Heavy quark pair production and parton saturation in pA collisions at the LHC

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Abstract: Heavy quark pair production in pA collisions is a good probe to study the parton (gluon) saturation in the nucleus. In this presentation, we report our numerical results on the nuclear modification factor (R_{pA}) of J/ψ and D productions for the minimum bias event in pA collisions at the RHIC and LHC energies within the Color Glass Condensate (CGC) and also discuss the impact parameter dependence of the J/ψ R_{pA}. In the latter case, we show that the R_{pA} of J/ψ productions in peripheral collisions is strongly suppressed at forward rapidity and differs from the data. This means that we need to carefully consider the nuclear geometry in order to compute the gluon distribution in the nucleus.

Introduction

- The goals of ultrarelativistic heavy ion collisions (HICs) physics are to create quark-gluon plasma (QGP) and to understand its properties.
- Heavy quarks produced in initial hard process
  → Subsequent interactions reflect medium properties.
- Initial cold nuclear matter (CNM) effects should be studied in pA collisions
  → A controlled baseline in the context of both HICs and QGP physics.
- We **focus on** the parton saturation effect in the target nucleus because the saturation scale becomes semi hard at the LHC and larger at forward rapidity (very small Bjorken's x).

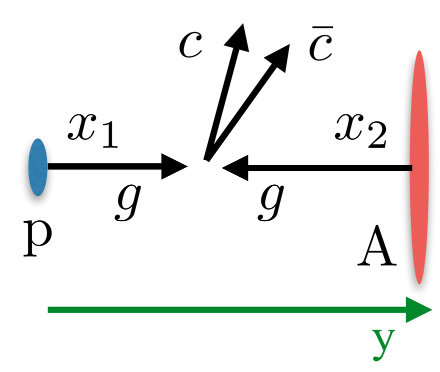
$$Q^2_{sA}(x) \sim A^{1/3}\left(\frac{0.01}{x}\right)^{0.3}\Lambda^2_{\rm QCD} \gg \Lambda^2_{\rm QCD}$$

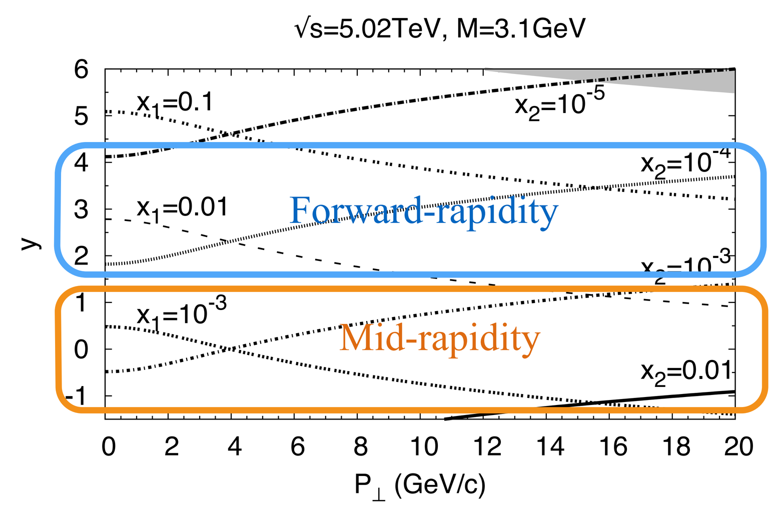
- Saturation scale will become relevant to both light hadron and heavy quark pair ($c\bar{c}$) productions at the LHC.

Momentum fraction of the incoming gluon

$$x_{1,2} = \sqrt{\frac{M^2+P_\perp^2}{s}}e^{\pm y}$$

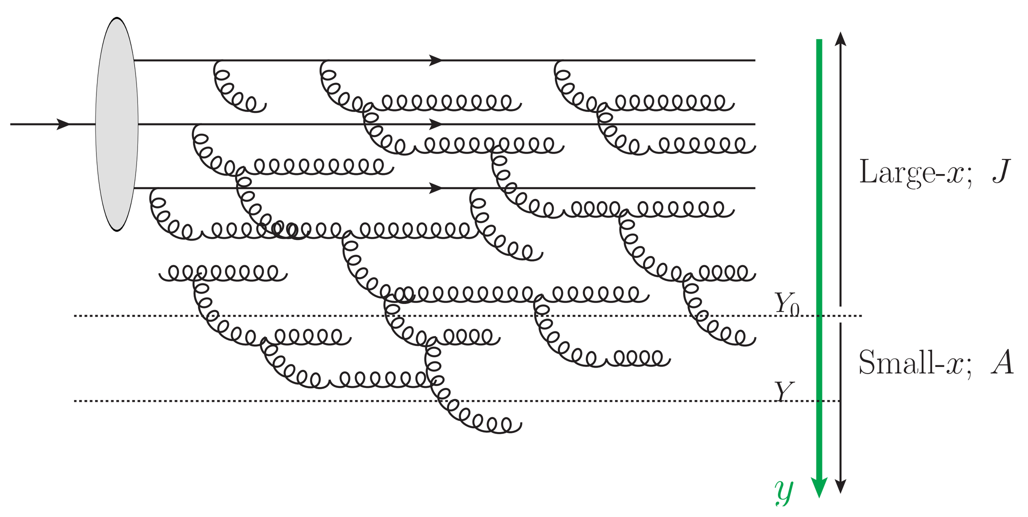
(M : invariant mass of the quark pair)





Framework

- Gluons from the target nucleus in the CGC.



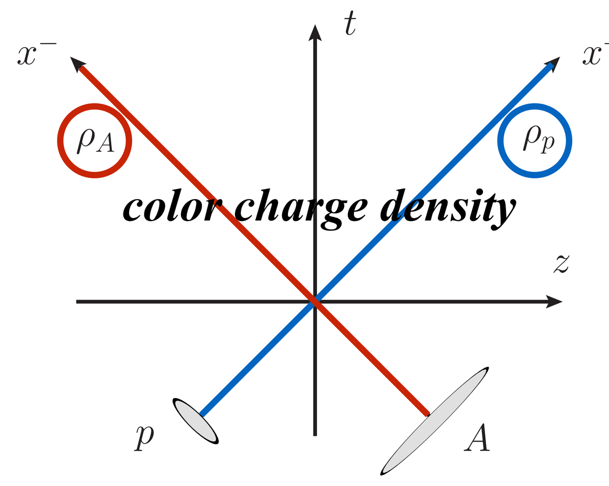
- Large-x gluon : Classical field from Yang-Mills equation

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

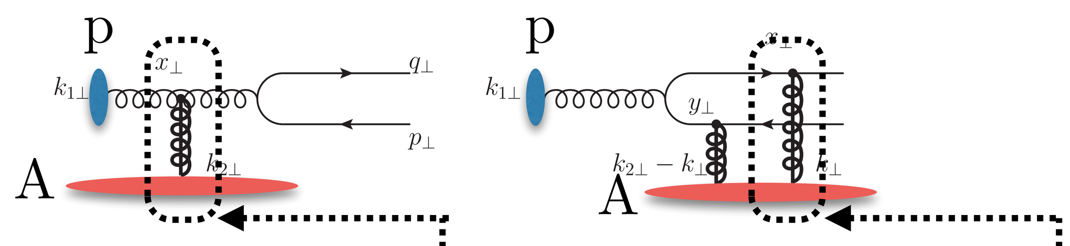
Color current on the lightcone axis (Right Figure)

$$J^\nu = g\delta^{\nu+}\delta(x^-)\rho_p(\vec{x}_\perp) + g\delta^{\nu-}\delta(x^+)\rho_A(\vec{x}_\perp)$$

- Small-x gluon : Fluctuation emerging from quantum evolution

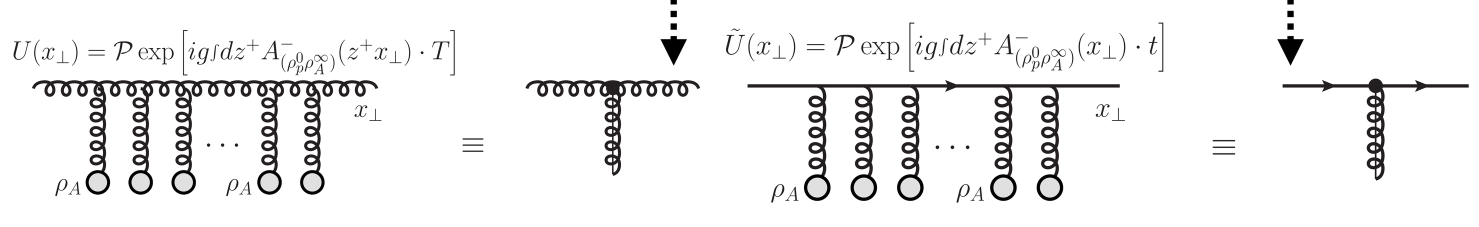


- Heavy quark pair production from the background gauge field at the order $\mathcal{O}(\rho_p^1\rho_A^\infty)$
  - Multiple scattering before and after the quark pair production. Blaizot, Gelis, Venugopalan (2004)



Squared amplitude

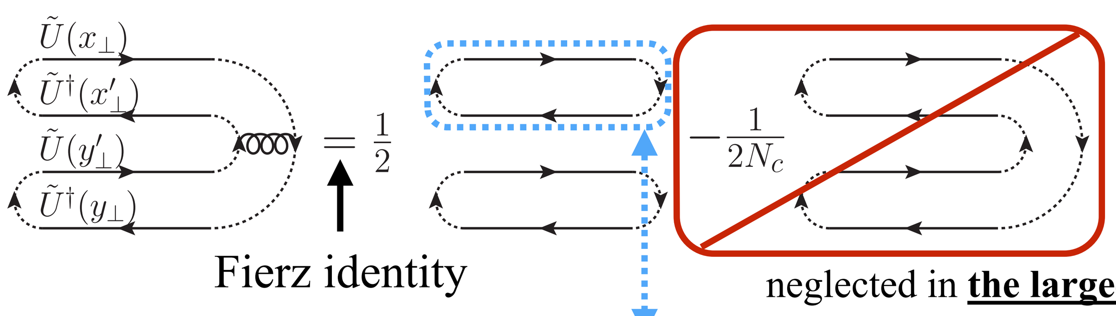
- *Eikonal phases (Wilson lines)*



In the covariant gauge, it is actually found that $gA \propto g^2\rho_A = \mathcal{O}(1)$.

4-point function (4 Wilson lines) appears in the quark pair production cross section.

(※ 2, 3-pt functions are easily obtained from 4-pt function.)



- Dipole amplitude: $N_Y(\vec{x}_\perp - \vec{x}'_\perp) \equiv 1 - \frac{1}{N_c}\langle {\rm tr}[\tilde{U}(\vec{x}_\perp)\tilde{U}^\dagger(\vec{x}'_\perp)]\rangle_Y$

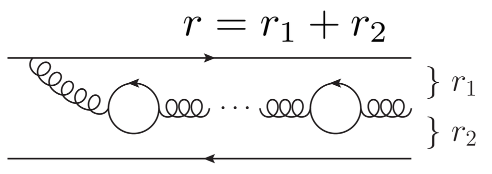
- **BK equation** describes quantum evolution of the dipole amplitude

$$\frac{d}{dY}N_Y(\vec{r}_\perp) = \int d\vec{r}_{1\perp}\mathcal{K}(\vec{r}_\perp,\vec{r}_{1\perp})\left[N_Y(\vec{r}_{1\perp}) + N_Y(\vec{r}_{2\perp}) - N_Y(\vec{r}_\perp) - N_Y(\vec{r}_{1\perp})N_Y(\vec{r}_{2\perp})\right]$$

BFKL cascade — Recombination

We use the running coupling evolution kernel Balistky (2007)

$$\mathcal{K}_{\rm run}(\vec{r}_\perp,\vec{r}_{1\perp}) = \frac{\alpha_s(r^2)N_c}{2\pi^2}\left[\frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)}-1\right) + \frac{r^2}{r_1^2r_2^2} + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)}-1\right)\right]$$



A part of NLO correction; quark loop

This calculation includes
- Multiple scattering of classical gluon
- Quantum evolution effect via BK equation.

Numerical results

- Set up : Initial condition of dipole amplitude

AAMQS model Albacete et.al. (2011)

$$N_{Y=0}(r_\perp) = \exp\left[-\frac{(r^2Q^2_{s0,p})^\gamma}{4}\ln\left(\frac{1}{\Lambda r}+e\right)\right]$$

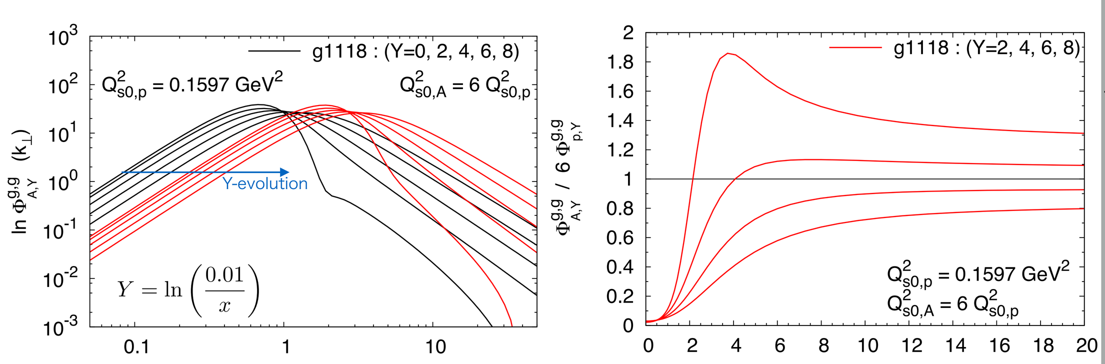
$Q^2_{s0,p} = 0.1597{\rm GeV}^2$ $\gamma = 1.118$ by global fitting of DIS

- Multi parton function for minimum bias event

$$\phi^{g,g}_{A,Y}(k_{2\perp}) = \frac{\pi R_A^2 N_c k_{2\perp}^2}{4\alpha_s}\int\frac{d^2k_\perp}{(2\pi)^2}\tilde{S}_Y(k_\perp)\tilde{S}_Y(k_{2\perp}-k_\perp)$$

$$\tilde{S}_Y(k_\perp) \equiv \int d^2x_\perp e^{-ik_\perp\cdot x_\perp}[1-N_Y(x_\perp)]$$

Leading twist ↓ $\phi^{g,g}_{A,Y}$ reduces to the unintegrated gluon distribution



- The number of net gluons increases with decreasing in Bjorken's x.
- low-$k_\perp$ distribution is suppressed by gluon saturation.
- high-$k_\perp$ region is enhanced by gluon radiations.

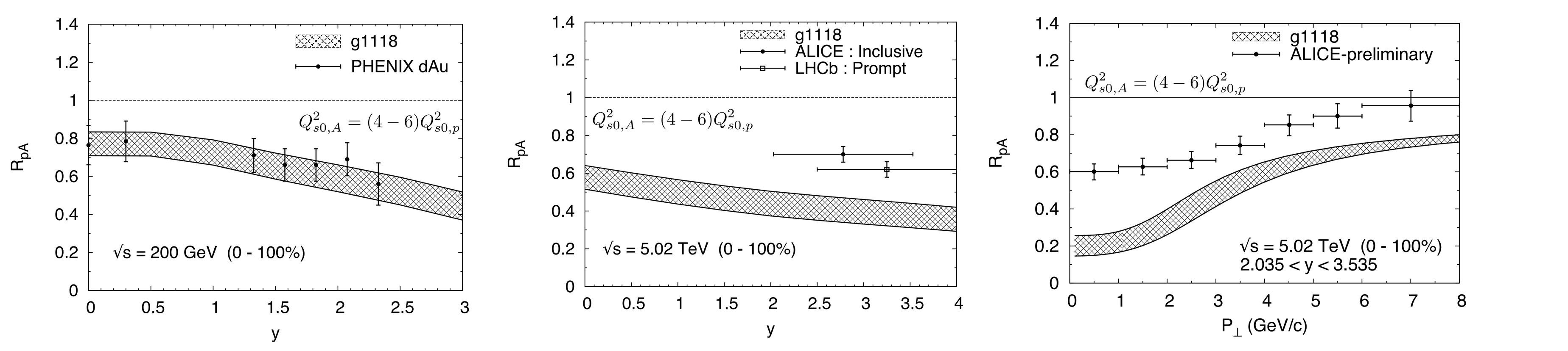
- R_{pA} of J/ψ production in the Color Evaporation Model

  - **Minimum bias event**

$$R_{pA} = \frac{\frac{dN_{pA}}{d^2P_\perp dy}}{N_{\rm coll}\frac{dN_{pp}}{d^2P_\perp dy}}$$

We assume the nucleus as cylindrical $Q^2_{s0,A} = A^{1/3}Q^2_{s0,p}$

and allow $Q^2_{s0,A} = (4-6)Q^2_{s0,p}$

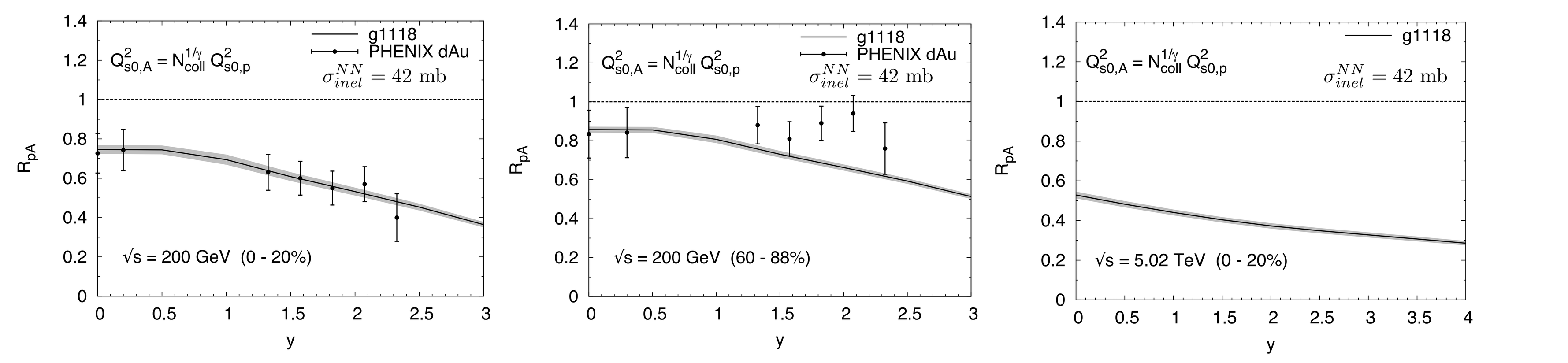


  - **Central and peripheral event**

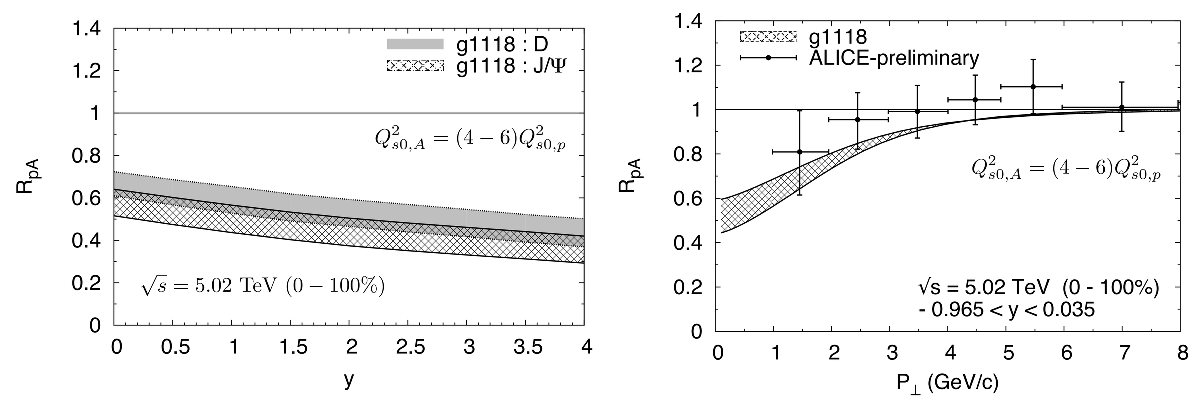
We assume $Q^2_{s0,A} = N_{\rm coll}^{1/\gamma}Q^2_{s0,p}$

by use of the Glauber model $N_{\rm coll}(b) = \sigma^{NN}_{inel}T_A(b)$

with simple thickness function $T_A(b) = \frac{3A}{2\pi R_A^3}\sqrt{R_A^2-b^2}\,\theta(R_A-b)$



- R_{pA} of D meson production (Minimum bias event)



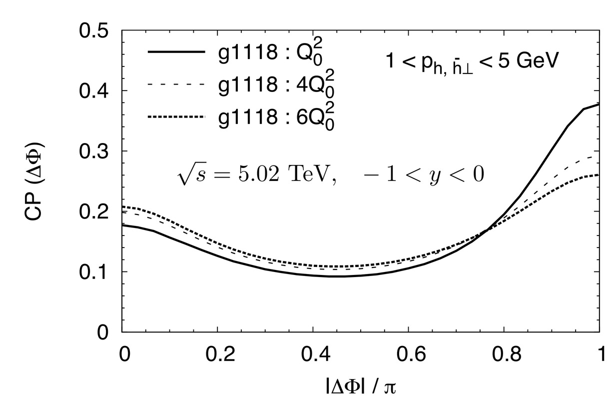
- Azimuthal angle correlation (Minimum bias event)

$$CP[\Delta\Phi] = \frac{2\pi}{N_{\rm tot}}\int\frac{dp^2_{\perp,}}{2}\frac{dp^2_{\perp,}}{2}\frac{dN_{DD}}{d^2p_{\perp}d^2p_{\perp}}$$

Q^2_{s0} : pp collision

$(4-6)Q^2_{s0}$: pA collision

- No leptonic/hadronic decay correction



Summary: In this CGC calculation with large-N_c approximation, we have shown that R_{pA} of J/ψ and D meson productions are strongly suppressed in the low-$p_\perp$ region at forward rapidity due to the multiple scattering and saturation effects in the target nucleus. Hadronization is treated in a simple model. These productions reflect the behavior of multi parton function. The results of central and peripheral collisions suggest an importance of more realistic treatment of nuclear geometry. In future work, we will use more sophisticated nuclear profile and consider the NLO correction in hard process and hadronization dynamics.