

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

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Workshop pA@LHC

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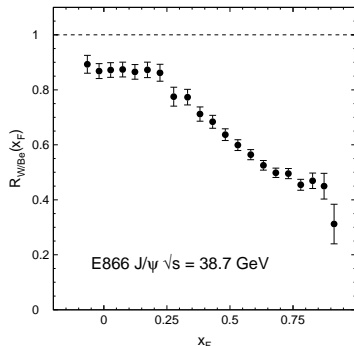
- **Motivations**
 - J/ψ suppression data in p A collisions
- **Revisiting energy loss**
 - New scaling properties from medium-induced coherent radiation
- **Phenomenology**
 - Model for J/ψ and Υ suppression in p A collisions
 - Comparison with data and LHC predictions

References

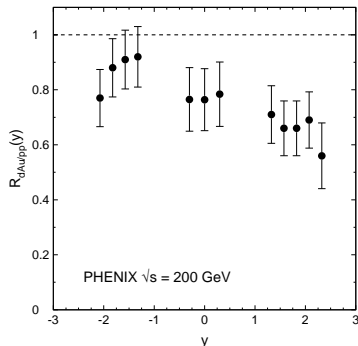
- FA, S. Peigné, T. Sami, 1006.0818
- FA, S. Peigné, 1204.4609 + in preparation

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

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]

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

- 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]

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 $t_{\text{octet}} \gg t_{\text{hard}}$

Medium-induced gluon spectrum

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

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

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

- $\Delta E \propto E$ 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

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

- pp cross section fitted from experimental data

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

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

- 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 $\omega_1 \ll \omega_2 \ll \dots \ll \omega_n$

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

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

For simplicity we assume

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

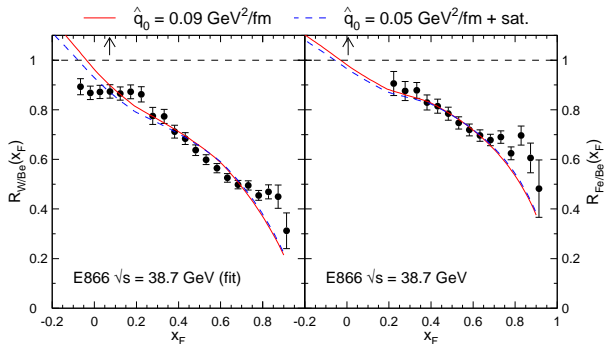
\hat{q}_0 only free parameter of the model

Procedure

- 1 Fit \hat{q}_0 from J/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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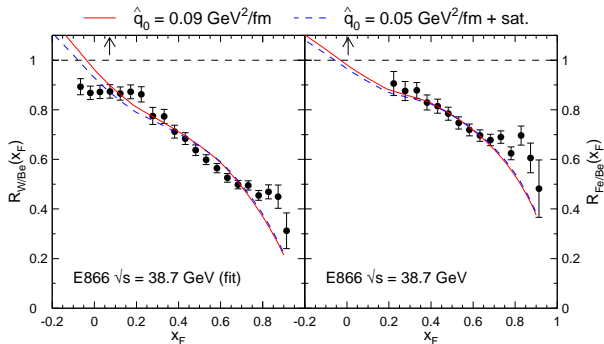


$$\hat{q}_0 = 0.09 \text{ GeV}^2/\text{fm}$$

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

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Let's investigate J/ψ suppression at 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 $\tau_{\text{form}} = 0.3 \text{ fm}$

Two competing mechanisms might alter heavy-quarkonium suppression

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

$$R_{pA} = R_{pA}^{\text{E.loss}}(\hat{q}) \times \mathcal{S}_A^{\text{sat}}(Q_s) / \mathcal{S}_p^{\text{sat}}(Q_s)$$

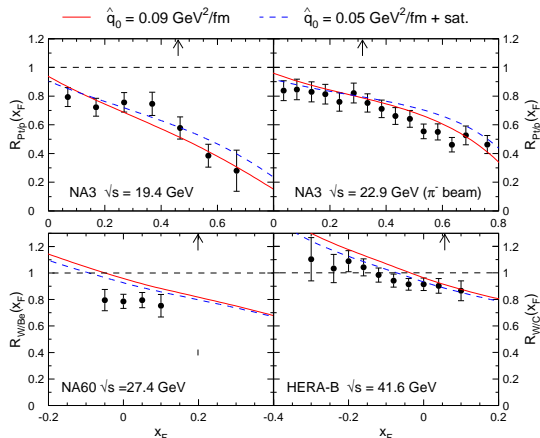
$\mathcal{S}_A^{\text{sat}}(Q_s)$ parametrized as [Fujii Gelis Venugopalan 2006]

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

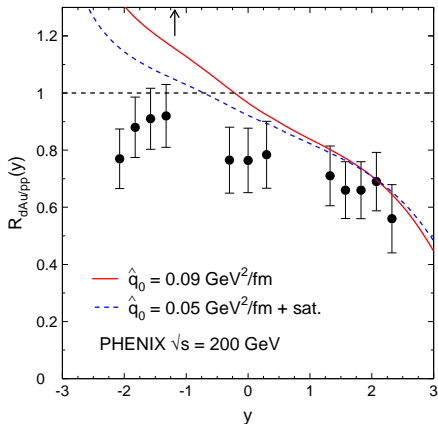
- No additional parameter: $Q_s^2(x, L) = \hat{q}(x)L$ [Mueller 1999]
- Reduces fitted transport coefficient: $\hat{q}_0 = 0.05 \text{ GeV}^2/\text{fm}$
- $Q_s^2(x = 10^{-2}) = 0.08 - 0.15 \text{ GeV}^2$ consistent with fits to DIS data

[Albacete et al AAMQS 2011]

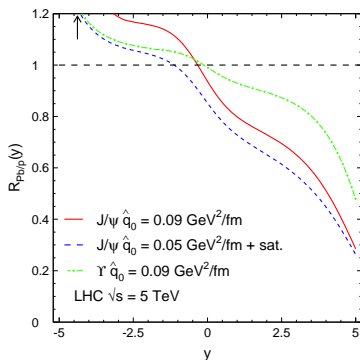
SPS predictions



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



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



- 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

- 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

Heavy-ion collisions in the LHC era

- **Dates:** 15 – 20 July 2012
- **Place:** Quy Nhon (Vietnam)
- **Web:** <https://indico.cern.ch/event/heavyions2012>
- **Organizers:** F. Arleo, C.A. Salgado, J. Tran Thanh Van