Forward J/ψ and D-meson production in pA collisions at the LHC

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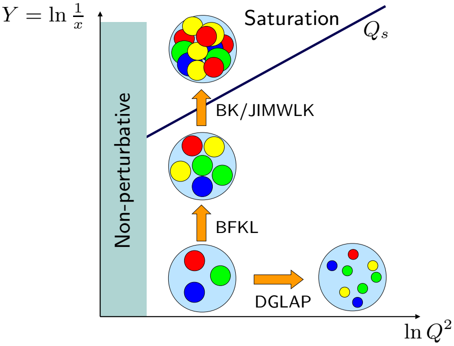
B. D., T. Lappi, H. Mäntysaari, Phys. Rev. D **91** (2015) 114005 & arXiv:1605.05680 [hep-ph]

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

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

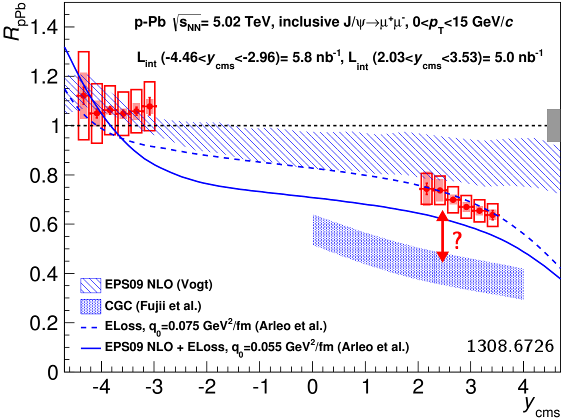
The nuclear modification factor is the standard observable to study nuclear effects:

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

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

Motivations

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



Much stronger suppression than observed later in LHC data

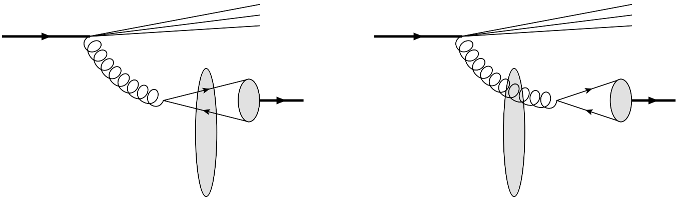
We will show that some part of this disagreement can be attributed to the lack of constraints on the unintegrated gluon distribution in a nucleus

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 unimportant when considering R_{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



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 $S_Y(\mathbf{k}_T)$, 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 DIS 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.)

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

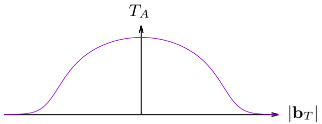
The initial condition to the Balitsky-Kovchegov equation that we used for the proton is obtained by a fit to HERA DIS data

There is no such precise data for eA collisions $\rightarrow$ 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 naive expected scaling (in practice: $Q^2_{s0,A} = (4-6)\, Q^2_{s0,p}$)

By contrast, here we use the optical Glauber model to generalize the proton 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

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

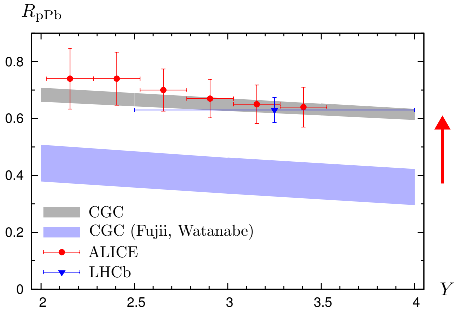
And we integrate explicitly over $\mathbf{b}_T$
(recall that $\phi_Y^{q\bar{q},g}(\mathbf{l}_T, \mathbf{k}_T) = \int \mathrm{d}^2\mathbf{b}_T \frac{N_c\,{}_\perp^2}{4\alpha_s}\, S_Y(\mathbf{k}_T)\, S_Y(\mathbf{l}_T - \mathbf{k}_T)$)

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

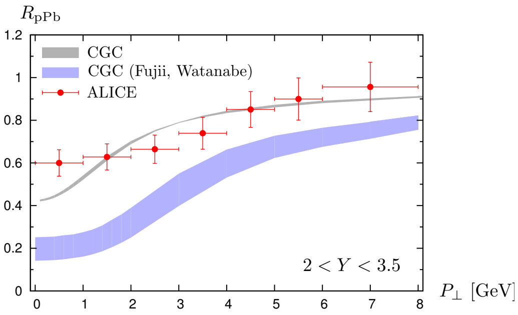
R_{pA} as a function of Y

The results obtained in this approach are in better agreement with data than the previous CGC calculation:



change of the initial condition for the nucleus
+ collinear treatment of the projectile proton

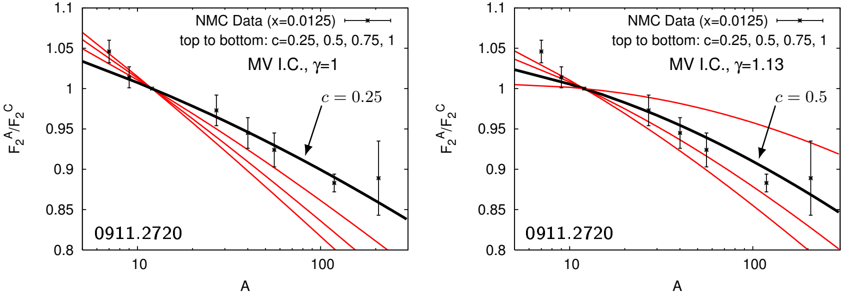
A similar increase is observed for R_{pA} as a function of $P_\perp$:



Similar agreement with data obtained by Ma, Venugopalan, Zhang using $Q^2_{s0\,,A} = 2\,Q^2_{s0\,,p}$ with NRQCD and by Fujii, Watanabe using $Q^2_{s0\,,A} = 3\,Q^2_{s0\,,p}$ with CEM

Results

These results are consistent with the fit to NMC data by Dusling, Gelis, Lappi, Venugopalan for $Q^2_{s0,A} = c\,A^{1/3} Q^2_{s0,p}$:

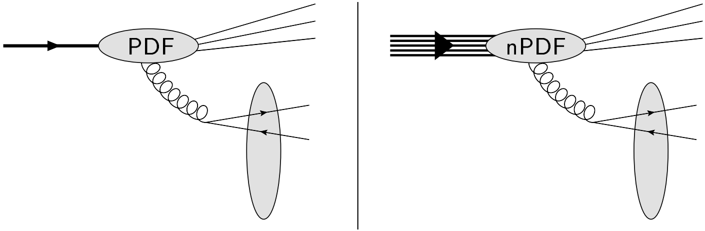


The best fit value for c depends on the initial condition parametrization but is always smaller than the naive expectation $c = 1$. For a lead nucleus this corresponds to $Q^2_{s0,Pb} \sim (1.5-3)\,Q^2_{s0,p}$

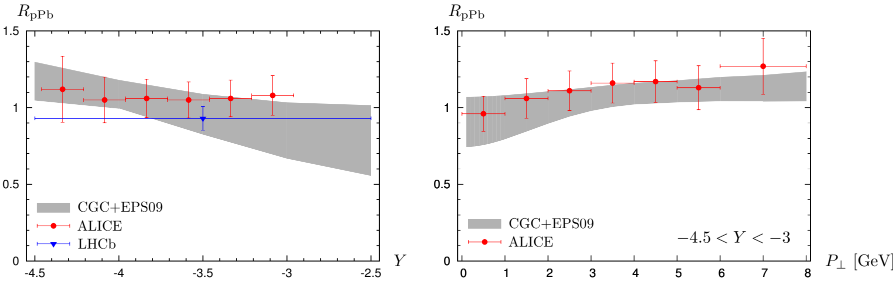
J/ψ suppression has also been measured at backward rapidity at the LHC

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

We compute this describing the nucleus by a collinear nuclear PDF while the proton is described by an unintegrated gluon distribution



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

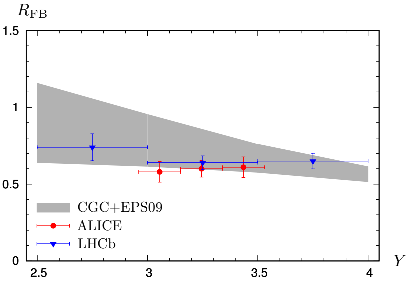


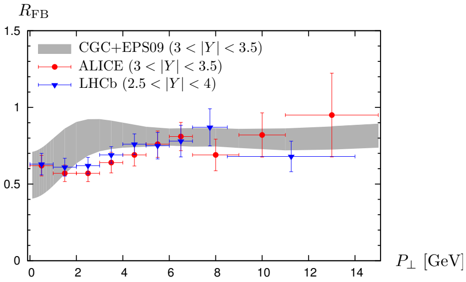
Nuclear effects come from nPDFs probed at $x = \frac{\sqrt{P_T^2 + M^2}}{\sqrt{s}} e^{-Y}$ and $Q = \sqrt{P_T^2 + M^2}$ with $\langle P_T \rangle \sim 2$ GeV

The calculation agrees with the data but the uncertainty is quite large, in particular because of the variation of Q and the EPS09 uncertainty

From results at forward and backward rapidities one can compute the forward to backward ratio:

$$R_{\mathsf{FB}}(Y) = \frac{R_{\mathsf{pA}}(Y)}{R_{\mathsf{pA}}(-Y)}$$





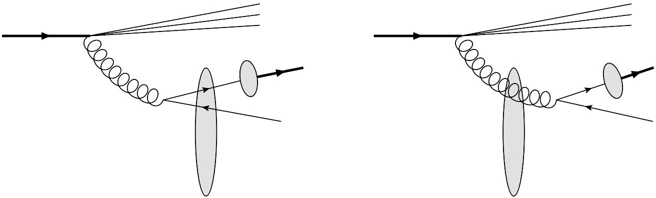
Quite large uncertainty as for $R_{\mathsf{pA}}(Y < 0)$

Too large R_{FB} at $P_\perp \sim 2 - 4$ GeV: same as for $R_{\mathsf{pA}}(Y > 0)$

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 study D-meson production:

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

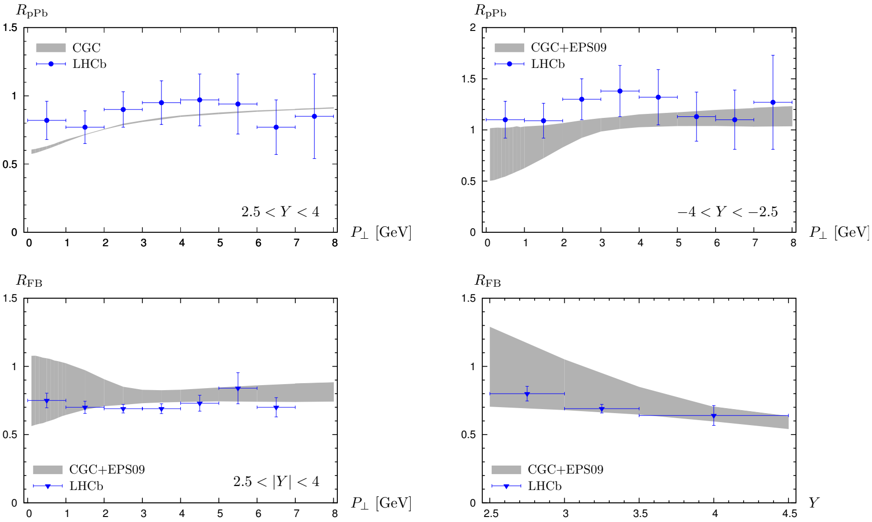
Here we use the fragmentation function parametrization from Kartvelishvili, Likhoded, Petrov: $D(z)=(\alpha+1)(\alpha+2)z^\alpha(1-z)$



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

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

D-meson production



Reasonable agreement with data but large uncertainty at backward rapidity due to the nPDFs as in the J/ψ case

Recently ALICE measured $R_{\mathsf{pA}}^{J/\psi}$ 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: $N_{\mathsf{coll}}(\mathbf{b}_T) = A\,T_A(\mathbf{b}_T)\,\sigma_{\mathsf{inel}}^{\mathsf{pp}}$ $\rightarrow$ centrality classes

Centrality class	$\langle N_{\mathsf{coll}}\rangle_{\mathsf{Glauber}}$	$\langle N_{\mathsf{coll}}\rangle_{\mathsf{ALICE}}$
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 $\langle N_{\mathsf{coll}}\rangle$ obtained with the optical Glauber model differ from those extracted by ALICE

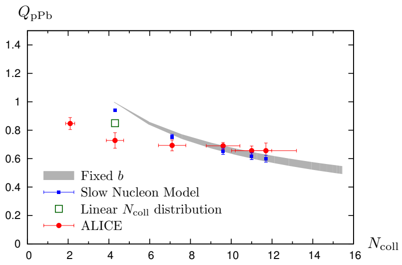
Results: centrality

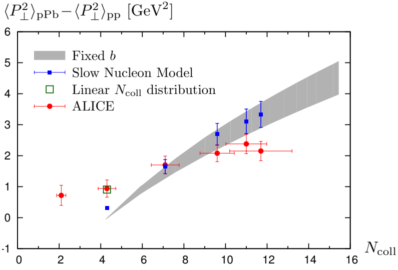
In the following we assume that the values of $\langle N_{\text{coll}} \rangle$ estimated by ALICE are correct

ALICE provides only the average number of binary collisions in each centrality class. However the exact shape of the N_{coll} distribution in each class can be important. In the following we use three models:

- Fixed impact parameter obtained by solving $N_{\text{coll Glauber}}(b) = \langle N_{\text{coll}} \rangle_{\text{ALICE}}$
- Distributions obtained in the Slow Nucleon Model provided by ALICE
- Linearly decreasing distribution to estimate the maximum importance of fluctuations for peripheral collisions (60-80% class only)
  Only two parameters, determined by $\langle N_{\text{coll}} \rangle = \langle N_{\text{coll}} \rangle_{\text{ALICE}}$ and normalization

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



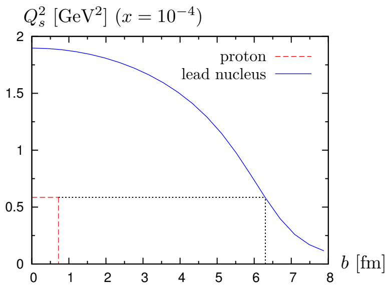


Not too bad agreement for central collisions

In general too strong variation with N_{coll}

The results for peripheral collisions depend quite strongly on the N_{coll} distribution used (but note that the linear distribution is quite extreme and not very realistic)

In our model the saturation scale of the nucleus becomes as small as the one of the proton at $b \sim 6.3$ fm or $N_{\mathsf{coll}} \sim 4.1$. This is the point where $Q_{\mathsf{pA}} = 1$



Some part of the strong centrality dependence in our model probably comes from the rather small proton transverse area (16.36 mb) obtained from the fit to HERA DIS data leading to a relatively dense proton

Conclusions

We have studied forward J/ψ and D-meson production in pp and pA collisions at the LHC in the Color Glass Condensate formalism

Use of the optical Glauber model to go from pp to pA collisions:

- Only additional input is the standard Woods-Saxon distribution
- Leads to smaller saturation scales than naive scaling $Q^2_{s0,A} = A^{1/3} Q^2_{s0,p}$
  $\Rightarrow$ Less suppression, better agreement with data than previous works
- Explicit impact parameter dependence
  - Relation with experimental centrality classes not straightforward
  - More reliable comparison: need N_{coll} distributions in each class
  - Apparently too strong centrality dependence in our model

Possible directions for future work:

- Better treatment of peripheral collisions
- Evaluation of the importance of hadronization (NRQCD vs. CEM)