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

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Outline

- Motivations
  - J/ψ suppression data in p A collisions
  - 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

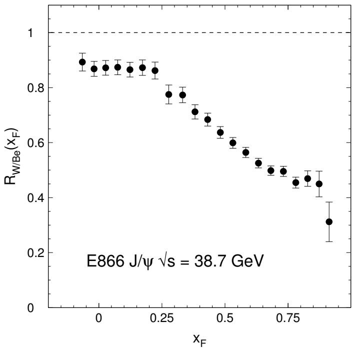
References

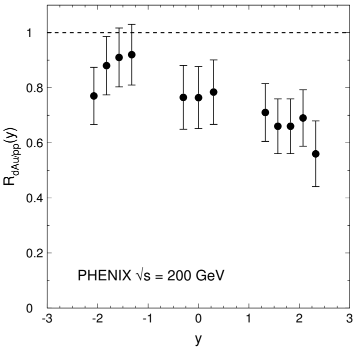
- FA, S. Peigné, PRL 109 (2012) 122301 [1204.4609]
- FA, S. Peigné, JHEP 03 (2013) 122 [1212.0434]
- FA, R. Kolevatov, S. Peigné, M. Rustamova, JHEP 05 (2013) 155 [1304.0901]

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

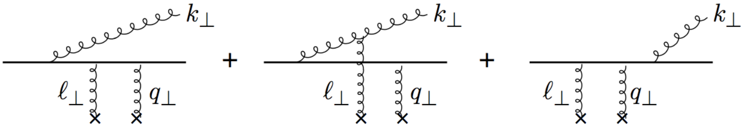
Interpretations

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



- 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

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

(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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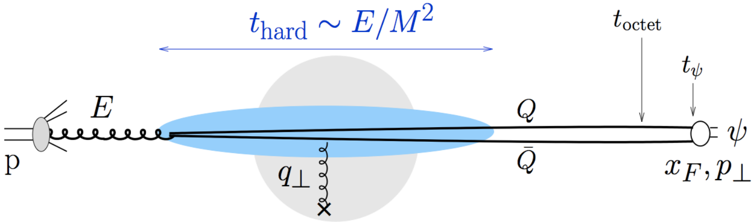
Back to the Future: listen to Stéphane's talk this morning (10am)

Phenomenology

Goal

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

Physical picture and assumptions



- Color neutralization happens on long time scales: $t_{\rm octet} \gg t_{\rm hard}$
- 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

$$\frac{1}{A}\frac{d\sigma^{\psi}_{\rm pA}}{dE}\left(E,\sqrt{s}\right) = \int_0^{\varepsilon_{\rm max}} d\varepsilon\, \mathcal{P}(\varepsilon, E)\, \frac{d\sigma^{\psi}_{\rm pp}}{dE}\left(E+\varepsilon,\sqrt{s}\right)$$

Ingredients

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

Quenching weight

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

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

- 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 $\omega_1 \ll \omega_2 \ll \ldots \ll \omega_n$

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

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

Transport coefficient

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

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

Typical value for x

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

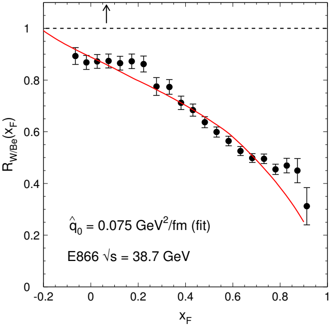
For simplicity we assume

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

- $\hat{q}_0 \equiv \hat{q}(x = 10^{-2})$ 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]

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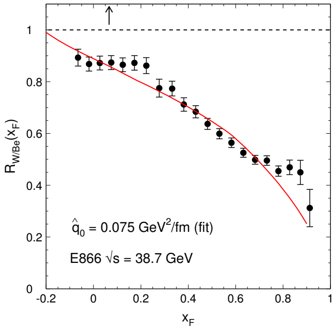

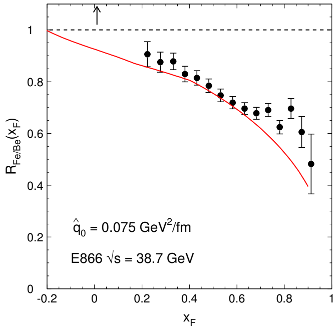

- Fe/Be ratio well described, supporting the L dependence of the model

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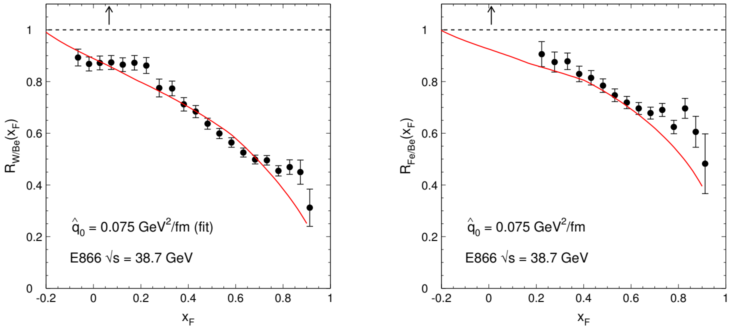


Let's investigate J/ψ suppression at other energies

NA3 predictions (slide for Louis)

Experimental J/ψ Hadronic Production from 150 to 280 GeV/c

NA 3 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. Runolfsson[2], P. Siegrist[1], A. Tilquin[3], J. Timmermans[2c], J. Valentin[3], S. Weisz[4]

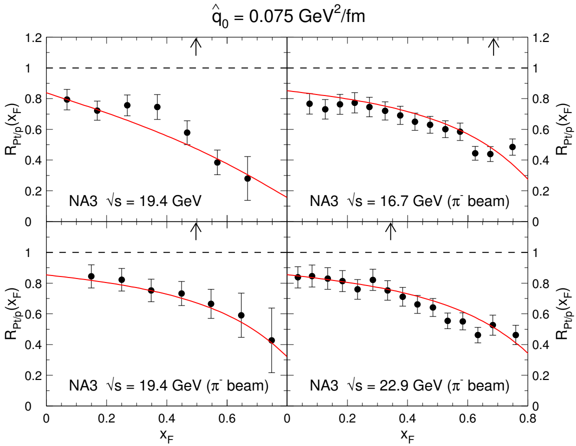
[1] CEN-Saclay, F-91190 Gif-sur-Yvette, France
[2] CERN, CH-1211 Geneva 23, Switzerland
[3] College de France, F-75231 Paris, France
[4] Ecole Polytechnique, F-91128 Palaiseau, France
[5] Laboratoire de l'Accélérateur Linéaire, F-91405 Orsay, France

Received 4 July 1983

Table 2. Number of J/ψ events obtained in this experiment

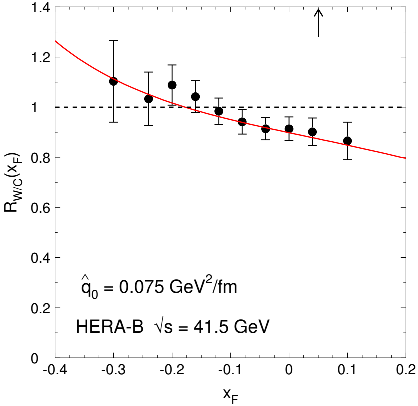
Momentum (GeV/c)	Target	π^+	K^+	p	π^-	K^-	$\bar{p}$
200	H_2	2,407	359	2,227	3,157	–	–
200	Pt	104,866	14,690	80,786	131,062	1,963	657
150	H_2	207	–	–	16,952	487	208
150	Pt	7,937	442	3,453	601,691	19,190	6,569
280	H_2	–	–	–	23,350	–	–
280	Pt	–	–	–	511,457	–	–

NA3 predictions (slide for Louis)



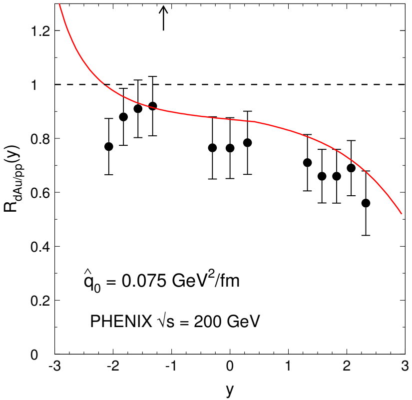
- Agreement when $x_F > x_F^{\text{hadro}}$ (and even below)
- Natural explanation from the different suppression in p A vs π A
- Little room for J/ψ absorption, weaker than previously thought

HERA-B predictions



- Also good agreement in the nuclear fragmentation region ($x_F < 0$)
- Enhancement predicted at very negative x_F

RHIC predictions



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

$p_\perp$ dependence

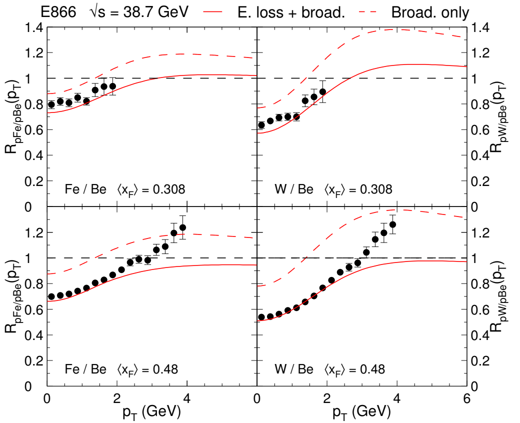
Most general case

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

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

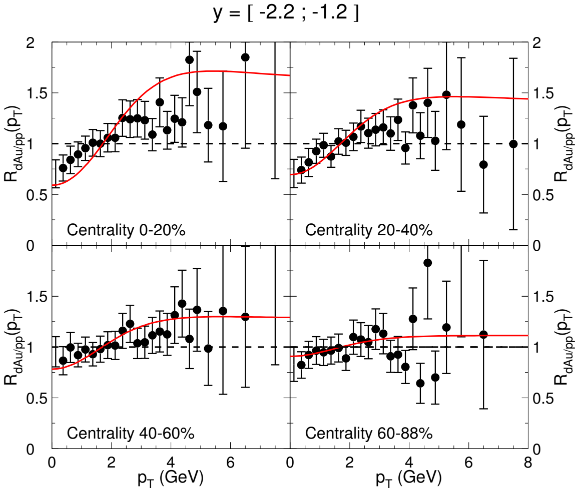
$$R_{\rm pA}^{\psi}(y, p_\perp) \simeq R_{\rm pA}^{\rm loss}(y, p_\perp)\cdot R_{\rm pA}^{\rm broad}(p_\perp)$$

$p_\perp$ dependence at E866



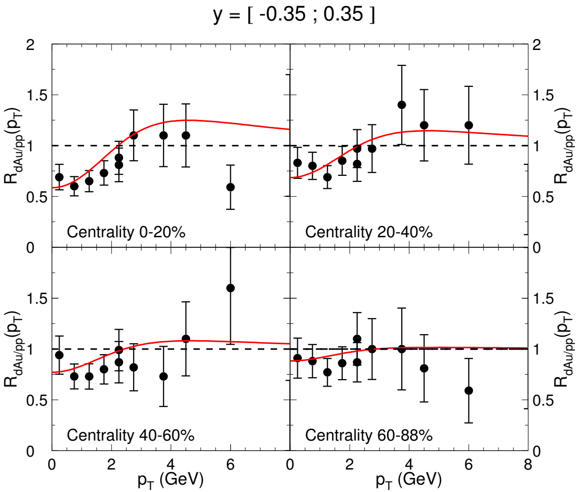
- Good description of E866 data (except at large $p_\perp$ and large x_F)
- Broadening effects only not sufficient to reproduce the data

$p_\perp$ dependence at RHIC



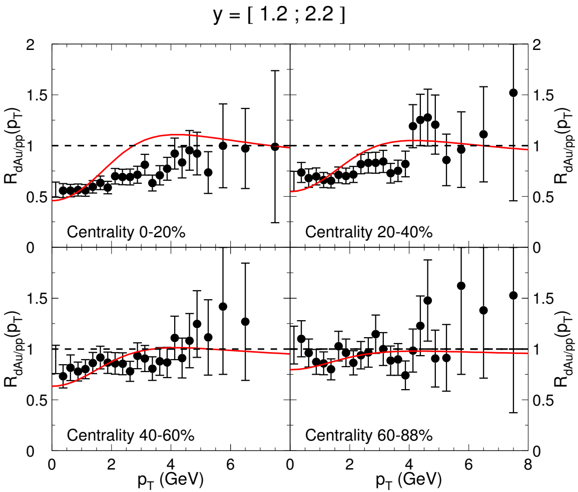
- Good description of $p_\perp$ and centrality dependence at $y = -1.7$

$p_\perp$ dependence at RHIC



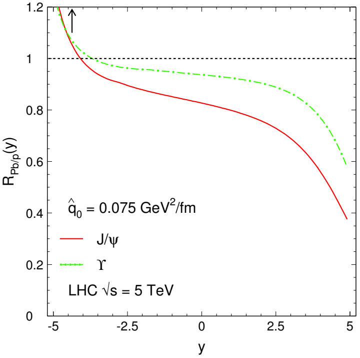
- Good description of $p_\perp$ and centrality dependence at $y = 0$

$p_\perp$ dependence at RHIC



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

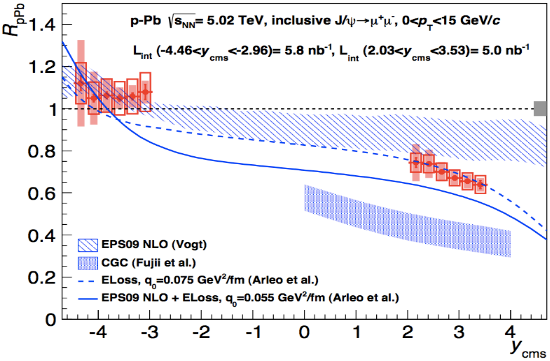
LHC predictions



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

Comparison with ALICE preliminary data

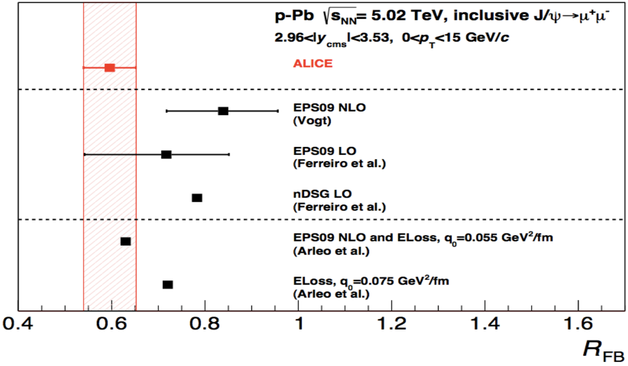
[ALICE 1308.6726]



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

Comparison with ALICE preliminary data

[ALICE 1308.6726]



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

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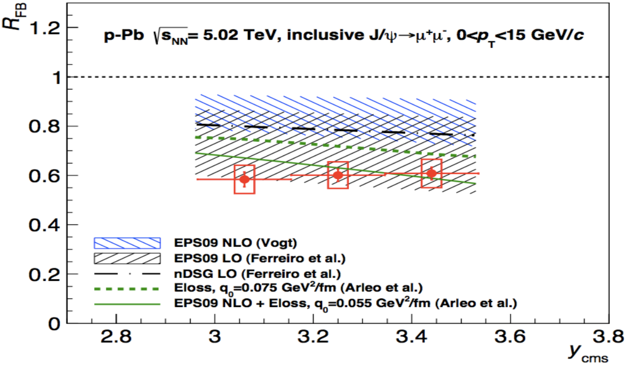

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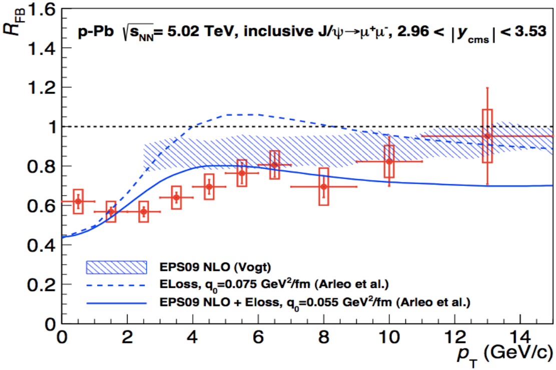
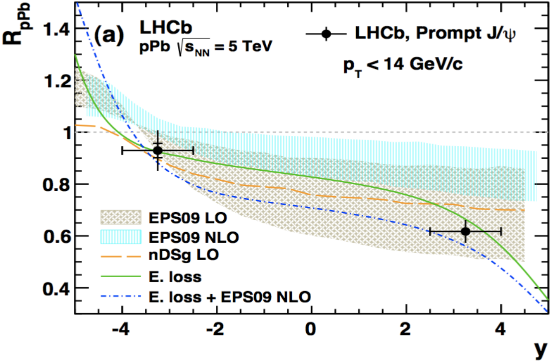


- $R_{\rm FB}(p_\perp)$: good agreement, better agreement with energy loss supplemented by shadowing

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 $dI/d\omega$ 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 p Pb preliminary data