Coherent energy loss and the production of hadrons in nuclear collisions

François Arleo

LLR Palaiseau

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Outline

- Scaling properties of medium-induced coherent radiation
  - A brief history of (gluon formation) time
  - LPM vs. coherent energy loss
- Phenomenology
  - Quarkonium suppression in p A and A A collisions
  - Light hadron suppression in p A collisions

References

- FA, S. Peigné, 1204.4609, 1212.0434, 1407.5054, w/ T. Sami, 1006.0818
- w/ R. Kolevatov, M. Rustamova, 1304.0901
- w/ R. Kolevatov, 1402.1671 + work in preparation

Radiative energy loss regimes

Different energy loss regimes depending on gluon formation time $t_{\rm f}$

- Bethe-Heitler (BH): $t_{\rm f} < \lambda$
  - Each scattering center acts as an independent source of radiation

$$\omega < \mu^2 \lambda$$

- Landau-Pomeranchuk-Migdal (LPM): $\lambda < t_{\rm f} < L$
  - A group of $(t_{\rm f}/\lambda)$ scattering centers acts as a single radiator
  - Relative suppression $\propto \omega^{-1/2}$ with respect to Bethe-Heitler

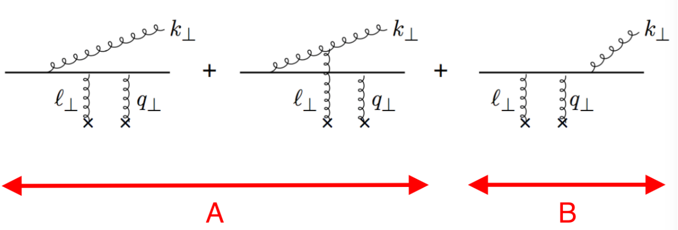
$$\mu^2 \lambda < \omega < \mu^2 L^2/\lambda \equiv \hat{q} L^2$$

- Fully coherent (aka factorization): $t_{\rm f} > L$
  - All scattering centers act coherently as a source of radiation

$$\omega > \hat{q} L^2$$

Theoretical set-up

Consider an incoming parton scattering at small angle, undergoing a hard process ($q_\perp$) and multiple soft scattering ($\ell_\perp \sim Q_s \ll q_\perp$)



- Initial-state radiation $|A|^2$ cancels out in the induced spectrum $dI/d\omega$
- Same for final-state radiation, $|B|^2$
- Interference terms, $\mathrm{Re}(A\ B^\star)$, do not cancel in the induced spectrum !
- Coherent radiation crucial for $t_f \gg L$
- Induced coherent gluon spectrum dominated by large formation times

Two regimes

LPM energy loss (small formation time $t_f \lesssim L$)

$$\Delta E_{\rm LPM} \propto \alpha_s \, \hat{q} \, L^2$$

- Hadron production in nuclear DIS or Drell-Yan in p A collisions
- Particle suddenly accelerated (e.g. jet in QGP)

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

$$\Delta E_{\rm coh} \propto \alpha_s \, F_c \, \frac{\sqrt{\hat{q} \, L}}{M_\perp} \, E \quad (\gg \Delta E_{\rm LPM})$$

- Needs color in both initial & final state (otherwise $F_c = 0$)
- Important at all energies, especially at large rapidity
- Hadron production in p A collisions

Induced gluon spectrum for $1 \to 1$ forward scattering

Gluon spectrum $dI/d\omega$ for $1 \to 1$ hard forward process

$$\omega \frac{dI}{d\omega}\bigg|_{1\to 1} = \frac{F_c\ \alpha_s}{\pi}\ \ln\left(1 + \frac{\hat{q}L\ E^2}{M_\perp^2\ \omega^2}\right)$$

- First determined in the simple model, later confirmed rigorously in the GLV opacity expansion

  [FA Peigné Sami, 1006.0818**, Peigné FA Kolevatov,** 1402.1671**]**

- Color factor F_c follows from simple color algebra: $F_c = C_R + C_{R'} - C_t$ where R (R') = color rep. of the incoming (outgoing) particle

  [Peigné FA Kolevatov, 1402.1671**]**

$$\begin{aligned} g \to g &\ : \ F_c = N_c + N_c - N_c = N_c \\ q \to g &\ : \ F_c = C_F + N_c - C_F = N_c \\ q \to q &\ : \ F_c = C_F + C_F - N_c = -1/N_c \quad (< 0\ !) \end{aligned}$$

Induced gluon spectrum for $1 \to 2$ forward scattering

Similar gluon spectrum derived for dijet production (logarithmic accuracy)

[Peigné, Kolevatov 1405.4241]

$$\omega \frac{dI}{d\omega}\bigg|_{1\to 2} = \frac{F_c\ \alpha_s}{\pi}\ \ln\left(\frac{\hat{q}L\ E^2}{K_\perp^2\ \omega^2}\right)$$

- The medium does not resolve the dijet: $\hat{q}L \ll K_\perp^2$
- $F_c = C_R + C_{R'} - C_t$ where $C_{R'}$ is the Casimir of the compact dijet
- Coincides with the calculation by Liou and Mueller, in a totally different formalism **[Liou, Mueller 1402.1647]**
- Conjectured to hold for $1 \to$ n processes **[Peigné Kolevatov , 1405.4241]**

Phenomenology

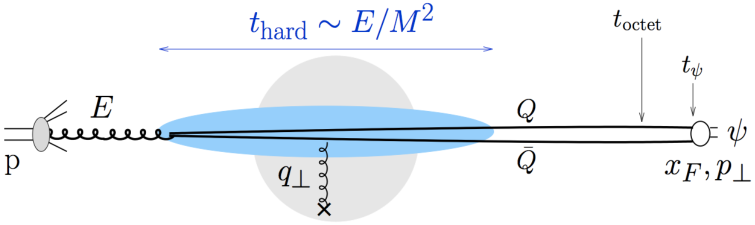
Goal

- Explore phenomenological consequences of coherent energy loss
- Approach as simple as possible with the least number of assumptions
- Observables
  - Quarkonium suppression in p A (and A A) collisions
  - Light hadron production in p A collisions (preliminary!)

Model for quarkonium suppression

Physical picture and assumptions

[FA Peigné, 1204.4609, 1212.0434]



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

Model for quarkonium suppression

Energy shift

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

- pp cross section fitted from experimental data
- $\mathcal{P}(\epsilon)$: quenching weight related to the induced gluon spectrum

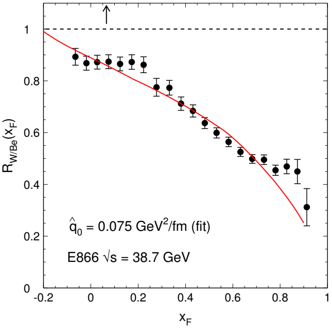
$$P(\epsilon) \simeq \frac{dI(\epsilon)}{d\omega}\, \exp\left\{-\int_{\epsilon}^{\infty} d\omega \frac{dI}{d\omega}\right\}$$

- Length L given by Glauber model
- Transport coefficient

$$\hat{q}(x) = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\,\rho\, xG(x) = \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$$

Procedure

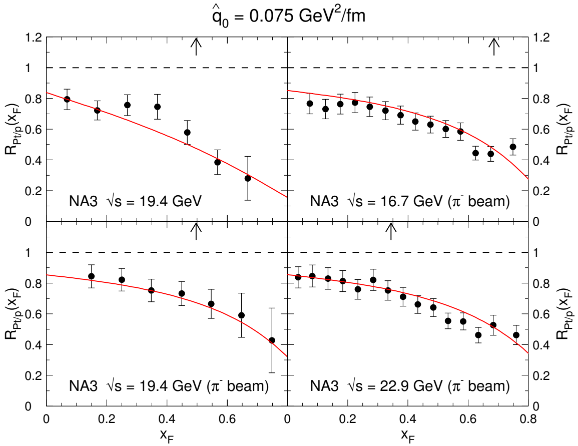
1. Fit $\hat{q}_0$ from J/ψ E866 suppression data in p W vs p Be
2. Predict J/ψ and Υ suppression for all nuclei and c.m. energies



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

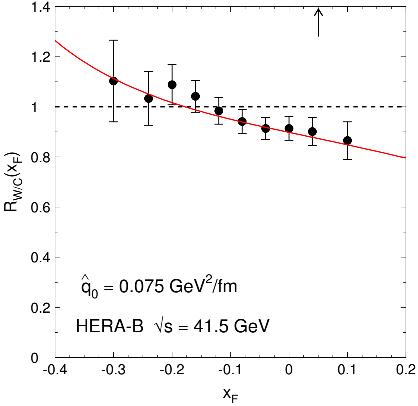
- Corresponds to $Q_{s\,\mathrm{p}}^2(x = 10^{-2}) = 0.11 - 0.14$ GeV^2 consistent with fits to DIS data **[Albacete et al AAMQS 2011]**

SPS predictions



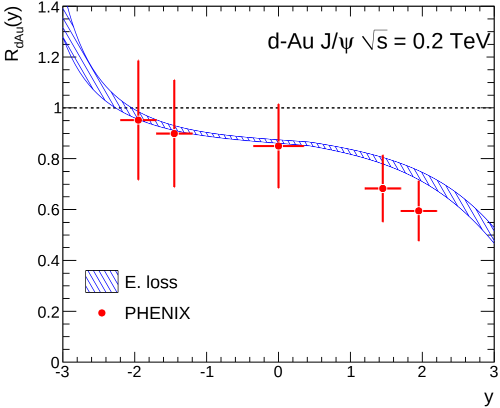
- Agreement even at small x_F
- Natural explanation from the different suppression in p A vs π A

HERA-B predictions



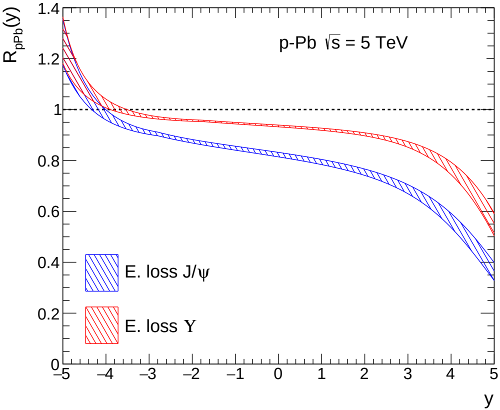
- Also good agreement in the nuclear fragmentation region ($x_F < 0$)
- Enhancement predicted at very negative x_F

RHIC predictions



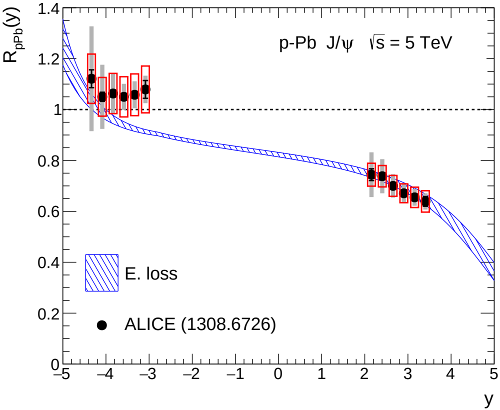
- Good agreement for R_{pA} vs rapidity
- Small uncertainty coming from the variation of the pp cross section and the transport coefficient

LHC predictions



- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$
- 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

Extrapolation to heavy-ion collisions

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

- Can be used to predict J/ψ suppression in heavy-ion collisions
- Obviously, many hot effects possibly at work!
- Goal: set a baseline for the effects of energy loss in cold matter

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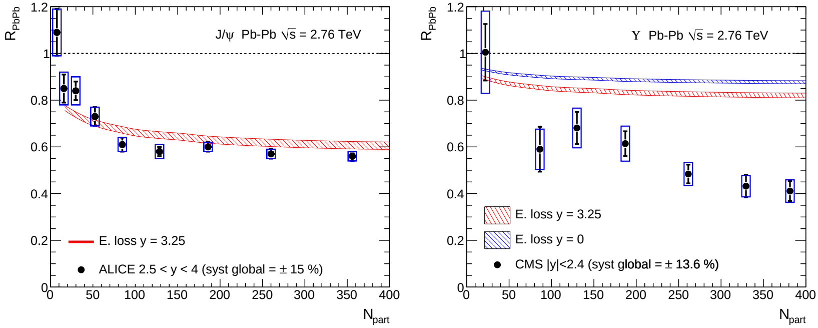
Model for A B collisions

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

Centrality dependence in Pb Pb collisions at LHC



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

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

Model for light hadron suppression at the LHC

- We assume $g \to gg$ scattering followed by collinear fragmentation
- Model similar to quarkonium suppression…except for the average over the color representations of the di-gluon final state

$$R^R_{\rm pA}(y, p_\perp) = \int_\delta \int_\phi \hat{\mathcal{P}}_R \left(x, \ell_{\rm A}, P_\perp = \frac{p_\perp}{\langle z \rangle} \right) \frac{d\sigma^h_{\rm pp}(y + \delta, \vec{p}_\perp + \Delta \vec{p}_\perp)}{d\sigma^h_{\rm pp}(y, \vec{p}_\perp)}$$

$$R^h_{\rm pA}(y, p_\perp) \simeq \sum_R \langle P_R(x_{\rm h}) \rangle_y \, R^R_{\rm pA}(y, p_\perp)$$

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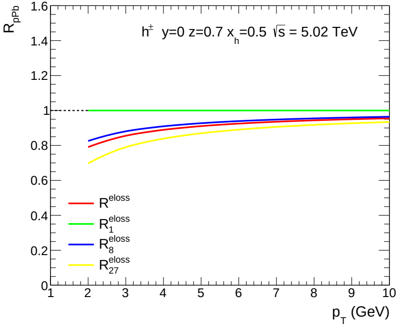
$$R^h_{\mathrm{pA}}(y, p_\perp) \simeq \sum_R \langle P_R(x_{\mathrm{h}}) \rangle_y \, R^R_{\mathrm{pA}}(y, p_\perp)$$

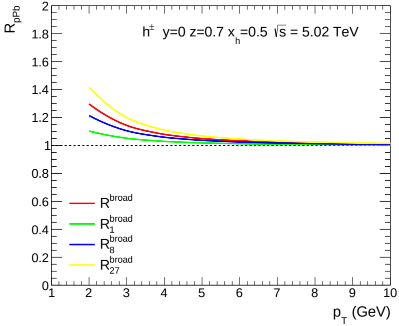
- Color representations: $R = \mathbf{1}, \mathbf{8}, \mathbf{27}$ ($P_{\mathbf{10}} = 0$ for $N_c = 3$) with Casimir

$$C_1 = 0, \quad C_8 = N_c, \quad C_{27} = 2(N_c + 1)$$

- Broadening (Cronin) effect depends on the average of initial and final Casimir factors: $\langle p_\perp^2 \rangle = (N_c + C_R)/(2N_c)\ \hat{q} L$

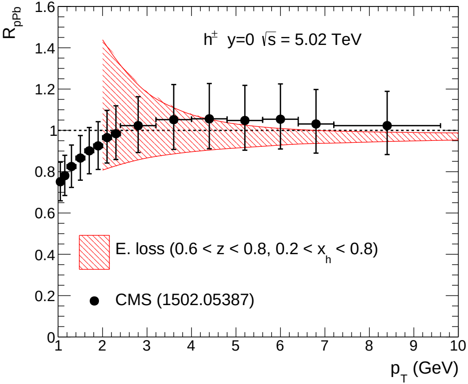
Energy loss vs. broadening at LHC





- Opposite trends between energy loss and broadening effects
- The average loss (red) somehow depends on the value of $x_{\rm h}$

Light hadron quenching vs. LHC data



- Calculations consistent with (ALICE and) CMS data
- . . . yet presently too large uncertainties
- Work in progress!

Summary

- Energy loss $\Delta E \propto E$ due to coherent radiation
  - Parametric dependence of $dI/d\omega$ predicted and used for phenomenology
- Quarkonium suppression in p A collisions
  - Good agreement with all existing data from SPS to LHC
  - Natural explanation for the strong J/ψ suppression at large x_F
  - Predictions in good agreement with LHC pPb data
- Light hadron suppression in p A collisions
  - Subtle interplay between energy loss and broadening effects
  - Preliminary calculations leads to moderate suppression at mid-rapidity, consistent with data
  - Rich color structure: suppression sensitive to the color state of the parent dijet

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

Medium-induced gluon spectrum

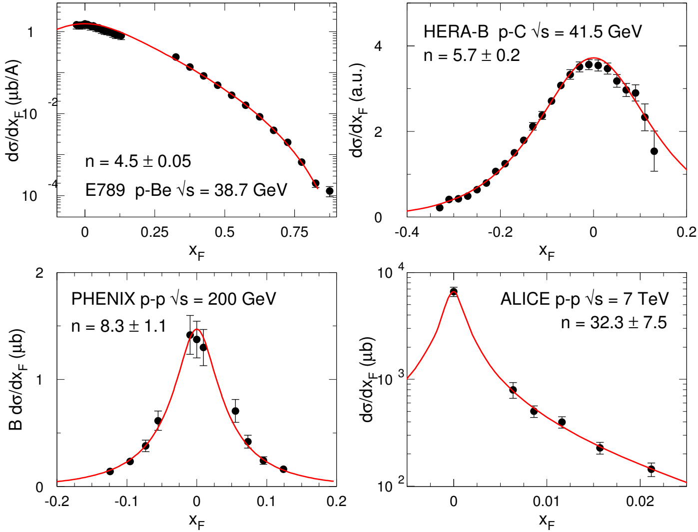
Gluon spectrum $dI/d\omega \sim$ Bethe-Heitler spectrum of massive (color) charge

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

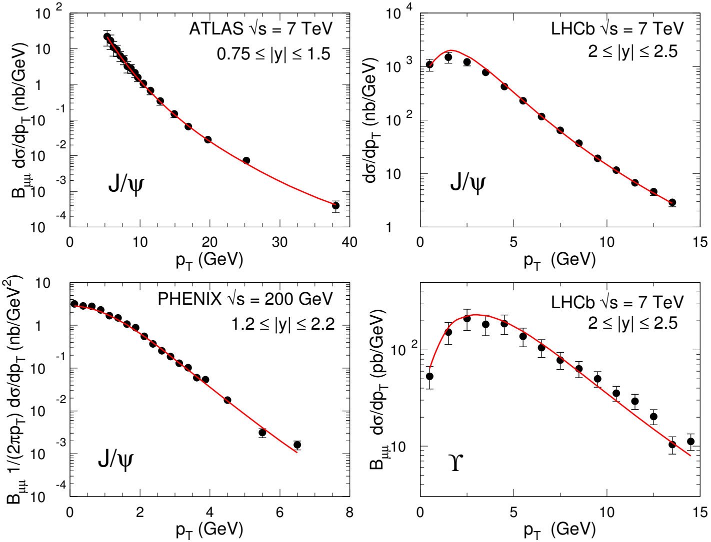
$$\Delta E = \int d\omega\, \omega\, \frac{dI}{d\omega}\bigg|_{\rm ind} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2} - \Lambda_{\rm QCD}}{M_\perp}\, E$$

- $\Delta E \propto E$ 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

Fit to pp data



Fit to pp data



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

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

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

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

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 $\hat{q}_0$

$p_\perp$ dependence

Most general case

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

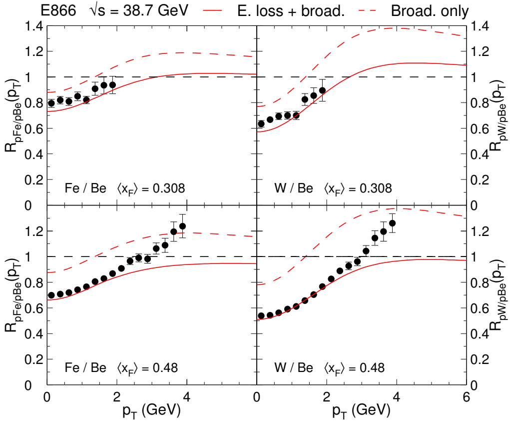
- pp cross section fitted from experimental data

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

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

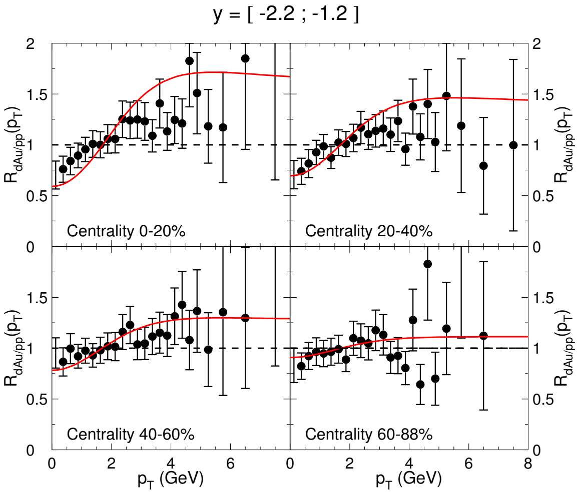
$$R_{\rm pA}^{\psi}(y, p_\perp) \simeq R_{\rm pA}^{\rm loss}(y, p_\perp)\cdot R_{\rm pA}^{\rm broad}(p_\perp)$$

$p_\perp$ dependence at E866



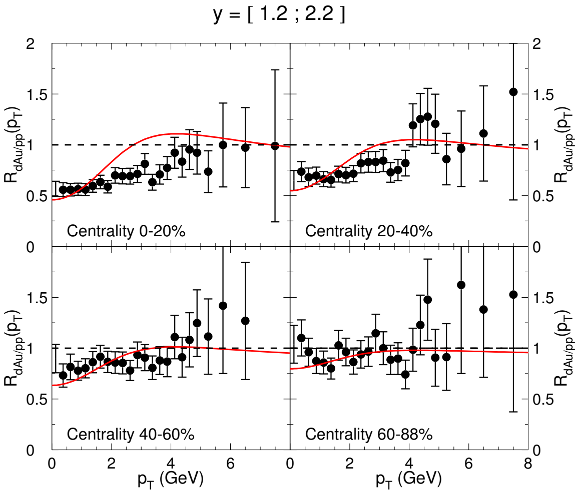
- Good description of E866 data (except at large $p_\perp$ and large x_F)
- Broadening effects only not sufficient to reproduce the data

$p_\perp$ dependence at RHIC



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

$p_\perp$ dependence at RHIC

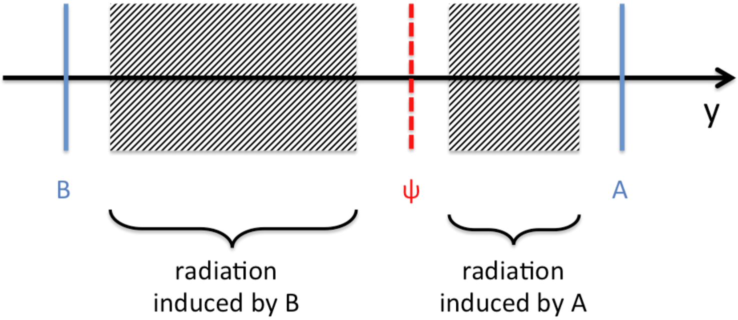


- Good description of $p_\perp$ and centrality dependence at $y = 1.7$

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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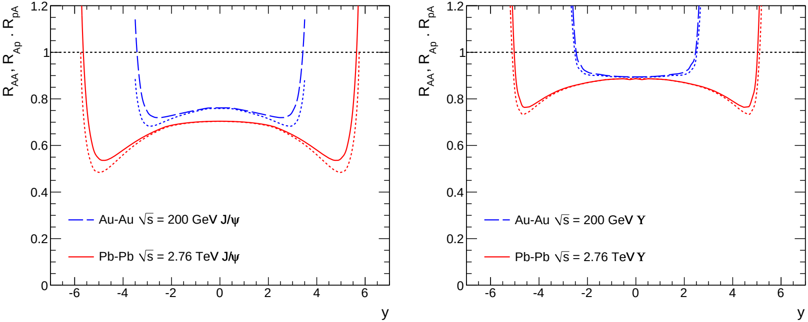
A good approximation (at not too large y)

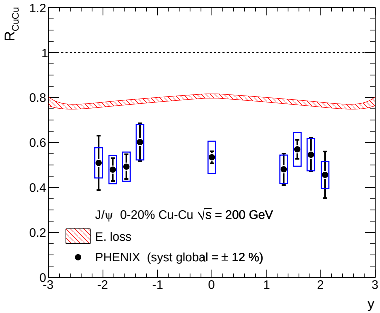
$$R_{AB}(+y) \simeq R_{Ap}(+y) \times R_{pB}(+y) = R_{pA}(-y) \times R_{pB}(+y)$$

Rapidity dependence in A A collisions



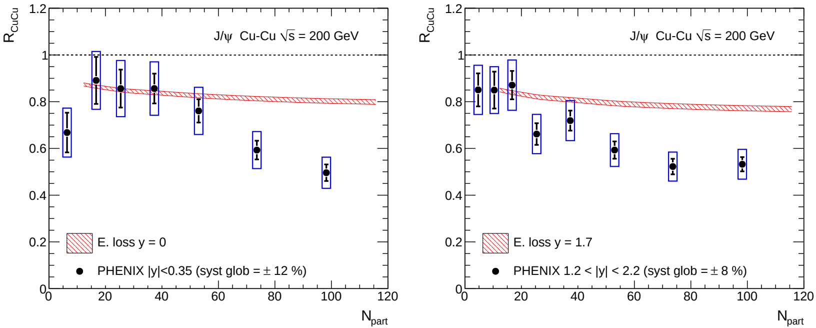
- Rather pronounced suppression, especially for J/ψ
- R_{AA} slightly decreasing at not too large y
- Fast increase at edge of phase space due to energy gain fluctuations

Rapidity dependence in A A collisions at RHIC



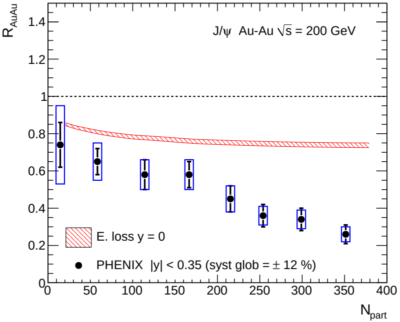
- Disagreement in both Cu Cu and Au Au collisions
- Disagreement more pronounced in Au Au collisions

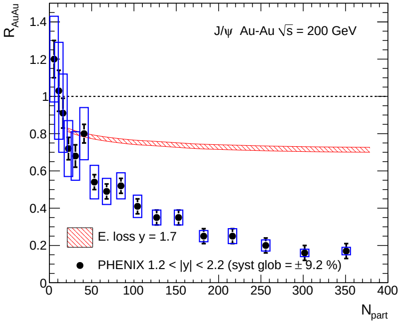
Centrality dependence in A A collisions at RHIC



- 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

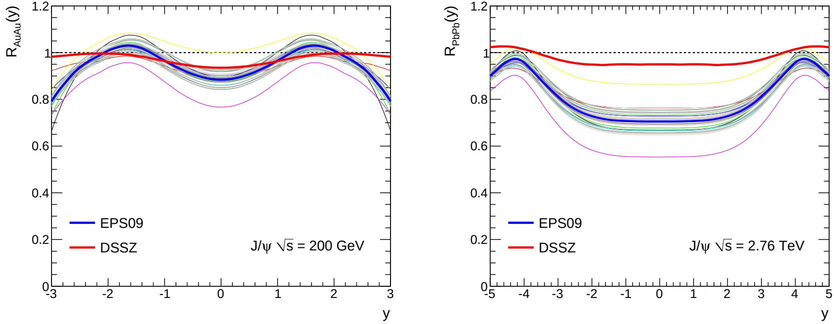
nPDF effects

- 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