

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

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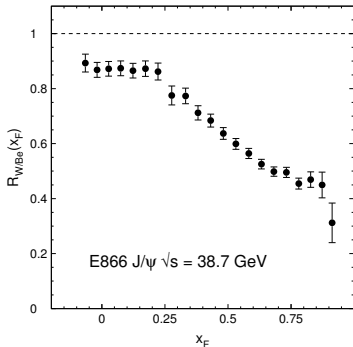
- **Motivations**
 - J/ψ suppression data in p A collisions
- **Revisiting energy loss**
 - New scaling properties from medium-induced coherent radiation
- **Phenomenology**
 - Model for J/ψ and Υ suppression in p A collisions
 - Comparison with data and LHC predictions

References

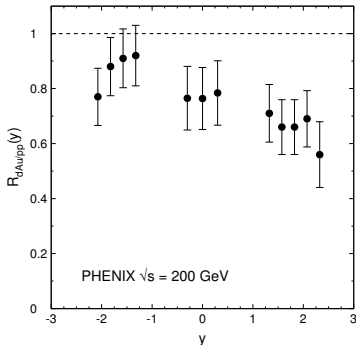
- FA, S. Peigné, PRL 109 (2012) 122301 [1204.4609]
- FA, S. Peigné, JHEP 03 (2013) 122 [1212.0434]
- FA, R. Kolevatov, S. Peigné, M. Rostamova, JHEP 05 (2013) 155 [1304.0901]

Data on J/ψ suppression in p A collisions

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

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

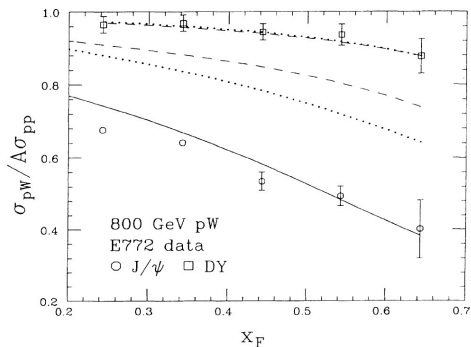
- Nuclear absorption
- nPDF effects and saturation
- Parton energy loss
 - requires $\Delta E \propto E$. . . supposedly ruled out

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)



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Caveats

- E , L , and M dependence of parton energy loss completely arbitrary
- Failure to describe Υ suppression
- $\Delta E \propto E$ claimed to be incorrect !

A bound on energy loss ?

- Induced gluon radiation needs to resolve the medium

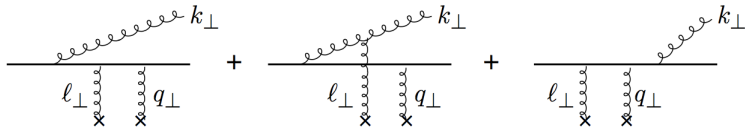
$$t_f \sim \frac{\omega}{k_{\perp}^2} \lesssim L \quad \omega \lesssim k_{\perp}^2 L \sim \hat{q} L^2$$

- Bound independent of the parton energy
- Apparently rules out energy loss models as a possible explanation

True only for incoherent radiation in the initial & final state !

Revisiting energy loss scaling properties

Coherent radiation (interference) in the initial/final state



- 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**

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

- **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

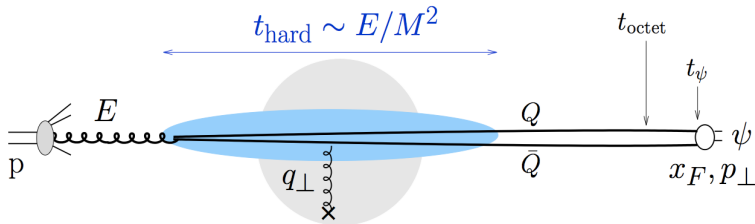
- **Coherent energy loss** (large formation time $t_f \gg L$)

$$\Delta E \propto \alpha_s \frac{\sqrt{\hat{q} L}}{M_{\perp}} E$$

- needs color in the initial & final state
- important at all energies, especially at large rapidity

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

Energy shift

$$\frac{1}{A} \frac{d\sigma_{pA}^{\psi}}{dE} (E, \sqrt{s}) = \int_0^{\epsilon_{\max}} d\epsilon \mathcal{P}(\epsilon, E) \frac{d\sigma_{pp}^{\psi}}{dE} (E + \epsilon, \sqrt{s})$$

Ingredients

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

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

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

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

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

- $\mathcal{P}(\epsilon)$ scaling function of $\hat{\omega} = \sqrt{\hat{q}L} / M_{\perp} \times E$
- $\hat{q}_0 \equiv \hat{q}(x = 10^{-2})$ only free parameter of the model

\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

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

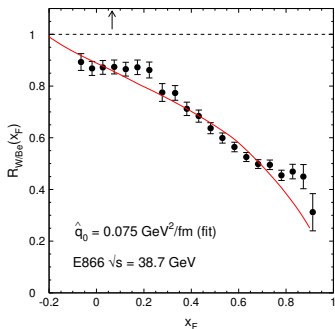
For simplicity we assume

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

- $\hat{q}_0 \equiv \hat{q}(x = 10^{-2})$ only free parameter of the model
- $\hat{q}(x)$ related to the saturation scale: $Q_s^2(x, L) = \hat{q}(x)L$ [Mueller 1999]

Procedure

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

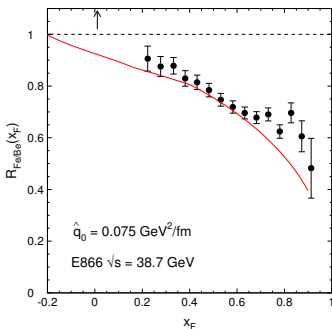
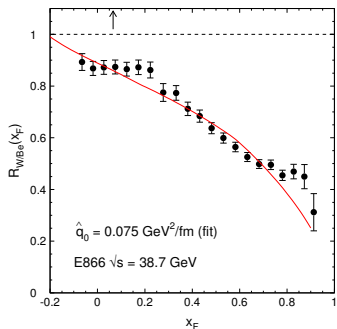


$$\hat{q}_0 = 0.075 \text{ GeV}^2/\text{fm}$$

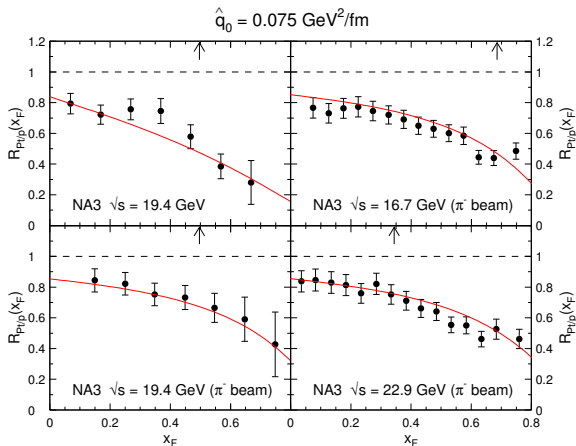
- Corresponds to $Q_s^2(x = 10^{-2}) = 0.11 - 0.14 \text{ GeV}^2$ consistent with fits to DIS data [Albacete et al AAMQS 2011]

Procedure

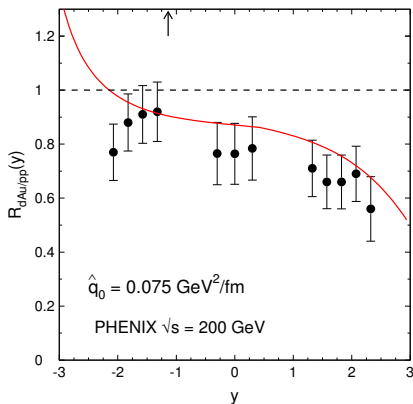
- 1 Fit \hat{q}_0 from J/ψ E866 data in p W collisions
- 2 Predict J/ψ and Υ suppression for all nuclei and c.m. energies



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



- 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/ψ absorption, weaker than previously thought



- Good agreement at all rapidity
- Saturation/shadowing effects could improve the agreement

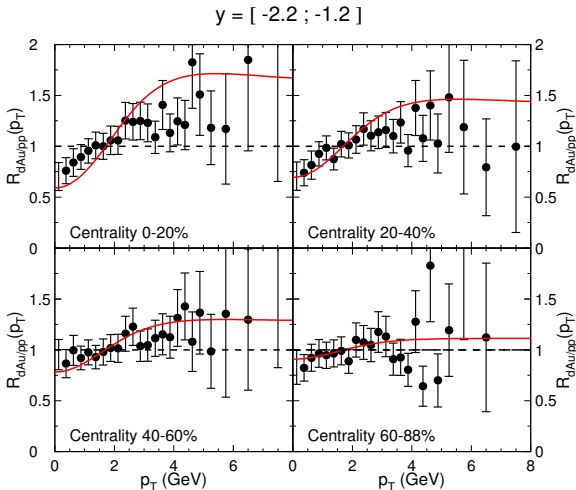
Most general case

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

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

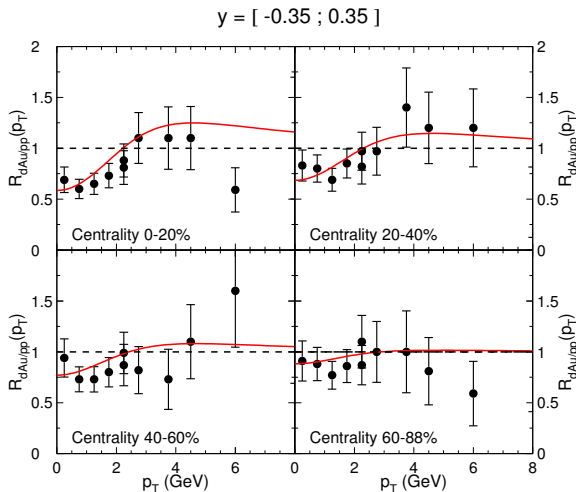
$$R_{pA}^{\psi}(y, p_{\perp}) \simeq R_{pA}^{\text{loss}}(y, p_{\perp}) \cdot R_{pA}^{\text{broad}}(p_{\perp})$$

p_{\perp} dependence at RHIC



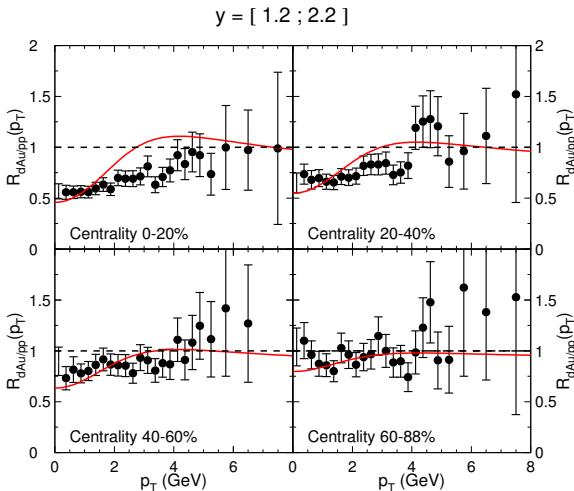
- Good description of p_{\perp} and centrality dependence at $y = -1.7$

p_{\perp} dependence at RHIC

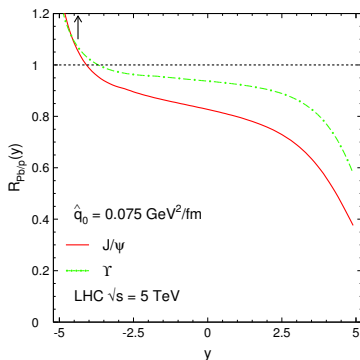


- Good description of p_{\perp} and centrality dependence at $y = 0$

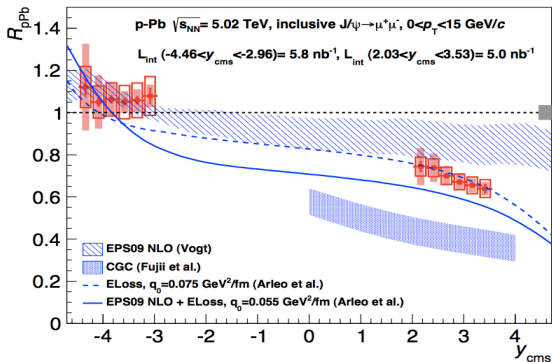
p_{\perp} dependence at RHIC



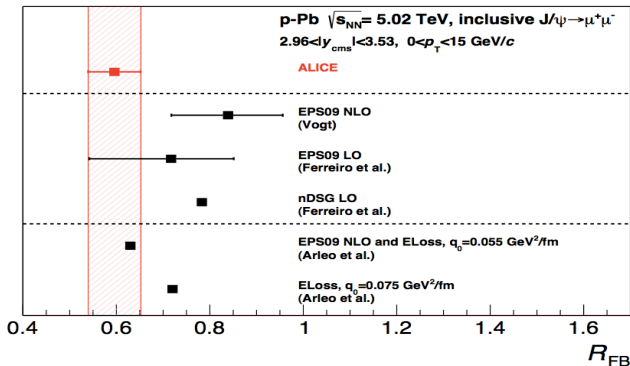
- Good description of p_{\perp} and centrality dependence at $y = 1.7$



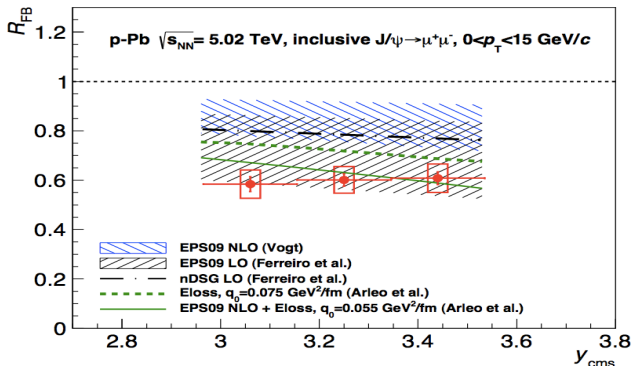
- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$
- Slightly smaller suppression expected in the Υ channel



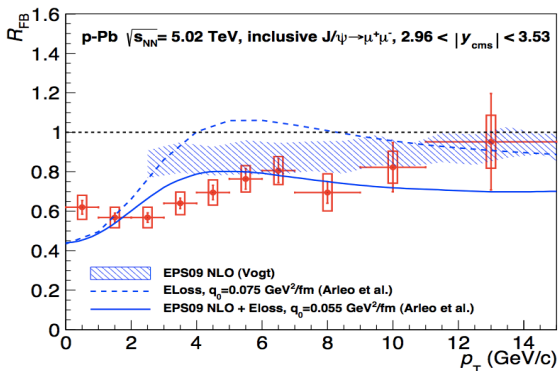
- $R_{pA}(y)$: good agreement despite large uncertainty on normalization



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



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- Predictions with only nPDF underestimate the suppression
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- $R_{FB}(p_{\perp})$: good agreement, better agreement with energy loss supplemented by shadowing

- 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 vs. y and p_{\perp}
 - Natural explanation for the large x_F J/ψ suppression
 - Supports the assumption of long-lived color octet $Q\bar{Q}$ pairs
 - Predictions in good agreement with LHC pPb preliminary data
 - Extrapolation to AA collisions in progress