Forward particle production in proton-nucleus collisions as a probe of saturation

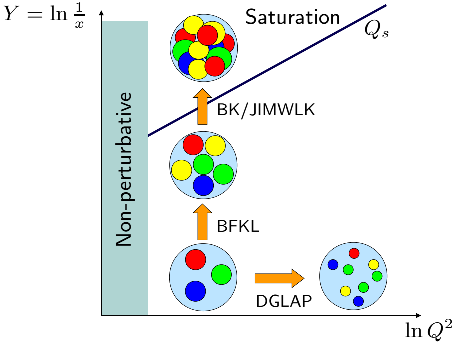
Bertrand Ducloué
University of Edinburgh

Second LHCb Heavy Ion Workshop

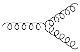
September 4, 2019

Motivations

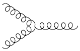
A longstanding question in QCD is to find evidence for small x effects, and in particular gluon saturation



The linear small x evolution (BFKL) is governed by the emission of multiple soft gluons ($1 \to 2$ scatterings):



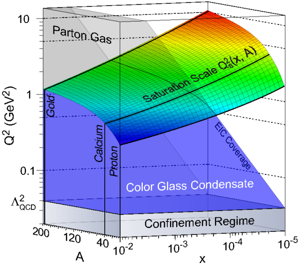
At large densities, recombination effects become important: Non-linear evolution (BK, JIMWLK)



Motivations

The importance of non-linear effects is quantified by the size of the saturation scale Q_s, which corresponds to the typical transverse momentum of the gluons in the target ⇒ need Q_s as large as possible

Roughly we have $Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{0.3}$



Therefore we need:

$$\left.\begin{array}{l}\bullet\ \text{Small } x \text{ values}\\ \bullet\ \text{Large nucleus}\end{array}\right\}\ \text{to enhance saturation effects}$$

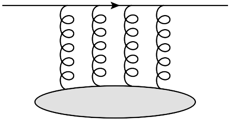
$$\left.\begin{array}{l}\bullet\ \text{A hard scale}\end{array}\right\}\ \text{to be in the perturbative regime}$$

Forward particle production in proton-nucleus collisions at the LHC seems to be the ideal way to probe these dynamics

The Color Glass Condensate

At very high energy the gluonic content of a hadron can be described using classical color fields

The eikonal interaction of a dilute probe (e.g. a large x parton coming from the projectile proton) with the dense target (nucleus) is described by a Wilson line V which resums multiple scatterings



The x evolution of the dipole correlator $S(\mathbf{r}=\mathbf{x}-\mathbf{y}) = \left\langle \frac{1}{N_c} \mathrm{Tr}\, V(\mathbf{x})V^\dagger(\mathbf{y}) \right\rangle$ is governed by the Balitsky-Kovchegov (BK) equation:

$$\frac{\partial S(\mathbf{r},x)}{\partial \ln x} = 2\alpha_s N_c \int \frac{\mathrm{d}^2\mathbf{x}}{(2\pi)^2} \frac{\mathbf{r}^2}{\mathbf{x}^2(\mathbf{r}-\mathbf{x})^2} \left[S(\mathbf{r},x) - S(\mathbf{x},x)S(\mathbf{r}-\mathbf{x},x)\right]$$

Fourier transform of S: unintegrated gluon distribution in the target

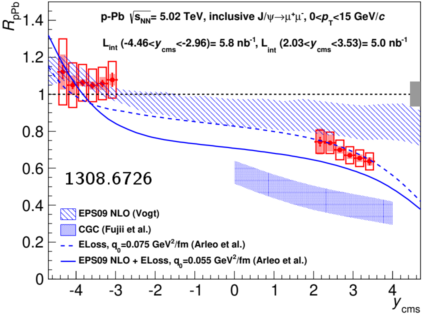
$$\mathcal{F}(k_\perp) = \int \mathrm{d}^2\mathbf{r} e^{-i\mathbf{k}_T\cdot\mathbf{r}} S(\mathbf{r})$$

The Color Glass Condensate

The BK equation predicts only the evolution as a function of x

It does not tell anything about the initial condition $S(\mathbf{r}, x_0)$ at moderate $x_0 \sim 0.01$. Usually obtained by a fit to HERA DIS data.

Obviously this works only for a proton target (no similar data for eA collisions). From dimensional arguments one expects $Q^2_{\mathrm{s}0,A} \sim A^{1/3} Q^2_{\mathrm{s}0,p}$ but this neglects nuclear geometry. This naive estimate leads to a huge suppression of forward J/ψ production at the LHC (Fujii, Watanabe): "smoking gun" of saturation?

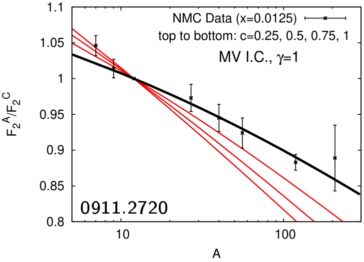


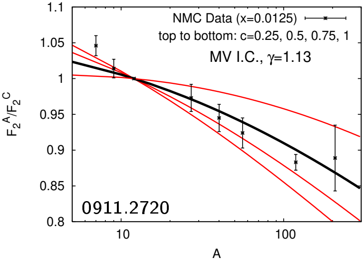
1308.6726

The Color Glass Condensate

Less naive ways to go from a proton to a nucleus:

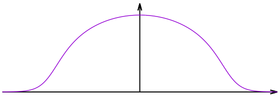
1. Using NMC data on the A dependence of F_2, fit of c in $Q^2_{s0,A} = c\,A^{1/3} Q^2_{s0,p}$:





The best fit value for c depends on the exact form of the initial condition and leads to $Q^2_{s0,A} \sim (1.5-3)\,Q^2_{s0,p}$ for a lead nucleus (Dusling, Gelis, Lappi, Venugopalan)

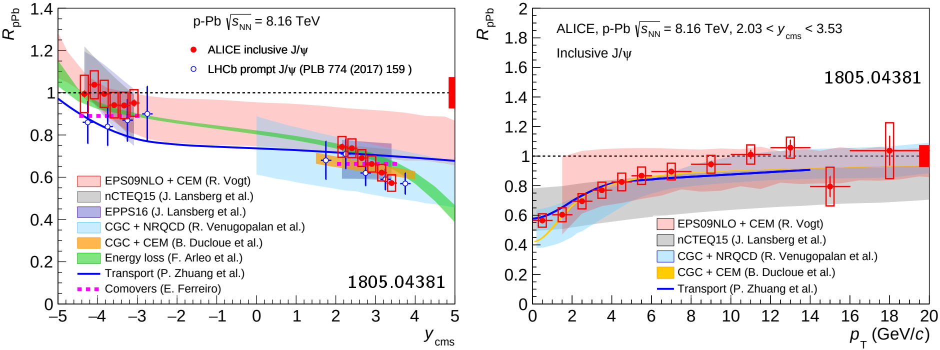
2. Optical Glauber model: the nuclear density in the transverse plane at the initial condition is given by the standard Woods-Saxon distribution $T_A(\mathbf{b})$:



These two approaches lead to similar results for minimum bias events

Comparison with data

Measurement of R_{pA} for J/ψ production at the LHC:



Several approaches are compatible with the data

What is the physical mechanism behind the observed suppression?

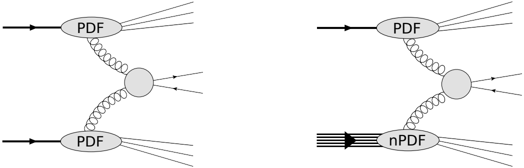
Initial state effect: nPDFs

The main other initial state effect from which one would like to distinguish CGC

This approach is based on standard collinear factorization

Assumption: all nuclear effects can be factorized into a modification of the parton distribution functions (PDFs)

The cross section is a convolution of the PDFs with the partonic cross section



proton-proton proton-nucleus

The nuclear PDFs (nPDFs) are usually given as $f^A(x,Q^2) = R(x,Q^2)f^p(x,Q^2)$

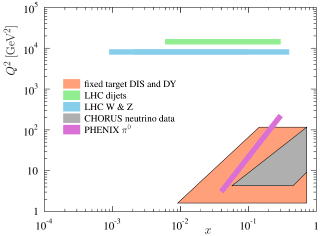
$R(x,Q^2)$ is the nuclear modification of the free proton PDF

Like PDFs, nPDFs are supposed to be process-independent (can be fitted to some processes and then used for others)

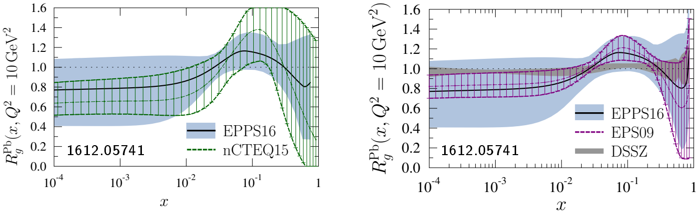
The Q^2 evolution of $f^A(x,Q^2)$ is governed by the DGLAP equation

Initial state effect: nPDFs

Up to now there is no small x, low Q^2 data included in nPDFs fits. Example with EPPS16: (Eskola, Paakkinen, Paukkunen, Salgado)



This leads to large uncertainties in this region, in particular for the gluon PDF, and explains the large error band for the J/ψ nuclear modification factor



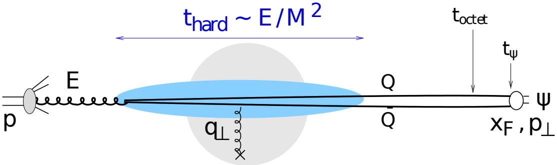
More recent sets seem to have larger uncertainties at small x despite more data in the fit: less biased parametrizations

Final state effect: coherent energy loss

The LHC J/ψ suppression can also be explained by taking into account only coherent energy loss

This approach is based on the fact that for large formation times all scattering centers in the medium act coherently. Leads to a behaviour $\Delta E \propto E$

Arleo, Kolevatov, Peigné, Rustamova



The medium-induced coherent radiation spectrum arises from the interference between gluon emission in the initial state and in the final state

Final state effect: coherent energy loss

The cross section in pA collisions can be written as

$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}^{\psi}}{\mathrm{d}E\,\mathrm{d}^2p_T} = \int_{\varphi}\int_{\varepsilon} \mathcal{P}(\varepsilon, E)\,\frac{\mathrm{d}\sigma_{\mathrm{pp}}^{\psi}}{\mathrm{d}E\,\mathrm{d}^2p_T}\,(E+\varepsilon, p_T - \Delta p_T)$$

The pp cross section can be parametrized from experimental data
Both $\mathcal{P}$ and Δp_T involve the transport coefficient $\hat{q}$, which is related to the gluon distribution by

$$\hat{q}(x) \simeq \frac{4\pi^2\alpha_s N_c}{N_c^2-1}\,\rho\,xG(x)$$

Using the power-law behavior $xG(x) \sim x^{-0.3}$ suggested by small x ($x < 10^{-2}$) fits to HERA data, one can write

$$\hat{q}(x) \simeq \hat{q}_0\left(\frac{10^{-2}}{x}\right)^{0.3}$$

where $\hat{q}_0$ is the only free parameter of the model. $\hat{q}_0 = 0.075$ GeV^2/fm from a fit to E866 pW data

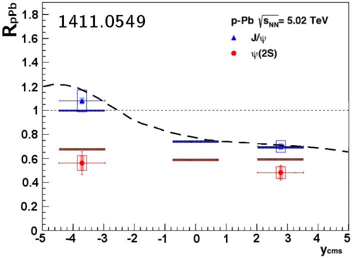
Final state effect: interaction with comovers

The produced quarkonium bound states can be destroyed by interacting with other soft particles moving in the same direction

Only free parameter in this model: $\sigma^{co-\psi}$, the cross section of charmonium dissociation due to interactions with the comovers

Fits to low energy data: $\sigma^{co-J/\psi} \sim 0.6$ mb, $\sigma^{co-\psi(2S)} \sim 6$ mb (Armesto, Capella). Values could be different at LHC energies

This leads to a different suppression for J/ψ and $\psi(2S)$ and can explain (together with EPS09 shadowing) ALICE data on this observable (Ferreiro):



Initial and final state effects

LHC data can be explained by models implementing

- only initial state effects (nPDFs, CGC)
- only final state effects (energy loss)
- a combination of both (comovers, transport)

There is no reason a priori to exclude one type of effect

- nPDFs + energy loss: current fits assume no energy loss
  The presence of such effects could spoil the extraction of nPDFs from data
  A consistent treatment would probably require a new fit taking into account energy loss for the processes which can be sensitive to it
- CGC + energy loss: recent works rederived the energy loss spectrum in the dipole formalism (suitable for saturation studies) for $1 \to 2$ (Liou, Mueller) and $1 \to 1$ (Munier, Peigné, Petreska) processes. Implementing small x (BK) evolution on top of energy loss is thus possible in principle

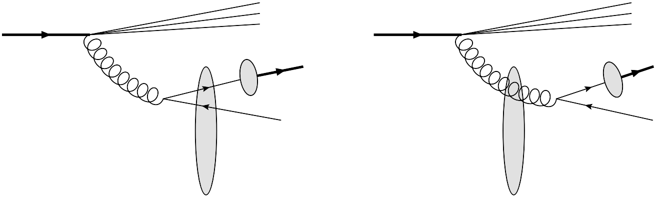
Could such calculations still be compatible with data?

D-meson production

From the $c\bar{c}$ pair production cross section one can also study D-meson production

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

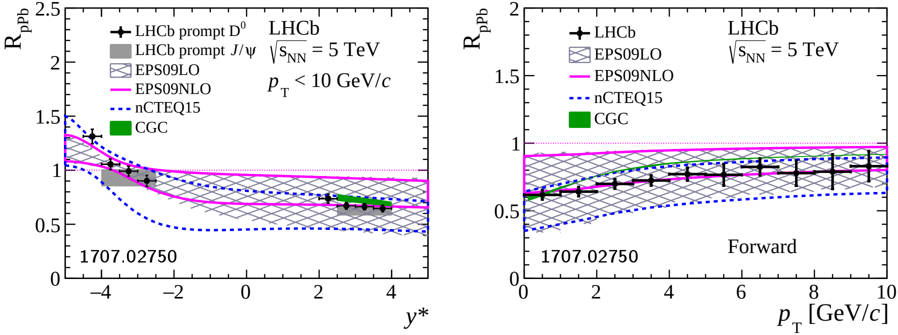
Physical picture in the CGC:



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

LHCb measured the nuclear modification factor for D-meson production:



Similar values for R_{pA} as for J/ψ production

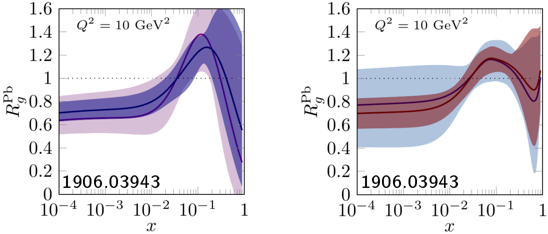
Here also several calculations are compatible with the data

→ need more processes/observables

D-meson production

Even if the LHCb D-meson data cannot distinguish between several approaches, it provides very useful constraints for nuclear PDFs

Example of CTEQ15 and EPPS16 reweighting:
(Eskola, Helenius, Paakkinen, Paukkunen)



Compatible with other data in the fit, significantly reduced uncertainty on the nuclear gluon PDF at small x

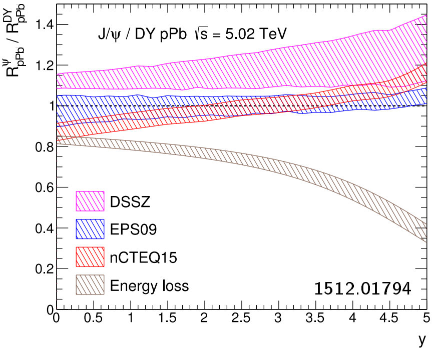
These data will probably be included in future nPDF fits (not so clear for J/ψ data because of hadronization issues)
→ more accurate predictions for other processes (e.g. forward photon production)

Drell-Yan production

Proposal to distinguish between the energy loss and nPDF approaches: study the double ratio $R_{\mathrm{pA}}^{J/\psi}/R_{\mathrm{pA}}^{\text{Drell-Yan}}$ (Arleo, Peigné)

Drell-Yan is insensitive to energy loss in first approximation

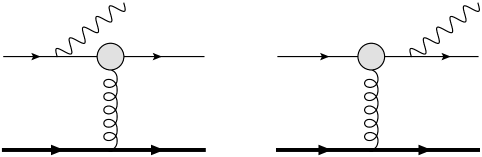
The double ratio seems to be very discriminant at large rapidity:



This observable can also be computed in the saturation approach

Drell-Yan production

Diagrams contributing to virtual photon production in the saturation approach:



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

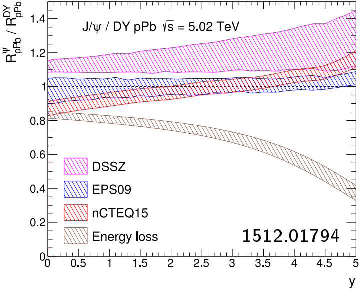
Kopeliovich, Raufeisen, Tarasov, Johnson

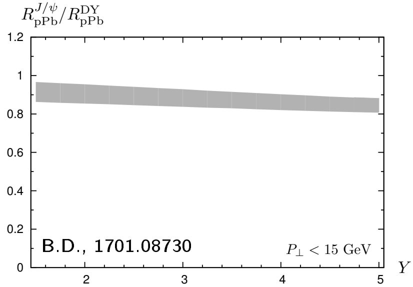
Basso, Goncalves, Krelina, Nemchik, Pasechnik

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

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





The ratio is rather flat and not very far from the nPDFs results

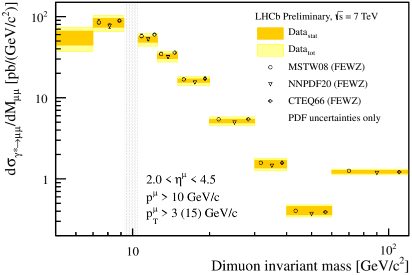
Potential to discriminate between initial and final state effects?

Drell-Yan production

This process is also interesting in itself: clean probe of small x dynamics (but sensitive to gluons only starting at NLO in the collinear approach)

Difficult to measure (small cross sections, heavy flavor decays background at low invariant mass)

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

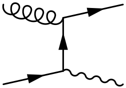


Isolated photon production

Natural 'extension' of Drell-Yan: real photon production

Larger cross sections, but still difficult to measure

Same diagrams as Drell-Yan in the CGC, but directly sensitive to gluons at LO in the collinear approach:

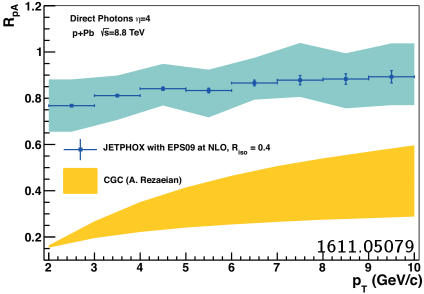


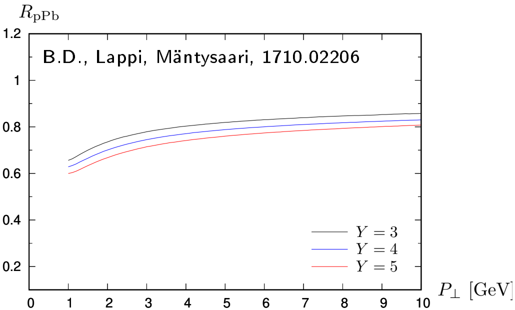
Could provide strong constraints for nPDFs

Note that R_{pA} at forward rapidity is really the observable we need if we want to be able to compare CGC and other approaches. Backward production (as needed to compute R_{FB}) involves a large x nucleus which should be treated in collinear factorization

Isolated photon production

Results and comparison with other calculations:



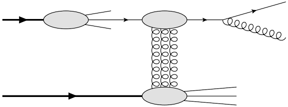


Recent CGC calculation using the same nuclear geometry treatment as for J/ψ production leads to similar results as nPDFs

Not very promising to distinguish between the two approaches, but could be used to constrain/test nPDFs

Azimuthal correlations

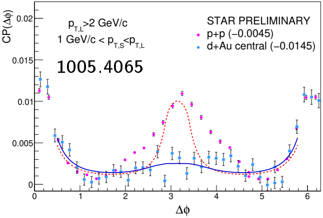
Beyond R_{pA}, the azimuthal correlations between particles produced at forward rapidity can be used as a probe of saturation



As long as the produced particles have a small momentum imbalance, a small $q_\perp$ is probed in the target → sensitivity to saturation effects. In particular expect a strong suppression of the away-side peak in pA collisions

Many processes to be studied: di-hadrons, γ+hadron, double D-meson, ...

e.g. for di-hadrons at RHIC (Albacete, Marquet):

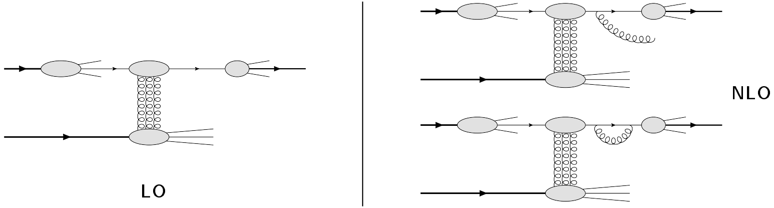


Going beyond leading order

While most collinear calculations using nPDFs are done at NLO, so far most CGC calculations are limited to LO + running coupling corrections

Thus absolute cross sections cannot really be trusted

There have been recent efforts to go to NLO, for now focusing on simpler processes, e.g. light hadron production:



New contributions → could change the large $p_\perp$ behavior significantly

Calculations with heavy flavors are much more involved → NLO phenomenology for J/ψ and D-meson production is probably still quite far away

Conclusions

Distinguishing between saturation and other approaches proves to be much more difficult than expected

- Recent CGC calculations show less suppression than early ones
  This is due to a better treatment of the initial condition/nuclear geometry
- Collinear calculations have large uncertainties
  Improvements to be expected with the inclusion of LHCb D-meson data in the fits

Outlook:

- More data to better constrain nPDFs (quark and gluons) at small x and Q^2
- Take into account both initial and final state effects
- Look at further observables (e.g. azimuthal correlations)
- Push CGC calculations beyond leading order