Forward J/ψ production in high energy proton-nucleus collisions

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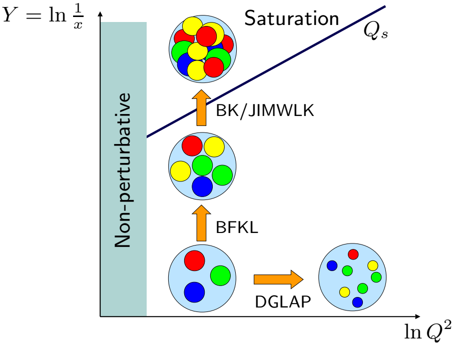
B. D., T. Lappi, H. Mäntysaari, Phys. Rev. D **91** (2015) 114005 [arXiv:1503.02789 [hep-ph]]

Motivations

Our goal is to study QCD in the saturation regime



The production of forward particles is a crucial tool to probe small x values

J/ψ: clean experimental signature $\rightarrow$ lots of data in pp and pA collisions

The mass of the J/ψ provides a hard scale $\rightarrow$ perturbative calculation

Saturation effects should be enhanced by the higher densities in pA collisions

Formalism

We use the color glass condensate (CGC) effective theory to compute the production of forward J/ψ in pp and pA collisions at the LHC

Forward rapidity: large rapidity of the produced J/ψ means:

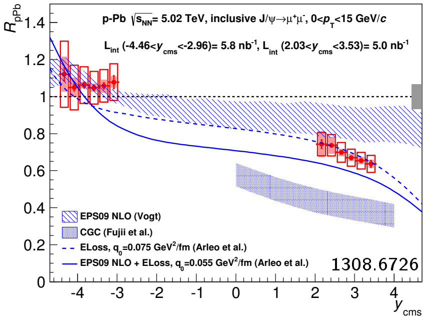
- large x probed in the projectile → use of collinear approximation (PDF) for the proton moving in the $+$ direction
- small x probed in the target moving in the $-$ direction → description in terms of unintegrated gluon distribution

The nuclear modification factor is the usual observable to study nuclear effects

$$R_{\mathrm{pA}} = \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{J}/\psi}/\mathrm{d}^2P_\perp \mathrm{d}y\big|_{\mathrm{pA}}}{\mathrm{d}\sigma_{\mathrm{J}/\psi}/\mathrm{d}^2P_\perp \mathrm{d}y\big|_{\mathrm{pp}}}$$

In this ratio the uncertainties common to pp and pA collisions cancel

First predictions for R_{pA} at the LHC in the CGC formalism: Fujii, Watanabe



Much stronger suppression than observed later in LHC data

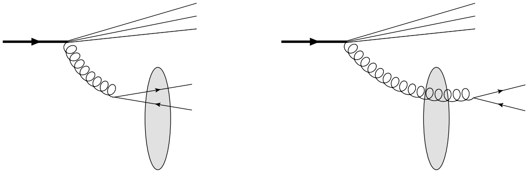
As we will see some part of this disagreement can be attributed to the lack of constraints on the unintegrated gluon distribution in a nucleus

We use the simple color evaporation model (CEM) to get the J/ψ cross section from the cross section for the production of a $c\bar{c}$ pair. In this model we have

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

where M is the invariant mass of the $c\bar{c}$ pair and $F_{\mathsf{J}/\psi}$ is a non-perturbative constant which has to be extracted from data

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



Taking the collinear limit for the projectile proton leads to

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

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

All the information about the target is contained in the unintegrated gluon distribution $S_Y(\mathbf{k}_T)$, which is the Fourier transform of the dipole correlator $S_Y(\mathbf{r}_T)$:

$$S_Y(\mathbf{x}_T - \mathbf{y}_T) = \frac{1}{N_c} \left\langle \mathrm{Tr}\, U^\dagger(\mathbf{x}_T) U(\mathbf{y}_T) \right\rangle$$

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

The evolution of $S_Y(\mathbf{r}_T)$ is governed by the Balitsky-Kovchegov equation which can be solved numerically. However the initial condition for the evolution is non-perturbative and has to be constrained by experimental data.

A possible parametrization for a proton target is

$$S_{Y_0}(\mathbf{r}_T) = \exp\left[-\frac{(\mathbf{r}_T{}^2 Q_{s0}^2)^\gamma}{4} \ln\left(\frac{1}{|\mathbf{r}_T|\Lambda_{\mathrm{QCD}}} + e_c \cdot e\right)\right]$$

And in $\phi_Y^{q\bar{q},g}(\mathbf{l}_T, \mathbf{k}_T)$ we make the replacement $\int \mathrm{d}^2\mathbf{b}_T \to \frac{\sigma_0}{2}$

Here we use the 'MV^e' fit to HERA data (Lappi, Mäntysaari)

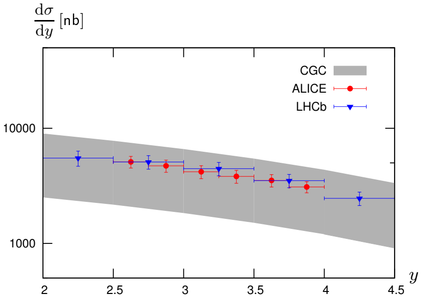
Model	χ^2/d.o.f	Q_{s0}^2 [GeV^2]	Q_s^2 [GeV^2]	γ	e_c	$\sigma_0/2$ [mb]
MV	2.76	0.104	0.139	1	1	18.81
MV$^\gamma$	1.17	0.165	0.245	1.135	1	16.45
MV^e	1.15	0.060	0.238	1	18.9	16.36

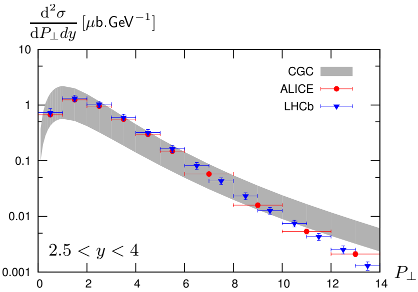
The MV$^\gamma$ parametrization is similar to the AAMQS one (Albacete et al.)

One advantage of MV^e is that $S_Y(\mathbf{k}_T)$ is positive definite

In practice, our results for LHC energies are not very sensitive to the exact form of the initial condition

Cross section as a function of y and $P_\perp$





The shape of the data is quite well described but the uncertainty on the normalization is quite large
(error band : variation of the charm quark mass and the factorization scale)

At large $P_\perp$ the calculation predicts a too large cross section

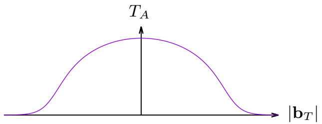
The initial condition to the Balitsky-Kovchegov equation that we used for the proton is obtained by a fit to HERA DIS data

There is no such precise data for eA collisions $\to$ the unintegrated gluon distribution in a nucleus is not well constrained

In their work, Fujii, Watanabe used the same initial condition as for a proton target, with $Q^2_{s0,A} \sim A^{1/3} Q^2_{s0,p}$ which is the expected asymptotic scaling (in practice: use $Q^2_{s0,A} = c\, Q^2_{s0,p}$ and vary c between 4 and 6)

By contrast, here we use the optical Glauber model to generalize this initial condition to a nucleus target. In this model the nuclear density in the transverse plane is given by the Woods-Saxon distribution $T_A(\mathbf{b}_T)$:

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



The initial condition in this model is

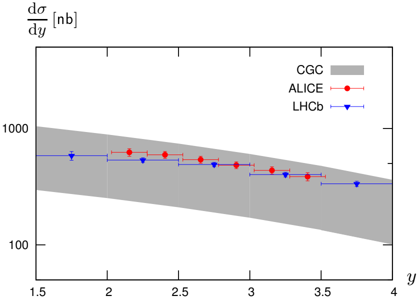
$$S^{A}_{Y_0}(\mathbf{r}_T, \mathbf{b}_T) = \exp\left[-A\, T_A(\mathbf{b}_T)\frac{\sigma_0}{2}\frac{({\mathbf{r}_T}^2 Q_{s0}^2)^\gamma}{4}\ln\left(\frac{1}{|\mathbf{r}_T|\Lambda_{\mathrm{QCD}}} + e_c \cdot e\right)\right]$$

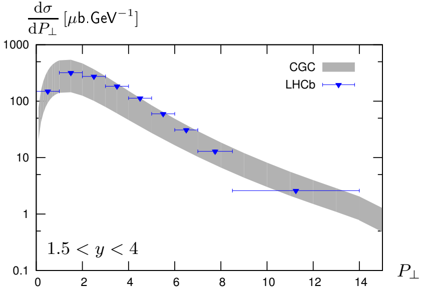
And we integrate explicitly over $\mathbf{b}_T$
(recall that $\phi_Y^{q\bar{q},g}(\mathbf{l}_T, \mathbf{k}_T) = \int \mathrm{d}^2\mathbf{b}_T \frac{N_c \, {}^2_\perp}{4\alpha_s}\, S_Y(\mathbf{k}_T)\, S_Y(\mathbf{l}_T - \mathbf{k}_T)$)

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

On average this leads to smaller saturation scales than in the work by Fujii, Watanabe $\rightarrow$ we expect that the nuclear suppression will be smaller

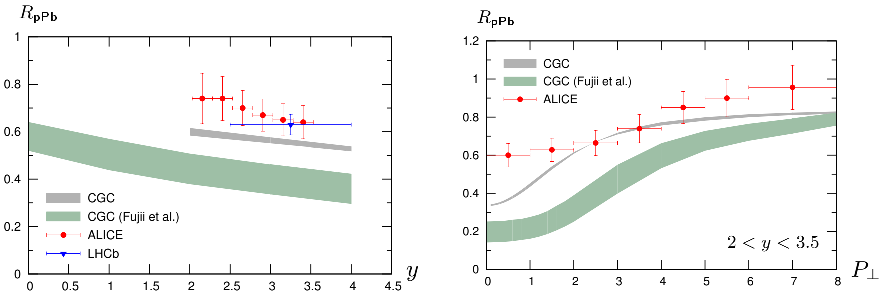
Cross section as a function of y and $P_\perp$





As in the pp case, the shape of the data is quite well described but the uncertainty on the normalization is quite large

R_{pA} as a function of y and $P_\perp$



The uncertainty is much smaller than for the (pp or pA) cross section

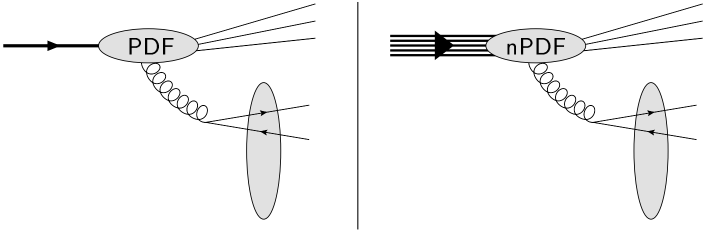
The results are closer to data than previous estimate by Fujii, Watanabe

R_{pA} is still slightly too small to describe experimental data (low $P_\perp$ region)

J/ψ suppression has also been measured at backward rapidity at the LHC

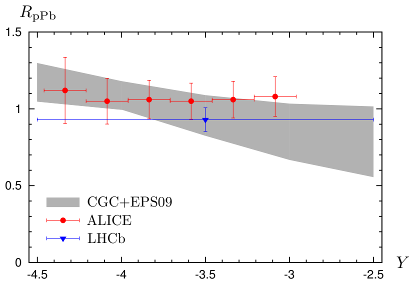
Here the nucleus is probed at large x while the proton is probed at small x

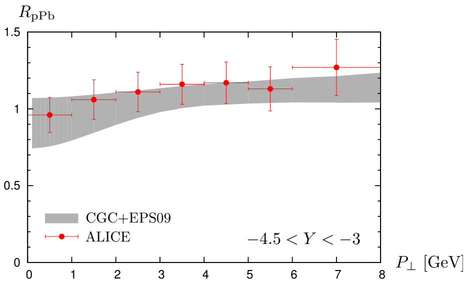
We compute this by exchanging the roles of the proton and the nucleus: the nucleus is described by a collinear (nuclear) PDF while the proton is described by an unintegrated gluon distribution



Results: backward rapidity

In practice we use the EPS09 (Eskola, Paukkunen, Salgado) nPDF set for the collinear gluon density in the nucleus





Nuclear effects come from nPDFs probed at $x = \frac{\sqrt{p_T^2 + M^2}}{\sqrt{s}} e^{-Y}$ and $Q = \sqrt{p_T^2 + M^2}$ with $\langle p_T \rangle \sim 2$ GeV

The calculation agrees with the data but the uncertainty is quite large

This uncertainty is due to a large extent to the variation of Q between $\frac{1}{2}\sqrt{p_T^2 + M^2}$ and $2\sqrt{p_T^2 + M^2}$. In particular $\frac{1}{2}\sqrt{p_T^2 + M^2} \sim 1.8$ GeV: quite small

Results: centrality

Recently ALICE measured R_{pA} in different centrality classes

Centrality class: the $(0-c)\%$ most central collisions give $c\%$ of the total inelastic proton-nucleus cross section

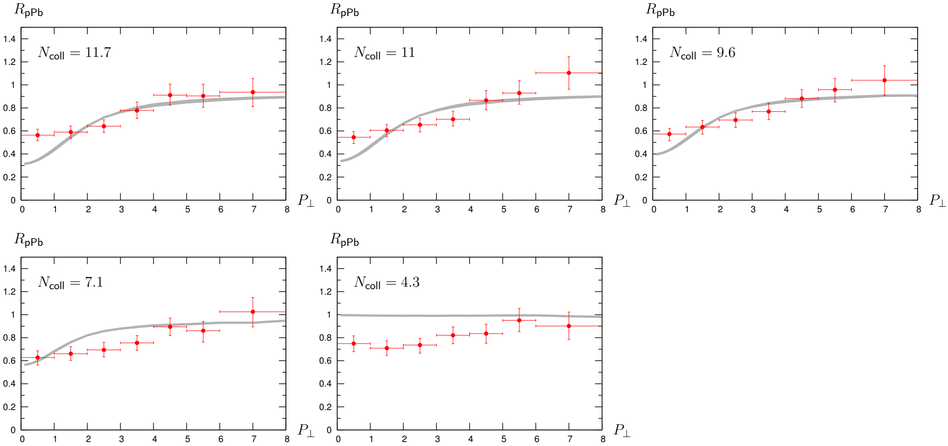
Optical Glauber model: relation between centrality, impact parameter and number of binary collisions

Centrality class	$\langle N_{\mathrm{coll}}\rangle_{\mathrm{opt.\ Glauber}}$	$\langle N_{\mathrm{coll}}\rangle_{\mathrm{ALICE}}$
2–10%	14.7	$11.7 \pm 1.2 \pm 0.9$
10–20%	13.6	$11.0 \pm 0.4 \pm 0.9$
20–40%	11.4	$9.6 \pm 0.2 \pm 0.8$
40–60%	7.7	$7.1 \pm 0.3 \pm 0.6$
60–80%	3.7	$4.3 \pm 0.3 \pm 0.3$
80–100%	1.5	$2.1 \pm 0.1 \pm 0.2$

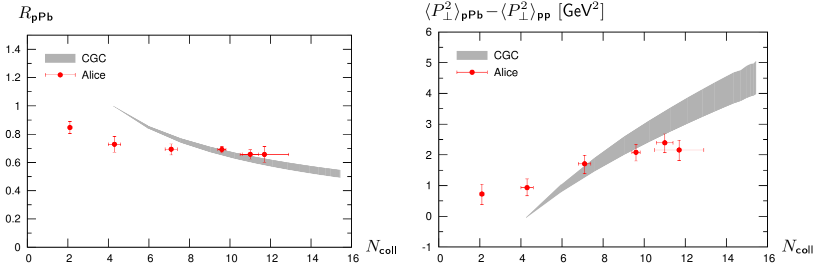
The values of $\langle N_{\mathrm{coll}}\rangle$ obtained with the optical Glauber model differ from those extracted by ALICE

In the following we compute observables at fixed values of $|\mathbf{b}_T|$ corresponding to $N_{\mathrm{coll,\ opt.\ Glauber}} = \langle N_{\mathrm{coll}}\rangle_{\mathrm{ALICE}}$

R_{pA} as a function of $P_\perp$



R_{pA} and $P_\perp$-broadening as a function of N_{coll}



Not too bad agreement for central collisions but the slope predicted is too steep

Problematic results for peripheral collisions

Note that in our calculation N_{coll} is fixed while for ALICE data it is actually $\langle N_{\mathsf{coll}}\rangle$ in each bin. For a more consistent comparison we would need to have access to the N_{coll} distributions at experiments

Conclusions

We have studied forward J/ψ production in pp and pA collisions at the LHC

For absolute cross sections:

- Large normalization uncertainty
- Shape is consistent with data

For ratios such as R_{pA}:

- No parameters specific to this process are needed
- Optical Glauber model to go from pp to pA:
  - Only new input is the standard Woods-Saxon distribution
  - Better agreement with minimum bias data than previous works
  - Access to centrality dependent observables

    reasonable agreement with data for not too peripheral collisions

Some additional effects to be investigated:

- Hadronization
- Treatment of the edge of the nucleus
- Consistency with centrality determination in experiments