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

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Outline

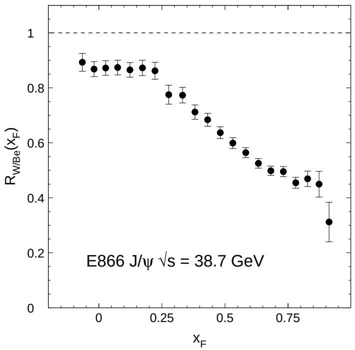
- Motivations
  - J/ψ suppression data in p A collisions
- Revisiting energy loss
  - New scaling properties from medium-induced coherent radiation
- Phenomenology
  - Model for J/ψ and Υ suppression in p A collisions
  - Comparison with data and LHC predictions

References

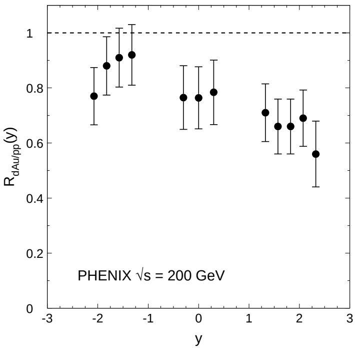
- FA, S. Peigné, T. Sami, 1006.0818
- FA, S. Peigné, 1204.4609 + in preparation

J/ψ suppression in p A collisions at forward rapidities

E866 $\sqrt{s} = 38.7$ GeV



PHENIX $\sqrt{s} = 200$ GeV



- Strong J/ψ suppression reported at large x_F and y
- Weaker suppression in the Drell-Yan process
- Observed at various $\sqrt{s}$

J/ψ 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

[Gavin Milana 1992]

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

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 Υ suppression
- $\Delta E \propto E$ claimed to be incorrect in the high energy limit due to uncertainty principle — so-called Brodsky-Hoyer bound

A bound on energy loss ?

Induced gluon radiation needs to resolve the medium [Brodsky Hoyer 93]

$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \qquad \omega \lesssim k_\perp^2 \, L \sim \hat{q} \, L^2$$

- 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]

Revisiting energy loss scaling properties

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 p A collisions
- Jets and hadrons produced in hadronic collisions at large angle

Revisiting energy loss scaling properties

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

$$\Delta E \propto \frac{\sqrt{\hat{q} L}}{M} \, E$$

- 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 $t_{\rm octet} \gg t_{\rm hard}$

Medium-induced gluon spectrum

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

$$\omega \frac{dI}{d\omega}\bigg|_{\rm ind} = \frac{N_c \alpha_s}{\pi} \left\{ \ln\left(1 + \frac{E^2 \Delta q_\perp^2}{\omega^2 M_\perp^2}\right) - \ln\left(1 + \frac{E^2 \Lambda_{\rm QCD}^2}{\omega^2 M_\perp^2}\right) \right\}$$

$$\Delta E = \int d\omega\, \omega\, \frac{dI}{d\omega}\bigg|_{\rm ind} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2} - \Lambda_{\rm QCD}}{M_\perp} E$$

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

Model for heavy-quarkonium suppression

[FA Peigné 1204.4609]

$$\frac{d\sigma_{pA}^{\psi}}{dx_{F}}\left(x_F,\sqrt{s}\right) = \int_0^{\epsilon_{max}} d\epsilon\,\mathcal{P}(\epsilon)\,\frac{d\sigma_{pp}^{\psi}}{dx_{F}}\left(x_{F}+\delta x_{F}(\epsilon)\right)$$

- pp cross section fitted from experimental data

$$\frac{d\sigma_{pp}^{\psi}}{dx_{F}} \propto \left(1-x'\right)^{n(\sqrt{s})}/x' \qquad x' \equiv \sqrt{x_{F}^2+4M_{\perp}^2/s}$$

- Shift given by $\delta x_{F}(\epsilon) \simeq \epsilon/E_{beam}$
- $\mathcal{P}(\epsilon)$: quenching weight, scaling function of $\hat{\omega} = \sqrt{\hat{q}L}/M_{\perp} \times E$
- Length L given by $L = 3/2\ r_0\ A^{1/3}$

Quenching weight

- Poisson approximation assuming independent emission [BDMS 2001]

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

- However, radiating ω_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 $\omega_1 \ll \omega_2 \ll \ldots \ll \omega_n$

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

Transport coefficient

$\hat{q}$ related to gluon distribution in a proton [BDMPS 1997]

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

Typical value for x

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

For simplicity we assume

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

$\hat{q}_0$ only free parameter of the model

Procedure

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

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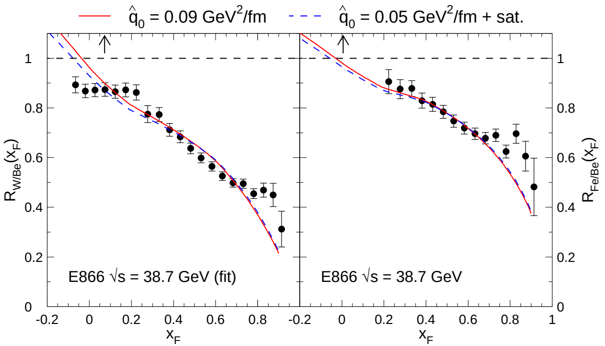

$\hat{q}_0 = 0.09\ \text{GeV}^2/\text{fm}$

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

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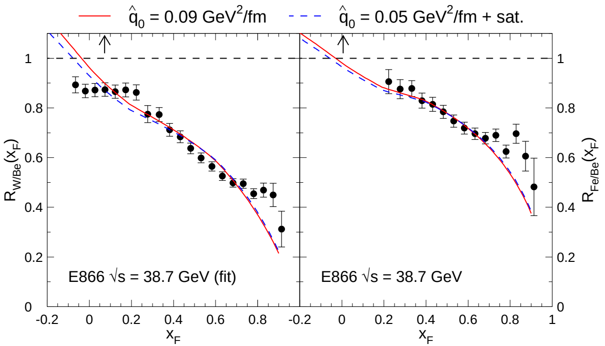

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Let's investigate J/ψ suppression at other energies

Extrapolating to other energies

Two competing mechanisms might alter heavy-quarkonium suppression

- Nuclear absorption if hadron formation occurs inside the medium

$$t_{\rm form} = \gamma\ \tau_{\rm form} \lesssim L$$

  - Low $\sqrt{s}$ and/or negative $x_{_F}$
  - Indicated later assuming $\tau_{\rm form} = 0.3$ fm

Extrapolating to other energies

Two competing mechanisms might alter heavy-quarkonium suppression

- nPDF/saturation effects when $Q_s^2 \sim m_c^2$

$$R_{\rm pA} = R_{\rm pA}^{\rm E.loss}(\hat{q}) \times \times \mathcal{S}_{\rm A}^{\rm sat}(Q_s)/\mathcal{S}_{\rm p}^{\rm sat}(Q_s)$$

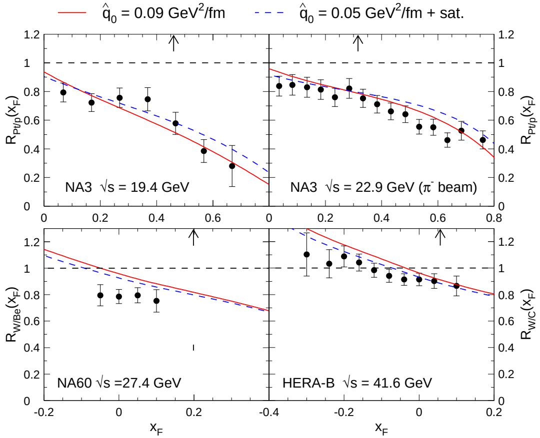
$\mathcal{S}_{\rm A}^{\rm sat}(Q_s)$ parametrized as [Fujii Gelis Venugopalan 2006]

$$\mathcal{S}_{\rm A}^{\rm sat}(Q_s) = \left(\frac{2.65}{2.65 + Q_s^2 \ [\text{GeV}^2]} \right)^{0.417}$$

- No additional parameter: $Q_s^2(x, L) = \hat{q}(x)L$ [Mueller 1999]
- Reduces fitted transport coefficient: $\hat{q}_0 = 0.05$ GeV^2/fm
- $Q_s^2(x = 10^{-2}) = 0.08 - 0.15$ GeV^2 consistent with fits to DIS data

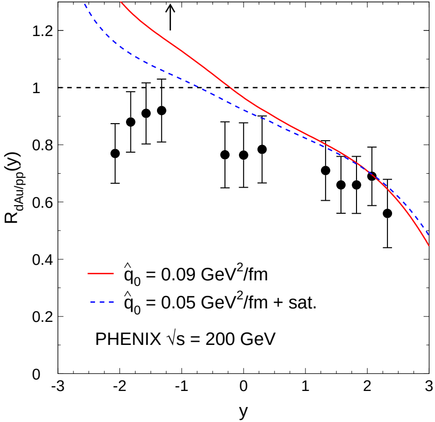
[Albacete et al AAMQS 2011]

SPS predictions



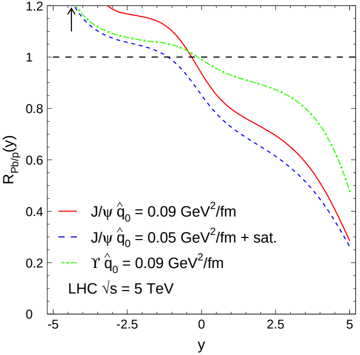
- Agreement when $x_F > x_F^{min}$
- Natural explanation from the different suppression in p A vs π A
- Room for J/ψ absorption, though weaker than previously thought

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 $y \simeq 0$
- Slightly smaller suppression expected in the Υ channel

Summary

- Energy loss $\Delta E \propto E$ due to coherent radiation
  - Neither initial nor final state effect
  - Parametric dependence of $dI/d\omega$ and ΔE predicted
- Heavy-quarkonium suppression predicted from SPS to LHC
  - Good agreement with all existing data
  - Natural explanation for the large x_F J/ψ suppression
  - Model supplemented consistently by saturation effects
  - Supports the assumption of long-lived color octet $Q\bar{Q}$ pair
  - More precise J/ψ and Υ data (and larger y) would help
- Similar phenomena expected for light / heavy hadrons
  - Work in progress