Onium production in p+A collisions and gluon saturation

Kazuhiro Watanabe

Old Dominion Univ / Jefferson Lab

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with Y.-Q. Ma (Peking U), R. Venugopalan (BNL), H.-F. Zhang (Third Medical U)
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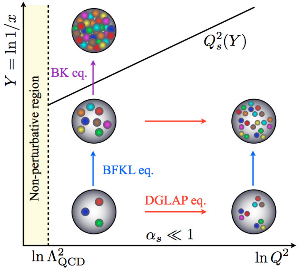
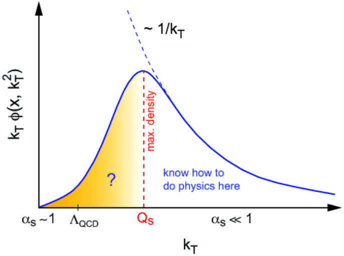
Probing gluon saturation



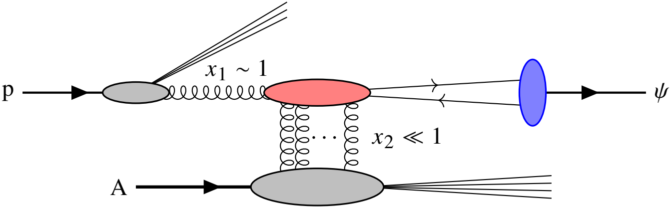


- Gluon recombination at small-x → Glauon Saturation [Gribov, Levin, Ryskin (1983)][Mueller, Qiu(1986)]
- NONLINEAR Balitsky-Kovchegov equation descries x-evolution of gluon distribution. [Balitsky(1996), Kovchegov(1996)]
- A def of Saturation scale

$$Q^2_{s,A}(x) = \frac{\alpha_s N_c}{S_{A\perp}} x G_A(x) \sim A^{1/3} \left(\frac{1}{x}\right)^{0.3}$$

- $Q > Q_s$: the dilute regime in which collinear factorization is applicable.
- $Q < Q_s$: the dense regime ⇒ the Color-Glass-Condensate (CGC) framework

Forward onium production in p+A collisions



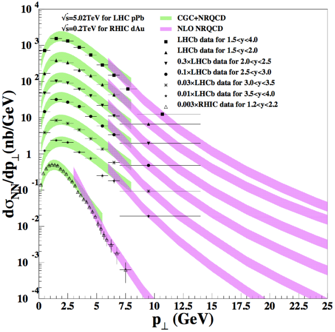
- Onium (J/ψ, $\psi(2S)$) production in p+A collisions at RHIC and the LHC provides unique playground to study gluon saturation or test the CGC framework.
  - ✓ $c\bar{c}$ is largely produced via initial gluon fusion.
  - ✓ The largest saturation scale for nuclei at the energy frontier : $m_c < Q_{sA}$
- The CGC can be helpful in understanding of Onium production mechanism at low-$P_\perp$
- Gluon saturation is Cold Nuclear Matter (CNM) effect. → Baseline for A+A collisions
- e+A at JLab or BNL : Not yet, but promising! p+A can be complementary to e+A.

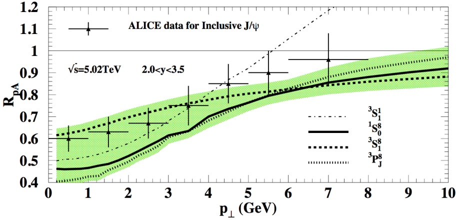
J/ψ production in the CGC + NRQCD

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

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

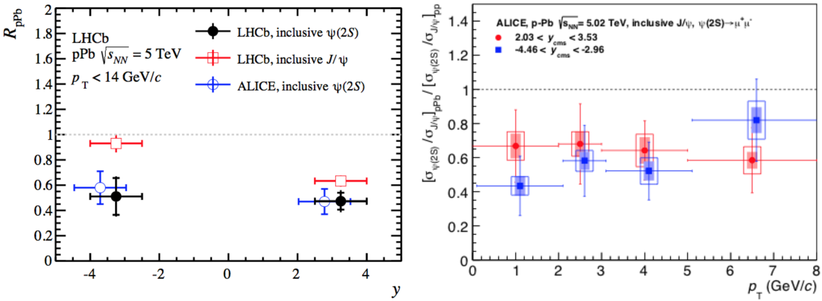
$$d\sigma^{H}_{pA} = \sum_{\kappa} \underbrace{d\hat{\sigma}^{\kappa}_{pA}}_{\text{CGC}} \times \underbrace{\langle \mathcal{O}^{H}_{\kappa} \rangle}_{\text{LDMEs}}$$





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

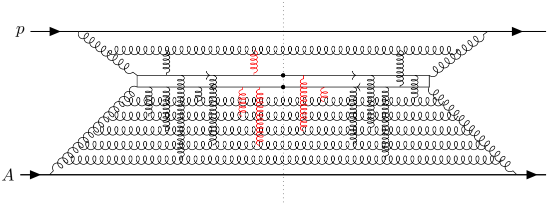
$\psi(2S)$ production : A puzzle



- $c\bar{c}$ produced at short distance $t_c \gtrsim 1/2m \sim 0.07$ fm does not know yet long distance information.
- The saturation effect is short distance physics at t_c and $M_{J/\psi} \sim M_{\psi(2S)} \Rightarrow$ The CGC frameowork predicts $R_{pA}^{J/\psi} \sim R_{pA}^{\psi(2S)}$.
- The large suppression of $\psi(2S)$ production in p+A at both RHIC and the LHC has widely been interpreted as arising from final state interactions with hadron comovers. see [Ferreiro (2015)]
- We shall argue this from an aspect of factorization breaking effect in the Onium formation.

Factorization breaking effect

- In the very forward rapidity region,bound state formation can happen far outside of nucleus. [Sun, Qiu, Xiao, Yuan (2013)]
- However, must be careful at low $P_\perp$ because soft color exchanges between spectators and $c\bar{c}$ pair is indispensable. $\Longrightarrow$ Breaking of factorization [Brodsky, Mueller (1988)]



- Indeed, soft color exchanges between partonic comovers and the $c\bar{c}$ can affect greatly $\psi(2S)$ production. $\Longrightarrow$ The strong nuclear suppression of $\psi(2S)$ at the LHC. (Later)

Next : We examine how the factorization breaking effect with soft color exchange affects J/ψ and $\psi(2S)$ production.

- Description of $\psi(2S)$ production is not clear in the CGC+NRQCD. Large uncertainties in association with charm mass and LDMEs. See [Ma, Venugopalan (2014)]
- We employ an Improved version of CEM (ICEM). [Ma, Vogt (2016)], See also Vogt's talk (Wed.)
  - The CGC+CEM is consistent with the CGC+NRQCD in the sense that color octet $c\bar{c}$ is mainly considered.
  - ICEM can reproduce different $P_\perp$ distributions of J/ψ and $\psi(2S)$ correctly.

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

where

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d^2q_\perp d^2p_\perp dy_q dy_p} = \frac{\alpha_s^2}{64\pi^6 C_F}\int \frac{d^2k_{2\perp}d^2k_\perp}{(2\pi)^4}\frac{\Xi(k_{1\perp},k_{2\perp},k_\perp)}{k_{1\perp}^2 k_{2\perp}^2}\,\varphi_{\mathrm{p},x_1}(k_{1\perp})\,\phi_{A,x_2}(k_{2\perp},k_\perp)\,.$$

with

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

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

Rapidity dependence of the dipole amplitude F_x follows the running coupling BK eq.

Setup of our approach

- $m = 1.3$ GeV, fixed coupling $\alpha_s(Q_0)$
- Matching between φ and CTEQ6M at $x = 0.01$ gives $R_p \sim 0.43$ fm, $Q_0 \sim 8.1$ GeV. R_A is chosen to reproduce $R_{pA} = 1$ when $p_\perp \to \infty$.
- Initial saturation scales : $Q^2_{sp,0}$ is chosen as MV model, $Q^2_{sA,0} = (1.5-2)Q^2_{sp,0}$.
- φ at large-x (forward rapidity) : matching to collinear PDF xG and switch from φ to xG at $x = x_0$.

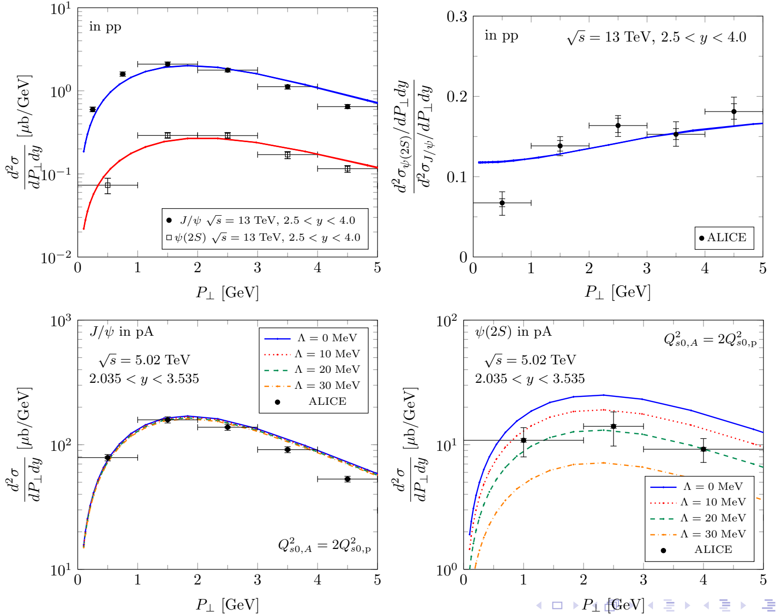
- In p+p collisions, $F_{q\bar{q}\to\psi}$ is fitted and should include the effect of soft color exchanges at final stage.
- Important assumption : the role of soft color exchanges should be enhanced in p+A collisions. $\rightarrow$ Λ is responsible for the nuclear enhancement effect.

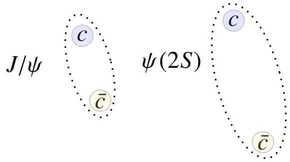
$$\frac{d\sigma_\psi}{d^2P_\perp dy} = F_{q\bar{q}\to\psi}\int_{m_\psi}^{2m_Q-\Lambda} dM\left(\frac{M}{m_\psi}\right)^2 \frac{d\sigma_{q\bar{q}}}{dMd^2P'_\perp dy}\bigg|_{P'_\perp=\frac{M}{m_\psi}P_\perp}$$

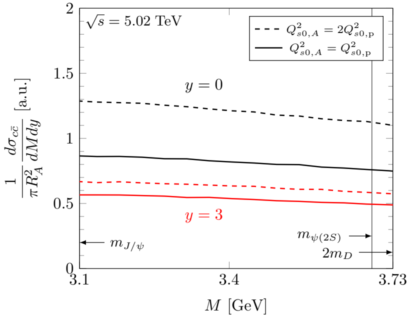
where Λ denotes the average momentum kick given by additional nuclear parton comovers.

- For simplicity, we assume that Λ is independent of $P_\perp$ and y.

$P_\perp$ spectra of J/ψ and $\psi(2S)$ in p+p/p+A



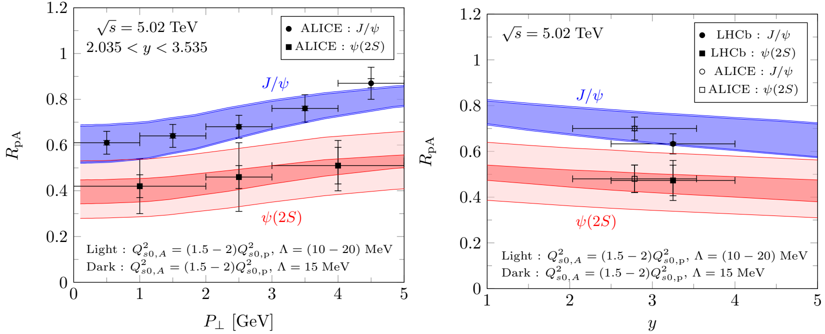




- The fact that $\psi(2S)$ is more massive object is not important.
- The phase space of the produced $c\bar{c}$ pair is limited to lie within the narrow range for $\psi(2S)$. For J/ψ production, the $c\bar{c}$ pair has a significantly larger phase space.
- Indeed, $\Delta E_{\psi(2S)} = 2m_D - m_{\psi(2S)} \sim 50$ MeV, $\Delta E_{J/\psi} = 2m_D - m_{J/\psi} \sim 650$ MeV.
- Additional soft color exchanges in p+A collisions can break up the $\psi(2S)$ by providing the energy to push the bound Onia over the $D\bar{D}$ decay threshold.

Nuclear modification factors for J/ψ and $\psi(2S)$

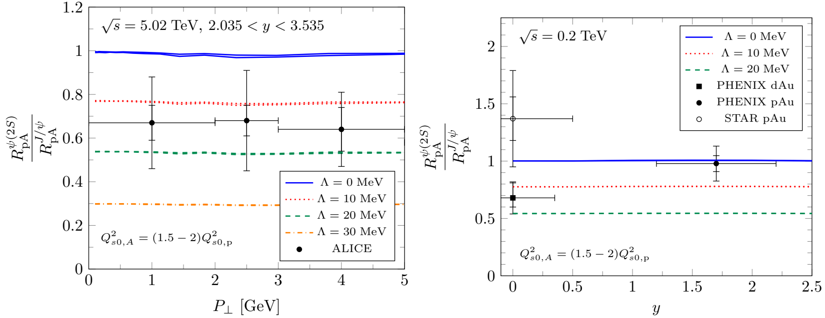
[Ma, Venugopalan, KW, Zhang (2017)]



- The factorization breaking effect clearly leads to a stronger $\psi(2S)$ suppression while it is negligible for J/ψ.
- The enhanced soft color exchanges in p+A are sufficient to explain the data.

Double ratio

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



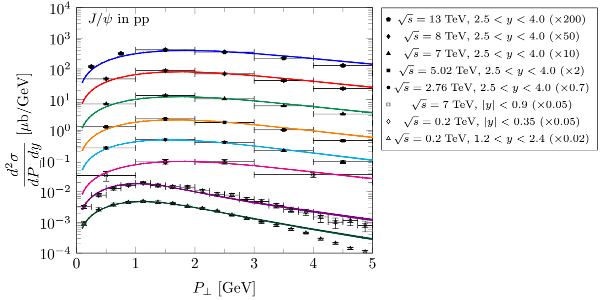
- Advantage of the double ratio : many systematic uncertainties including Q^2_{sA} can cancel.
- The suppression of the double ratio can be controlled by Λ alone clearly.
- The relative factorization breaking effect is seen at the LHC but it is ambiguous at RHIC.

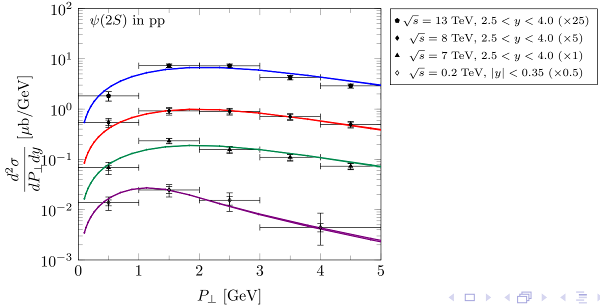
Summary

- Onium production in p+A collisions provides unique opportunity to study gluon saturation phenomena inside high energy hadron/nucleus.
- We need careful calculations since there are soft color exchanges between partonic comover spectator and $c\bar{c}$.
- The CGC+ICEM can provide a systematic description of J/ψ and $\psi(2S)$ production in p+p collisions.
- Recent data of R_{pA} for Onia production at the LHC suggest that factorization breaking effect associated with nuclear enhanced soft color exchanges is significant for $\psi(2S)$ but not so much striking for J/ψ.

Thank you!

$P_\perp$ spectra





Predictions at RHIC