Probing cold nuclear matter effects with quarkonium and DY production

François Arleo

LLR Palaiseau

Second LHCb Heavy Ion Workshop

Chia, Sardegna, Italia – Settembre 2019
Outline

- Probing **fully coherent energy loss** with quarkonia at all energies
- Probing **LPM energy loss** with DY at fixed-target energies
- Probing **nPDF** with DY at LHC
- Probing **transverse momentum broadening** with quarkonia and DY

References

- FA, C. Naïm, S. Platchkov, [1810.05120](http://arxiv.org/abs/1810.05120)
- FA, S. Peigné, [1512.01794](http://arxiv.org/abs/1512.01794)
- FA, C. Naïm, in preparation
ALICE and LHCb measured $J/\psi$ production in pPb collisions at 5 TeV

\[ R_{pA}(y) \equiv \frac{1}{A} \frac{d\sigma_{pA}}{dy} / \frac{d\sigma_{pp}}{dy} \]

- Rather strong suppression at forward rapidity
- No (or modest) nuclear modification at backward rapidity
ALICE and LHCb measured $J/\psi$ production in pPb collisions at 5 TeV

$$R_{pA}(y) \equiv \frac{1}{A} \frac{d\sigma_{pA}}{dy} \Big/ \frac{d\sigma_{pp}}{dy}$$

- Rather strong suppression at forward rapidity
- No (or modest) nuclear modification at backward rapidity
ALICE and LHCb measured $J/\psi$ production in pPb collisions at 5 TeV

Possible explanations

- Shadowing of nuclear parton distribution functions (nPDF)
- Coherent energy loss in nuclear matter
- ...or both (not mutually exclusive)

Note: nPDF calculations fail to reproduce $J/\psi$ suppression pA data due to lack of $x_2$ scaling → another effect at work to be understood
ALICE and LHCb measured $J/\psi$ production in pPb collisions at 5 TeV

Possible explanations:
- Shadowing of nuclear parton distribution functions (nPDF)
- Coherent energy loss in nuclear matter
... or both (not mutually exclusive)

Note: nPDF calculations fail to reproduce $J/\psi$ suppression pA data due to lack of $x_2$ scaling

\begin{itemize}
\item $\sqrt{s} = 19$ GeV (NA3)
\item $\sqrt{s} = 39$ GeV (E866)
\item $\sqrt{s} = 200$ GeV (PHENIX)
\item $\sqrt{s} = 5$ TeV (ALICE)
\item $\sqrt{s} = 8$ TeV (LHCb)
\end{itemize}
Context

ALICE and LHCb measured $J/\psi$ production in pPb collisions at 5 TeV

Possible explanations
- Shadowing of nuclear parton distribution functions (nPDF)
- Coherent energy loss in nuclear matter
- ... or both (not mutually exclusive)

Note: nPDF calculations fail to reproduce $J/\psi$ suppression pA data due to lack of $x_2$ scaling → another effect at work to be understood

Issue
- Large uncertainties do not allow for precise predictions of nPDF effects on $J/\psi$ at LHC (even more true with EPPS16)
- Then, how to disentangle the effects of nPDF v. energy loss?
Energy loss-es

On top of momentum broadening, parton multiple scattering in nuclei induces gluon radiation $\rightarrow$ energy loss in cold nuclear matter

\[ E \rightarrow E - \epsilon \]
Initial/final state energy loss

LPM regime, small formation time \( t_f \ll L \)

\[ \Delta E_{\text{LPM}} \propto \alpha_s \hat{q} L^2 \log(E) \]

- Energy dependence at most logarithmic
- Best probed in
  - Hadron production in nuclear semi-inclusive DIS
  - Drell-Yan in pA collisions at low energy
- Should be negligible in pA at the LHC
  - Fractional energy loss \( \Delta E_{\text{LPM}}/E \sim 1/E \ll 1 \)
  - ... could play a role in fixed target experiments! (see later)
Fully coherent energy loss

Interference between initial and final state, large formation time $t_f \gg L$

\[ \Delta E_{\text{coh}} \propto \alpha_s \frac{\sqrt{\hat{q} L}}{M_\perp} E \quad (\gg \Delta E_{\text{LPM}}) \]
Fully coherent energy loss

Interference between initial and final state, large formation time \( t_f \gg L \)

\[ \Delta E_{\text{coh}} \propto \alpha_s \frac{\sqrt{\hat{q} L}}{M_\perp} E \left( \gg \Delta E_{\text{LPM}} \right) \]

- Important at all energies, especially at large rapidity

- Needs color in both initial & final state
  - no effect on W/Z nor Drell-Yan, no effect in DIS

- Hadron production in pA collisions
  - applied to quarkonia
  - light hadrons currently investigated

- Power suppressed: negligible when \( M_\perp \gg \sqrt{\hat{q}L} \)
  - weaker effects on \( \Upsilon \), let alone on jets
Parton energy loss in hard processes

Drell-Yan process: $hA \rightarrow \ell^+\ell^- + X$
- Initial state LPM energy loss

Hadrons in SIDIS: $eA \rightarrow e + h + X$
- Final LPM energy loss

Hadrons in $hA$: $hA \rightarrow q/g(\rightarrow h') + X$
- Initial/final state interference fully coherent energy loss
Probing fully coherent energy loss with quarkonia
Comparing to low energy pA and $\pi$A data

Simple fully coherent energy loss model able to solve the longstanding issue of $J/\psi$ forward suppression pA data

[FA Peigné, 1212.0434]

- Good agreement with E866, NA3, NA60, HERA-B data
- no nPDF global fit can explain these data
RHIC predictions ($\sqrt{s} = 200$ GeV)

- Good agreement for $R_{pA}$ vs rapidity
- Small uncertainty coming from the variation of the pp cross section and the transport coefficient
LHC predictions ($\sqrt{s} = 5$ TeV)

- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$
- Smaller suppression expected in the $\Upsilon$ channel
LHC predictions ($\sqrt{s} = 5$ TeV)

- Very good agreement with ALICE and LHCb results, despite large uncertainty on normalization
- Data at $y \gtrsim 4$ would be helpful
Suppression could already be seen even at $y = 1$

Enhancement (?) at negative rapidity

- although beyond the validity domain of the model
Probing LPM energy loss with Drell-Yan
Probing LPM energy loss with Drell-Yan

- Drell-Yan is sensitive to LPM energy loss
  - sensitivity only at low energy!
  - COMPASS/E906 ideal in this respect

- NA3 data (1983!) allow to set constraints on the amount of $\hat{q}$
  [FA, hep-ph/0201066]

- More precise data on a large $x_F$ range would help

Naïm, Thu 5, 10:00
Probing LPM energy loss with Drell-Yan

- Drell-Yan is sensitive to LPM energy loss
  - sensitivity only at low energy!
  - COMPASS/E906 ideal in this respect

Recent analysis

- Drell-Yan cross section at NLO
- $\mathcal{P}(\epsilon)$: quenching weight related to the LPM gluon spectrum
- $\hat{q}_0 = [0.07 - 0.09]$ GeV$^2$/fm fixed $\rightarrow$ no free parameter in the model!
Comparison with E906 preliminary data

- Clear disagreement with nPDF expectations
- Qualitative agreement of energy loss shape and E906
  - First hints of energy loss in DY data
Violation of QCD factorization in DY

Factorization leads to $x_2$ scaling: $R_{pA}^{DY} = R_{pA}(x_2, \sqrt{s}) = R_{pA}(x_2)$

- No $x_2$ scaling between E866/E772 and E906 data
- Violation of QCD factorization in DY in pA collisions at low energy
Visible effect (∼10%) beyond isospin corrections
- Almost as large as nPDF (nCTEQ) effects
- Need to be taken into account for clean nPDF extraction
Probing nPDF with Drell-Yan
Which processes?

Naively all hard processes, especially at rather low $Q^2$!

Particularly within easy reach in LHCb

- **Heavy-quarkonia ($\psi$, $\Upsilon$)**
  - including exciting states

- **Open heavy-flavour**
  - D, B, ... and non-prompt $J/\psi$

- **Drell-Yan** at rather low mass $M = \mathcal{O}(10 \text{ GeV})$

What makes these observables & LHCb that interesting?

- Small masses & forward acceptance (small $x$)
  - access to the saturation region, $M \gtrsim Q_s \propto x^{-\alpha}$, where shadowing is expected to be maximal
Which processes?

Naively all hard processes, especially at rather low $Q^2$!

Problem: significant energy loss effects expected on all hadrons

How to reliably extract nPDF in pA collisions?

- Include energy loss effects in nPDF global fit analyses
  - Tempting, but ambitious (and vice versa)
- Focus on color neutral final states
  - Drell-Yan, weak bosons, diphotons
- Focus on color neutral initial state
  - Ultra-peripheral collisions

FA Peigné, in preparation

Goncalves, Fri 6, 10:35
Drell-Yan at LHC

A golden probe of sea quark (and gluon) shadowing

- Low scale $Q \sim 10$ GeV can be reached
  - better than weak bosons, jets, prompt photons
  - mass can be varied
- Very well understood in QCD
  - better than light or heavy hadron production
Shadowing effects on DY

- Forward DY sensitive to sea antiquark shadowing: \( q^p \bar{q}^A \rightarrow \gamma^* \)
- Sea antiquark and gluon shadowing pretty similar (EPS09, nCTEQ15)

\[
\begin{align*}
R_{\psi}(x, Q=10 \text{ GeV}) &\quad \text{DSSZ} \quad \text{EPS09} \quad \text{nCTEQ15} \\
R_{\psi}(x, Q=3 \text{ GeV}) &\quad \text{DSSZ} \quad \text{EPS09} \quad \text{nCTEQ15}
\end{align*}
\]

nPDF \( R^\psi \simeq R^{\text{DY}} \) \( \Rightarrow R^\psi / R^{\text{DY}} \equiv R^\psi / R^{\text{DY}} \simeq 1 \)
Shadowing effects on DY

- Forward DY sensitive to sea antiquark shadowing: $q^p \bar{q}^A \rightarrow \gamma^*$
- Sea antiquark and gluon shadowing pretty similar (EPS09, nCTEQ15)

\[ nPDF \quad R^\psi \simeq R^{DY} \]
\[ R^\psi < 1 \; ; \; R^{DY} \gtrsim 1 \]
\[ \rightarrow R^{\psi/DY} \simeq 1 \]
\[ \rightarrow R^{\psi/DY} < 1 \]
Comparing $J/\psi$ and DY

- As expected, qualitatively similar shadowing effects on $J/\psi$ and DY using EPS09 and nCTEQ15 (unlike DSSZ)
- Noticeable isospin effects in the Pb fragmentation region ($y < 0$)
Spectacular difference between shadowing and coherent energy loss

Significantly reduced nPDF uncertainty because of the correlation between gluon and sea quark nPDF individual sets
This observable should clarify the respective role of both effects.

- LHCb appears to be the best experiment in this respect.
  - Around 1000 pairs in $2.5 < y < 4$ using $\mathcal{L}_{\text{int}} = 15$ nb$^{-1}$
Probing multiple scattering with quarkonia and DY
\( p_\perp \) broadening as a probe for transport coefficient

\[
\Delta p_\perp^2 = \langle p_\perp^2 \rangle_{hA} - \langle p_\perp^2 \rangle_{hp} = \hat{q}(x)L
\]

- At high energy

\[
\hat{q}(x) = \frac{4\pi^2\alpha_s N_c}{N_c^2 - 1}\rho xG(x)
\]
Goals

- Independent extraction of the transport coefficient
- Check consistency between radiative energy loss and $p_\perp$ broadening
- Probe $x$ dependence of the gluon distribution and saturation scale

World data analysis in hA collisions

- From SPS to LHC
- Drell-Yan, $J/\psi$, $\Upsilon$ data
  - Probing different color states

[FA Naïm, in preparation]
### Data analysed

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Beam</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Process</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA3</td>
<td>p</td>
<td>19.3</td>
<td>$J/\psi$</td>
<td>Pt</td>
</tr>
<tr>
<td></td>
<td>π⁻</td>
<td>16.7/19.3/22.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>π⁺</td>
<td>19.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA10</td>
<td>π⁻</td>
<td>16.2/23.1</td>
<td>DY</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23.1</td>
<td>$J/\psi$</td>
<td></td>
</tr>
<tr>
<td>E772</td>
<td>p</td>
<td>38.7</td>
<td>DY</td>
<td>Ca, Fe, W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\Upsilon$</td>
<td>Ca, Fe, W</td>
</tr>
<tr>
<td>RHIC</td>
<td>d</td>
<td>200</td>
<td>$J/\psi$</td>
<td>Au</td>
</tr>
<tr>
<td>ALICE</td>
<td>p</td>
<td>5020</td>
<td>$J/\psi$</td>
<td>Pb</td>
</tr>
<tr>
<td>LHCb</td>
<td>p</td>
<td>8160</td>
<td>$J/\psi$</td>
<td>Pb</td>
</tr>
</tbody>
</table>
Colorimetry

Broadening depends on initial and final Casimir color factors

$$\Delta p^2_\perp = \frac{C_R + C_{R'}}{2N_c} (\hat{q}_A L_A - \hat{q}_p L_p)$$

<table>
<thead>
<tr>
<th>Process</th>
<th>Collision</th>
<th>$C_R + C_{R'}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drell-Yan</td>
<td>$\pi$ A</td>
<td>$C_F$</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>$p$ A</td>
<td>$C_F$</td>
</tr>
<tr>
<td>Quarkonium</td>
<td>$\pi$ A</td>
<td>$C_F + N_c$</td>
</tr>
<tr>
<td>Quarkonium</td>
<td>$p$ A</td>
<td>$N_c + N_c$</td>
</tr>
</tbody>
</table>
Scaling

![Graph showing the relationship between $\Delta \langle p_T^2 \rangle$ and $F_C (\bar{q}_A L_A - \bar{q}_p L_p)$ with data points for various experiments and theoretical expectations.]

- Simple model used
  \[ \hat{q}_g(x) = \hat{q}_0 \left( \frac{10^{-2}}{x} \right)^{0.25} \]

- Linear scaling according to expectations

- Extraction of $\hat{q}_0$
  \[ \hat{q}_0 = 0.050 \pm 0.002 \text{ GeV}^2/\text{fm} \]
Extraction of transport coefficient for each experiment

\[ \bar{q}_0 = (0.051 \pm 0.001) \text{ GeV}^2/\text{fm} \]

- Good consistency within all data points
  - Universal transport coefficient
- Consistent with \( \hat{q} \) from coherent energy loss
Summary

DY and quarkonia versatile tools to investigate cold nuclear matter effects

- Fully coherent energy loss successfully reproduce quarkonium world data in nuclear collisions

- LPM energy loss probed in DY production at low energy
  - First evidence in E906 data

- nPDF best probed in
  - color neutral final states (DY and weak bosons)
  - DIS or UPC events

- Multiple scattering and $p_{\perp}$ broadening
  - Scaling observed from low to high energy
  - Consistency between broadening and energy loss