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

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Outline

- Motivations
  - $J/\psi$ suppression data in p A collisions
- Revisiting energy loss
  - New scaling properties from medium-induced coherent radiation
- Phenomenology
  - Model for $J/\psi$ and $\Upsilon$ suppression in p A collisions
  - Comparison with data from SPS to LHC
  - Extrapolation to heavy-ion collisions

References

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- w/ R. Kolevatov, M. Rustamova, 1304.0901
Data on $J/\psi$ suppression in $pA$ collisions

E866 $\sqrt{s} = 38.7$ GeV

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

PHENIX $\sqrt{s} = 200$ GeV
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- **Strong** $J/\psi$ 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
  - 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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All these effects may lead to some $J/\psi$ suppression

but cannot alone explain current pA data
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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

\[ \Delta E \propto E \cdot L \cdot M^{-2} \]

for both Drell-Yan and \( J/\psi \) (though larger due to final-state energy loss)
Gavin–Milana model

Simple model assuming (mean) energy loss scaling like parton energy

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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 $\gamma$ 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 \[ \text{[ Brodsky Hoyer 93 ]} \]

- No contribution from large formation times \( t_f \gg L \)
- Induced gluon radiation needs to resolve the medium
  \[
  t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \quad \omega \lesssim k_\perp^2 \quad L \sim \hat{q} \ L^2
  \]

  - 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
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

\[
\Delta E = \int d\omega \omega \left. \frac{dI}{d\omega} \right|_{\text{ind}} = N_c\alpha_s \frac{\sqrt{\Delta q_{\perp}^2}}{M_{\perp}} E
\]
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: $J/\psi$ and $\Upsilon$ 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: \( t_{\text{octet}} \gg t_{\text{hard}} \)
- 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

\[ \frac{1}{A} \frac{d\sigma_{pA}^{\psi}}{dE} (E, \sqrt{s}) = \int_{0}^{\varepsilon_{\text{max}}} d\varepsilon \mathcal{P}(\varepsilon, E) \frac{d\sigma_{pp}^{\psi}}{dE} (E + \varepsilon, \sqrt{s}) \]

Ingredients

- pp cross section fitted from experimental data

\[ E \frac{d\sigma_{pp}^\psi}{dE} = \frac{d\sigma_{pp}^\psi}{dy} \propto \left( 1 - \frac{2M_{\perp}}{\sqrt{s}} \cosh y \right)^{n(\sqrt{s})} \]

- Length $L$ given by Glauber model for minimum bias and centrality dependence

- $\mathcal{P}(\varepsilon)$: probability distribution (quenching weight)
Quenching weight

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

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

- However, radiating $\omega_i$ 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

- Usually one assumes independent emission \(\rightarrow\) Poisson approximation

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

- However, radiating \(\omega_i\) 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 \(\omega_1 \ll \omega_2 \ll \ldots \ll \omega_n\)

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

- \(P(\epsilon)\) scaling function of \(\hat{\omega} = \sqrt{\hat{q} L / M_{\perp}} \times E\)
\( \hat{q} \) related to gluon distribution in a proton

[BDMPS 1997]

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

For simplicity we assume

\[
\hat{q}(x) = \hat{q}_0 \left( \frac{10^{-2}}{x} \right)^{0.3}
\]

(\( \hat{q} \) 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 $J/\psi$ E866 data in p W collisions
2. Predict $J/\psi$ and $\Upsilon$ suppression for all nuclei and c.m. energies

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

- Corresponds to $Q_s^2(\chi = 10^{-2}) = 0.11 - 0.14 \text{ GeV}^2$ consistent with fits to DIS data

[ Albacete et al AAMQS 2011 ]
Procedure

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

- Fe/Be ratio well described, supporting the $L$ dependence of the model
• Agreement even at small $x_F$
• Natural explanation from the different suppression in $p$ A vs $\pi$ A
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)

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

\[
(\Delta R^-)^2 = \sum_{k=\hat{q}_0,n} \left[ \max \{ R(S^0) - R(S_k^-), 0 \} \right]^2
\]
Uncertainties

Two sources of uncertainties are identified

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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 $\hat{q}_0$
- 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

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

- pp cross section fitted from experimental data

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

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

$$R_{pA}^\psi(y, p_\perp) \simeq R_{pA}^{loss}(y, p_\perp) \cdot R_{pA}^{broad}(p_\perp)$$
$p_\perp$ 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
Good description of $p_{\perp}$ and centrality dependence at $y = -1.7$
$p_\perp$ dependence at RHIC

$y = [1.2; 2.2]$ 

- 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 $\Upsilon$ channel
LHC predictions

- Very good agreement despite large uncertainty on normalization
- Data at $y \gtrsim 4$ would be helpful
Forward $J/\psi$ suppression under estimated using EPS09 NLO

Forward $J/\psi$ suppression over estimated in the CGC calculation
$R_{FB}(p_\perp)$: good agreement, better agreement with energy loss supplemented by nPDF effects.
The model successfully reproduces all p A (π A) data vs y and $p_\perp$

$\rightarrow$ can be used to predict $J/\psi$ 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
Extrapolation to heavy-ion collisions

Model for A B collisions

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- Two distinct regions of phase space for gluon emission → no interference effects in the radiation induced by nucleus A and B

\[
\frac{1}{A} \frac{d\sigma_{AB}}{dy} (y, \sqrt{s}) = \int d\delta y_B \mathcal{P}_B(\varepsilon_B, y) \int d\delta y_A \mathcal{P}_A(\varepsilon_A, -y)
\]

\[
\frac{d\sigma_{pp}}{dy} (y + \delta y_B - \delta y_A, \sqrt{s})
\]

with \(\delta y_B\) defined as \(E(y + \delta y_B) \equiv E(y) + \epsilon_B\)
Extrapolation to heavy-ion collisions

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\]

\[
\frac{d\sigma_{pp}}{dy}(y + \delta y_B - \delta y_A, \sqrt{s})
\]

A good approximation (at not too large y)

\[
R_{AB}(+y) \approx R_{Ap}(+y) \times R_{pB}(+y) = R_{pA}(-y) \times R_{pB}(+y)
\]
Rapidity dependence in A A collisions

- Rather pronounced suppression, especially for $J/\psi$
- $R_{AA}$ slightly decreasing at not too large $y$
- Fast increase at edge of phase space due to energy gain fluctuations
Disagreement in both Cu Cu and Au Au collisions

Disagreement more pronounced in Au Au collisions
Disagreement only in most central Cu Cu collisions
Disagreement only in most central Cu Cu collisions

Strong disagreement in most central Au Au collisions, fair agreement within uncertainties in peripheral collisions
Very good agreement with ALICE data, except in the largest $y$ bins

No hot medium effects? Or medium effects compensate?
Excellent agreement with ALICE $J/\psi$ data
Centrality dependence in Pb Pb collisions at LHC

- Excellent agreement with ALICE $J/\psi$ data
- Disagreement with CMS $\Upsilon$ data
Excellent agreement with ALICE $J/\psi$ data
Disagreement with CMS $\Upsilon$ data

- Indication of hot suppression medium effects for $\Upsilon$
- ...implying (?) hot enhancement medium effects for $J/\psi$
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 still large uncertainty on small $x$ gluon shadowing (within a single set or comparing existing sets)

For simplicity we provided “energy loss only” calculations
Ratio of gluon densities (using EPS09 NLO, $x_1, x_2$ given by $2 \rightarrow 1$ 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
Energy loss $\Delta E \propto E$ due to coherent radiation

- Parametric dependence of $dl/d\omega$ predicted and used for phenomenology

Phenomenology of quarkonium suppression in pA collisions

- Good agreement with all existing data vs. $y$ and $p_{\perp}$, from SPS to LHC
- Natural explanation for the large $x_F$ $J/\psi$ suppression
- Predictions in good agreement with LHC pPb data

Phenomenology of quarkonium suppression in AA collisions

- Model extrapolated from pA to AA collisions
- Disagreement observed for $J/\psi$ at RHIC, especially in most central collisions and heavier systems
- Excellent (accidental?) agreement observed for $J/\psi$ at LHC, disagreement observed for $\Upsilon$
Medium-induced gluon spectrum

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

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

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

- $\Delta E \propto E$ 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

E789 $p$-Be $\sqrt{s} = 38.7$ GeV
$n = 4.5 \pm 0.05$

HERA-B $p$-C $\sqrt{s} = 41.5$ GeV
$n = 5.7 \pm 0.2$

PHENIX $p$-$p$ $\sqrt{s} = 200$ GeV
$n = 8.3 \pm 1.1$

ALICE $p$-$p$ $\sqrt{s} = 7$ TeV
$n = 32.3 \pm 7.5$
Fit to pp data

\[ \frac{B_{\mu\mu}}{1/(2\pi p_T)} \frac{d\sigma}{dp_T} (\text{nb/GeV}^2) \]

ATLAS \( \sqrt{s} = 7 \text{ TeV} \)
\[ 0.75 \leq |y| \leq 1.5 \]

PHENIX \( \sqrt{s} = 200 \text{ GeV} \)
\[ 1.2 \leq |y| \leq 2.2 \]

LHCb \( \sqrt{s} = 7 \text{ TeV} \)
\[ 2 \leq |y| \leq 2.5 \]