Heavy-quarkonium suppression in p-A collisions from parton energy loss in cold QCD matter

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Motivations

- $J/\psi$ suppression data in p A collisions
- New scaling properties from medium-induced coherent radiation

Phenomenology

- Model for $J/\psi$ and $\Upsilon$ suppression in p A collisions
- Comparison with data and LHC predictions

References

- FA, S. Peigné, PRL 109 (2012) 122301 [1204.4609]
- FA, S. Peigné, JHEP 03 (2013) 122 [1212.0434]
- FA, R. Kolevatov, S. Peigné, M. Rustamova, JHEP 05 (2013) 155 [1304.0901]
Data on $J/\psi$ suppression in p A collisions

**E866** $\sqrt{s} = 38.7$ GeV

- Strong $J/\psi$ suppression reported at large $x_F$ and $y$
- Weaker suppression in the Drell-Yan process

**PHENIX** $\sqrt{s} = 200$ GeV
Interpretations

Many explanations suggested... yet none of them fully satisfactory

- Nuclear absorption
- nPDF effects and saturation
- Parton energy loss
  - requires $\Delta E \propto E$ ... supposedly ruled out
Revisiting energy loss scaling properties

**Coherent radiation (interference) in the initial/final state**

\[
\Delta E = \int d\omega \omega \left. \frac{dI}{d\omega} \right|_{\text{ind}} = N_c \alpha_s \frac{\sqrt{\Delta q_{\perp}^2}}{M_{\perp}} E
\]

- IS and FS radiation cancels out in the **induced** spectrum
- Interference terms do not cancel in the **induced** spectrum!
- Induced gluon spectrum dominated by **large formation times**
(intermediate) Summary

- **Incoherent energy loss** (small formation time $t_f \sim L$)
  \[ \Delta E \propto \alpha_s \hat{q} L^2 \]
  - prompt photons, Drell-Yan, weak bosons
  - should be negligible at LHC
  - important in hot media

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  - important at all energies, especially at large rapidity
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Back to the Future: listen to Stéphane’s talk this morning (10am)
Phenomenology

Goal

- Explore phenomenological consequences of coherent energy loss
- Approach as simple as possible with the least number of assumptions
- Observable: $J/\psi$ and $\Upsilon$ suppression in p A collisions
  - rapidity and transverse momentum dependence
  - compare to all available data
  - making predictions for p Pb collisions at the LHC
Model for heavy-quarkonium suppression

Physical picture and assumptions

- Color neutralization happens on long time scales: $t_{\text{octet}} \gg t_{\text{hard}}$
- Hadronization happens outside of the nucleus: $t_\psi \gtrsim L$
- $c\bar{c}$ pair produced by gluon fusion
- Medium rescattering do not resolve the octet $c\bar{c}$ pair
Model for heavy-quarkonium suppression

Energy shift

\[
\frac{1}{A} \frac{d\sigma_{\psi}^{pA}}{dE}(E, \sqrt{s}) = \int_0^{\varepsilon_{\text{max}}} d\varepsilon \, \mathcal{P}(\varepsilon, E) \frac{d\sigma_{\psi}^{pp}}{dE}(E + \varepsilon, \sqrt{s})
\]

Ingredients

- pp cross section fitted from experimental data
- Length \( L \) given by Glauber model
- \( \mathcal{P}(\varepsilon) \): probability distribution (quenching weight)
Quenching weight

- Usually one assumes independent emission $\rightarrow$ Poisson approximation

$$
\mathcal{P}(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} \int d\omega_i \frac{dl(\omega_i)}{d\omega} \right] \delta \left( \epsilon - \sum_{i=1}^{n} \omega_i \right)
$$

- However, radiating $\omega_i$ takes time $t_f(\omega_i) \sim \omega_i/\Delta q^2 \gg L$

  For $\omega_i \sim \omega_j \Rightarrow$ emissions $i$ and $j$ are not independent

- For self-consistency, constrain $\omega_1 \ll \omega_2 \ll \ldots \ll \omega_n$

  $$
P(\epsilon) \simeq \frac{dl(\epsilon)}{d\omega} \exp \left\{ - \int_{\epsilon}^{\infty} d\omega \frac{dl}{d\omega} \right\}
$$

- $\mathcal{P}(\epsilon)$ scaling function of $\hat{\omega} = \sqrt{\hat{q}L/M} \times E$
Transport coefficient

$\hat{q}$ related to gluon distribution in a proton

\[\hat{q}(x) = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \rho x G(x, \hat{q}L)\]

Typical value for $x$

- $t_{\text{hard}} \lesssim L$: $x = x_0 \approx (m_N L)^{-1} \rightarrow \hat{q}(x) = \text{constant}$
- $t_{\text{hard}} > L$: $x \approx x_2 \rightarrow \hat{q}(x) \propto x^{-0.3}$

For simplicity we assume

\[\hat{q}(x) = \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3} \quad x = \min(x_0, x_2)\]

- $\hat{q}_0 \equiv \hat{q}(x = 10^{-2})$ only free parameter of the model
- $\hat{q}(x)$ related to the saturation scale: $Q_s^2(x, L) = \hat{q}(x)L$
Procedure

1. Fit $\hat{q}_0$ from $J/\psi$ E866 data in p W collisions
2. Predict $J/\psi$ and $\Upsilon$ suppression for all nuclei and c.m. energies

\[ \hat{q}_0 = 0.075 \text{ GeV}^2/\text{fm} \]

- Corresponds to $Q_s^2(x = 10^{-2}) = 0.11 - 0.14 \text{ GeV}^2$ consistent with fits to DIS data

[ Albacete et al AAMQS 2011 ]
## Procedure

1. Fit $\hat{q}_0$ from $J/\psi$ E866 data in p W collisions
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
1. Fit $\hat{q}_0$ from $J/\psi$ E866 data in $pW$ collisions
2. Predict $J/\psi$ and $\Upsilon$ suppression for all nuclei and c.m. energies

Let’s investigate $J/\psi$ suppression at other energies
Experimental $J/\psi$ Hadronic Production from 150 to 280 GeV/c

NA3 Collaboration

J. Badier$^4$, J. Boucrot$^5$, J. Bourotte$^4$, G. Burgun$^1$, O. Callot$^5$, Ph. Charpentier$^1$, M. Crozon$^3$, D. Decamp$^5$, P. Delpierre$^3$, B. Gandois$^1$, R. Hagelberg$^2$, M. Hansroul$^2$, Y. Karyotakis$^4$, W. Kienzle$^2$, P. Le Dû$^1$, J. Lefrançois$^5$, Th. Leray$^3a$, J. Maillard$^3$, A. Michelini$^2$, Ph. Miné$^4$, G. Rahal$^{1b}$, O. Runolfssson$^2$, P. Siegrist$^1$, A. Tilquin$^3$, J. Timmermans$^{2c}$, J. Valentin$^3$, S. Weisz$^4$

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Table 2. Number of $J/\psi$ events obtained in this experiment

| Momentum (GeV/c) | Target | $\pi^+$ | $K^+$ | $p$   | $\pi^-$ | $K^-$ | $\bar{p}$ |
|-----------------|--------|--------|-------|-------|--------|-------|---------|
| 200             | $H_2$  | 2,407  | 359   | 2,227 | 3,157  |       |         |
| 200             | $Pt$   | 104,866| 14,690| 80,786| 131,062| 1,963 | 657     |
| 150             | $H_2$  | 207    |       |       |        | 16,952| 487     | 208     |
| 150             | $Pt$   | 7,937  | 442   | 3,453 | 601,691| 19,190| 6,569   |
| 280             | $H_2$  |       |       |       | 23,350 |       |         |
| 280             | $Pt$   |       |       |       | 511,457|       |         |
Agreement when $x_F > x_F^{\text{hadro}}$ (and even below)

Natural explanation from the different suppression in p A vs π A

Little room for $J/\psi$ absorption, weaker than previously thought
HERA-B predictions

Also good agreement in the nuclear fragmentation region ($x_F < 0$)

Enhancement predicted at very negative $x_F$
Good agreement at all rapidity

Saturation/shadowing effects could improve the agreement
$p_\perp$ dependence

Most general case

$$\frac{1}{A} \frac{d\sigma_{p^A}}{dE \, d^2 \vec{p}_\perp} = \int_\varepsilon \int_\varphi \mathcal{P}(\varepsilon, E) \frac{d\sigma_{pp}}{dE \, d^2 \vec{p}_\perp} (E + \varepsilon, \vec{p}_\perp - \Delta \vec{p}_\perp)$$

- pp cross section fitted from experimental data
- Overall depletion due to parton energy loss
- Possible Cronin peak due to momentum broadening

$$R_{p^A}^\psi (y, p_\perp) \simeq R_{p^A}^{\text{loss}} (y, p_\perp) \cdot R_{p^A}^{\text{broad}} (p_\perp)$$
$p_{\perp}$ dependence at E866

- Good description of E866 data (except at large $p_{\perp}$ and large $x_F$)
- Broadening effects only not sufficient to reproduce the data
Good description of $p_{\perp}$ and centrality dependence at $y = -1.7$.
\( p_\perp \) dependence at RHIC

\[ y = [-0.35 ; 0.35] \]

- Good description of \( p_\perp \) and centrality dependence at \( y = 0 \)
$p_{\perp}$ dependence at RHIC

$y = [1.2 ; 2.2]$

- Good description of $p_{\perp}$ and centrality dependence at $y = 1.7$. 

Francois Arleo (LAPTh & LLR)
LHC predictions

- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$
- Slightly smaller suppression expected in the $\Upsilon$ channel
Comparison with ALICE preliminary data

\[ R_{pA}(y) \]: good agreement despite large uncertainty on normalization
Comparison with ALICE preliminary data

- No pp data at 5 TeV needed → smaller uncertainty
- Predictions with only nPDF underestimate the suppression
- Excellent agreement between data and “energy loss + EPS09”
Comparison with ALICE preliminary data

No pp data at 5 TeV needed → smaller uncertainty
Predictions with only nPDF underestimate the suppression
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Comparison with ALICE preliminary data

- \( R_{FB}(p_{\perp}) \): good agreement, better agreement with energy loss supplemented by shadowing
Comparison with LHCb preliminary data

- Similar results by LHCb

[ LHCb 1308.6729 ]
Summary

- Energy loss $\Delta E \propto E$ due to coherent radiation
  - Neither initial nor final state effect
  - Parametric dependence of $dl/d\omega$ and $\Delta E$ predicted

- Heavy-quarkonium suppression predicted from SPS to LHC
  - Good agreement with all existing data vs. $y$ and $p_\perp$
  - Natural explanation for the large $x_F$ $J/\psi$ suppression
  - Supports the assumption of long-lived color octet $Q\bar{Q}$ pairs
  - Predictions in good agreement with LHC p Pb preliminary data