Heavy-quarkonium suppression in p A collisions from induced gluon radiation

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Motivations
- \( J/\psi \) suppression data in p A collisions

Revisiting energy loss
- 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, T. Sami, 1006.0818
- FA, S. Peigné, 1204.4609 + in preparation
Strong J/$\psi$ suppression reported at large $x_F$ and $y$
Weaker suppression in the Drell-Yan process
Observed at various $\sqrt{s}$
J/$\psi$ suppression in p A collisions

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

- Nuclear absorption
  - requires unrealistically large cross section
- nPDF effects and saturation
  - constrained by Drell-Yan
- Intrinsic charm
  - assuming a large amount of charm in the proton
- Parton energy loss
  - requires $\Delta E \propto E$ ... supposedly ruled out
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This talk: revisiting energy loss processes
Gavin–Milana model

Simple model assuming (mean) energy loss scaling like parton energy

$$\Delta E \propto E \ L \ M^{-2}$$

for both Drell-Yan and J/ψ (though larger due to final-state energy loss)

Caveats

- Ad hoc assumption regarding $E$, $L$, and $M$ dependence of parton energy loss, no link with induced gluon radiation
- Failure to describe $\Upsilon$ suppression
- $\Delta E \propto E$ claimed to be incorrect in the high energy limit due to uncertainty principle — so-called Brodsky-Hoyer bound
Induced gluon radiation needs to resolve the medium \[ t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \quad \omega \lesssim k_\perp^2 L \sim \hat{q} L^2 \]

- Bound independent of the parton energy
- Energy loss cannot be arbitrarily large in a finite medium
- Apparently rules out energy loss models as a possible explanation

However
- Not necessarily true in QCD

[ FA Peigné Sami 10 ]
Two cases whether gluon radiation is coherent or incoherent

(i) Incoherent radiation in the initial/final state

Radiation of gluons with large formation times cancels out in the induced gluon spectrum, leading to $t_f \sim L$

$$\Delta E \propto \hat{q}L^2$$

- Hadron production in nuclear DIS and Drell-Yan in $pA$ collisions
- Jets and hadrons produced in hadronic collisions at large angle
Two cases whether gluon radiation is coherent or incoherent

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

Induced gluon spectrum dominated by large formation times

\[ \Delta E \propto \sqrt{qL} E \]

- Production of light and open heavy-flavour hadrons at forward rapidities in the medium rest frame (nuclear matter or QGP)
- Production of heavy-quarkonium if color neutralisation occurs on long time-scales \( t_{\text{octet}} \gg t_{\text{hard}} \)
Medium-induced gluon spectrum

Gluon spectrum $dl/d\omega \sim$ Bethe-Heitler spectrum of massive (color) charge

$$\frac{dl}{d\omega}\bigg|_{\text{ind}} = \frac{N_c\alpha_s}{\pi} \left\{ \ln \left( 1 + \frac{E^2\Delta q^2_\perp}{\omega^2 M^2_\perp} \right) - \ln \left( 1 + \frac{E^2\Lambda^2_{\text{QCD}}}{\omega^2 M^2_\perp} \right) \right\}$$

$$\Delta E = \int d\omega \omega \frac{dl}{d\omega}\bigg|_{\text{ind}} = N_c\alpha_s\frac{\sqrt{\Delta q^2_\perp - \Lambda^2_{\text{QCD}}}}{M_\perp} E$$

- $\Delta E \propto E$ neither initial nor final state effect nor ‘parton’ energy loss: arises from coherent radiation
- Physical origin: broad $t_f$ interval: $L, t_{\text{hard}} \ll t_f \ll t_{\text{octet}}$ for medium-induced radiation
Model for heavy-quarkonium suppression

\[
\frac{d\sigma_{\psi}^{pA}}{dx_F}(x_F, \sqrt{s}) = \int_{0}^{\epsilon_{\text{max}}} d\epsilon \, P(\epsilon) \frac{d\sigma_{\psi}^{pp}}{dx_F}(x_F + \delta x_F(\epsilon))
\]

- pp cross section fitted from experimental data

\[
\frac{d\sigma_{\psi}^{pp}}{dx_F} \propto (1 - x')^{n(\sqrt{s})} / x' \quad x' \equiv \sqrt{x_F^2 + 4M_{\perp}^2 / s}
\]

- Shift given by \( \delta x_F(\epsilon) \approx \epsilon / E_{\text{beam}} \)
- \( P(\epsilon) \): quenching weight, scaling function of \( \hat{\omega} = \sqrt{qL / M_{\perp}} \times E \)
- Length \( L \) given by \( L = 3/2 \, r_0 \, A^{1/3} \)
Quenching weight

- Poisson approximation assuming independent emission [BDMS 2001]

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

- However, radiating \( \omega_i \) takes time \( t_f(\omega_i) \sim \omega_i / \Delta q_{\perp}^2 \gg L \)

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

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

\[ P(\epsilon) \sim \frac{dl(\epsilon)}{d\omega} \exp \left\{ - \int_{\epsilon}^{\infty} d\omega \frac{dl}{d\omega} \right\} \]
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 \( x \)

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

For simplicity we assume

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

\( \hat{q}_0 \) only free parameter of the model
Procedure

1. Fit $\hat{q}_0$ from $J/\psi$ suppression E866 data in $pW$ collisions
2. Predict $J/\psi$ and $\Upsilon$ suppression for all nuclei and c.m. energies
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Fe/Be ratio well described, supporting the $L$ dependence of the model

$\hat{q}_0 = 0.09$ GeV$^2$/fm
Procedure

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Let’s investigate $J/\psi$ suppression at other energies

$\hat{q}_0 = 0.09 \text{ GeV}^2/\text{fm}$
Extrapolating to other energies

Two competing mechanisms might alter heavy-quarkonium suppression

- **Nuclear absorption** if hadron formation occurs inside the medium

\[ t_{\text{form}} = \gamma \tau_{\text{form}} \lesssim L \]

- Low \( \sqrt{s} \) and/or negative \( x_F \)
- Indicated later assuming \( \tau_{\text{form}} = 0.3 \) fm
Extrapolating to other energies

Two competing mechanisms might alter heavy-quarkonium suppression:

- **nPDF/saturation effects** when \( Q_s^2 \sim m_c^2 \)

\[
R_{pA} = R_{pA}^{E,\text{loss}}(\hat{q}) \times S_{A}^{\text{sat}}(Q_s)/S_{p}^{\text{sat}}(Q_s)
\]

\( S_{A}^{\text{sat}}(Q_s) \) parametrized as [Fujii, Gelis, Venugopalan 2006]

\[
S_{A}^{\text{sat}}(Q_s) = \left( \frac{2.65}{2.65 + Q_s^2 [\text{GeV}^2]} \right)^{0.417}
\]

- No additional parameter: \( Q_s^2(x, L) = \hat{q}(x)L \) [Mueller 1999]
- Reduces fitted transport coefficient: \( \hat{q}_0 = 0.05 \text{ GeV}^2/\text{fm} \)
- \( Q_s^2(x = 10^{-2}) = 0.08 - 0.15 \text{ GeV}^2 \) consistent with fits to DIS data [Albacete et al AAMQS 2011]
Agreement when $x_F > x_F^{\text{min}}$

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

Room for J/ψ absorption, though weaker than previously thought
RHIC predictions

Energy loss model fails in the most backward bins
Saturation effects improve the agreement
Smaller experimental uncertainties would help
LHC predictions

- Moderate effects ($\sim 10 - 15\%$) around mid-rapidity
- Large effects above $y \gtrsim 2 - 3$
- Saturation might be the dominant effect at the LHC around $y \approx 0$
- Slightly smaller suppression expected in the $\Upsilon$ channel
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
  - Natural explanation for the large $x_F$ $J/\psi$ suppression
  - Model supplemented consistently by saturation effects
  - Supports the assumption of long-lived color octet $Q\bar{Q}$ pair
  - More precise $J/\psi$ and $\Upsilon$ data (and larger $y$) would help

- Similar phenomena expected for light/heavy hadrons
  - Work in progress