Quarkonium suppression in p-A & A-A collisions from parton energy loss in cold QCD matter

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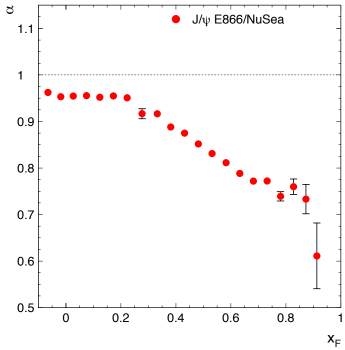
Outline

- 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 from SPS to LHC
  - Extrapolation to heavy-ion collisions

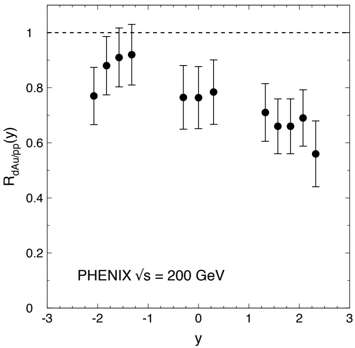
References

- FA, S. Peigné, 1204.4609, 1212.0434, 1407.5054
- w/ R. Kolevatov, 1402.1671
- w/ R. Kolevatov, M. Rustamova, 1304.0901

E866 $\sqrt{s} = 38.7$ GeV



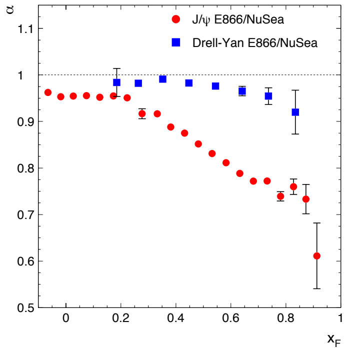
PHENIX $\sqrt{s} = 200$ GeV



- Strong J/ψ suppression reported at large x_F and y
- Weaker suppression in the Drell-Yan process

Data on J/ψ suppression in p A collisions

E866 $\sqrt{s} = 38.7$ GeV



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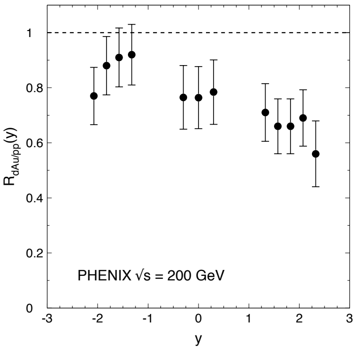

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Interpretations

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

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This talk: revisiting energy loss processes in a simple approach

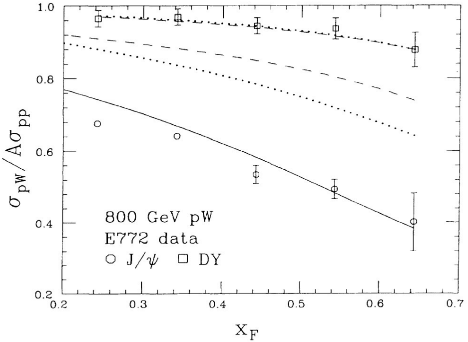
Gavin–Milana model

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)



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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 ?

Considering an asymptotic charge in a QED model [Brodsky Hoyer 93]

- No contribution from large formation times $t_f \gg L$
- Induced gluon radiation needs to resolve the medium

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

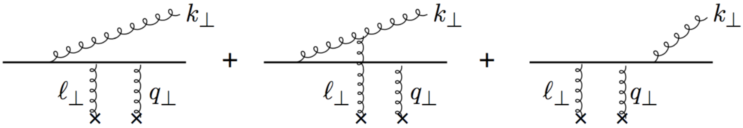
  - Bound independent of the parton energy
  - Energy loss cannot be arbitrarily large in a finite medium
  - Apparently rules out energy loss models as a possible explanation

However

- Not true in QED when the charge is deflected
- Not necessarily true in QCD due to color rotation

Revisiting energy loss scaling properties

Coherent radiation (interference) in the initial/final state crucial for $t_f \gg L$



- 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

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

Two regimes

Incoherent energy loss (small formation time $t_f \sim L$)

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

- No color flow in the initial or final state
- Large angle particle production
- Hadron production in nuclear DIS or Drell-Yan in p A collisions

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 both initial & final state
- Important at all energies, especially at large rapidity
- Hadron production in p A collisions

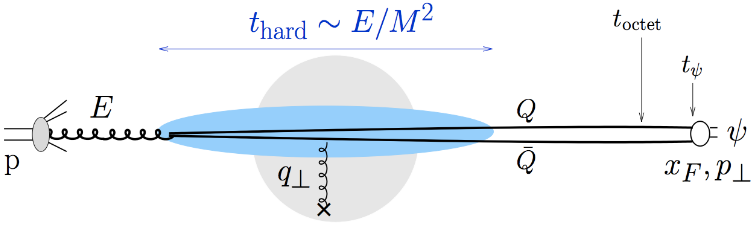
Phenomenology

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
- Compare to all available p A data
  - rapidity and transverse momentum dependence
  - predictions for the p Pb run at the LHC
- Provide baseline predictions in heavy-ion collisions

Model for quarkonium suppression

Physical picture and assumptions



- Color neutralization happens on long time scales: $t_{\rm octet} \gg t_{\rm hard}$
- Medium rescatterings do not resolve the octet $c\bar{c}$ pair
- Hadronization happens outside of the nucleus: $t_\psi \gtrsim L$
- $c\bar{c}$ pair produced by gluon fusion

Model for quarkonium suppression

Energy shift

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

Ingredients

- pp cross section fitted from experimental data

$$E\,\frac{d\sigma^{\psi}_{\mathrm{pp}}}{dE} = \frac{d\sigma^{\psi}_{pp}}{dy} \propto \left(1 - \frac{2M_{\perp}}{\sqrt{s}}\cosh y\right)^{n(\sqrt{s})}$$

- Length L given by Glauber model for minimum bias and centrality dependence
- $\mathcal{P}(\epsilon)$: probability distribution (quenching weight)

Quenching weight

- Usually one assumes independent emission → 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

Quenching weight

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

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

$$P(\epsilon) \simeq \frac{dI(\epsilon)}{d\omega} \exp\left\{ - \int_{\epsilon}^{\infty} d\omega \frac{dI}{d\omega} \right\} \qquad \omega \frac{dI}{d\omega}\bigg|_{\text{ind}} \simeq \frac{N_c \alpha_s}{\pi} \ln\left(1 + \frac{E^2 \hat{q} L}{\omega^2 M_\perp^2}\right)$$

- $\mathcal{P}(\epsilon)$ 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]

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

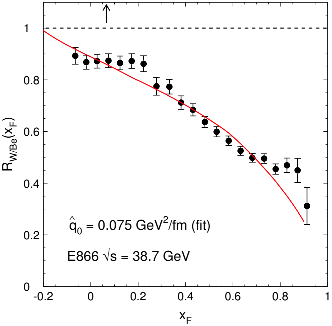
For simplicity we assume

$$\hat{q}(x) = \hat{q}_0 \left(\frac{10^{-2}}{x} \right)^{0.3} \qquad (\hat{q} \text{ frozen at } x \gtrsim 10^{-2})$$

- $\hat{q}_0 \equiv \hat{q}(x = 10^{-2})$ 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 $Q_s^2(x = 10^{-2}) = 0.11 - 0.14$ GeV^2 consistent with fits to DIS data [Albacete et al AAMQS 2011]

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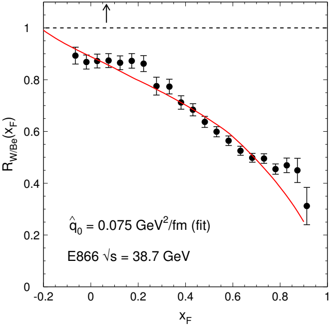
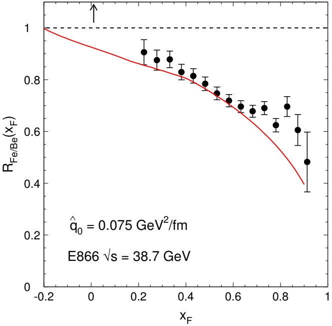
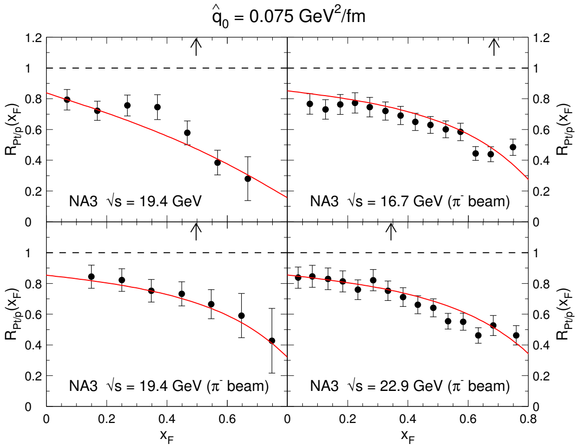




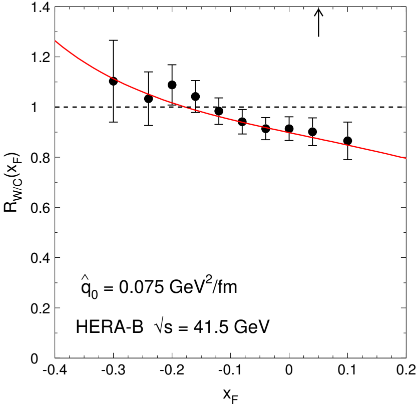
- Fe/Be ratio well described, supporting the L dependence of the model

SPS predictions



- Agreement even at small x_F
- Natural explanation from the different suppression in p A vs π A

HERA-B predictions



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

Uncertainties

Two sources of uncertainties are identified

- Transport coefficient $\hat{q}_0$ (default 0.075 GeV^2/fm) to be varied from 0.07 to 0.09 GeV^2/fm
- Parameter ("slope") of the pp cross section to be varied within its uncertainty extracted from the fit of pp data

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Uncertainty band determined from the independent variation of $\hat{q}_0$ and n (4 error sets)

$$
\begin{aligned}
\left(\Delta R^+\right)^2 &= \sum_{k=\hat{q}_0,n} \left[\max\left\{R(S_k^+) - R(S^0), R(S_k^-) - R(S^0), 0\right\}\right]^2 \\
\left(\Delta R^-\right)^2 &= \sum_{k=\hat{q}_0,n} \left[\max\left\{R(S^0) - R(S_k^+), R(S^0) - R(S_k^-), 0\right\}\right]^2
\end{aligned}
$$

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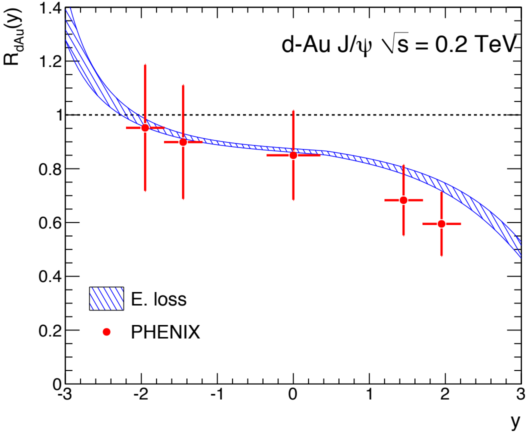
- Parameter ("slope") of the pp cross section to be varied within its uncertainty extracted from the fit of pp data

- Largest uncertainty comes from the variation of $\hat{q}_0$ around mid-rapidity
- At very large rapidity (e.g. $y \gtrsim 4$ at LHC), uncertainty coming from n becomes comparable or larger than that coming from $\hat{q}_0$

RHIC predictions



- Good agreement for R_{pA} vs rapidity
- Rather small uncertainty coming from the variation of the pp cross section and the transport coefficient

$p_\perp$ dependence

Most general case

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

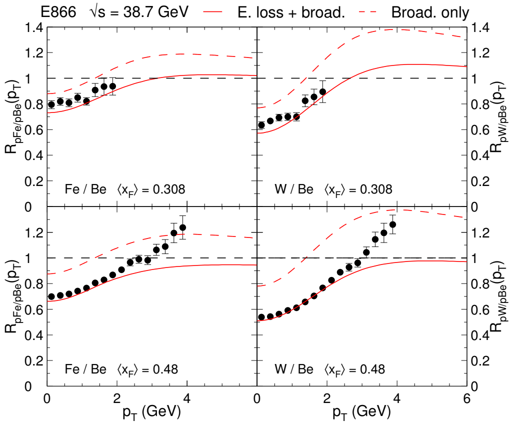
- pp cross section fitted from experimental data

$$\frac{d\sigma_{\rm pp}^{\psi}}{dy\, d^2\vec{p}_\perp} \propto \left(\frac{p_0^2}{p_0^2+p_\perp^2}\right)^m \times \left(1-\frac{2M_\perp}{\sqrt{s}}\cosh y\right)^n$$

- Overall depletion due to parton energy loss
- Possible Cronin peak due to momentum broadening

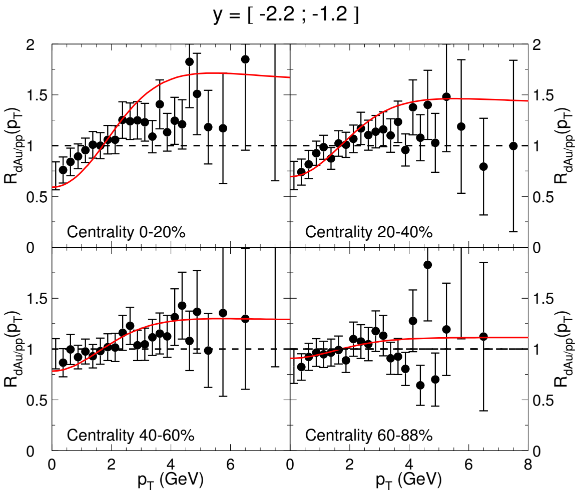
$$R_{\rm pA}^{\psi}(y,p_\perp) \simeq R_{\rm pA}^{\rm loss}(y,p_\perp)\cdot R_{\rm pA}^{\rm broad}(p_\perp)$$

$p_\perp$ dependence at E866



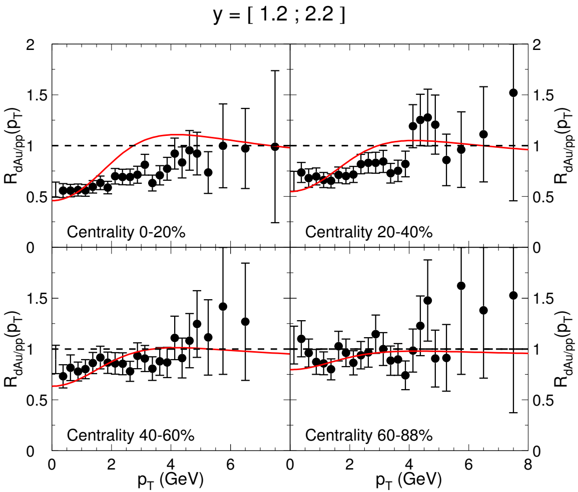
- Good description of E866 data (except at large $p_\perp$ and large x_F)
- Broadening effects only not sufficient to reproduce the data

$p_\perp$ dependence at RHIC



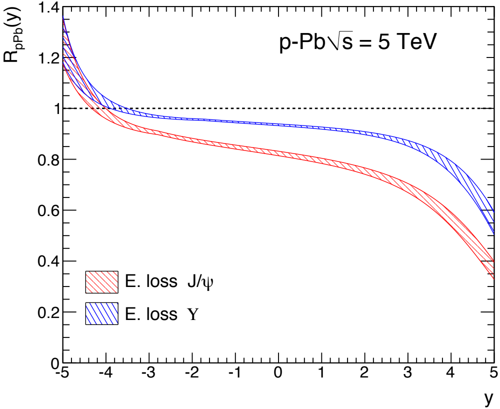
- Good description of $p_\perp$ and centrality dependence at $y = -1.7$

$p_\perp$ dependence at RHIC



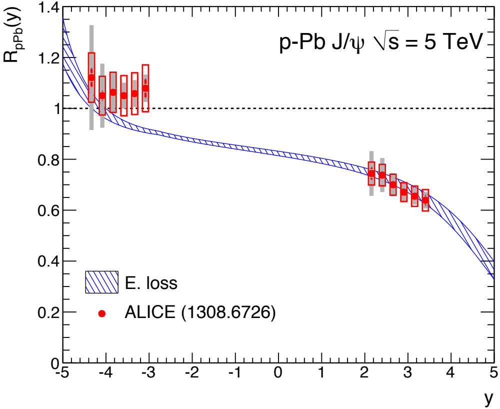
- Good description of $p_\perp$ and centrality dependence at $y = 1.7$

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

LHC predictions

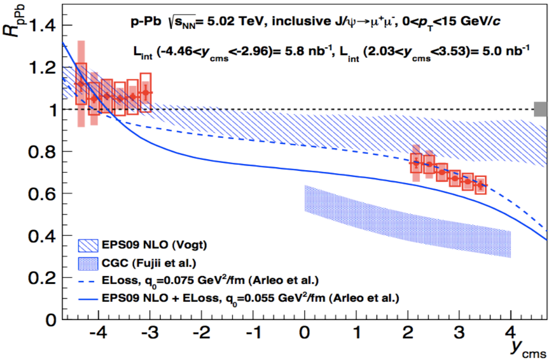


- Very good agreement despite large uncertainty on normalization
- Data at $y \gtrsim 4$ would be helpful

LHC predictions

Comparing to other model predictions

[ALICE 1308.6726]

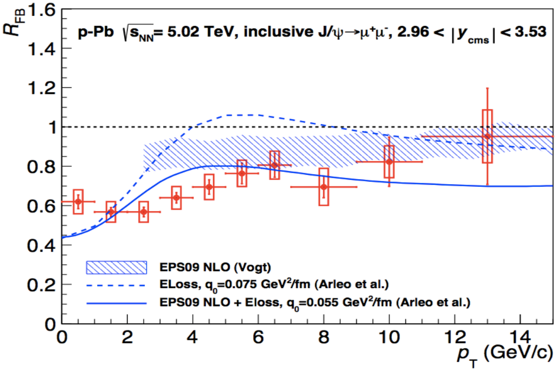


- Forward J/ψ suppression underestimated using EPS09 NLO
- Forward J/ψ suppression overestimated in the CGC calculation

LHC predictions

Transverse momentum dependence

[ALICE 1308.6726]



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

Extrapolation to heavy-ion collisions

The model successfully reproduces all p A (π A) data vs y and $p_\perp$

$\rightarrow$ can be used to predict J/ψ suppression in heavy-ion collisions

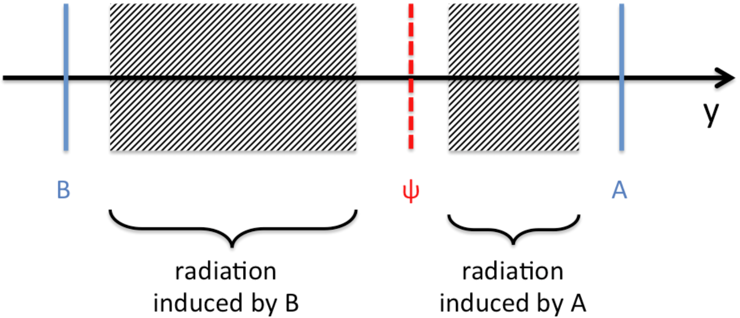
Naturally

- Many other effects possibly at work: Debye screening, recombination, energy loss in hot medium...
- Goal: to set a baseline for the effects of energy loss in cold QCD matter

Extrapolation to heavy-ion collisions

Model for A B collisions

- Both incoming (projectile & target) partons lose energy in the (target & projectile) nucleus, respectively
- Two distinct regions of phase space for gluon emission $\rightarrow$ no interference effects in the radiation induced by nucleus A and B



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$$\frac{1}{A\ B}\frac{d\sigma_{AB}^{\psi}}{dy}\left(y,\sqrt{s}\right) = \int d\ \delta y_B\,\mathcal{P}_B(\varepsilon_B,y)\int d\delta y_A\,\mathcal{P}_A(\varepsilon_A,-y)\,\frac{d\sigma_{\rm pp}^{\psi}}{dy}\left(y+\delta y_B-\delta y_A,\sqrt{s}\right)$$

with δy_B defined as $E(y+\delta y_B)\equiv E(y)+\epsilon_B$

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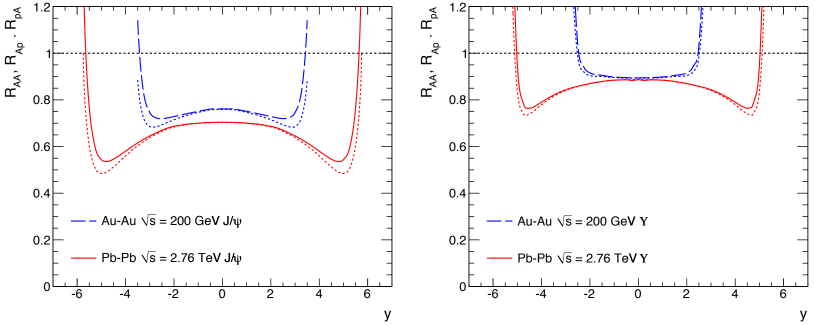
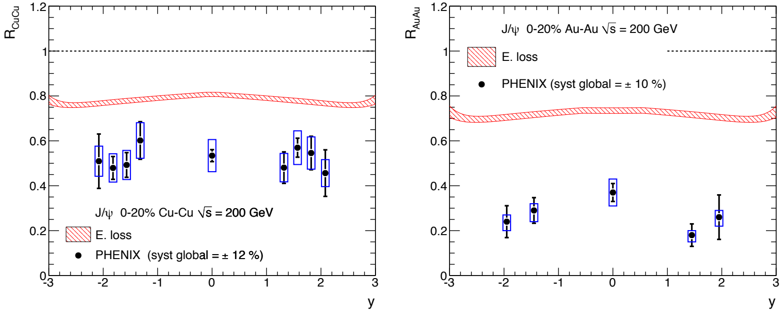
A good approximation (at not too large y)

$$R_{AB}(+y) \simeq R_{Ap}(+y) \times R_{pB}(+y) = R_{pA}(-y) \times R_{pB}(+y)$$



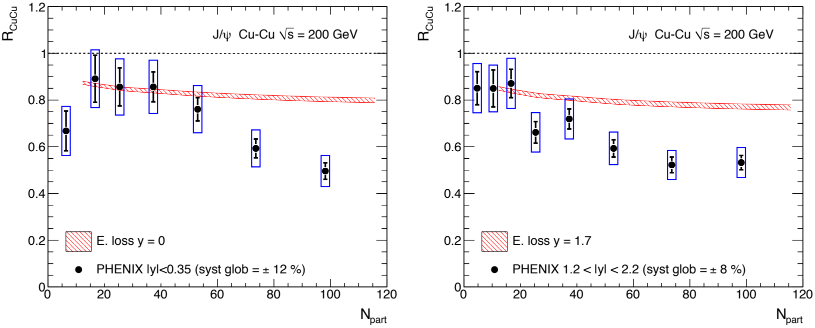
- Rather pronounced suppression, especially for J/ψ
- R_{AA} slightly decreasing at not too large y
- Fast increase at edge of phase space due to energy gain fluctuations

Rapidity dependence in A A collisions at RHIC



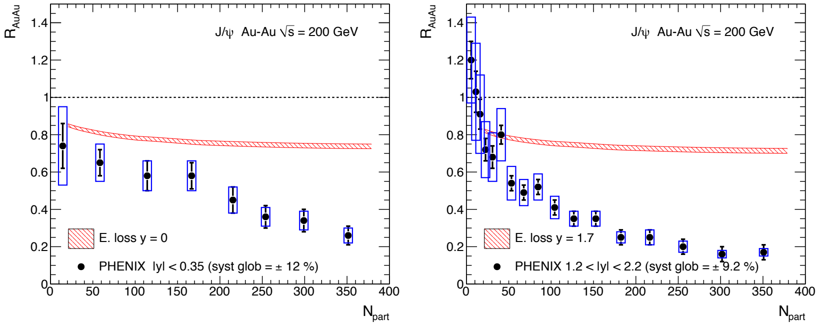
- Disagreement in both Cu Cu and Au Au collisions
- Disagreement more pronounced in Au Au collisions

Centrality dependence in A A collisions at RHIC



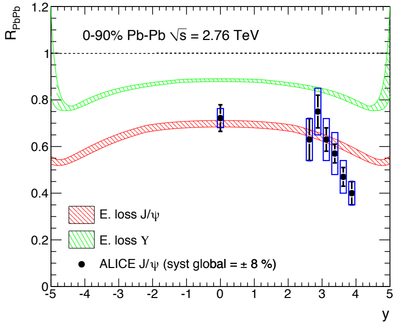
- Disagreement only in most central Cu Cu collisions

Centrality dependence in A A collisions at RHIC

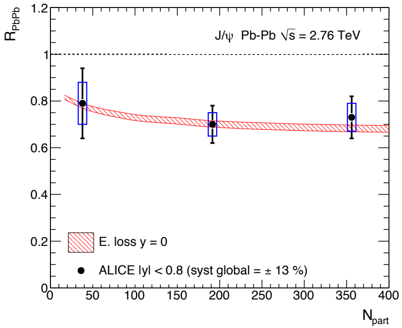


- Disagreement only in most central Cu Cu collisions
- Strong disagreement in most central Au Au collisions, fair agreement within uncertainties in peripheral collisions

Rapidity dependence in Pb Pb collisions at LHC

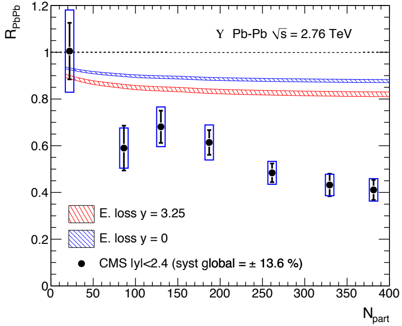


- Very good agreement with ALICE data, except in the largest y bins
- No hot medium effects ? Or medium effects compensate ?

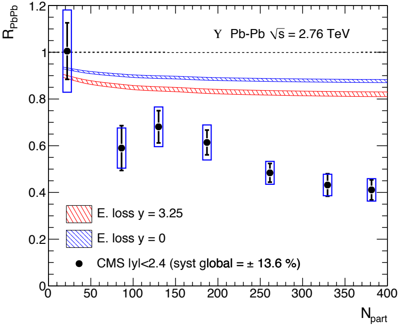


- Excellent agreement with ALICE J/ψ data

Centrality dependence in Pb Pb collisions at LHC



- Excellent agreement with ALICE J/ψ data
- Disagreement with CMS Υ data



- Excellent agreement with ALICE J/ψ data
- Disagreement with CMS Υ data

- Indication of hot suppression medium effects for Υ
- . . . implying (?) hot enhancement medium effects for J/ψ

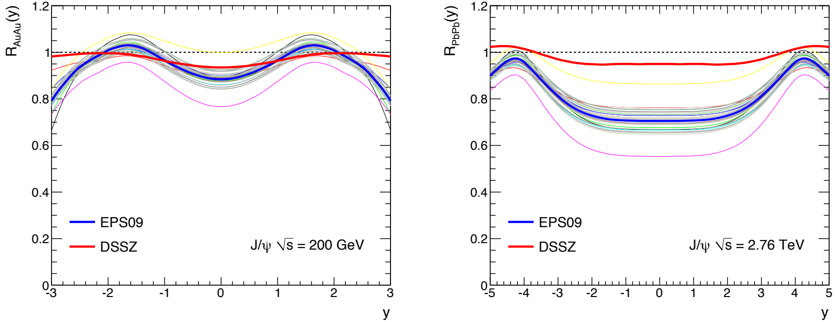
nPDF effects

- nPDF effects may affect quarkonium suppression in p A & A A collisions and could be added (incoherently) to present energy loss effects
- However sill large uncertainty on small x gluon shadowing (within a single set or comparing existing sets)

For simplicity we provided "energy loss only" calculations

nPDF effects

Ratio of gluon densities (using EPS09 NLO, x_1, x_2 given by $2 \to 1$ kin.)



- At RHIC, energy loss is the leading effect
- At LHC
  - Energy loss leading effect as compared to DSSZ
  - Same order of magnitude as EPS09 around mid-rapidity but leading effect at large rapidity

Summary

- Energy loss $\Delta E \propto E$ due to coherent radiation
  - Parametric dependence of $dI/d\omega$ predicted and used for phenomenology
- Phenomenology of quarkonium suppression in p A collisions
  - Good agreement with all existing data vs. y and $p_\perp$, from SPS to LHC
  - Natural explanation for the large x_F J/ψ suppression
  - Predictions in good agreement with LHC pPb data
- Phenomenology of quarkonium suppression in A A collisions
  - Model extrapolated from p A to AA collisions
  - Disagreement observed for J/ψ at RHIC, especially in most central collisions and heavier systems
  - Excellent (accidental?) agreement observed for J/ψ at LHC, disagreement observed for Υ

Medium-induced gluon spectrum

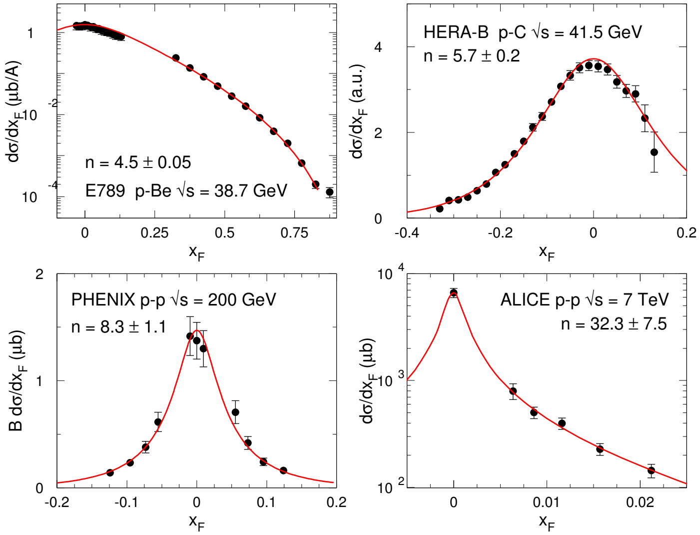
Gluon spectrum $dI/d\omega \sim$ Bethe-Heitler spectrum of massive (color) charge

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

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

- $\Delta E \propto E$ 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

Fit to pp data



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