Forward J/ψ production in pA collisions at the LHC

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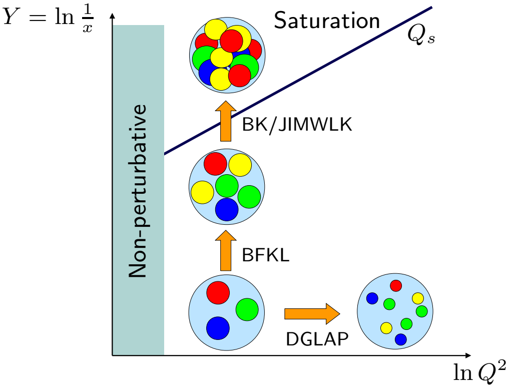
B. D., T. Lappi, H. Mäntysaari, Phys. Rev. D **91** (2015) 114005 [arXiv:1503.02789 [hep-ph]]

Motivations

We want to study QCD in the saturation regime



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

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

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

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 $\to$ use of collinear approximation (PDF) for the proton moving in the $+$ direction
- small x probed in the target moving in the $-$ direction

CGC: the dense target (proton at small x or nucleus) is described in terms of classical color sources

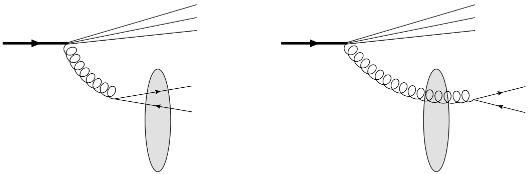
This process was already studied in this framework by Fujii, Watanabe. The main differences here are the parametrization of the initial condition of the BK equation and the treatment of the nuclear geometry

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

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

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

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

All the information about the target is contained in the function $S_Y(\mathbf{k}_T)$, 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 but for this one needs an initial condition. A possible parametrization for a proton target is

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

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

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

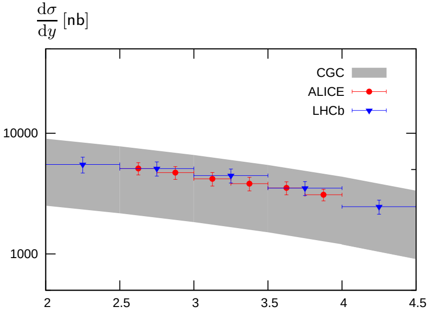
The MV$^\gamma$ parametrization is similar to AAMQS (Albacete et al.)

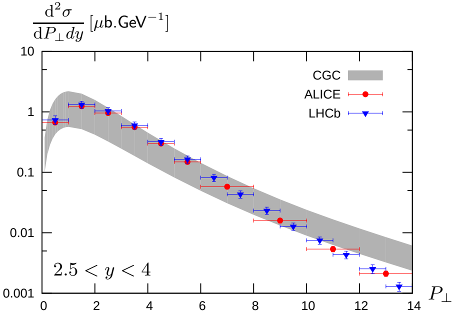
One advantage of MV^e is that $S_Y(\mathbf{k}_T)$ is positive definite

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

Results: proton-proton collisions ($\sqrt{s} = 7$ TeV)

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)

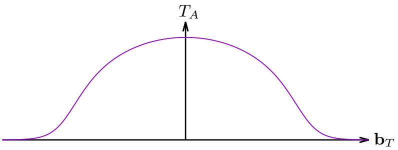
At large $P_\perp$ the calculation predicts a too large cross section

From HERA data we can extract the initial condition for a proton target

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

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



The initial condition in this model is then

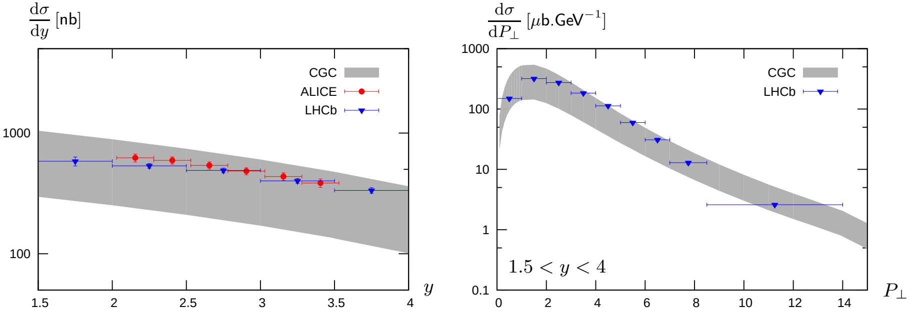
$$S^{A}_{Y_0}(\mathbf{r}_T,\mathbf{b}_T)=\exp\left[-A\,T_A(\mathbf{b}_T)\frac{\sigma_0}{2}\frac{(\mathbf{r}_T{}^2Q^2_{s0})^{\gamma}}{4}\ln\left(\frac{1}{|\mathbf{r}_T|\Lambda_{\mathrm{QCD}}}+e_c\cdot e\right)\right]$$

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 used to go from a proton to a nucleus target

This is in contrast with the work of Fujii, Watanabe where the same initial condition as for a proton target is used but with $Q^2_{s0,A}\sim A^{1/3}Q^2_{s0,p}$

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

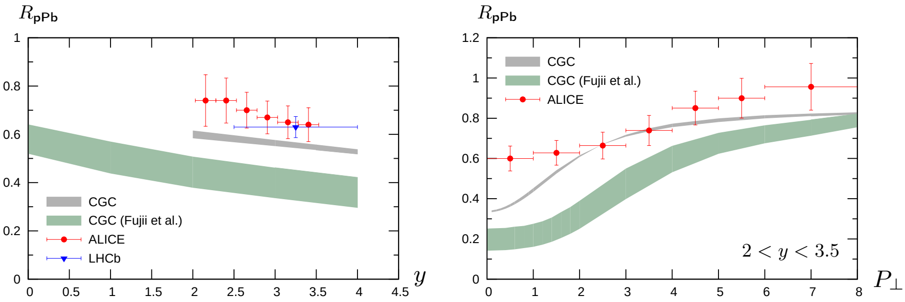
We have seen that the uncertainty on the normalization is quite large for the cross section, both in pp and pA collisions

These uncertainties should partly cancel when one computes the nuclear modification factor, defined as

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

Measurements by the ALICE and LHCb collaborations showed that previous CGC calculations underestimate significantly this ratio

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



The uncertainty is indeed quite small

The agreement with data is better than previous estimate by Fujii, Watanabe

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

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

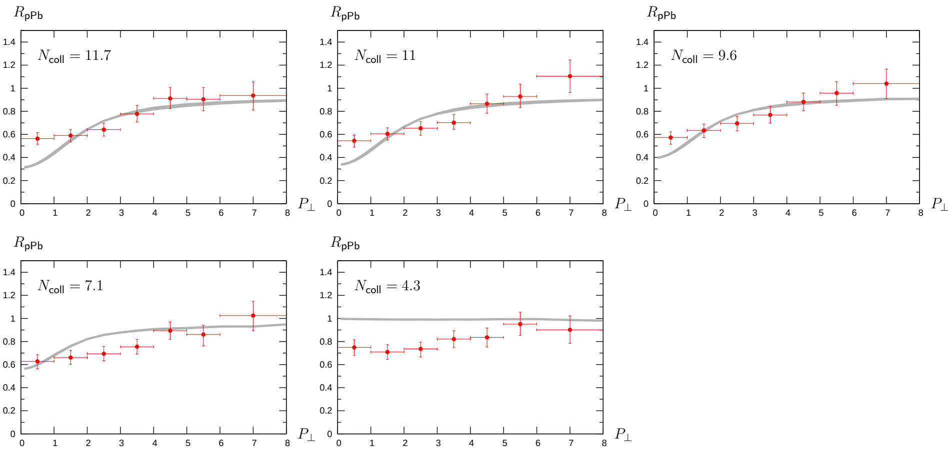
Centrality class	$\langle N_{\mathrm{coll}} \rangle_{\mathrm{opt.\ Glauber}}$	$\langle N_{\mathrm{coll}} \rangle_{\mathrm{ALICE}}$
2–10%	14.7	$11.7 \pm 1.2 \pm 0.9$
10–20%	13.6	$11.0 \pm 0.4 \pm 0.9$
20–40%	11.4	$9.6 \pm 0.2 \pm 0.8$
40–60%	7.7	$7.1 \pm 0.3 \pm 0.6$
60–80%	3.7	$4.3 \pm 0.3 \pm 0.3$
80–100%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

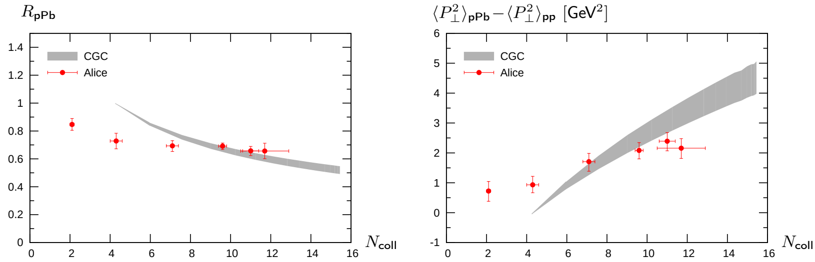
Results: centrality

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



Results: centrality

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



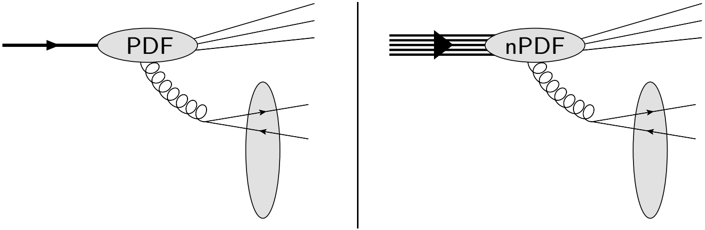
Not too bad agreement for central collisions but the slope predicted is too steep

Problematic results for peripheral collisions

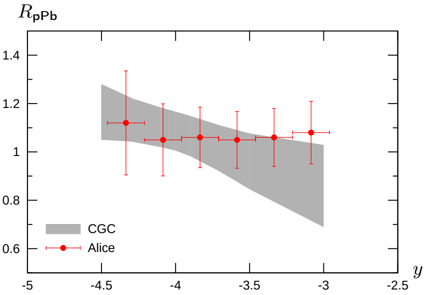
J/ψ suppression has also been measured at backward rapidity at the LHC

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

Same process as for pp with the replacement proton PDF $\rightarrow$ nuclear PDF



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



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

Nuclear effects come from nPDF probed at $x \sim \frac{P_\perp}{\sqrt{s}} e^y$, $Q^2 \sim \langle P_\perp \rangle^2_{\mathrm{pp}}$

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:
  - 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 (CEM crude approximation $\rightarrow$ NRQCD?)
- Treatment of the edge of the nucleus
- Consistency with centrality determination in experiments