Heavy quark production in pA collisions from CGC

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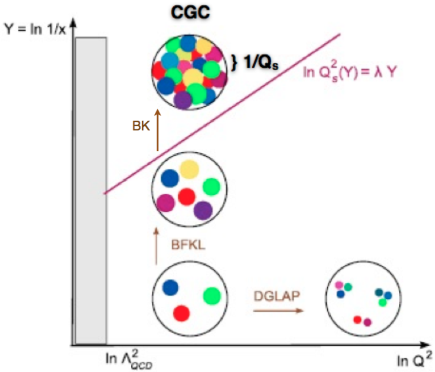
Nucl. Phys. **A 920**, 78 (2013), [arXiv:1308.1258 [hep-ph]]



The saturation momentum scale $Q_s^2(x)$ emerges dynamically as a semi-hard scale below which virtuality $Q^2 < Q_s^2(x)$, coherence and nonlinearity of the x evolution become important: Color Glass Condensate.

Color Glass Condensate (CGC)

see e.g. Iancu, Leonidov and McLerran, arXiv:hep-ph/0202270,
Iancu and Venugopalan, arXiv:hep-ph/0303204

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

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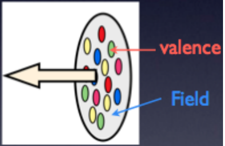
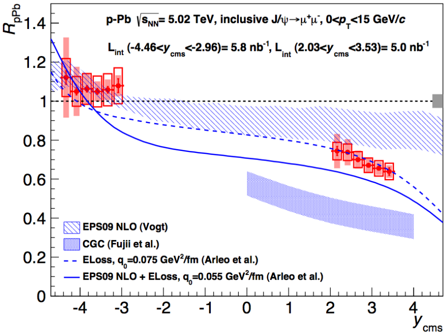


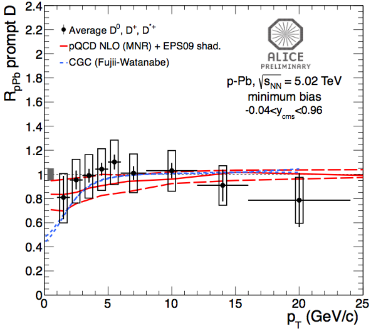
Quantum evolution of MV model : CGC

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

CGC provides us the framework to study the parton multiple scattering and quantum evolution effects.

J/ψ and D meson productions from the CGC in pA collisions.





Nuclear modification factor:

$$R_{\mathrm{pA}} = \frac{dN_{\mathrm{pA}}}{N_{\mathrm{coll}}\ dN_{\mathrm{pp}}}$$

Outline

1. Introduction
   - Approach in large-N_c
   - Quantum evolution
2. Quarkonium production
3. Heavy meson production
   - Heavy quark pair correlation

Introduction

Proton-nucleus (pA) collisions

pA collisions are regarded as a controlled baseline in the context of both heavy ion collision and QGP physics and playing a crucial role to separate cold nuclear matter (CNM) effects from hot plasma effects.

- CNM effects
  - Multiple scattering of partons
  - Modification of the initial parton distribution (e.g. shadowing)
  - Parton saturation effects

Why heavy quarks??

Heavy quarks are produced only in initial hard process and sensitive to the gluon distribution in hadron.

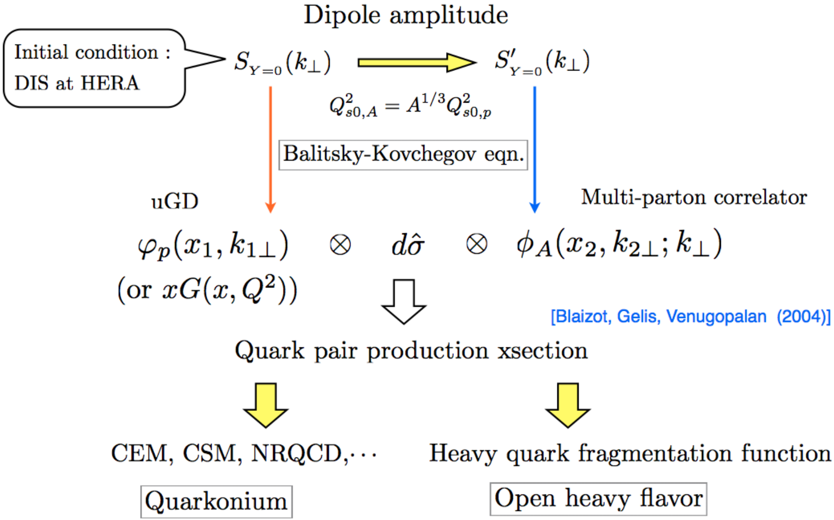
- In AA collisions:
  - Quarkonium is recognized as a thermometer inside the QGP.
  - Energy loss in medium and collective flow of D and B mesons.
- In pA collisions:
  - CNM effects.
  - Provides us with an unique opportunity to investigate the parton saturation phenomenon at small Bjorken's x of gluon in the incoming nucleus.

$$Q_{sA}^2(x) = Q_{s0}^2 A^{1/3}(x_0/x)^\lambda \sim m_c^2 \quad \text{(RHIC, the LHC)}$$

We study the heavy quark production in pA collisions at collider energies in order to quantify the effects of saturation.

Approach

For mean bias event in dilute-dense colliding system:



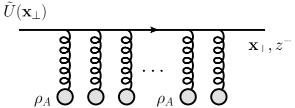
Quantum evolution of dipole amplitude

- Nonlinear BK equation

$$-\frac{d}{dY}S_Y(r_\perp)=\int dr_{1\perp}\,\mathcal{K}(r_\perp,r_{1\perp})\left[S_Y(r_\perp)-S_Y(r_{1\perp})S_Y(r_{2\perp})\right]$$

- $S_Y(x)$ is the eikonal scattering matrix element, probed by a quark-antiquark pair moving along the light-cone direction in the background gauge field in the target nucleus.

$$S_Y(x_\perp)\equiv\frac{1}{N}\mathrm{tr}\left\langle\widetilde{U}(x_\perp)\widetilde{U}^\dagger(0)\right\rangle_Y$$



- The large-N_c limit reduces the JIMWLK equation to the BK equation which is very convenient for numerical computations.

rcBK equation

- Running coupling kernel [Balitsky (2007)]

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

  rcBK equation includes a part of NLO contribution.
- Constrained initial condition: [AAMQS (2011)]
  Global fit analysis of the compiled HERA e+p data at $x < x_0 = 0.01$ using the rcBK equation with the initial condition at $x = x_0$

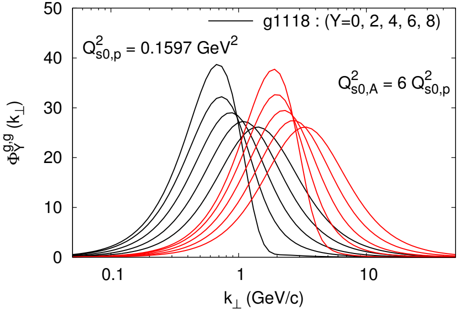
$$S_{Y0}(r_\perp) = \exp\left[-\frac{(r^2 Q_{s0,\mathrm{p}}^2)^\gamma}{4}\ln\left(\frac{1}{\Lambda r}+e\right)\right]$$

set	$Q_{s0,\mathrm{p}}^2/\mathrm{GeV}^2$	γ
g1118	0.1597	1.118
MV	0.2	1

- $Q_{s0,A}^2 = A^{1/3} Q_{s0,p}^2$ in the nucleus for MB event.

Unintegrated Gluon Distribution (uGD)

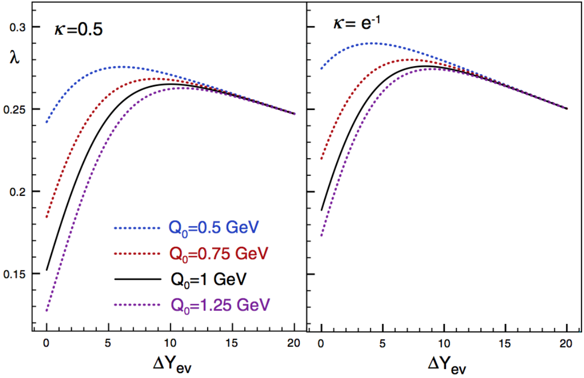
$$\phi^{g,g}_{A,Y}(l_\perp) = \frac{\pi R_A^2 N l_\perp^2}{4\alpha_s} \widetilde{S}^2_Y(l_\perp)$$



- The peak position (*i.e.*, the saturation scale) drifts with evolution rapidity Y.
- The number of gluon at lower-$k_\perp$ is strongly suppressed due to the nonlinear gluon merging, while more gluons are emitted in the large $k_\perp$ region by the BFKL cascade.

rcBK phenomenology 1

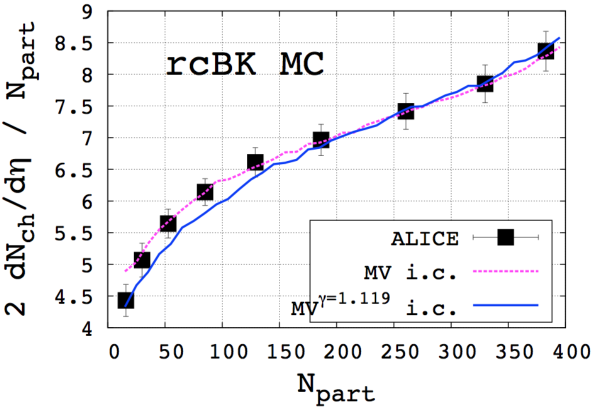
Speed of evolution : $\lambda = \frac{d \ln Q_s^2(Y)}{dY}$ with $Y = \ln(1/x)$
[Albacete (2007)]



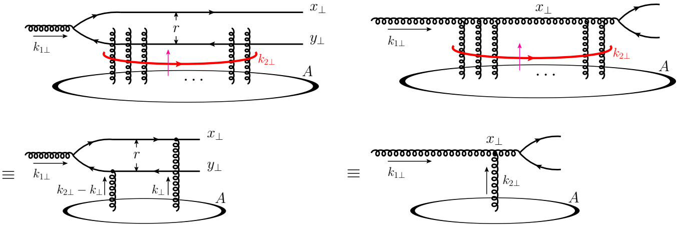
∗ HERA DIS : $\lambda \approx 0.288$ [Golec-Biernat, Wusthoff (1998)]

rcBK phenomenology 2

Charged particles multiplicity [Albacete, Dumitru (2010)]

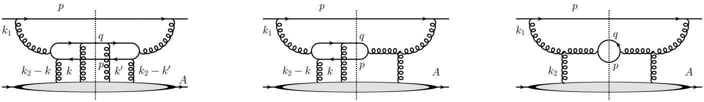


Pair production amplitude



- Multiple scattering effect of back ground gauge field on heavy quark pair production after the quark pair creation (Left) and before (Right).

Multi parton correlator in the nucleus



- Sum rule: $\int_{k_\perp, k'_\perp} \phi_A^{q\bar{q},q\bar{q}} = \int_{k_\perp} \phi_A^{q\bar{q},g} = \phi_A^{g,g}$.
- 4-point correlator (Leftmost) is reduced to 3-point correlator in the large-N_c limit.

$$\phi_{A,Y}^{q\bar{q},g}(l_\perp, k_\perp) = \frac{\pi R_A^2 N l_\perp^2}{4\alpha_s} \widetilde{S}_Y(k_\perp)\, \widetilde{S}_Y(l_\perp - k_\perp)$$

- 2-point correlator is just the uGD.

Quarkonium production

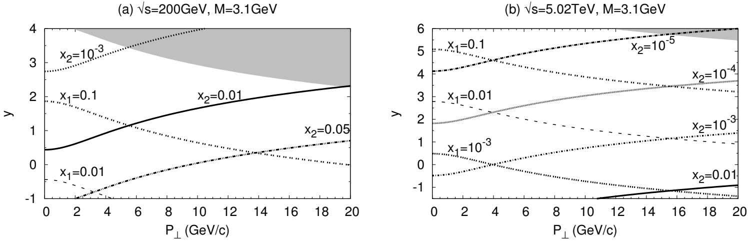
Color Evaporation Model

- J/ψ production cross section reads

$$\frac{d\sigma_{\mathrm{J}/\psi}}{d^2P_\perp dy} = F_{\mathrm{J}/\psi} \int_{4m_c^2}^{4M_D^2} dM^2 \frac{d\sigma_{c\bar{c}}}{d^2P_\perp dM^2 dy}$$

  where m_c (M_D) is the charm quark (D meson) mass and $F_{\mathrm{J}/\psi} = 0.02$ as representative values.
- A phenomenological constant $F_{\mathrm{J}/\psi}$ represents the non-perturbative transition rate for the charm pairs, produced in the invariant mass range $M \in [2m_c, 2M_D]$, to bound into a quarkonium.

Kinematical regions of $x_{1,2}$

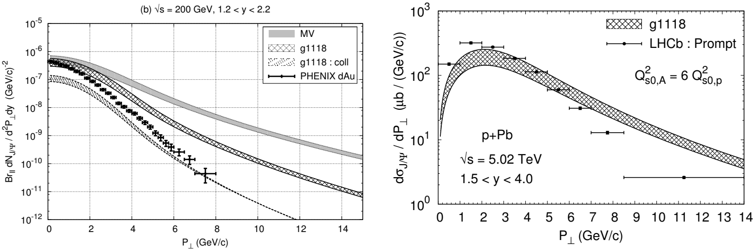


$$gg \longrightarrow \mathrm{J}/\psi \text{ or } \Upsilon : \quad x_{1,2} = \frac{\sqrt{P_\perp^2 + M^2}}{\sqrt{s}} e^{\pm y}$$

- LHC energy
  At forward rapidity, it probes x_2 as low as $\sim 10^{-4}$ to 10^{-5}.

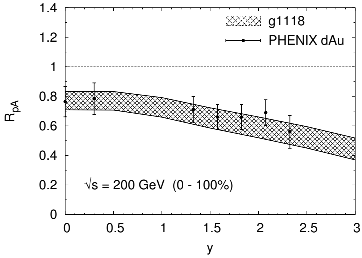
∗Take account that in the small x_2 region but large $P_\perp$, the gluon with large $k_{1\perp}$ in the proton can reduces the saturation effect.

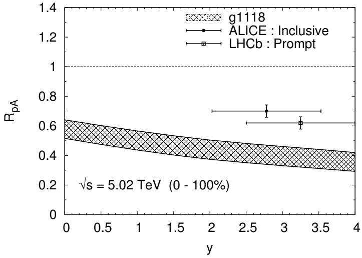
Cross section in pA



- Spectrum shows the harder slope at large $P_\perp$: BFKL tail of uGD.
- The collinear approximation on the proton side gives a better description of the data.
- Parameter dependence of the absolute value is indispensable.

Rapidity dependence of R_{pA} of J/ψ





- At the LHC energy $R_{\mathrm{pA}}(y)$ is further suppressed, which reflects through CEM the stronger effects of multiple scatterings and gluon saturation in the quark-pair production process.

($*$The band includes uncertainty for $m_c = 1.2$ GeV to 1.5 GeV and $Q^2_{s0,A} = (4-6)Q^2_{s0,p}$.)

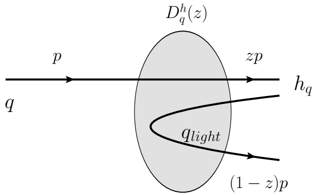
Heavy meson production

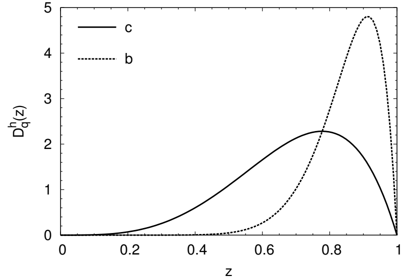
Single heavy meson production

$$\frac{d\sigma_h}{d^2p_{h\perp}dy} = f_{q\to h}\int dz \frac{D_q^h(z)}{z^2}\frac{d\sigma_q}{d^2q_\perp dy}$$

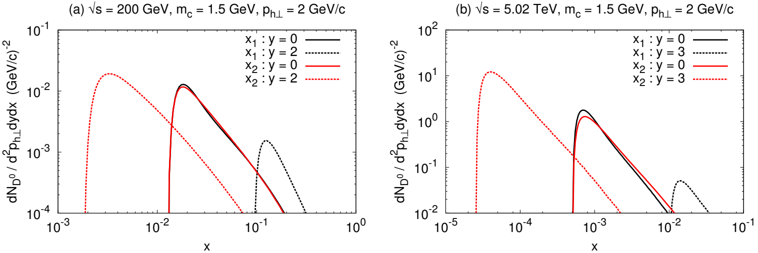
Kartvelishvili fragmentation function: $D_q^h(z)=(\alpha+1)(\alpha+2)z^\alpha(1-z)$

The only parameter: α is set to 3.5 (13.5) for D (B).
(∗No factorization scale dependence.)





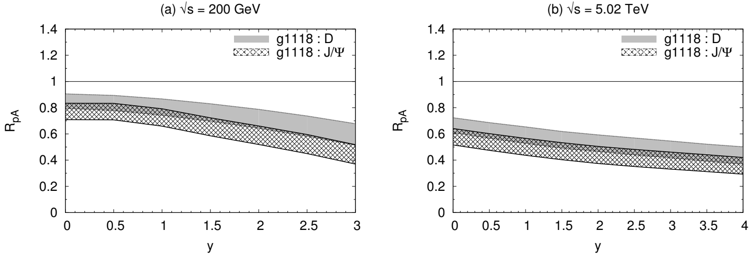
Kinematical coverage



$$x_{1,2}=\frac{1}{\sqrt{s}}\left(\sqrt{m^2+q_\perp^2}\,e^{\pm y_q}+\sqrt{m^2+p_\perp^2}\,e^{\pm y_p}\right)$$

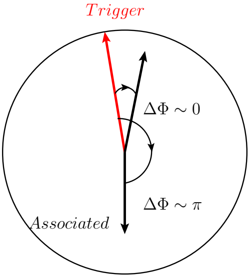
- x_1 and x_2 contributing to single charmed meson production at $p_{h\perp} = 2$ GeV and $y = 0$ at $\sqrt{s} = 200$ GeV are larger than $x_0 = 0.01$
- Small x gluons around $10^{-3} \sim 10^{-4}$ dominate the lower $p_{h\perp}$ production.

$R_{\rm pA}(y)$ of D meson



- J/ψ production is more suppressed than D meson.
- The produced quark pair experiences the multiple scatterings with the gluons in the target and is kicked beyond the invariant mass threshold though the CEM.

Azimuthal angle correlation between $D\bar{D}$

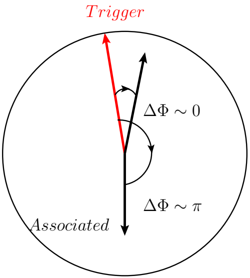


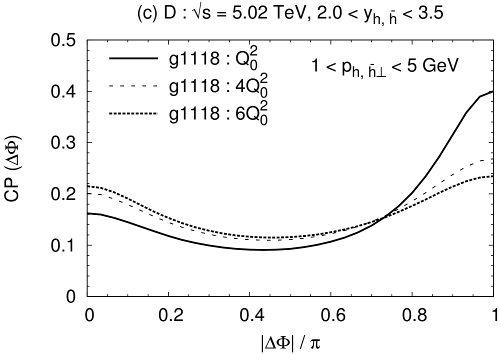
Pair production of heavy meson covers wider kinematic region of the participating partons than quarkonium production.

$$CP[\Delta\Phi] = \frac{2\pi}{N_{\text{tot}}} \int p_{h\perp} dp_{h\perp} p_{\bar{h}\perp} dp_{\bar{h}\perp} dy_h dy_{\bar{h}} \frac{dN_{h\bar{h}}}{d^2p_{h\perp} d^2p_{\bar{h}\perp} dy_h dy_{\bar{h}}}$$

N_{tot} is the pair multiplicity per event integrated over the same kinematic region and further integrated over the angle between the pair.

Azimuthal angle correlation between $D\bar{D}$





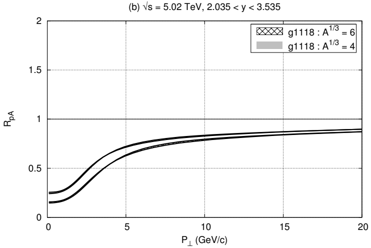
- Gluon bremsstrahlung and multiple scatterings, which are encoded in $\phi_{p}^{q\bar{q},g} \longrightarrow$ near-side peak.
- The away-side peak is gradually suppressed in pA collisions, while the near-side peak is slightly enhanced due to the stronger multiple scatterings and saturation effects.

Summary

- Effects of multiple scatterings and saturation on heavy quark production in pA collisions can be studied systematically in the CGC framework.
- $\boldsymbol{R}_{\mathrm{pA}}$ of J/ψ and $\boldsymbol{D}$ meson, and also $\boldsymbol{D\bar{D}}$ correlation in pA collisions can provide the valuable information of saturation effects in the heavy nucleus.
- Outlook
  - NLO corrections (e.g. Sudakov factor) [Mueller, Xiao, Yuan (2013)]
  - NRQCD matching [Kang, Ma, Venugopalan (2013)] [Qiu, Sun, Xiao, Yuan (2013)].

Backup

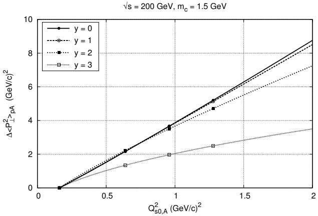
$P_\perp$ dependence of R_{pA} of J/ψ

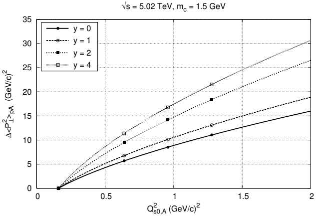


- R_{pA} of J/ψ production is suppressed at low $P_\perp$.

Broadening in medium

$$\Delta\langle P_\perp^2\rangle_{\text{pA}} \equiv \langle P_\perp^2\rangle_{\text{pA}} - \langle P_\perp^2\rangle_{\text{pp}} = \frac{\int d\sigma_{\text{pA}} P_\perp^2}{\int d\sigma_{\text{pA}}} - \frac{\int d\sigma_{\text{pp}} P_\perp^2}{\int d\sigma_{\text{pp}}}$$





- The measured value of $\Delta\langle P_\perp^2\rangle_{\text{dAu}}$ at RHIC seems to be smaller by a factor of 5 than our results, if we naively translate $Q_{s0,A}^2$ to the centrality parameter N_{coll} evaluated for dAu collisions.
- At $\sqrt{s} = 5.02$ TeV, the mean momentum of J/ψ as moving to the forward-rapidity region.

Azimuthal angle correlation between $D\bar{D}$