Quarkonia in pA collisions: cold nuclear matter effects

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Quarkonium production in proton-nucleus collisions is a key process to understand cold nuclear matter effects

- pA: baseline for AA collisions
- Can also be used to probe the content of nuclei
- ALICE and LHCb can measure quarkonia at very forward rapidity
  $\rightarrow$ access to the low x, low Q^2 region

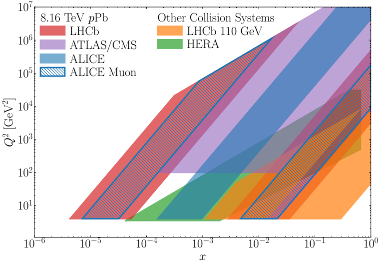


Figure by T. Boettcher

One key observable to quantify nuclear effects: nuclear modification factor

$$R_{\mathsf{pA}} = \frac{1}{A}\frac{\mathrm{d}\sigma^{\mathsf{pA}}}{\mathrm{d}\sigma^{\mathsf{pp}}}$$

$R_{\mathsf{pA}} = 1 \Leftrightarrow$ the nucleus behaves like a superposition of independent nucleons

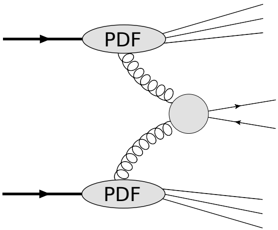
Quarkonium production can be modified in pA vs pp collisions because of several mechanisms

- Modification of parton densities (nuclear PDFs, saturation, ...)
- Destruction of the bound states (absorption, comovers, ...)

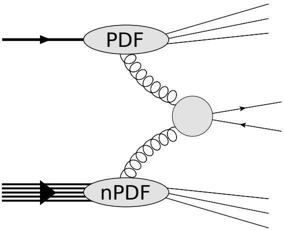
Several effects can contribute simultaneously

Nuclear PDFs

Based on collinear factorization, assume that nuclear effects can be factorized in a modification of PDFs compared to a free proton



proton-proton



proton-nucleus

The nuclear PDF (nPDF) can be written as $f^A(x,Q) = R(x,Q) f^p(x,Q)$

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

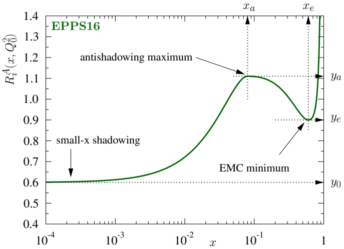
Like proton PDFs, nPDFs are supposed to be universal (can be fitted to some processes and then used for others)

Nuclear PDFs

Like proton PDFs, fit x-dependence at a given initial scale $Q_0 \sim 1$ GeV
Then can be evolved to higher Q^2 values using the DGLAP equation

Typically 4 regions:

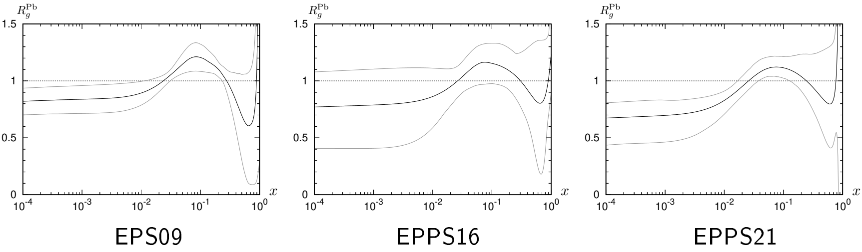
- Shadowing
- Anti-shadowing
- EMC effect
- Fermi motion



Much less data available to fit nPDFs than for proton PDFs
$\rightarrow$ much larger uncertainties, especially in the low x, low Q^2 region

Nuclear PDFs

Comparison of the gluon modification in Pb for three generations of nPDFs at $Q^2 = 10$ GeV^2:

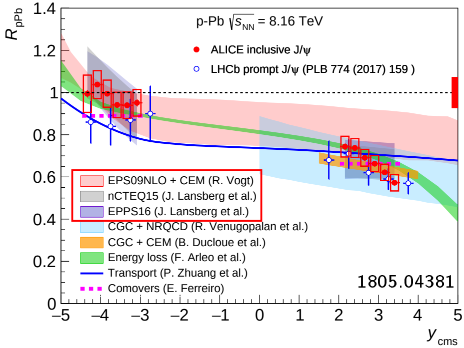


Includes LHC dijets and W & Z data
Less biased parametrization

Includes LHC D-meson data

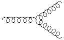
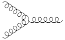
Newer nPDF sets tend to have more gluon shadowing at small x (in particular due to LHCb forward D-meson data) and less biased parametrizations/errors

Calculation based on EPS09 nPDFs overshoots LHC data at forward rapidity:

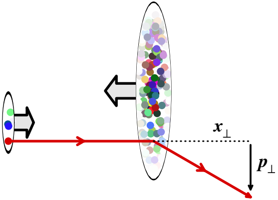


Better agreement with newer PDF sets having more gluon shadowing at small x

Color glass condensate

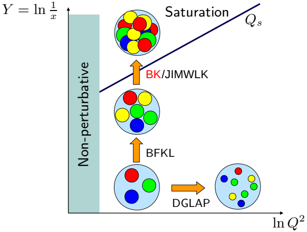
At very high energy the gluon density in hadrons becomes so large that one has to take into account not only gluon splitting  but also recombination 

One considers the eikonal interaction of a projectile (e.g. a large x parton coming from a proton) with the dense target which is described using classical color fields



- in the dilute proton: $x_1 = \frac{p_\perp}{\sqrt{s}} e^{y} \sim 1$
- in the dense nucleus: $x_2 = \frac{p_\perp}{\sqrt{s}} e^{-y} \ll 1$

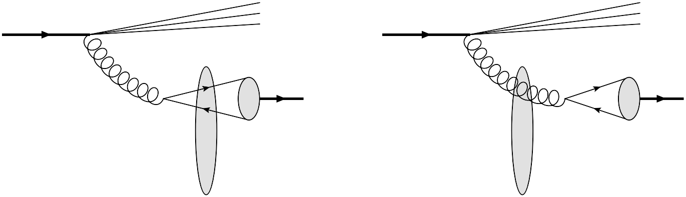
The evolution of the gluon density in the nucleus as a function of x is governed by the Balitsky-Kovchegov (BK) equation



Quarkonium production in the CGC: a large x gluon from the projectile proton can split into a heavy quark-antiquark pair either before or after the interaction with the dense target

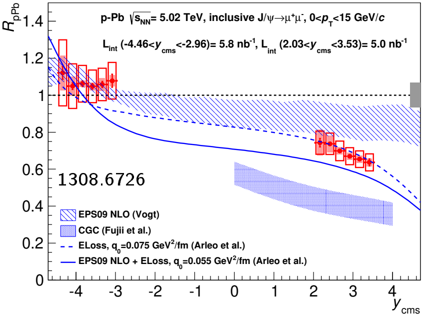
The state propagating through the target acquires some transverse momentum via multiple scatterings

Computed by Blaizot, Gelis, Venugopalan (2004)



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

First calculation of R_{pA} by Fujii, Watanabe (2013): overestimates the observed suppression at the LHC



The real prediction in this formalism is the rapidity dependence of R_{pA} which comes from the evolution of gluon densities when going to smaller x values, governed by the Balitsky-Kovchegov equation

A nucleus is more dense than a proton, therefore it is closer to saturation and its gluon density will grow slower with decreasing x (or increasing rapidity), leading to a decreasing $\sigma^{\mathsf{pA}}/\sigma^{\mathsf{pp}}$ (and thus R_{pA}) as a function of Y

The BK equation tells us how to go from an initial $x_0(\sim 0.01)$ to smaller x values

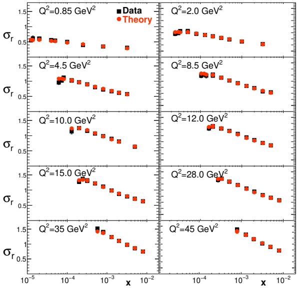
It doesn't say anything about the initial condition at x_0, which cannot be computed perturbatively

For a proton target (needed for the pp reference): the initial condition is usually obtained by a fit to HERA DIS data

But no similar data for nuclear targets

In their original calculation Fujii & Watanabe used the same initial condition as for a proton but with an initial saturation scale $Q^2_{s0,A} \sim A^{1/3} Q^2_{s0,p}$

This scaling is only approximate



AAMQS fit (arXiv:1012.4408)

Possible ways to constrain the initial condition of a nucleus:

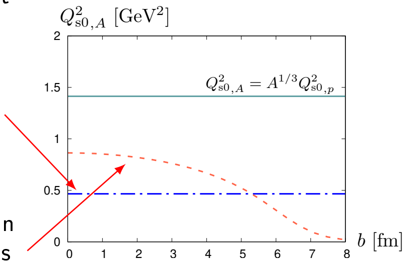
- Fit NMC data on the A dependence of F_2 at $x = 0.0125$

  Depending on the exact form of the initial condition, the data is described when taking $Q^2_{s0,A} \sim (0.25 - 0.5)\, A^{1/3} Q^2_{s0,p}$

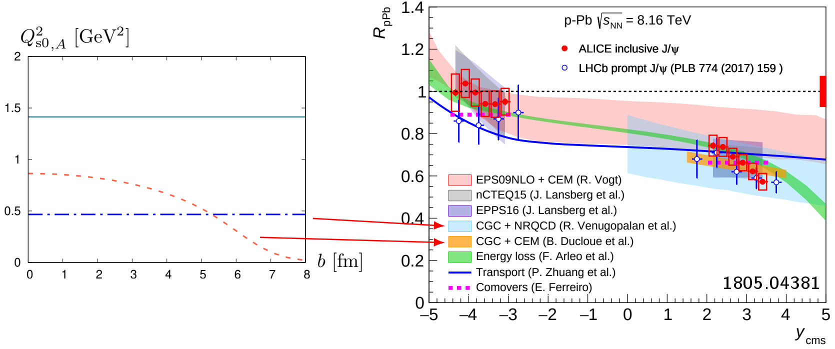
  Dusling, Gelis, Lappi, Venugopalan (2009)

- Optical Glauber model: the nuclear density in the transverse plane at the initial condition is given by the Woods-Saxon distribution $T_A(b)$

  Lappi, Mäntysaari (2013)

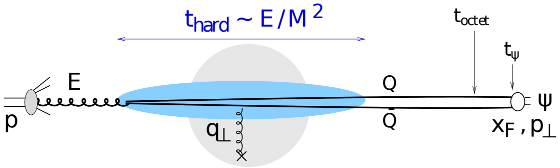


These two approaches lead to a much better agreement with data:



Arleo, Kolevatov, Peigné, Rustamova (2013)

For a state with a long formation time $t_f > L$ all scattering centers in the medium can act coherently



The medium-induced coherent radiation spectrum arises from the interference between gluon emission in the initial and final states: need a coloured final state

Leads to an energy loss $\Delta E \propto E$: important at high energy

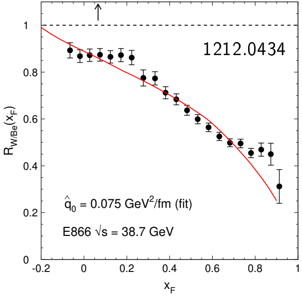
Different from the Landau-Pomeranchuk-Migdal (LPM) effect which applies to formation times smaller than the medium $t_f < L$

In this model the pA cross section reads

$$\frac{1}{A}\frac{\mathrm{d}\sigma^{\mathrm{pA}}}{\mathrm{d}E}(E) = \int_0^{\varepsilon_{\max}} d\varepsilon\, \mathcal{P}(\varepsilon, E)\, \frac{\mathrm{d}\sigma^{\mathrm{pp}}}{\mathrm{d}E}(E+\varepsilon)$$

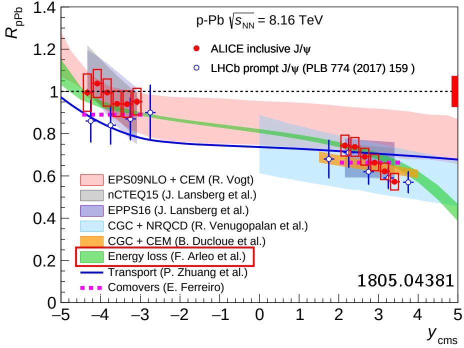
σ^{pp}: can be parametrized from experimental data

The probability distribution $\mathcal{P}$ depends on a single parameter $\hat{q}_0$ (transport coefficient) which can be fitted e.g. to E866 data:



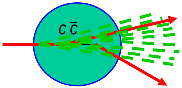
Using this only fitted parameter one can describe J/ψ suppression data in a wide range of kinematics

In particular this model gives a good agreement with LHC data at both backward and forward rapidity:



If coherent energy loss alone can explain the observed suppression, what about other processes, possibly not sensitive to this effect (colourless final states)?

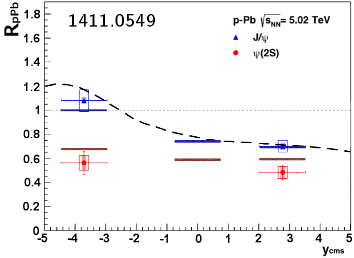
The produced quarkonium bound states can be destroyed by interacting with soft particles moving in the same direction (Not the same as nuclear absorption where the bound states are destroyed by scatterings inside the medium)



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

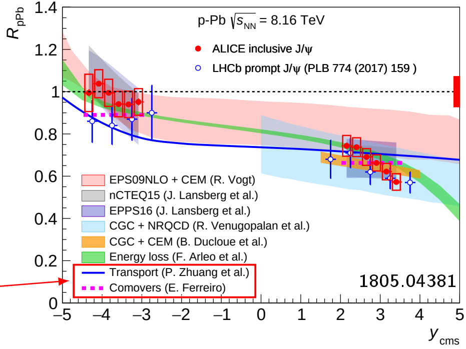
This leads to a different suppression for excited states and can explain (together with EPS09 shadowing) ALICE data on $\psi(2S)$ vs J/ψ (Ferreiro):



Models comparison

For now difficult to distinguish between various cold nuclear effects models

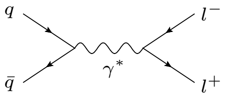
Note these include nPDF effects



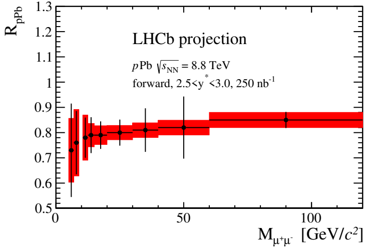
Need to study more processes and observables

Drell-Yan production

- Good perturbative control: no hadronization effects
- Not sensitive to coherent energy loss
- Constraints for nPDF and CGC models



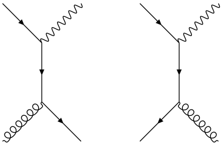
LHCb projections:



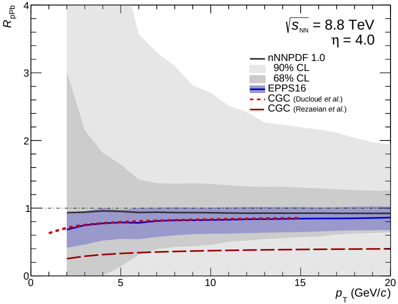
LHCb-CONF-2018-005

Significant suppression expected at low invariant mass, both from nPDFs (EPPS16) and CGC

- Also insensitive to hadronization and energy loss
- Sensitive to the gluon nPDF at LO in the collinear approach



Measurement expected by FoCal at ALICE



CERN-LHCC-2020-009

- Very different CGC predictions
- Recent CGC prediction very close to EPPS16 central result

Conclusions

- Quarkonium production in proton-nucleus collisions is an important probe of cold nuclear matter effects
- Several models can describe existing data
- Need more systematic approaches for some models (higher orders, theoretical uncertainties, inclusion of LHC data)
- Recent (LHCb light hadrons) and future (Drell-Yan, isolated photons) measurements of additional processes will provide crucial information to constrain models (and maybe invalidate some of them)
- Complementarity of LHC and EIC experiments