + p_{\bar{q}\perp} = k_{2\perp}$ and $x_1 G(x_1,\mu) \equiv C\int^{\mu^2} dk_\perp^2 \varphi_{{\rm p},Y_p}(k_\perp)$



Quarkonium Production Models

- Color Evaporation Model Fritzsch (1977) . . .
  - Constant transition rate : $F_{J/\psi}$
- Color Singlet Model Chang (1980) . . .
  - α_s expansion
- Gluon Jet fragmentation Braaten and Yuan (1993) . . .
  - High $P_\perp$ production
- NRQCD Braaten and Fleming (1995) . . .
  - α_s and $v \sim \alpha_s(mv)$ expansion : $mv^2 \ll mv \ll m$
- Power expansion Nayak, Qiu, and Sterman (2005) . . .
  - $M/P_\perp$ and α_s expansion : High $P_\perp$ production

$\cdots$ and More!

Quarkonium production at low $P_\perp < M$

Interesting but challenging! ⇒ Small-x/CGC framework provides important information of quarkonium production mechanism.

CGC framework + NRQCD

[Kang, Ma, Venugopalan (2013)]

Color singlet channel

$$\frac{d\sigma^{CS}_{q\bar{q}}}{d^2P_\perp dy} \propto$$

$$\int \frac{d^2k_{1\perp}d^2k_\perp d^2k'_\perp}{(2\pi)^6}\frac{\varphi_{p,Y_p}(k_{1\perp})}{k^2_{1\perp}}\frac{1}{2J+1}\sum_{J_z}\mathcal{F}^{J_z}_{q\bar{q}}(P,k_{1\perp},k_\perp)\mathcal{F}^{J_z\dagger}_{q\bar{q}}(P,k_{1\perp},k'_\perp)$$

$$\times \int d^2x_\perp d^2x'_\perp d^2y_\perp d^2y'_\perp e^{i(k_\perp\cdot x_\perp - k'_\perp\cdot x'_\perp)}e^{i(k_{2\perp}-k_\perp)\cdot y_\perp}e^{-i(k_{2\perp}-k'_\perp)\cdot y'_\perp}$$

$$\times \underbrace{\frac{1}{N_c}\langle \mathrm{tr}[U(x_\perp)t^aU^\dagger(y_\perp)]\mathrm{tr}[U(y'_\perp)t^aU^\dagger(x'_\perp)]\rangle_{Y_A}}_{\approx\frac{1}{2}\left[Q_{Y_A}(x_\perp,y_\perp;y'_\perp,x'_\perp)-S_{Y_A}(x_\perp,y_\perp)S_{Y_A}(y'_\perp,x'_\perp)\right]}.$$

The quadrupole amplitude

$$Q_{Y_A}(x_\perp,y_\perp;y'_\perp,x'_\perp) \equiv \frac{1}{N_c}\mathrm{tr}\langle U(x_\perp)U^\dagger(x'_\perp)U(y'_\perp)U^\dagger(y_\perp)\rangle_{Y_A}.$$

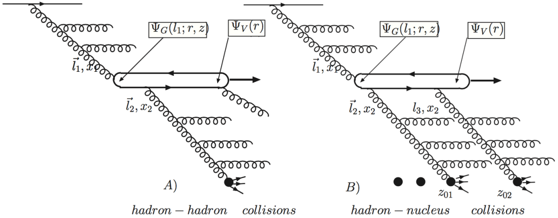
Enhancement mechanism

[D. Kharzeev, E. Levin, M. Nardi and K. Tuchin]

[1]

- J/ψ has $J^{PC} = 1^{--}$: odd number of gluons are needed.
- pp collisions : $g + g \to J/\psi + \text{soft-}g \longrightarrow O(\alpha_s^5)$
- pA collisions : $g + g + g \to J/\psi \longrightarrow O(\alpha_s^6 A^{2/3}) \sim O(\alpha_s^2)$ when $\alpha_s^2 A^{1/3} \sim 1$.

The color singlet production in pA collisions is enhanced compared to pp collisions.



[1] Phys. Rev. Lett. **102**, 152301 (2009)

CGC framework + NRQCD

Color Octet state

$$\frac{d\sigma_{q\bar{q}}^{\mathrm{CO}}}{d^2P_\perp dy} = \frac{\alpha_s S_\perp}{(2\pi)^3(N_c^2-1)}\int \frac{d^2k_{1\perp}d^2k_\perp}{(2\pi)^4}\frac{\varphi_{\mathrm{p},Y_p}(k_{1\perp})}{k_{1\perp}^2} \times F_{Y_A}(k_{2\perp}-k_\perp)F_{Y_A}(k_\perp)\Xi^{\mathrm{CO}}$$

- Of particular importance is that the nuclear effect is the same both in CEM and the color octet state in NRQCD with the large-N_c approximation.

Conventional TMD framework

One loop calculations in NRQCD factorization framework [Sun, Yuan, Yuan (2012)]

$$\left.\frac{d\sigma}{d^2P_\perp dy}\right|_{|P_\perp|\ll M} = \int \frac{d^2b_\perp}{(2\pi)^2} e^{iP_\perp\cdot b_\perp} W(M, b_\perp, x_1, x_2) + (\mathrm{Y-term})$$

with

$$W(M, b_\perp, x_1, x_2) = e^{-S_{sud}(M,b_\perp)} W(M, b_\perp, C_1, C_2)$$

$$W(M, b_\perp, C_1, C_2) = \sigma_0 \frac{M^2}{s} \int \frac{dx}{x}\frac{dx'}{x'} C_{gg}\left(\frac{x_1}{x}\right) C_{gg}\left(\frac{x_2}{x'}\right) G(x_1,\mu) G(x_2,\mu)$$

- TMD factorization [Collins-Soper-Sterman (1985)] [Collins (2011)]
- Y-term is power suppressed by $P_\perp/M$ at low $P_\perp$
- $\mu = \frac{c_0}{b_\perp}$ with $c_0 = 2e^{-\gamma_E} \simeq 1$

Collins-Soper-Sterman (CSS) formalism

Split the Sudakov factor into two parts

$$\boxed{S_{\text{Sud}}(M,b) = S_{\text{perp}}(M,b_\star) + S_{\text{NP}}(M,b)} \quad \text{with } b_\star = \frac{b}{\sqrt{1+(b/b_{\text{max}})^2}}$$

- Perturbative : $b_\star \sim b \ll b_{max}$

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

$A = \sum_{i=1} A^{(i)}\left(\frac{\alpha_s}{\pi}\right)^i$, $B = \sum_{i=1} B^{(i)}\left(\frac{\alpha_s}{\pi}\right)^i$. $A^{(1)} = C_A$ and $B^{(1)} = -(b_0 + \delta_{8c}/2)N_c$ with $b_0 = \left(\frac{11}{6}N_c - \frac{n_f}{3}\right)\frac{1}{N_c}$.

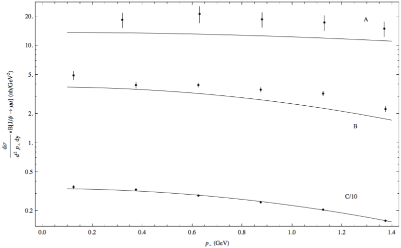
- Non-perturbative : $b > b_{max}$ [Sun, Yuan, Yuan (2012)]

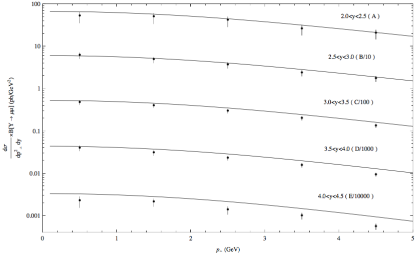
$$S_{\text{NP}}(M,b) = \exp\left[b^2\left(-g_1 - g_2\ln\left(\frac{M}{2Q_0}\right) - g_1 g_3 \ln(100 x_1 x_2)\right)\right]$$

$g_1 = 0.03$, $g_2 = 0.87$, $g_1 g_3 = -0.17$ with $Q_0 = 1.6$ GeV, $b_{\text{max}} = 0.5$ GeV.

Lesson from conventional TMD calculation

[Sun, Yuan, Yuan (2012)]





- Left fig: J/ψ at LHC forward, RHIC mid and forward. Right fig: Υ at LHC forward.
- The agreement between theoretical results and experimental data for J/ψ production is not as good as that for Υ production