Heavy flavor and Quarkonium production in pp/pA collisions using the small-x CGC framework

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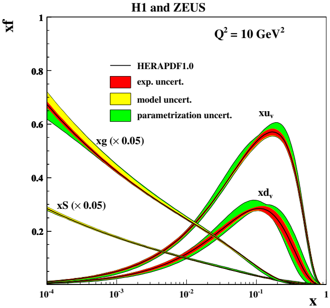
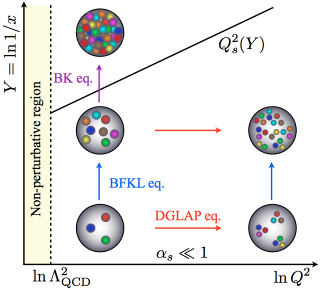
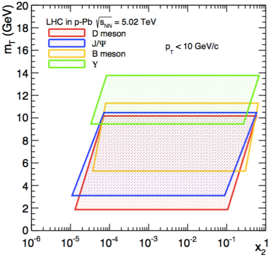
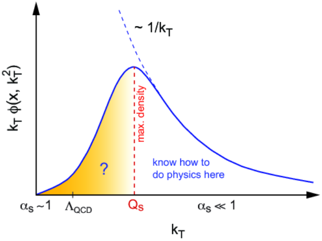




- Rapid growth of gluon density at small-x → a consequence of BFKL evolution
- Gluon recombination at small-x → Glauon Saturation [Gribov, Levin, Ryskin (1983)][Mueller, Qiu(1986)]
- Color Glass Condensate (CGC) framework systematically accounts for the logs in x and higher twist contributions which give rise to the saturation.

Heavy flavor and quarkonium production in pp/pA





- $Q_{sA}^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{0.3} \gg \Lambda_{\rm QCD}^2 \rightarrow k_\perp$-dependent gluon distribution provides information on the saturation.

Physics Motivation

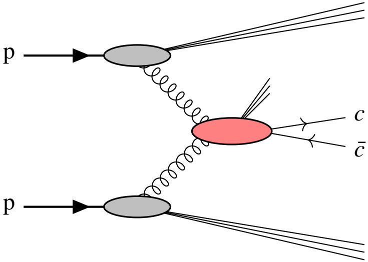
- Heavy quark pair is produced via gluon-gluon fusion at collider energies → Using heavy quark to probe purely small-x gluons in high energy hadrons/nuclei, and test the CGC framework.
- Understanding of heavy flavor and quarkonium production mechanisms at low-$P_\perp$
- Quantitative evaluation of cold nuclear matter effect.

Talk Plan

1. The CGC framework
2. Open heavy flavor
   - D production
   - $D\bar{D}$ correlation
3. Quarkonium
   - J/ψ production
   - $\psi(2S)$ production
   - $\Upsilon(1S)$ production
4. Summary

Heavy quark pair production in the collinear factorization

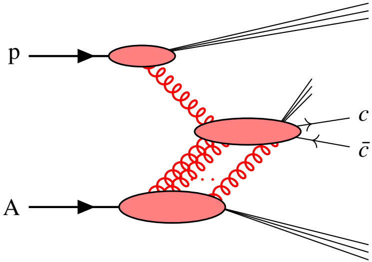
Collinear factorization (Robust when $m \ll P_\perp$)



- $d\sigma_{pp\to c\bar{c}} \approx \underbrace{G(x_1,\mu)\otimes G(x_2,\mu)}_{\text{No } P_\perp} \otimes \underbrace{H_{gg\to c\bar{c}(+g\ldots)}}_{P_\perp \text{ dep.}}$
- pA collisions : PDFs $\to$ nPDFs (Shadowing, Antishadowing)

Heavy quark production in the CGC framework

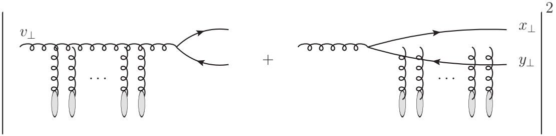
the Color-Glass-Condensate framework



- Many $P_\perp$ sources!
- $d\sigma_{pA\to c\bar{c}} \approx \underbrace{\varphi(x_1, k_{1\perp}) \otimes \phi_A(x_2, k_{2\perp})}_{P_\perp \text{ dep}} \otimes \underbrace{H_{gg\to c\bar{c}(+g\ldots)}}_{P_\perp \text{ dep.}}$
- Multiple scattering with target nucleus is essential in p+A $\to$ $k_\perp$-factorization is violated. [Fujii, Gelis, Venugopalan (2005)]

Heavy quark pair production in dilute-dense system

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



- The scattering contributions are coherent as a whole.
- The incident gluon or the produced quark pair passes through the background gauge field ← Solving classical Yang-Mills eq.

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

- Semi-hard multiple gluon scattering is encoded in the Wilson lines.

$$U(x_\perp) = \mathcal{P}_+ \exp\left[-ig^2 \int_{-\infty}^{+\infty} dz^+ \frac{1}{\nabla_\perp^2} \rho_A(z^+, x_\perp)\cdot t \right]$$

$$W(x_\perp) = \mathcal{P}_+ \exp\left[-ig^2 \int_{-\infty}^{+\infty} dz^+ \frac{1}{\nabla_\perp^2} \rho_A(z^+, x_\perp)\cdot T \right]$$

Rapidity or Energy dependence of the cross section

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

$$= \frac{\alpha_s^2}{64\pi^6 C_F} \int \frac{d^2k_{2\perp} d^2k_\perp}{(2\pi)^4} \frac{\Xi(k_{1\perp}, k_{2\perp}, k_\perp)}{k_{1\perp}^2 k_{2\perp}^2} \varphi_{\mathrm{p},x_1}(k_{1\perp})\, \phi_{\mathrm{A},x_2}(k_{2\perp}, k_\perp)\,.$$

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

- Rapidity evolution of the dipole amplitude F_x obeys Balitsky-Kovchegov eq.

$$\varphi_{\mathrm{p},x}(k_{1\perp}) = \pi R_\mathrm{p}^2 \frac{N_c k_{1\perp}^2}{4\alpha_s} \int \frac{d^2l_\perp}{(2\pi)^2} F_x(k_\perp - l_\perp) F_x(l_\perp)$$

$$\phi_{\mathrm{A},x}(k_{2\perp}) = \pi R_\mathrm{A}^2 \frac{N_c k_{2\perp}^2}{4\alpha_s} F_x(k_{2\perp} - k_\perp) F_x(k_\perp)$$

πR_p^2 (πR_A^2) is the transverse area occupied by gluons in the proton (nucleus).

- Matching between φ and CTEQ6M at $x = 0.01$ gives $R_p \sim 0.43 \sim 0.48$ fm.
- R_A is chosen to reproduce $R_{pA} = 1$ when $p_\perp \to \infty$.

Note on the CGC framework

- We are able to control only the rapidity or energy dependence of the cross section.
- Information of $b_\perp$ dependence is embedded in the saturation scale.
- The CGC framework is robust at small-x. How small is x? → We presume $x < x_0 = 0.01$.
- φ at large-x (forward rapidity): We need an extrapolation or matching to collinear PDF xG and switch from φ to xG at $x = x_0$. See [Ma, Venugopalan (2014)]
- Initial condition of the BK eq. for proton: MV model or parametrization set constrained by DIS global data fitting. See [AAMQS (2010)]
- Initial condition of the BK eq. for nucleus: It depends on Model. Familiar and simple choice is the replacement, $Q_{s,A} = cA^{1/3}Q_{s,\mathrm{p}}$. (MB event)

∗ Data comparisons could provide a constarint on c.

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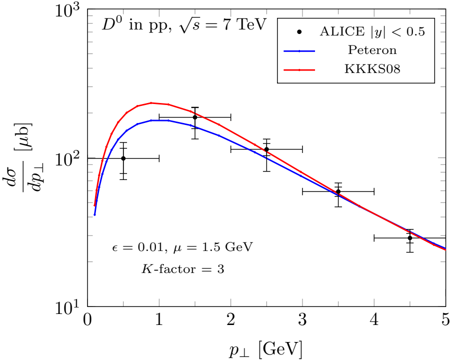
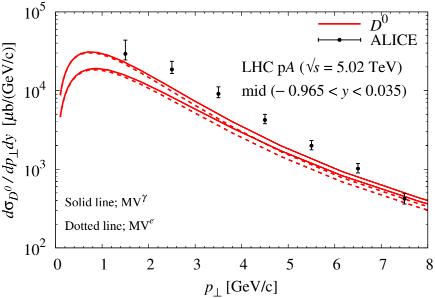
$p_\perp$ distribution of D production at the LHC

[Fujii, KW (2013)(2015)]

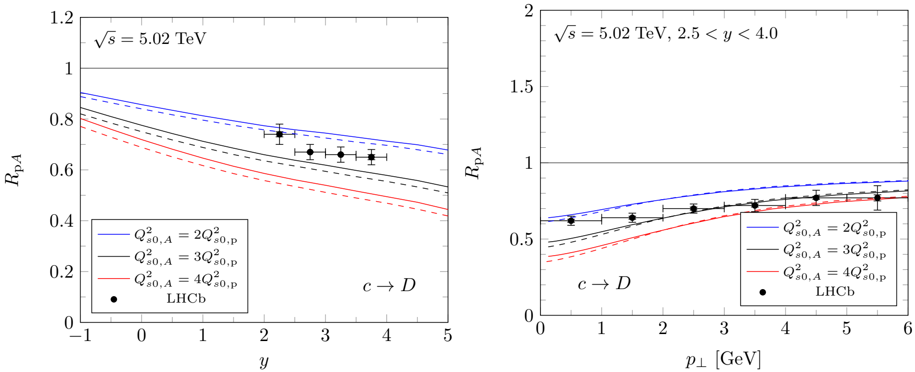
$$\frac{d\sigma_D}{d^2 p_{D\perp} dy} = \int \frac{dz}{z^2} D(z) \frac{d\sigma_c}{d^2 p_{c\perp} dy}$$





- Suppose that c fragments into D far outside the proton and nucleus.
- Large uncertainties about fragmentation process : Mass dependence, FF dependence, $p_{D_\perp} = z p_{c_\perp}$ or $p_D = z p_c$, or ..., and more.

[Fujii, KW (2013)(2015)(2017)][Ducloué, Lappi, Mäntysaari (2016)]



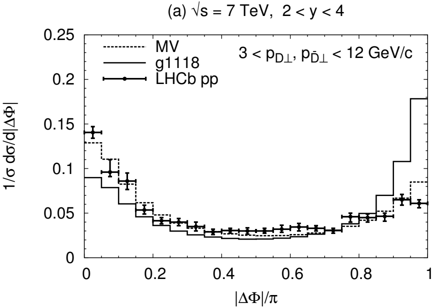
- More reliable observable for the CGC.
- Important Lesson: The smaller $Q^2_{s0,A}$ is favored at forward rapidity.

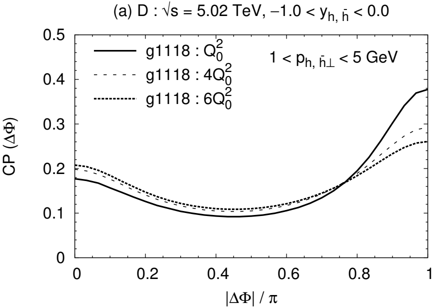
* A small value of $Q^2_{s0,A} \sim (1.5 - 3.0) Q^2_{s0,p}$ was shown to fit the New Muon Collaboration data on $F_{2,A}(x, Q^2)$. [Dusling, Gelis, Lappi, Venugopalan (2009)]

Forward $D\bar{D}$ correlation at the LHC

[Fujii, KW (2013)]

$$\frac{d\sigma_{D\bar{D}}}{d^2p_{D\perp}d^2p_{\bar{D}\perp}dy_pdy_q} = \int \frac{dz_1}{z_1^2}\frac{dz_2}{z_2^2}D(z_1)D(z_2)\frac{d\sigma_{c\bar{c}}}{d^2p_{c\perp}d^2p_{\bar{c}\perp}dy_pdy_q}$$





- $|P_{tot}| = |P_{D\perp} + P_{\bar{D}\perp}| \sim Q_s \lesssim |P_{rel}|, |P_{D\perp}|, |P_{D\perp}|$ at away side.
- Moderate peak at away side ⇒ Saturation effect?? We must be careful. Another multiple scattering (Sudakov) effect could also be important. [Mueller, Xiao, Yuan(2013)]

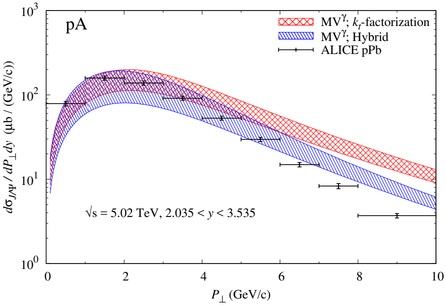
Talk Plan

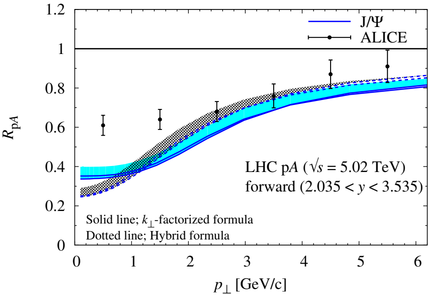
J/ψ production in the CGC + CEM

[Fujii, Gelis, Venugopalan (2006)][Fujii, KW (2013)(2015)][Ducloué, Lappi, Mäntysaari (2015)]

- Assume that J/ψ forms far outside the proton and nucleus.

$$\frac{d\sigma_\psi}{d^2P_\perp dy} = F_{q\bar{q}\to\psi}\int_{2m_q}^{2m_Q} dM \frac{d\sigma_{q\bar{q}}}{dM d^2P_\perp dy}$$





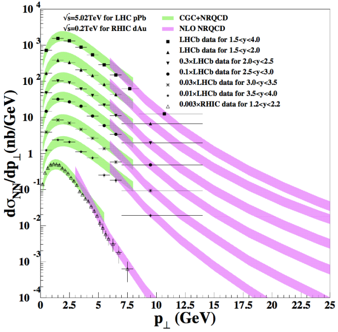
- Early prediction : $Q^2_{s0,A} = (4-6)Q^2_{s0,p} \Longrightarrow$ Present prediction : $Q^2_{s0,A} \lesssim 3Q^2_{s0,p}$

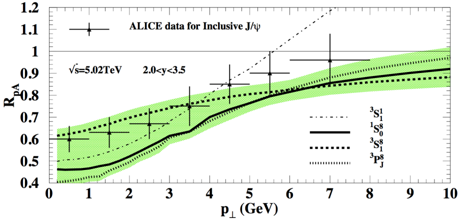
J/ψ production in the CGC + NRQCD

[Kang, Ma, Venugopalan (2013)][Ma, Venugopalan (2014)][Ma, Venugopalan, Zhang (2015)]

- The CGC cross sections at short distance are matched to NRQCD LDMEs.

$$d\sigma_{pA}^{H} = \sum_{\kappa} \underbrace{d\hat{\sigma}_{pA}^{\kappa}}_{\text{CGC}} \times \underbrace{\langle \mathcal{O}_{\kappa}^{H} \rangle}_{\text{LDMEs}}$$

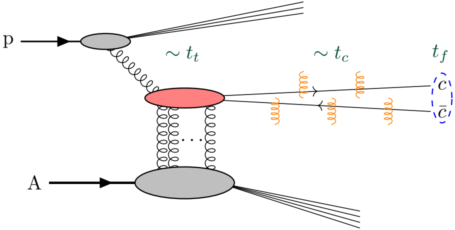


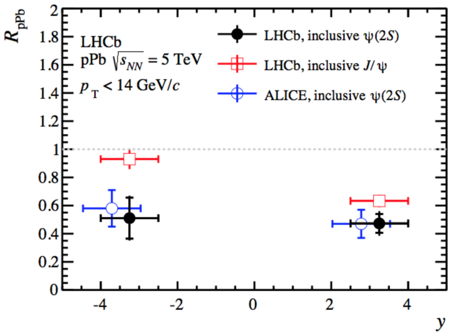


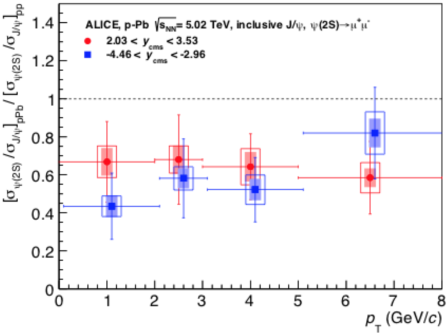
- Overlap region between the CGC and the NLO NRQCD factorization : $P_{\perp} \sim 5$ GeV.
- The contribution of CS channel is relatively small. (10% in pp, 15% – 20% in pA at small-$P_{\perp}$)

Caveats

- Description of $\psi(2S)$ production is not clear in the NRQCD. Large uncertainties in association with charm mass and LDMEs. See [Ma, Venugopalan (2014)]
- Must be careful to consider whether matching between the short distance CGC and NRQCD LDMEs is applicable to low $P_\perp$ quarkonium production because of soft color exchanges between the comoving spectators and the charm pair. See [Brodsky, Mueller (1988)]



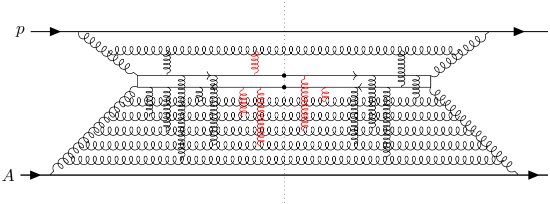




- Heavy quark pair is produced locally at $t_c \gtrsim 1/2m \sim 0.07$ fm
- The saturation effect is short distance physics at t_c and mass difference between J/ψ and $\psi(2S)$ is negligible compared to any other large scale, say $\sqrt{s}$ and so $R_{pA}^{J/\psi} \sim R_{pA}^{\psi(2S)}$ is naively expected.
- The data suggests that some kind of final state effect should be essential. E.g. hadron comover, [Ferreiro, Pajares (2012)]

Factorization breaking effect

- In the very forward rapidity region $y \gg \ln \frac{2mv}{p_\perp} \sim \ln \frac{Mv}{Q_{sA}}$, the factorization is effectively OK for J/ψ. [Sun, Qiu, Xiao, Yuan (2013)]
- However, the soft color exchange at last stage breaks factorization of quarkonium production. $\psi(2S)$ production gives a nice test of factorization breaking effect.



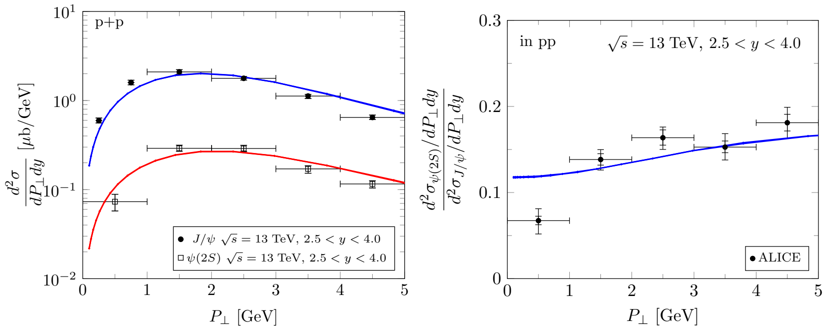
- Indeed, soft color exchanges between long lived comovers and the $c\bar{c}$ can affect greatly $\psi(2S)$ production because $\psi(2S)$ is much more weakly bound. $\Longrightarrow$ Strong nuclear suppression of $\psi(2S)$ at RHIC and the LHC. (We shall come back later)

J/ψ and $\psi(2S)$ in the CGC + Improved CEM

Improved CEM [Ma, Vogt (2016)]

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

- ICEM takes account of modification of $P_\perp$ of the $c\bar{c}$ during fragmentation process.
- The CGC+ICEM succeeds in describing different $P_\perp$ distributions of J/ψ and $\psi(2S)$.

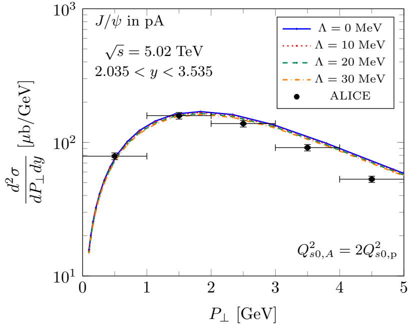


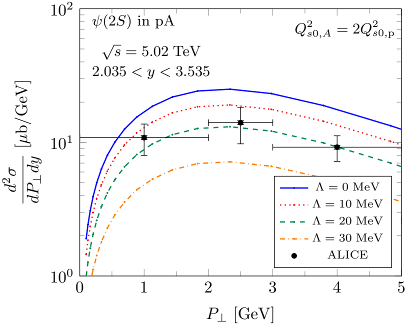
- We regards that $F_{q\bar{q}\to\psi}$ should include the effect of soft color exchanges at final stage.

Assumption: the role of soft color exchanges should be A dependent.

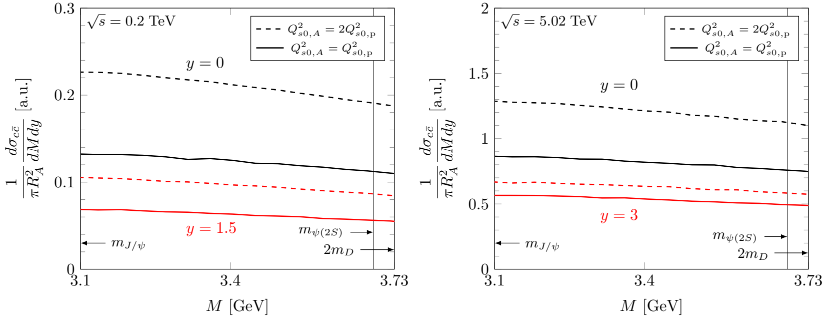
$$\frac{d\sigma_\psi}{d^2P_\perp dy} = F_{q\bar{q}\to\psi}\int_{m_\psi}^{2m_Q-\Lambda} dM\left(\frac{M}{m_\psi}\right)^2 \frac{d\sigma_{q\bar{q}}}{dM\,d^2P'_\perp dy}\Bigg|_{P'_\perp=\frac{M}{m_\psi}P_\perp}$$

$\Lambda > 0 \rightarrow$ the average momentum kick given by nuclear parton comovers.





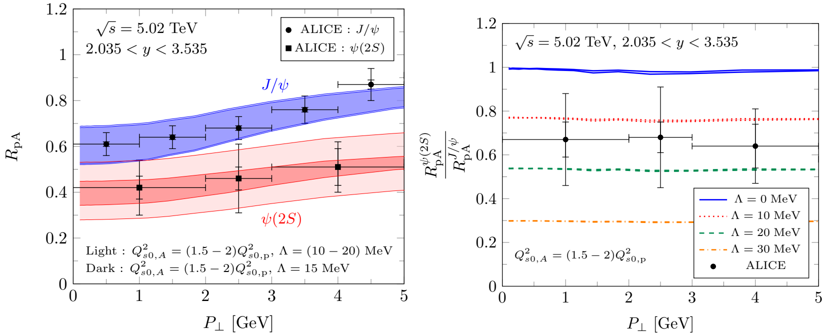
Why is Λ so important for $\psi(2S)$?



- The phase space of the produced $c\bar{c}$ pair is limited to lie within the narrow range for $\psi(2S)$. For J/ψ production, the $c\bar{c}$ pair has a significantly larger phase space than that for $\psi(2S)$.
- $\Delta E_{\psi(2S)} \sim 50$ MeV!

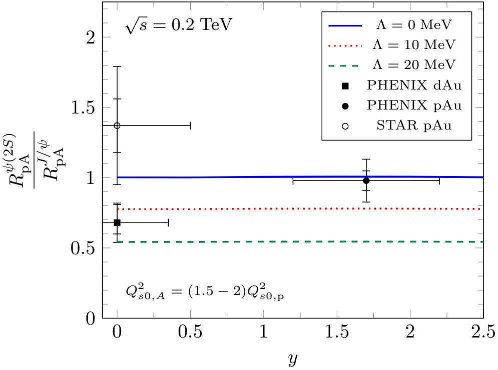
Strong $\psi(2S)$ suppression relative to J/ψ

[Ma, Venugopalan, KW, Zhang (2017)]



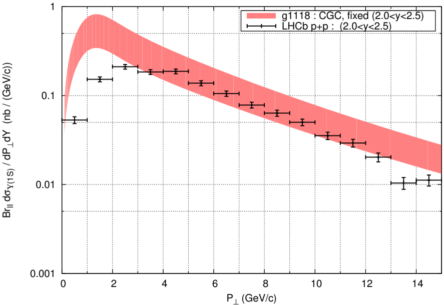
- The factorization breaking effect clearly leads to a stronger $\psi(2S)$ suppression while it is negligible for J/ψ.
- The double ratio can be the better prediction because it depends on only Λ.
- Λ is much smaller than Λ_{QCD} and the typical freeze-out temperature in HIC.
- The enhanced soft color exchanges in p+A are sufficient to explain the data.

[Ma, Venugopalan, KW, Zhang (2017)]



- No clear suppression at forward rapidity, and large uncertainty at mid rapidity.
- $\Lambda_{\rm RHIC} < \Lambda_{\rm LHC}$: More partons are produced at the LHC

$\Upsilon(1S)$ production in the CGC+CEM



Small-x saturation vs Sudakov

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

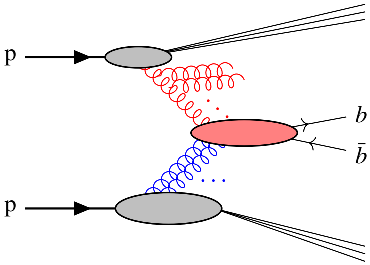
$$\frac{\alpha_s N_c}{2\pi^2} \ln \frac{1}{x_g} \sim \mathcal{O}(1) \Longrightarrow \text{BK/JIMWLK evolution eq.}$$

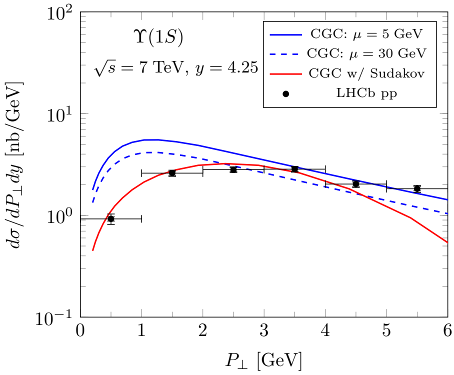
- $M^2 \gg p_\perp^2$: Sudakov resummation

$$\frac{\alpha_s N_c}{2\pi} \ln^2 \frac{M^2}{p_\perp^2} \sim \mathcal{O}(1) \Longrightarrow \text{Collins-Soper-Sterman resummation formalism}$$

$\Upsilon(1S)$ production in the CGC+CEM with Sudakov

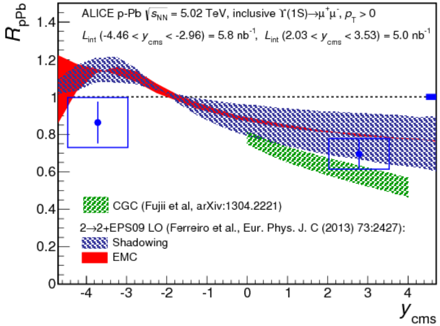
[KW, Xiao (2015)]

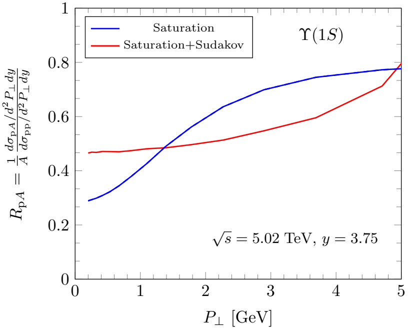




- Sudakov effect is predominant over the saturation effect in p+p.
- However, Sudakov effect could be comparable to the saturation effect in p+A.

[Fujii, KW (2013)][KW, Xiao (2015)]





- y distribution of R_{pA} of Υ production can be described by the CGC. No Sudakov effect.
- $P_\perp$ distribution of the R_{pA} could provide good tests on the CGC framework.

Talk Plan

Summary

- The CGC framework with smaller $Q^2_{s0,A}$ provides a nice agreement with data of R_{pA} of D. We may need careful analyses to describe $D\bar{D}$ correlation.
- R_{pA} of J/ψ is described in the CGC+CEM or ICEM or NRQCD with use of the smaller $Q^2_{s0,A}$. The interaction between parton comovers and the $c\bar{c}$ is indeed negligible.
- To understand $\psi(2S)$ suppression in p+A, final state interaction is more essential. Clearly factorization breaking effect due to parton comovers interaction in final state suppresses $\psi(2S)$ yields largely because $\psi(2S)$ is loosely bound.
- Soft gluon shower (Sudakov) is essential for describing $P_\perp$ distribution of $\Upsilon(1S)$ production in p+p. However, it is comparable to the saturation effect in p+A.

Works in progress

- D and J/ψ production vs N_{ch}
- $\cdots$

Thank you!

Talk Plan

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

$$\frac{dT_{x_g}(r)}{d\ln 1/x_g} = \mathcal{K} \otimes \left[\underbrace{T_{x_g}(r_1) + T_{x_g}(r - r_1) - T_{x_g}(r)}_{\text{BFKL}} \underbrace{- T_{x_g}(r_1) T_{x_g}(r - r_1)}_{\text{Recombination}} \right]$$

- The running coupling kernel in Balitsky's prescription is well controllable numerically. [Balitsky (2006)]

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

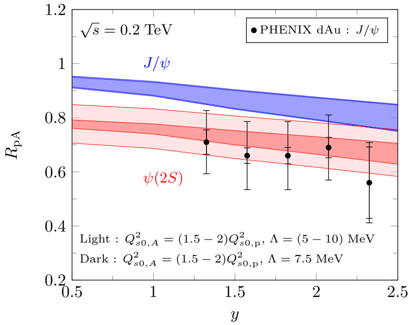
- Set Initial condition to be McLerran-Venugopalan model like functional form:

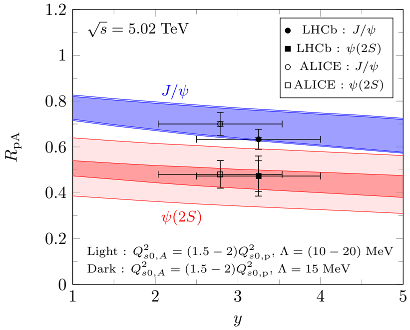
$$S_{x=0.01}(r_\perp) = \exp\left[-\frac{\left(r_\perp^2 Q_{s0,\mathrm{p}}^2\right)^\gamma}{4} \ln\left(\frac{1}{r_\perp \Lambda} + e \right) \right]$$

✓ Input parameters γ, $Q_{s0,\mathrm{p}}^2$ are precisely constrained from HERA-DIS global data fitting. [AAMQS (2010)]

Strong $\psi(2S)$ suppression relative to J/ψ

[Ma, Venugopalan, KW, Zhang (2017)]





[Collins-Soper-Sterman (1985)][Berger, Qiu, Wang (2005)][Sun, Yuan, Yuan (2012)]
Heavy quark pair production with soft gluon emissions:

$$\frac{d\sigma^{\mathrm{pp}\to q\bar{q}+X}}{d^2P_\perp dy} = \int e \frac{d^2b_\perp}{(2\pi)^2} e^{iP_\perp\cdot b_\perp} \underbrace{W(M, b_\perp, x_1, x_2)}_{\text{resum}} + \underbrace{(d\sigma_{\mathrm{perp}} - d\sigma_{\mathrm{asy}})}_{\text{Y-term}}$$

where W satisfies $\frac{\partial}{\partial \ln Q^2} W = [K+G]W$: resummation of the large logs. It can be written as $W(M, b_\perp, x_1, x_2) = \sum_{ij} d\hat{\sigma}_{\mathrm{LO}}^{ij\to q\bar{q}} W_{ij}(M, b_\perp) e^{-S_{ij}(M, b_\perp)}$ with

$$\begin{cases} W_{ij}(M, b_\perp) = \sum_{a,b} \int \frac{d\xi}{\xi} \frac{d\xi'}{\xi'} C_{a\to i}\left(\frac{x_A}{\xi}\right) C_{b\to j}\left(\frac{x_B}{\xi'}\right) \underbrace{\phi_{a/A}(\xi, \mu)\phi_{b/B}(\xi', \mu)}_{\text{collinear-pdfs}} \\ S_{ij}(M, b) = \int_{c_0/b^2}^{M^2} \frac{d\mu^2}{\mu^2} \left[A_{ij} \ln\left(\frac{M^2}{\mu^2}\right) + B_{ij}\right] \end{cases}$$

A, B, C are calculated perturbatively.

Nonperturbative form factor

- CSS type extrapolation

$$W(M, b_\perp) = W^{\text{perp}}(M, b_\star) F^{\text{NP}}(M, b_\perp)$$

with $b_\star = \frac{b}{\sqrt{1+(b/b_{\text{max}})^2}} < b_{\text{max}} = 0.5\ \text{GeV}^{-1}$.

✓ NP form factor at $b > b_{max}$:for example, [Sun, Yuan, Yuan (2012)]

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

g_1, g_2, g_3 are obtained by data fitting.

- Matching type extrapolation [Qiu, Zhang (2001)]

$$W(M, b_\perp) = \begin{cases} W^{\text{perp}}(M, b_\perp) & b_\perp \le b_{\text{max}} \\ W^{\text{perp}}(M, b_{\text{max}}) F^{\text{NP}}(M, b_\perp; b_{\text{max}}) & b_\perp > b_{\text{max}} \end{cases}$$

✓ NP form factor at $b_\perp > b_{\text{max}}$

$$F^{\text{NP}}(b_\perp, M) = \exp\left[-\ln\left(\frac{M^2 b_{\text{max}}^2}{c^2}\right)\left[g_1((b_\perp^2)^\alpha - (b_{\text{max}}^2)^\alpha) + g_2(b_\perp^2 - b_{\text{max}}^2)\right] - \bar{g}_2(b_\perp^2 - b_{\text{max}}^2)\right]$$

g_1, α are obtained by connecting W^{perp} and F^{NP} smoothly at $b_\perp = b_{\text{max}}$. g_2, $\bar{g}_2$ are obtained from data fitting.

Υ production in TMD framework

[Qiu, KW (2017)]