# Heavy quark(onium) production in the high energy limit

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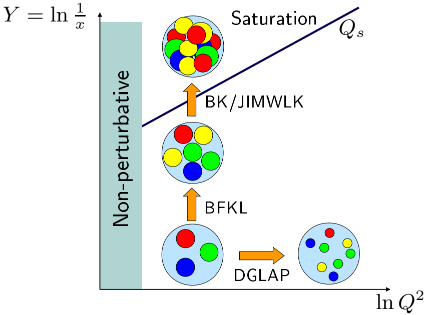
The high energy limit of QCD should be described by the BK/JIMWLK equation

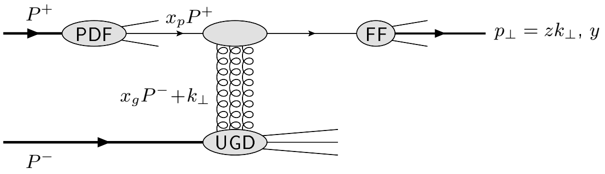



Forward heavy quark(onium) production in high energy proton-nucleus collisions can be a useful probe of these dynamics:

- Probes very small values of $x$: down to $x \sim 10^{-6}$ at the LHC
- Heavy quark mass should provide a hard scale $\rightarrow$ perturbative calculation
- Experimental data to compare with
- Quarkonium suppression possible probe of QGP in AA collisions: need to understand cold nuclear matter effects in pA collisions first

- A projectile probing a hadron at very small $x$ can acquire some transverse momentum from the target via multiple scatterings
- In this case $2 \to 1$ kinematics with non-zero final $p_T$ are allowed
- The saturation scale $Q_s$ of the target corresponds to the typical transverse momentum than can be acquired by the projectile
- $Q_s$ increases when $x$ gets smaller
- At high $p_\perp \gg Q_s$ collinear calculation should give the correct description
- Description of the dense target in terms of classical color fields: 'color glass condensate' (CGC)

Simple example: single inclusive hadron production

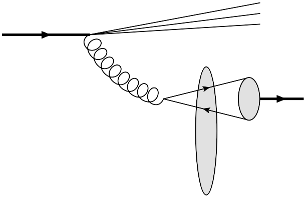


The hadronization of $c\bar{c}$ ($b\bar{b}$) pairs into $J/\psi$ ($\Upsilon$) mesons is not well understood already in proton-proton collisions

Hadronization long-range mechanism: should not be modified in proton-nucleus collisions $\to$ study the nuclear modification factor

$$R_{\mathsf{pA}} = \frac{\sigma^{\mathsf{pA}}}{A \times \sigma^{\mathsf{pp}}}$$

CGC calculation: a large $x$ gluon from the dilute projectile can split into a heavy quark-antiquark pair either before or after the interaction with the dense target



The $x$ values probed in the projectile and the target are $x_{1,2} = \frac{\sqrt{P_\perp^2 + M^2}}{\sqrt{s}} e^{\pm Y}$

Hadronization model 1: Color Evaporation Model (CEM)

Simple assumption: a fixed fraction of all $c\bar{c}$ pairs produced below the $D$-meson mass threshold are assumed to hadronize into $J/\psi$ mesons

$$\frac{\mathrm{d}\sigma_{J/\psi}}{\mathrm{d}^2\mathbf{P}_\perp \mathrm{d}Y} = F_{J/\psi} \int_{4m_c^2}^{4M_D^2} \mathrm{d}M^2 \frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}^2\mathbf{P}_\perp \mathrm{d}M^2 \mathrm{d}Y}$$

where we have summed over spins and colors of the $c\bar{c}$ pair, $M$ is the invariant mass of the pair and $F_{J/\psi}$ is a non-perturbative constant which cancels in $R_{\mathrm{pA}}$

$\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}^2\mathbf{P}_\perp \mathrm{d}M^2 \mathrm{d}Y}$ in the CGC framework: Blaizot, Gelis, Venugopalan

## Hadronization model 2: Non-relativistic QCD (NRQCD)

Systematic expansion in powers of $v$, the relative velocity of the heavy quark pair in the bound state. The quarkonium production cross section is

$$\mathrm{d}\sigma_H = \sum_{\kappa} \mathrm{d}\hat{\sigma}^{\kappa} \langle \mathcal{O}_{\kappa}^{H} \rangle$$

where $\mathrm{d}\hat{\sigma}^{\kappa}$ is the cross section for the production of a heavy quark pair with given quantum numbers $\kappa = {}^{2S+1}L_J^{[C]}$, computed perturbatively by applying projection operators on the heavy quark pair production amplitude

$\langle \mathcal{O}_{\kappa}^{H} \rangle$ are universal non-perturbative long distance matrix elements (LDME) which can be extracted from data

Contributing states for $J/\psi$ and $\Upsilon$ production: ${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$
${}^3S_1^{[1]}$ is leading power in $v$ but suppressed by powers of $p_\perp$ compared to the others

Simplest case: color evaporation model in the large $N_c$ limit and collinear approximation on the proton side (justified at forward rapidity since $x_1 = \frac{\sqrt{P_\perp^2+M^2}}{\sqrt{s}} e^Y$ is not small):

$$\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}^2\mathbf{p}_T \mathrm{d}^2\mathbf{q}_T \mathrm{d}y_p \mathrm{d}y_q} = \frac{\alpha_s^2 N_c}{8\pi^2 d_A} \frac{1}{(2\pi)^2} \int_{\boldsymbol{k}_\perp} \frac{\Xi_{\rm coll}(\mathbf{p}_T+\mathbf{q}_T, \boldsymbol{k}_\perp)}{(\mathbf{p}_T+\mathbf{q}_T)^2} \phi^{q\bar{q},g}_{Y=\ln\frac{1}{x_2}}(\mathbf{p}_T+\mathbf{q}_T, \boldsymbol{k}_\perp) x_1 g(x_1, Q^2)$$

with $\phi_Y^{q\bar{q},g}(\mathbf{l}_T, \mathbf{k}_T) = \int \mathrm{d}^2\mathbf{b}_T \frac{N_c\, \mathbf{l}_\perp^2}{4\alpha_s}\, S_Y(\mathbf{k}_T)\, S_Y(\mathbf{l}_T - \mathbf{k}_T)$

The gluon density in the projectile is described by a usual collinear PDF $xg(x)$

The information about the target is contained in $S_Y(\mathbf{k}_T)$, which can be related to its unintegrated gluon distribution and is the Fourier transform of $S_Y(\mathbf{r})$:

$$S_Y(\mathbf{k}_T) = \int \mathrm{d}^2\mathbf{r} e^{i\mathbf{k}_T\cdot\mathbf{r}} S_Y(\mathbf{r})\ , \quad S_Y(\mathbf{r}) = S_Y(\mathbf{x}-\mathbf{y}) = \frac{1}{N_c}\left\langle \mathrm{Tr}\, U^\dagger(\mathbf{x}) U(\mathbf{y})\right\rangle$$

where $U(\mathbf{x})$ is a fundamental representation Wilson line in the target color field

The evolution of $S_Y(\mathbf{r})$ as a function of $Y = \ln \frac{1}{x}$ is governed by the Balitsky-Kovchegov equation:

$$\frac{\partial S_Y(\mathbf{x}-\mathbf{y})}{\partial Y} = \frac{\alpha_s N_c}{2\pi^2} \int \mathrm{d}^2\mathbf{z} \frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{z}-\mathbf{y})^2} \left[ S_Y(\mathbf{x}-\mathbf{z}) S_Y(\mathbf{z}-\mathbf{y}) - S_Y(\mathbf{x}-\mathbf{y}) \right]$$

Given an initial condition for $S$ at some $x_0$, one can solve numerically the BK equation to obtain $S$ at any $x < x_0$

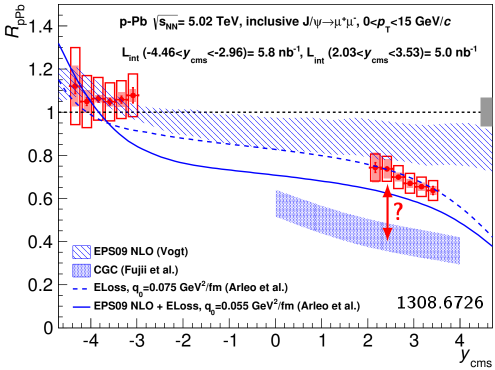
The initial condition involves non-perturbative dynamics and can't be computed

It can be for example obtained by a fit to HERA data for $F_2$ and $F_L$ which can be expressed as functions of $S_Y(\mathbf{r})$ in this formalism

Typical value for $x_0$ in such fits is 0.01

Predictions for $R_{\text{pA}}^{J/\psi} = \sigma^{\text{pA}}/(A \times \sigma^{\text{pp}})$ in pPb collisions at the LHC in the CGC formalism with color evaporation model: Fujii, Watanabe

Measurement of this observable at the LHC by ALICE:




Much smaller suppression than predicted

We will see that some part of this disagreement can be attributed to the lack of constraints on the unintegrated gluon distribution in a nucleus

# Choice of the nucleus initial condition

Initial condition for the BK evolution of the proton (used for the proton-proton reference): fit to HERA DIS data $\rightarrow$ relatively well constrained

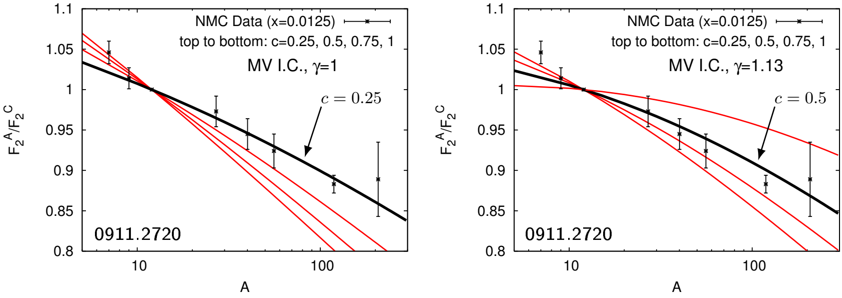
Initial condition for a nucleus target (pA collisions): no accurate enough DIS data to perform a similar fit. Fujii, Watanabe: same initial condition as for a proton but with an initial saturation scale scaled by $A^{1/3}$

Argument: saturation scale related to the typical transverse momentum taken by the projectile from the target. Proton-nucleus collisions: the projectile will see about $A^{1/3}$ nucleons when crossing the nucleus and therefore can pick up a $p_\perp \sim A^{1/3} Q^2_{s0,p}$ (initial condition: rather large $x$ $\rightarrow$ assume independent scatterings)

This is only approximate and neglects nuclear geometry

# Choice of the nucleus initial condition

Fit to NMC data by Dusling, Gelis, Lappi, Venugopalan for $Q^2_{s0,A} = c\,A^{1/3} Q^2_{s0,p}$:
($x \sim 0.01$ close to the initial condition)

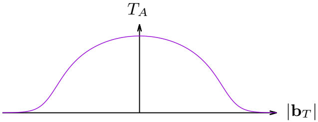



The best fit value for $c$ depends on the exact form of the initial condition parametrization but is always smaller than the naive expectation $c = 1$. For a lead nucleus this corresponds to $Q^2_{s0,Pb} \sim (1.5 - 3)\,Q^2_{s0,p}$

Smaller initial saturation scale: expect less nuclear suppression

Other possible approach to get the initial condition for a nucleus: use of the Glauber model. In this model the nuclear density in the transverse plane is given by the Woods-Saxon distribution $T_A(\mathbf{b}_T)$:

$$T_A(\mathbf{b}_T) = \int dz \frac{n}{1 + \exp\left[\frac{\sqrt{\mathbf{b}_T{}^2 + z^2} - R_A}{d}\right]}$$

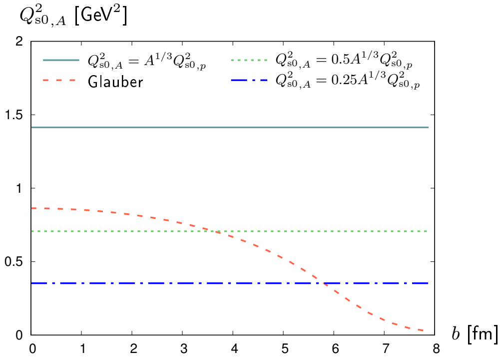



This introduces an impact-parameter dependence for the nucleus initial condition

The standard Woods-Saxon transverse thickness $T_A$ is the only additional input needed to go from a proton to a nucleus target

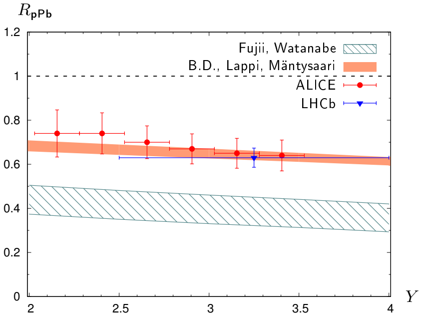
(No need to introduce new parameters for the transverse area of the nucleus or the total inelastic proton-nucleus cross section)

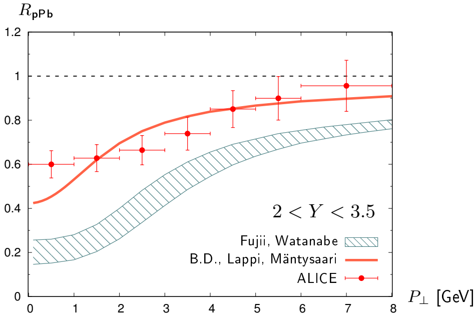
Initial saturation scale at $x_0 = 0.01$ of the lead nucleus in different models:



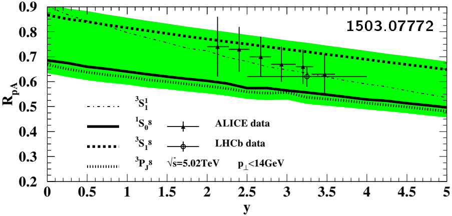

The scaling $Q^2_{s0,A} = A^{1/3} Q^2_{s0,p}$ leads to much larger saturation scales than the optical Glauber model or fits to NMC data $\rightarrow$ more suppression

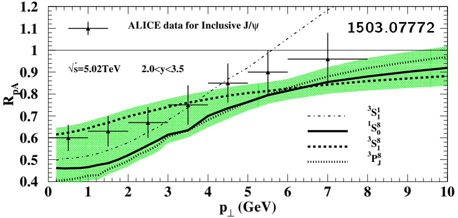
Using the Glauber approach (again with CEM) leads to a much better agreement with experimental data:



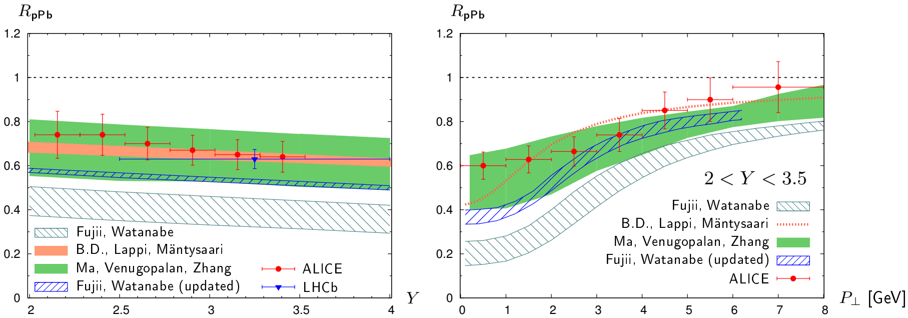
Ma, Venugopalan, Zhang also obtained good agreement with data using $Q^2_{s0,A} = 2\,Q^2_{s0,p}$ with NRQCD hadronization:




The uncertainty band is obtained by taking the envelope of $R_{\mathrm{pA}}$ for each channel (independent of the LDME values) excluding the color singlet channel (small contribution to the cross section, especially at large $P_\perp$)

Summary: forward $J/\psi$ suppression in pPb collisions at the LHC:

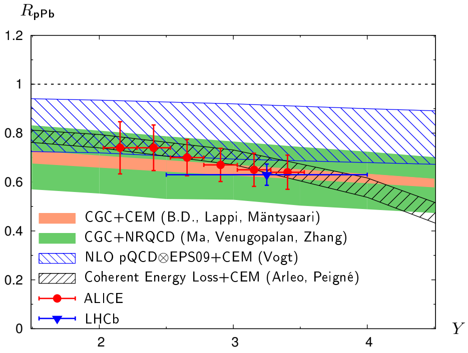



Updated results by Fujii, Watanabe: use $Q^2_{s0,A} = 3\,Q^2_{s0,p}$

Recent calculations quite close to each other and to the data

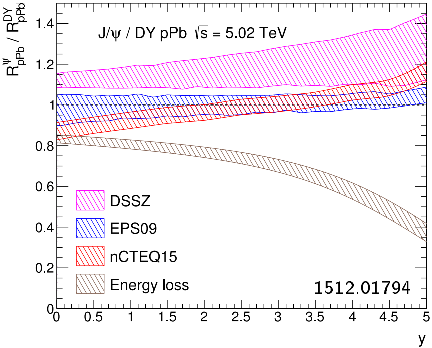
# Comparison with other formalisms

Several calculations in different formalisms are compatible with data within uncertainties :




Apparently not a good observable to discriminate between these approaches

Recent proposal (Arleo, Peigné): study $R_{\text{pA}}^{J/\psi}/R_{\text{pA}}^{\text{DY}}$




The calculations based on nuclear PDFs and coherent energy loss have very different behaviours $\rightarrow$ potential to discriminate between these approaches

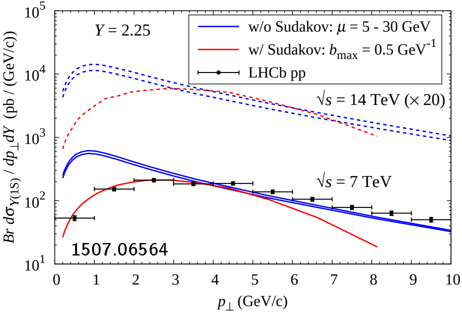
It would be very interesting to compare with results in the CGC formalism

(Maybe $R_{\text{pA}}^{D}/R_{\text{pA}}^{\text{DY}}$ would be cleaner with respect to hadronization)

In the CEM one can in principle compute $\Upsilon$ production in the same way as $J/\psi$ replacing $m_c \to m_b$ and $m_D \to m_B$

However this leads to a bad description of $p_\perp$ spectra at low $P_\perp$

Possible explanation: for heavy states it may be necessary to resum logs of $\frac{M^2}{P_\perp^2}$ (Watanabe, Xiao)

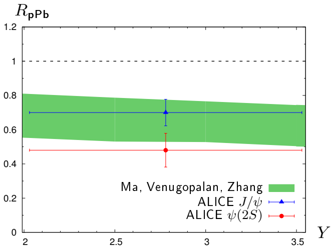


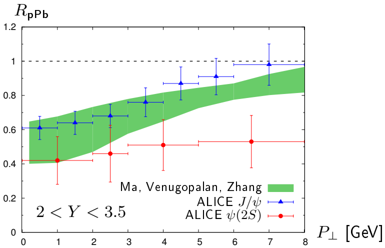

Noticeable improvement in the small $P_\perp$ region where this resummation should be valid

($J/\psi$: smaller mass $\to$ much smaller effect)

ALICE: $R_{\mathrm{pA}}^{\psi(2S)}$ significantly smaller than $R_{\mathrm{pA}}^{J/\psi}$. Can't be explained in the color evaporation model in which the ratio of $\psi(2S)$ and $J/\psi$ is a constant

NRQCD: same color states contributing but with different relative weights $\to$ same uncertainty band as for $J/\psi$

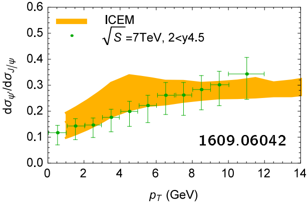



Potential agreement for $R_{\mathrm{pA}}(Y)$ but problems for $R_{\mathrm{pA}}(P_\perp)$

See also improved color evaporation model (Ma, Vogt): can describe $\sigma^{\psi(2S)}/\sigma^{J/\psi}$ in pp collisions in collinear factorization

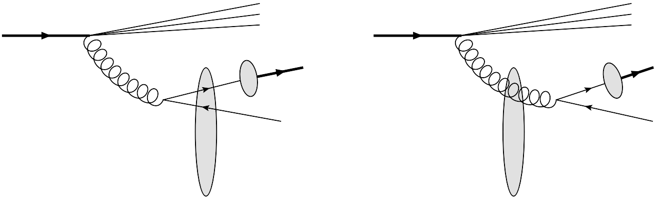
Could also be implemented in CGC



From $\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}^2\mathbf{p}_T \mathrm{d}^2\mathbf{q}_T \mathrm{d}y_p \mathrm{d}y_q}$ one can also compute $D$-meson production:

$$\frac{\mathrm{d}\sigma_{D^0}}{\mathrm{d}^2\mathbf{P}_\perp \mathrm{d}Y} = Br(c \to D^0) \int \frac{\mathrm{d}z}{z^2} D(z) \int \mathrm{d}^2\mathbf{q}_T \, \mathrm{d}y_q \frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}^2\mathbf{p}_T \mathrm{d}^2\mathbf{q}_T \mathrm{d}y_p \mathrm{d}y_q}, \; \mathbf{p}_T = \mathbf{P}_\perp / z, \; y_p = Y$$

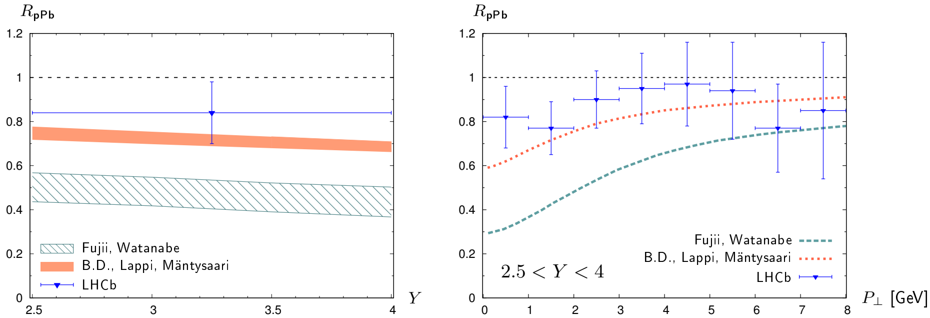
Results in the following use the fragmentation function parametrization from Kartvelishvili, Likhoded, Petrov: $D(z) = (\alpha+1)(\alpha+2)z^\alpha(1-z)$



From the point of view of saturation this process is not as clean as $J/\psi$ production since the $x$ values probed in the projectile and target are not bounded:

$$x_{1,2} = \frac{\sqrt{m_c^2 + p_T^2}}{\sqrt{s}} e^{\pm y_p} + \frac{\sqrt{m_c^2 + q_T^2}}{\sqrt{s}} e^{\pm y_q}$$

Similar conclusions as for $J/\psi$: predictions by Fujii, Watanabe using $Q^2_{s0,A} = A^{1/3} Q^2_{s0,p}$ leads to strong suppression. Glauber model: less suppression, better agreement with data




Experimental uncertainties still quite large, only one bin in rapidity

- Forward heavy quark(onium) production at high energies probes very small values of $x$ $\rightarrow$ study of the saturation regime
- Hadronization mechanism not well understood
  The study of $R_{\mathrm{pA}}$ can partially alleviate this problem
- First CGC calculation: used $Q^2_{\mathrm{s}0,A} = A^{1/3} Q^2_{\mathrm{s}0,p}$
  $\rightarrow$ too strong suppression compared to data
- More recent calculations: initial condition for the BK evolution of the nucleus more consistent with other observables
  $\rightarrow$ less suppression, much better agreement with data
- Different suppression of excited states difficult to explain even in NRQCD

# Prospects

- Better constraints for the nucleus initial condition could come from accurate nuclear DIS data (EIC)

- The CGC calculations shown are still performed at leading order accuracy, resumming terms proportional to $(\alpha_s \ln 1/x)^n$
  The extension of this framework to NLO, which is necessary to have more reliable predictions, is being worked on

- Several formalisms (nPDFs, coherent energy loss, CGC) can reproduce experimental data for $R_{\mathsf{pA}}^{J/\psi}$ at forward rapidity
  The study of $R_{\mathsf{pA}}^{J/\psi}/R_{\mathsf{pA}}^{\mathsf{DY}}$ (or $R_{\mathsf{pA}}^{D}/R_{\mathsf{pA}}^{\mathsf{DY}}$) could help to discriminate between these approaches