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

**Nuclear effects on Quarkonia and Heavy Quarks**

Andry Rakotozafindrabe

IS 2013, Sept. 12th, Illa da Toxa – Galicia (Spain)
A ride into the cold lands ...

International Conference on the Initial Stages in High-Energy Nuclear Collisions, Illa da Toxa, Galicia
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necessary to unravel hot (QGP) from cold effects
A ride into the cold lands ...

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?)

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Workflow: from pp to pA

- Quarkonia in pp
  - partonic production process used as an input

- Quarkonia in pA
  - estimate
  - CNM effects + uncertainties

2 → 2 process
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/ψ from b @ LHC

$b$-quarks prod. @ LHC


good agreement with:
- data vs $y$
- other approaches at low $p_T$ of the $b$ quark

Nuclear modification of $g(x)$

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

Ratio of nuclear struct. f. per nucleon:

$$R_g^A = \frac{g \text{ PDF} \in \text{bound nucleon}}{g \text{ PDF} \in \text{free nucleon}}$$

Initial-state effect measured in $p(d)+A$
Let us focus in the **EMC region** and pick the EPS09 sets that are the limiting cases in this region:

\[ R_{pA} = \frac{\sigma_{pA}}{\langle N_{\text{coll}} \rangle \sigma_{pp}} \]

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

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**E. G. Ferreiro, F. Fleuret, J. P. Lansberg, N. Matagne and A. R.**

**EPJ C (2013) 73:2427**
$\gamma$ 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:

**HKN disfavoured**

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

---

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$\Upsilon$ in dAu \@ RHIC : shadowing

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EPJ C (2013) 73:2427

$\Upsilon$ could be a nice tool to check antishadowing (still under debate) 
⇒ need much more precise data (AFTER\@LHC ? see talk by J.P. Lansberg)

absence of antishadowing ?

Data:
STAR Preliminary, Nucl. Phys. A855 (2011) 440,
The pPb run @ LHC

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

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

⇒ naively, we thought that it would be a source of a sizeable systematic error for \( R_{pPb} \)

(apparently, it is not the case, why ?)

⇒ we propose to use in priority :

\[
R_{\text{FB}} (|y_{\text{c.m.}}|) \equiv \frac{R_{pPb}(y_{\text{c.m.}})}{R_{pPb}(-y_{\text{c.m.}})}
\]

forward / backward

\[
R_{\text{CP}} \equiv \frac{R_{0-20\%}^{pPb}}{R_{60-90\%}^{pPb}}
\]

central / peripheral

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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.
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More precision needed at backward-\(y\) to conclude about antishadowing.
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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.

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For the first time, measurement of $b$-quarks production at LHC in pA, using non-prompt $J/\psi$ down to $p_T = 0$. 

data: LHCb non-prompt $J/\Psi$, arXiv:1308.6729
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

E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R.
arXiv:1305.4569

Forward / backward

data : ALICE inclusive $J/\Psi$, arXiv:1308.6726
LHCb prompt $J/\Psi$, arXiv:1308.6729
J/ψ in pPb @ LHC

Forward / backward

data: ALICE inclusive J/Ψ, arXiv:1308.6726
LHCb prompt J/Ψ, arXiv:1308.6729
Our model: fair agreement with data.

E-loss: need more observables (open heavy flavor?) to determine the size of the effect.
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/Ψ, arXiv:1308.6726
LHCb prompt J/Ψ, arXiv:1308.6729
**Fair agreement with the data**

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**Is the difference between ALICE and LHCb due to the pp interpolation or to prompt vs inclusive, or ...?**
Scale uncertainty

- What enters the evaluation is $R_g^A(x, \mu_F)$
- What value to take for $\mu_F$?
- In DIS, $\mu_F \leftrightarrow Q$ ($Q$ is measured).
- For quarkonia? $\mu_F = M, m_c, m_T$?

The scale uncertainty must be added on top the EPS09 error evaluation.
$J/\psi$ in pPb @ LHC

centrality dependence

$R_{pPb}$ vs $y_{c.m.}$ for different centrality intervals:
- Cent. 0-20 %
- Cent. 20-40 %
- Cent. 40-60 %
- Cent. 60-90 %

$pPb 5$ TeV

Models:
- EPS09 LO central set
- EPS09 LO min. EMC
- EPS09 LO max. EMC
- EPS09 LO min. shadowing
- EPS09 LO max. shadowing
- nDSg LO
central / peripheral
At RHIC energies:

- **Backward-γ ϒ** data favours the presence of a **gluon EMC effect** (maybe stronger than the quark one).

At LHC energies:

- **For J/ψ**, nPDF fits reproduce the data. **No need for saturation?**

- **Scale uncertainty**: large. To be added to the uncertainties of the nPDFs.

- **Backward-γ ϒ** and non-prompt J/ψ can be used to constrain the gluon antishadowing. **More data is needed.**

- **Grain of salt**: no pp cross section measured @ 5 TeV!
EXTRA SLIDES
Adding a $p_T$ cut (CMS acceptance):
**J/ψ in pPb @ LHC**

LO vs NLO EPS09:

![Graph](image)

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Adding absorption:

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

Different production models a priori results in different shadowings

Extrinsic scheme \(2 \rightarrow 2\) process
How prod. models can differ?

**Intrinsic scheme**

2 → 1 process

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

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

- 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
2→1 vs 2→2 prod. models:

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

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

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


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CSM LO
integrated cross section

\[ \frac{d\sigma_{J/\psi}^{\text{direct}}}{dy}|_{y=0} \times \text{Br} \ (\text{nb}) \]

\[ F_{J/\psi}^{\text{direct}} = 59 \pm 10 \% \]

LO gg CSM
PHENIX / CDF /ALICE data


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


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

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

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 $pW$ collisions:
   $\hat{q}_0 = 0.075 \text{ GeV}^2/\text{fm}$

2. Predict $J/\psi$ and $\gamma$ 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]
$J/\psi$ vs in $\psi(2S)$ @ RHIC

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

$t_f \sim r_{dAu}$  \hspace{1cm}  $t_f \gg r_{dAu}$

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EKS98

EPS08

nDSg

arXiv:1305.5516

ψ(2S) final data : arXiv:1305.5516
$\Upsilon$ in dAu @ RHIC: abs. effective x-section

$\sigma_{\text{abs}}$ should be small:

- At 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 ($\leq 1$ mb)
Uncertainty on gluon nPDF

Increasing $t_f$ in the Au rest frame

Propagating in Au:

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

$x_F = 0 \quad x_F \sim 0.28$


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