Heavy flavor and electromagnetic probes of saturation in pA collisions at the LHC

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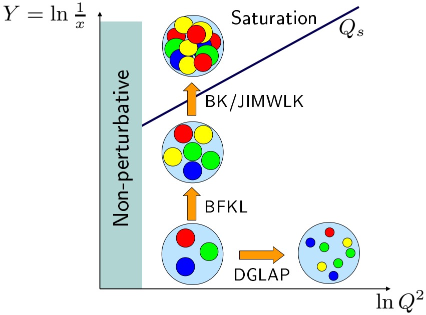
Synergies of pp and pA Collisions with an Electron-Ion Collider

BNL, June 28, 2017

The high energy limit of QCD is expected to be described by BK/JIMWLK



The production of particles at forward rapidity can probe very small values of x

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

To stay in the saturation regime, one should avoid transverse scales (p_T, mass of the produced particle) much larger than the saturation scale Q_s

The ALICE and LHCb detectors are adapted to such measurements at the LHC

In this talk:

- Charmonium (J/ψ) production
- Open charm (D-meson) production
- Drell-Yan production
- Isolated photon production

We will see that these processes can be interesting probes of saturation as they are complementary and have already been measured or could be measured in the future at the LHC

Formalism

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

Large rapidity of the produced particle means:

- not very small x probed in the projectile proton $\rightarrow$ use of collinear approximation, description by well-known PDFs
- very small x probed in the target proton (pp) or nucleus (pA) $\rightarrow$ description in terms of classical color fields

In the following we will mostly focus on the nuclear modification factor

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

$R_{\mathrm{pA}} = 1$ in the absence of nuclear effects

Uncertainties common to pp and pA collisions cancel to some extent in R_{pA}

- Scale uncertainty
- Normalization uncertainty (calculations leading order in $\alpha_s \ln 1/x$ for now)

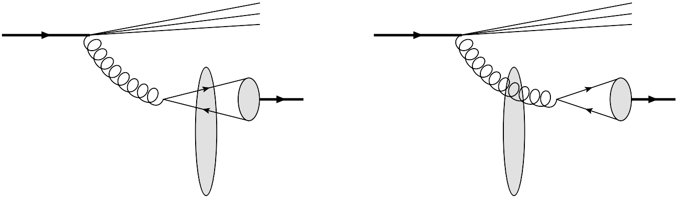
J/ψ production

Motivations to study the nuclear modification of J/ψ production:

- The charm quark mass should be large enough to provide a hard scale (perturbative treatment) but small enough to be sensitive to saturation
- Nuclear modification in pA: important reference for the interpretation of AA measurements (J/ψ melting possible probe of QGP formation)
- Gives access to very small ($< 10^{-5}$) x values in the target
- Relatively easy to reconstruct via dilepton decays
- R_{pA} already measured by ALICE and LHCb

Physical picture: 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 state propagating through the target acquires some transverse momentum via multiple scatterings



Later on the $c\bar{c}$ pair will hadronize non-perturbatively into a J/ψ meson

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

The main ingredient we need is the $c\bar{c}$ pair production cross section in the CGC (Blaizot, Gelis, Venugopalan)

Taking the collinear limit for the projectile proton leads to

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

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

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 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 (BK) 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 evolve perturbatively S down to smaller x values

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

It can be for example obtained by a fit to DIS data for F_2 and F_L

Possible parametrization for the initial condition of a proton target:

$$S_{Y_0}(\mathbf{r}) = \exp\left[-\frac{(\mathbf{r}^2 Q_{\mathrm{s}0}^2)^\gamma}{4}\ln\left(\frac{1}{|\mathbf{r}|\Lambda_{\mathrm{QCD}}} + e_c \cdot e\right)\right]$$

$\gamma = 1$, $e_c = 1$: original McLerran-Venugopalan (MV) model

No impact parameter dependence: replace $\int \mathrm{d}^2\mathbf{b}_T \to \frac{\sigma_0}{2}$

Here we use the 'MV^e' fit to HERA DIS data shown to lead to a rather good description of single inclusive forward hadron production (Lappi, Mäntysaari)

Model	χ^2/d.o.f	$Q_{\mathrm{s}0}^2$ [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

Model-independent Q_{s}^2: defined as $S(\mathbf{r}^2 = 2/Q_{\mathrm{s}}^2) = e^{-1/2}$

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

Advantage of the MV^e parametrization: positive Fourier transform

The hadronization of $c\bar{c}$ pairs into J/ψ mesons is not yet fully understood

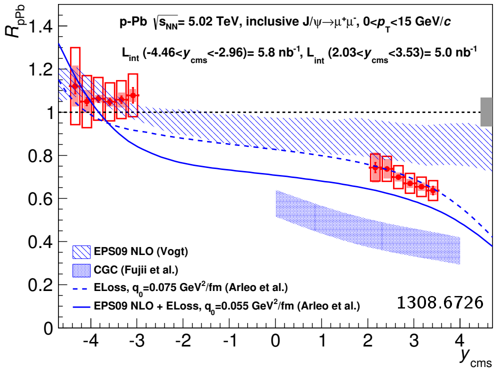
Simple model: color evaporation model (CEM). A fixed fraction of all $c\bar{c}$ pairs produced below the D-meson mass threshold are assumed to become J/ψ's

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

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_{pA}

Results: first CGC calculation

Prediction for $R_{\mathrm{pA}}^{J/\psi}$ in pPb collisions at the LHC in the CGC formalism with color evaporation model: Fujii, Watanabe



Much smaller suppression observed at the LHC

We will see that some part of this disagreement may be due to the lack of high precision nuclear DIS data

Choice of the nucleus initial condition

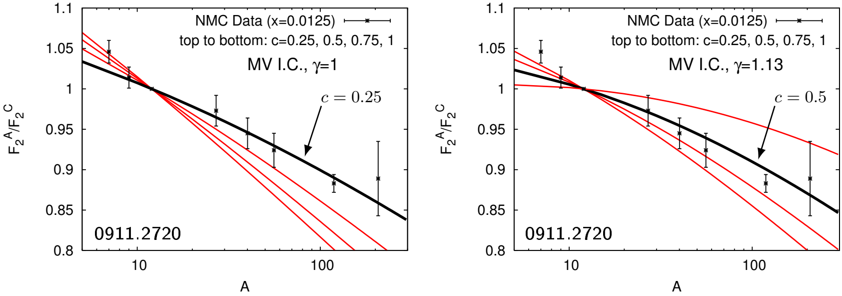
Let's consider the initial condition for the BK evolution of the target

Initial condition for a proton target (used for the proton-proton reference): relatively well constrained by HERA DIS data

Initial condition for a nucleus target (pA collisions): no accurate enough nuclear DIS data to perform a similar fit. Fujii, Watanabe: use the same initial condition as for a proton with $Q^2_{\mathrm{s}0,A} \sim A^{1/3} Q^2_{\mathrm{s}0,p}$

This is only approximate and neglects nuclear geometry

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



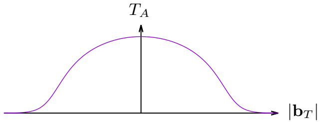
The best fit value for c depends on the exact initial condition parametrization but is always smaller than 1

For lead nucleus: $Q^2_{s0,\mathbf{Pb}} \sim (1.5-3)\,Q^2_{s0,p}$

Smaller initial saturation scale with same evolution: expect less suppression

Other possible approach to get the initial condition for a nucleus: use the optical 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 of the nucleus

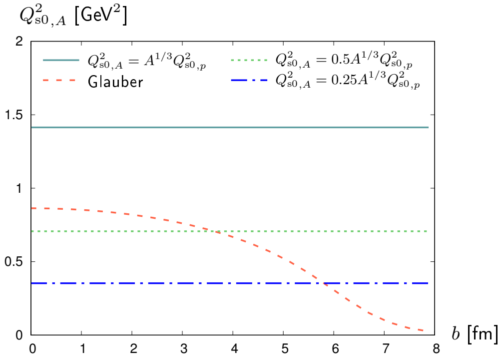
The standard Woods-Saxon transverse thickness T_A is the only additional input needed to go from a proton to a nucleus target

The initial condition for a nucleus in this model is

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

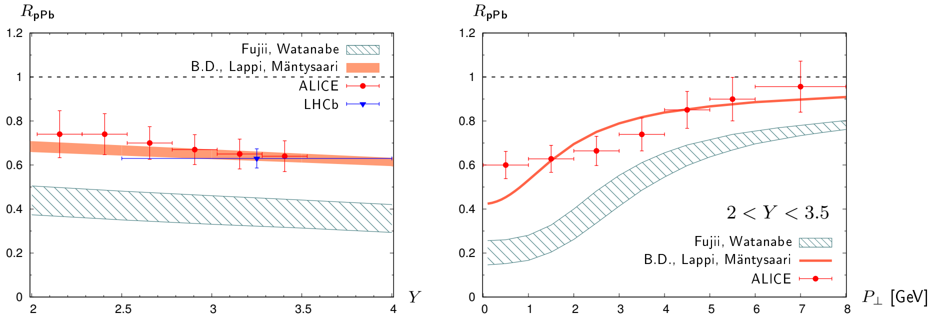
Choice of the nucleus initial condition

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



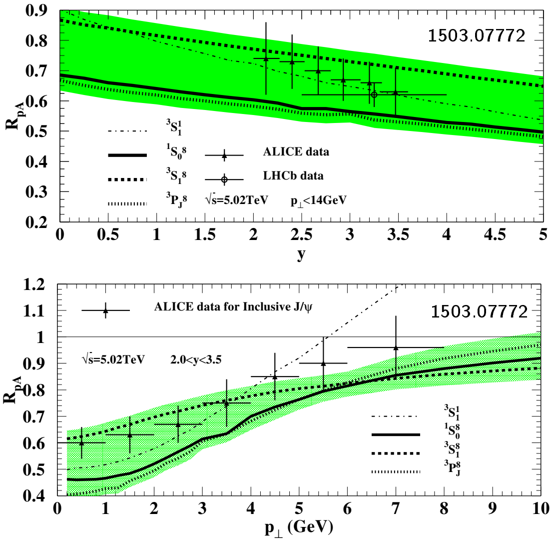
The scaling $Q^2_{s0,A} = A^{1/3} Q^2_{s0,p}$ leads to much larger saturation scales than the optical Glauber model or fits to NMC data

Using the Glauber approach (still with CEM hadronization) leads to better agreement with experimental data:



An EIC could provide valuable constraints for the initial condition of the nucleus

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



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

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

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

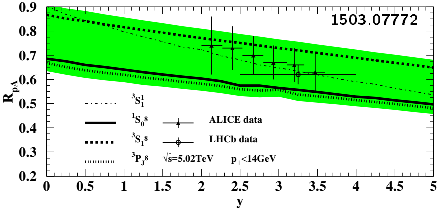
$\langle \mathcal{O}^H_\kappa \rangle$ are universal non-perturbative long distance matrix elements (LDME) which can be extracted from data

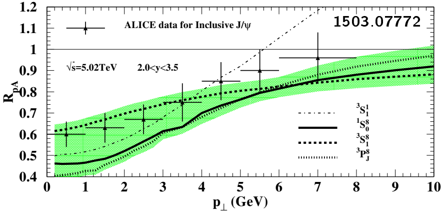
Contributing states for J/ψ production: ${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$

${}^3S_1^{[1]}$ is leading power in v but suppressed by powers of $p_\perp$ compared to the others

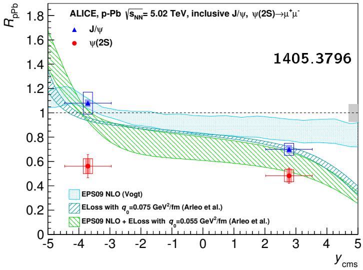
NRQCD hadronization

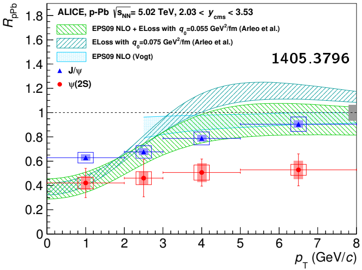
Uncertainty band: compute R_{pA} for each channel (independent of the LDME values) and take the envelope, excluding the color singlet channel (small contribution to the cross section, especially at large $P_\perp$)





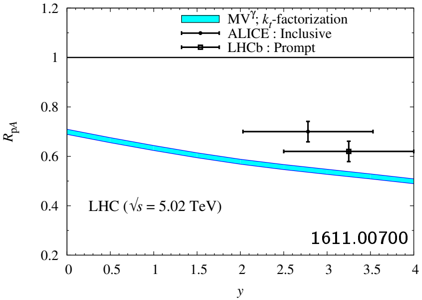
NRQCD: one could have different R_{pA} for excited states, contrary to CEM

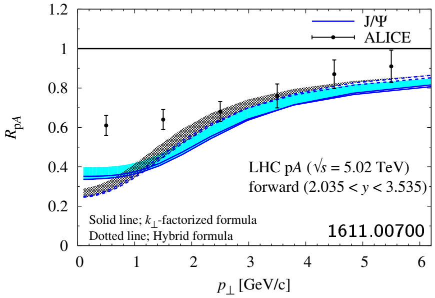




Updated CEM calculation

Also updated calculation by Fujii, Watanabe using $Q^2_{s0,A} = 3\,Q^2_{s0,p}$:



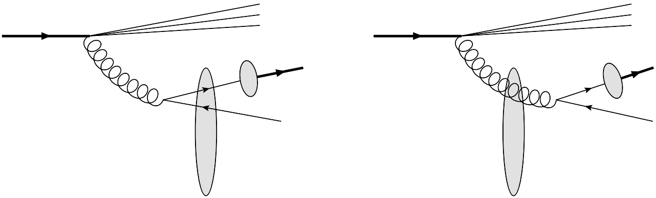


As expected the results are closer to data

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:

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

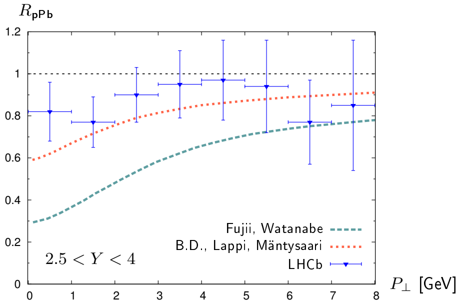
Here we use the fragmentation function parametrization from Kartvelishvili, Likhoded, Petrov: $D(z)=(\alpha+1)(\alpha+2)z^\alpha(1-z)$

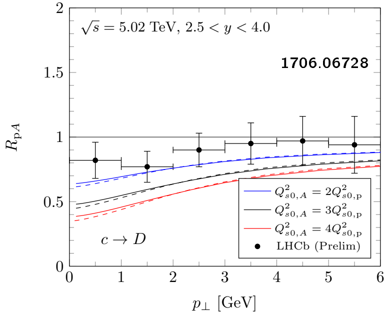


x's probed in the projectile and the target: $x_{1,2}=\frac{\sqrt{m_c^2+p_T^2}}{\sqrt{s}}e^{\pm y_p}+\frac{\sqrt{m_c^2+q_T^2}}{\sqrt{s}}e^{\pm y_q}$

D-meson production

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

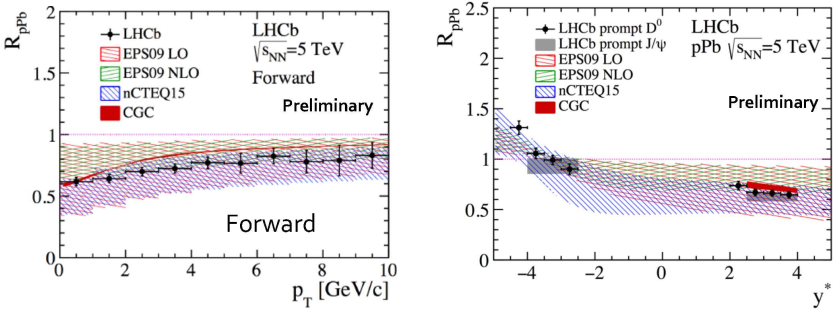




Preliminary LHCb data: used interpolated 5 TeV pp reference

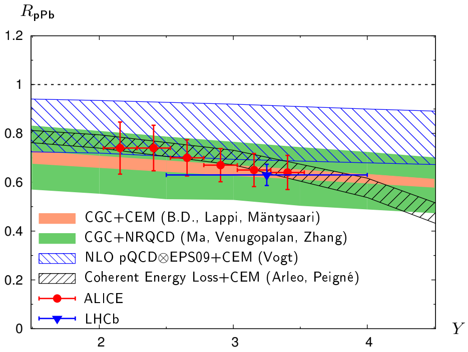
D-meson production

New LHCb data with measured 5 TeV pp reference: smaller uncertainties, slightly more suppression



(Plots from B. Schmidt's talk at LHCP 2017)

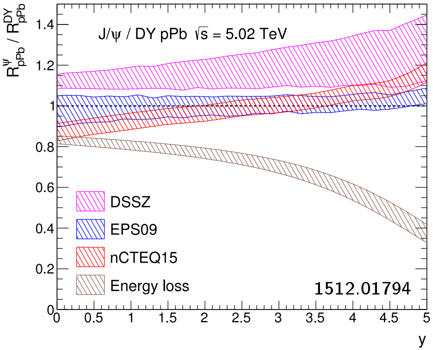
Several formalisms are compatible with measured $R_{\mathrm{pA}}^{J/\psi}(Y)$ at 5 TeV:



Visibly not a good observable to discriminate between these approaches

Comparison with other formalisms

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

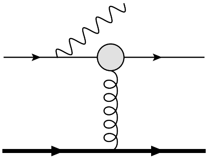


Drell-Yan insensitive to energy loss in first approximation, $R_{\mathrm{pA}}^{\mathrm{DY}} = 1$ at forward rapidity in this formalism

This ratio seems to be very discriminant between coherent energy loss and nPDFs

Comparison with results in the saturation approach?

Diagrams contributing to virtual photon production in the saturation approach:



The Drell-Yan nuclear modification factor has already been studied in this approach

Kopeliovich, Raufeisen, Tarasov, Johnson

Basso, Goncalves, Krelina, Nemchik, Pasechnik

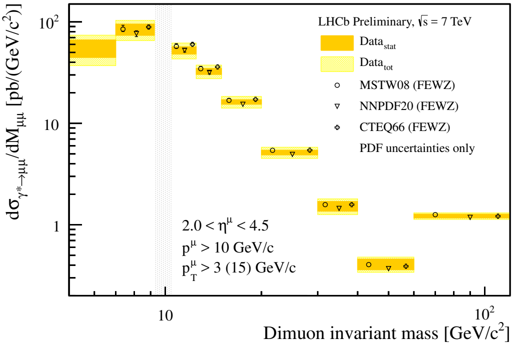
However to compute the ratio $R_{\mathsf{pA}}^{J/\psi}/R_{\mathsf{pA}}^{\mathsf{DY}}$ consistently we need to use the same dipole correlators as for J/ψ production

Drell-Yan production

This process is also interesting in itself: cleaner probe of small x dynamics than J/ψ production

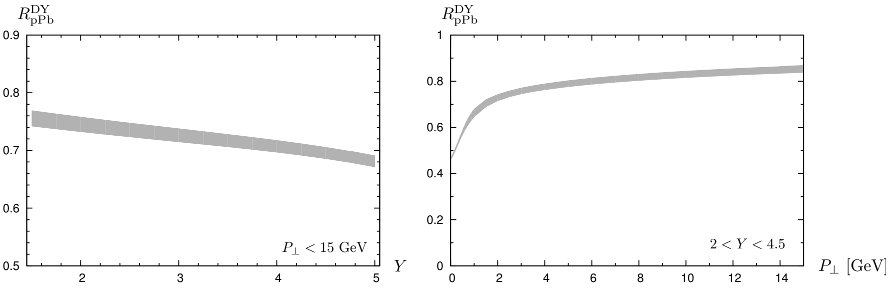
But difficult to measure (small cross sections, heavy flavor decays background at small M)

Preliminary LHCb study in pp collisions at 7 TeV (LHCb-CONF-2012-013):



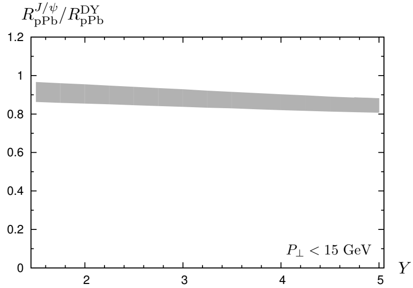
Measurement down to $M = 5$ GeV
In the following we take $5 < M < 9.25$ GeV

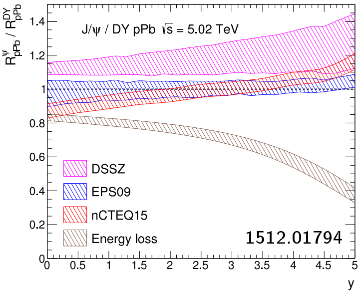
Nuclear modification factor at $\sqrt{s} = 8$ TeV as a function of Y and $P_\perp$:



The measurement of this observable would provide an additional test of the dipole correlators used in other processes

Results for the ratio $R_{\mathsf{pA}}^{J/\psi}/R_{\mathsf{pA}}^{\mathsf{DY}}$:





Ratio close to 1, contrary to the energy loss prediction
$\rightarrow$ potential to discriminate between the approaches

Note that on the right plot $\sqrt{s} = 5$ TeV and $10.5 < M < 20$ GeV

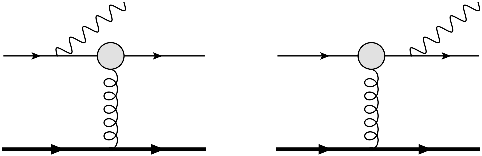
Real photon production

Drell-Yan: small cross sections, difficult to measure

Natural 'extension': real photon production

Not yet measurable at forward rapidity at the LHC, but possible in the future with FoCal at ALICE

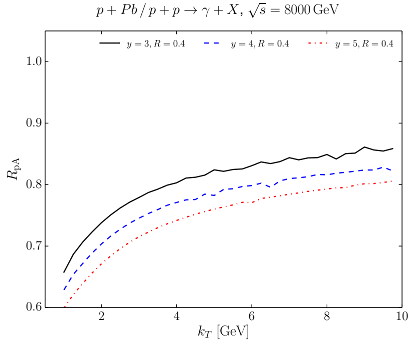
The diagrams are the same as for Drell-Yan production:

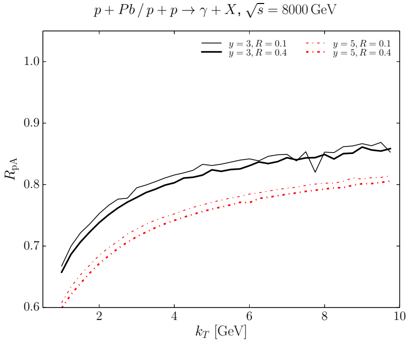


To remove fragmentation contributions we use a simple isolation cut, requiring that $(Y_\gamma - Y_q)^2 + (\phi_\gamma - \phi_q)^2 > R^2$

R should be related to the experimental isolation cut

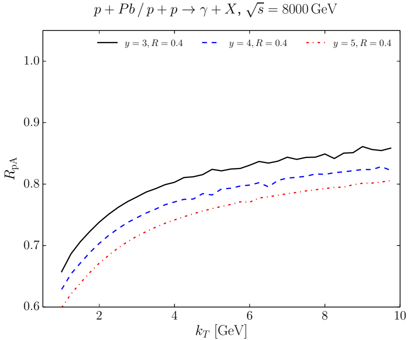
Nuclear modification factor at $\sqrt{s} = 8$ TeV:

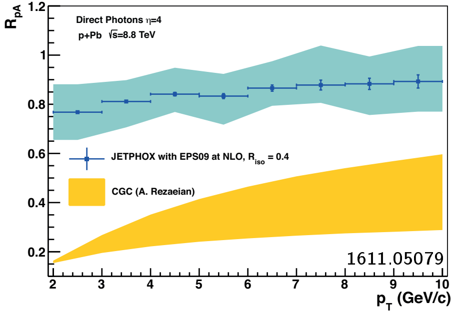




Dependence on R quite small $\rightarrow$ stable prediction

Comparison with other calculations:





Significantly larger R_{pA} than previous CGC calculation (Jalilian-Marian, Rezaeian) in similar kinematics

Results not very far from collinear factorization+nPDFs
Maybe not so discriminant observable?

Here also EIC data would be helpful to better constrain these calculations

It will be very interesting to compare these results with future measurements

Conclusions

- Forward heavy flavor and (real/virtual) photon production in pA collisions can be complementary probes of saturation at the LHC
- Interesting prospects for future measurements (Drell-Yan, real photons)
- EIC data will help to improve the robustness of the calculations by providing better constraints on the initial condition for the BK evolution of the nucleus

For now LO calculations (+ running coupling corrections in BK evolution)
Recent progresses to extend this formalism to NLO:

- NLO BK equation numerically solved (Lappi, Mäntysaari), including resummation of large collinear logarithms (Iancu, Madrigal, Mueller, Soyez, Triantafyllopoulos)
- Many works devoted to understanding NLO corrections to single inclusive forward hadron production
- Calculation of NLO corrections to real photon production Benic, Fukushima, Garcia-Montero, Venugopalan
- The study of DIS at NLO will be very important to obtain the initial condition for the BK evolution of the target