Nuclear effects on Quarkonia and Heavy Quarks

In collaboration with
Z. Conesa del Valle, E. G. Ferreiro, F. Fleuret, J. P. Lansberg & N. Matagne

Andry Rakotozafindrabe

ICHEP conference, July 2014 – Valencia (Spain)
A ride into the cold lands ...
A ride into the cold lands ...

- necessary to unravel hot (QGP) from cold effects
necessary to unravel hot (QGP) from cold effects

interesting on its own!

complex features, challenging for theories/models

- hidden vs open charm/beauty
- ground state vs excited state
- hadronised or pre-resonant state
- initial (shadowing ... ) or final-state effect (absorption ?)
Workflow: from pp to pA

- Quarkonia in pp
  - Partonic production
    - Process used as an input

- Quarkonia in pA
  - Estimate
    - CNM effects + uncertainties
p+p
CSM @ LO
$g + g \rightarrow \Upsilon + g$

CSM LO sufficient to describe $p_T$ integrated data

LO $g + g \rightarrow b + \bar{b}$ for $b$-quark production

J/$\psi$ from $b$ @ LHC

b-quarks prod. @ LHC

Good agreement with:

- data vs $y$
- other approaches at low $p_T$ of the $b$ quark

$\sqrt{s} = 7$ TeV

$\sqrt{s} = 14$ TeV

2.5 < $|y| < 4$


Z. Conesa del Valle, E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R.
arXiv:1402.1747
p+A
Large uncertainties for gluons:

- « qualitative » i.e. shape of the nPDF
  - antishadowing?
  - EMC effect / Fermi motion?
- « quantitative »
  - strength of the shadowing?
  - strength of the EMC effect

Initial-state effect measured in p(d)+A

\[ R_g^A = \frac{g \text{ PDF } \in \text{ bound nucleon}}{g \text{ PDF } \in \text{ free nucleon}} \]
$\gamma$ in dAu @ RHIC: gluon EMC effect

Let us focus in the **EMC region** and pick the EPS09 sets that are the limiting cases in this region:

$$R_{pA} = \frac{\sigma_{pA}}{\langle N_{coll}\rangle\sigma_{pp}}$$

**EMC effect stronger for $g$ than for $q$?**

E. G. Ferreiro, F. Fleuret, J. P. Lansberg, N. Matagne and A. R.
EPJ C (2013) 73:2427
\[ \gamma \ \text{in} \ \text{dAu} @ \ \text{RHIC} : \text{gluon EMC effect} \]

Let us focus in the **EMC region** and pick the EPS09 sets that are the limiting cases in this region:

**EMC effect stronger for g than for q?**

\[ \gamma \text{ in } dAu \oplus \text{RHIC : shadowing} \]

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\[ \gamma \text{ could be a nice tool to check antishadowing (still under debate)} \]
\[ \Rightarrow \text{ need much more precise data (AFTER@LHC ? see A.R.’s talk in the Accelerator Physics and Future Colliders session on July 3rd)} \]

Data:
STAR Preliminary, Nucl. Phys. A855 (2011) 440,

absence of antishadowing ?
(preliminary STAR data)

entering shadowing
**Y in dAu @ RHIC : antishadowing**

Final d+Au results from STAR


- Invariant mass for $|y|<0.5$
- Cross-section in $pp$ and $dAu$ vs $y$
- Too small uncertainties?
- Nuclear effects beyond shadowing and E loss?

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The pPb run @ LHC

\( \text{pPb } \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \)

🤔 No pp reference at the same \( \sqrt{s} \)

⇒ thorny procedures to get the interpolated pp cross-section (especially for the \( y \) and \( p_T \) dependence)

⇒ we propose to use in priority:

\[
\begin{align*}
R_{\text{FB}}(|y_{\text{c.m.}}|) & \equiv \frac{R_{\text{pPb}}(y_{\text{c.m.}})}{R_{\text{pPb}}(-y_{\text{c.m.}})} \\
R_{\text{CP}} & \equiv \frac{R_{\text{pPb}}^{0-20\%}}{R_{\text{pPb}}^{60-90\%}}
\end{align*}
\]

for e.g. \( J/\psi \): interpolation from 2.76 and 7 TeV data (ALICE), adding 8 TeV data (LHCb)

ALICE-PUBLIC-2013-002
LHCB-CONF-2013-013
Absorption can safely be considered as negligible. Focus on shadowing effects:

Experiments probe the shadowing and antishadowing regions. The interesting EMC region will be out of reach.
Absorption can safely be considered as negligible. Focus on shadowing effects:

Experiments probe the shadowing and antishadowing regions. The interesting EMC region will be out of reach. More precision needed at backward-y to conclude about antishadowing.
For the first time, measurement of $b$-quarks production at LHC in pA, using non-prompt $J/\psi$ down to $p_T = 0$. 
For the first time, measurement of $b$-quarks production at LHC in pA, using non-prompt $J/\psi$ down to $p_T = 0$.

The $b$-quark is a colored object. Arléo et al. : there should be a coherent energy loss.
The effect of the energy loss nearly cancels out in the forward / backward ratio.
$J/\psi$ in pPb @ LHC

Forward / backward

data: ALICE inclusive $J/\Psi$, JHEP 1402 (2014) 073
LHCb prompt $J/\Psi$, JHEP 1402 (2014) 072

E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R.
PRC 88 (2013) 047901
**J/ψ in pPb @ LHC**

Forward / backward

- **data**: ALICE inclusive J/Ψ, JHEP 1402 (2014) 073
- **LHCb prompt J/Ψ**, JHEP 1402 (2014) 072

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Our model: fair agreement with data.

E-loss: it would be interesting to add more observables (open heavy flavor), as in the beauty sector.
\[ J/\psi \text{ in } pPb \atop \text{@ LHC} \]

Fair agreement with the data

Alice
- box: correlated errors (partially + fully)
- bar: uncorrelated errors (stat. + syst.)

LHCb
only an overall syst. error was published
- bar: stat. + syst

data: ALICE inclusive \( J/\Psi \), JHEP 1402 (2014) 073
LHCb prompt \( J/\Psi \), JHEP 1402 (2014) 072

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The scale uncertainty must be added on top the EPS09 error evaluation.

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**J/ψ in pPb @ LHC**

centrality dependence

![Graphs showing centrality dependence of J/ψ in pPb collisions at LHC](image_url)

central / peripheral

At RHIC energies:

- **Backward-$y$ $\Upsilon$** data favours the presence of a **gluon EMC effect** (maybe stronger than the quark one)

At LHC energies:

- **For $J/\psi$, nPDF fits reproduce the data. No need for saturation?**
- **Scale uncertainty : large.** To be added to the uncertainties of the nPDFs.
- **Backward-$y$ $\Upsilon$ and non-prompt $J/\psi$ can be used to constrain the gluon antishadowing.** More data is needed.

- **Grain of salt : no pp cross section measured @ 5 TeV!**
$J/\psi$ vs in $\psi(2S)$ @ RHIC

EKS98  
EPS08  
nDSg

$\psi(2S)$ PHENIX preliminary data in dAu

ratio of the nuclear modif. $\psi(2S)$ over $J/\psi$

\[ t_f \sim r_{dAu} \quad \quad t_f \gg r_{dAu} \]

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E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R.
Double ratio of excited states to ground states @ LHC

L. Benhabib for CMS, HP2013

CMS Preliminary

\[ \frac{\Gamma(nS)/\Gamma(1S)}{\Gamma(3S)/\Gamma(1S)} \]

\[ \begin{array}{c}
pPb/pp \\
PbPb/pp
\end{array} \]

ALICE pPb @ 5 TeV

PHENIX dAu @ 0.2 TeV

LHCb

\[ R^{2S/1S}(-5.0 < y < -2.5) = 0.28 \pm 0.14 \pm 0.05, \]
\[ R^{3S/1S}(-5.0 < y < -2.5) = 0.02 \pm 0.09 \pm 0.02, \]
\[ R^{2S/1S}(1.5 < y < 4.0) = 0.20 \pm 0.05 \pm 0.01, \]
\[ R^{3S/1S}(1.5 < y < 4.0) = 0.07 \pm 0.04 \pm 0.01. \]

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\( \Upsilon \) in dAu @ RHIC: abs. effective x-section

\( \sigma_{\text{abs}} \) should be small:

- At \( \text{bkwd-}y, \ t_f < r_{Au} \), fully formed \( \Upsilon \).
- But no diff. exp. seen between \( \Upsilon(1S) \) and \( \Upsilon(2S+3S) \) \( \sigma_{\text{abs}} \).

- At \( y>0, \ t_f > r_{Au} \), same small-size pre-resonance for all \( \Upsilon \) states

\[ \sigma_\Upsilon \sim 0.1 \sigma_{J/\psi} \]

Uncertainty on abs. x-section (\( \leq 1 \text{ mb} \))

Uncertainty on gluon nPDF


Increasing \( t_f \) in the Au rest frame

- Propagating in Au:
  - Fully formed \( \Upsilon \)
  - Pre-resonant state \( \sigma_\Upsilon \sim \left( \frac{m_c}{m_b} \right)^2 \sigma_{J/\psi} \)

\( x_F = 0 \)
\( x_F \approx 0.28 \)

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Adding a $p_T$ cut (CMS acceptance):


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LO vs NLO EPS09:
The forward/backward ratio is much less sensitive to the absorption effect.
Shadowing computation

- in pA: quarkonia production cross-section e.g. modified by a shadowing correction factor:
  \[ R_g^A (x_2, Q^2) \]

- 4-mom conservation relates \((x_1, x_2)\) to quarkonia \((y, p_T)\)

- models (CEM, NRQCD, CSM ...) in p+p explain quarkonium prod. via various mechanisms, each with:
  - a given phase-space in \((x_1, x_2, y, p_T)\)
  - a given differential cross-section (weight) for each point in this phase-space

 tmpl_red {Different production models a priori results in different shadowings}
How prod. models can differ?

intrinsic scheme
2 → 1 process

\[ g + g \rightarrow \bar{c}c \text{ or } \bar{b}b \]

\[ x_{1,2} = \frac{m}{\sqrt{s_{NN}}} e^{\pm y} \]

- Handy: unequivocal correspondence
- \((x_1, x_2) \Leftrightarrow (y, p_T)\)

- Quarkonia \(p_T\) comes from initial partons
  - e.g. CEM LO

extrinsic scheme
2 → 2 process

\[ g + g \rightarrow \{J/\psi, \Upsilon\} + g \]

more degrees of freedom in the kinematics:

- several \((x_1, x_2) \Leftrightarrow (y, p_T)\)

\[ y, p_T, x_1 \Rightarrow x_2 = \frac{x_1 m_T \sqrt{s e^{-y} - M^2}}{\sqrt{s} (\sqrt{s x_1} - m_T e^y)} \]

- Quarkonia \(p_T\) is balanced by the outgoing gluon
  - e.g. CSM LO, COM LO

- Use reasonably good models in p+p to compute CNM effects in p+A, A+A
CNM effects at RHIC: $J/\psi$ in dAu

$$g + g \rightarrow c\bar{c} \quad g + g \rightarrow J/\psi + g$$

For a given $y$, $\langle x \rangle$ is larger in the $2 \rightarrow 2$ process.
$\sigma_{\text{abs}}(y)$ from Rcp in dAu @ 200 GeV

$\sigma_{\text{abs}}(y)$ much flatter for the $2\rightarrow 2$ process

$\sigma_{\text{abs}}(y)$ from Rcp in dAu @ 200 GeV

2→1 vs 2→2 prod. models:

nDSg

EKS98

EPSo8

[1] A. D. Frawley, INT, Seattle USA, June 2009


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The $p_T$ spectra in $p+p$ at RHIC

Andry Rakotozafindrabe (CEA Saclay)


Brodsky, Lansberg, PRD 81:051502 (R) (2010)
LHC (7 TeV): CSM in good agreement with data vs $p_T$.

CSM provides a good description of the direct production of both $\Upsilon(1S)$ and $\Upsilon(3S)$ states at low $p_T$.

LHCb Collaboration, arXiv 1202.6579.
Coherent energy loss

\[ t_f^{\text{gluon}} \gg r_{Au} \quad \Delta E / E = \Delta x_1 / x_1 \simeq N_c \alpha_s \sqrt{\Delta \langle p_T^2 \rangle} / M_T \]

Radiation off the incoming parton and outgoing colored object is coherent (small scattering angle in the rest frame of the nucleus)

Different E loss for CSM vs COM?
Max. E loss for octet.

\[ R_{\text{loss}}(x_1, Q^2) = \frac{g(x_1', Q^2)}{g(x_1, Q^2)} \]
Coherent energy loss

Procedure

1. Fit $\hat{q}_0$ from $J/\psi$ E866 data in p W collisions:
   $\hat{q}_0 = 0.075 \text{ GeV}^2/\text{fm}$

2. Predict $J/\psi$ and $\Upsilon$ suppression for all nuclei and c.m. energies

- Fe/Be ratio well described, supporting the $L$ dependence of the model

[F. Arleo, R. Kolevatov, S. Peigné, M. Rustamova, ECT* Trento, May 2013]