Charmonium dynamics in dA and AA at RHIC and LHC


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Outline

1. Motivation

2. Initial state effects in charmonium production
   - shadowing, absorption, energy-momentum conservation
   - results for J/psi in d+Au @ RHIC

3. Charmonium suppression in a final state model
   - Comovers’ interaction model
   - results for J/psi in Cu+Cu and Au+Au @ RHIC
   - predictions for Pb+Pb @ LHC

4. Conclusions
Production of a heavy-quark state at high-energy

Why is it important?

\( J/\psi \) production in pA collisions:

- absorption in nuclear matter \((\sigma^{abs} \sim 5 \text{ mb})\) at low energies, interpreted within a probabilistic Glauber model

- puzzle at RHIC: vanishing \(\sigma^{abs}\)

- at high energies, production of heavy state probes the very low-x distribution of the nuclear structure function

\( J/\psi \) production in AA collisions:

- what is the underlying mechanism behind \( J/\psi \) suppression
  - QGP screening, melting, comovers’ interaction

- puzzle at RHIC I: same amount of suppression as at SPS

- puzzle at RHIC II: stronger suppression at forward than at mid-rap

- from color screening to recombination?
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Motivation

Space-time picture of high-energy interactions

Mandelstam Nuov. Cim. 30 (1963) 1113, 1127,1148; Gribov JETP 56 (1959) 982

“Planar” diagram

- low energy scattering - longitudinal ordering
  → Glauber multiple scattering
  → absorptive cross section

“Non-planar” diagram

- high energy scattering - change in space-time picture
  → Gribov inelastic shadowing
  → fluctuation prepared long before the collision

- critical energy scale depends on mass
  → observables sensitive to this transition?
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**Space-time picture of high-energy interactions**

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**“Planar” diagram**

\[
\begin{align*}
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  \text{absorptive cross section} & \\
  \text{high energy scattering} & \rightarrow \text{Gribov inelastic shadowing} \\
  \text{fluctuation prepared long before the collision} & \\
  \text{critical energy scale depends on mass} & \rightarrow \text{observables sensitive to this transition?}
\end{align*}
\]

**“Non-planar” diagram**
Nuclear shadowing in Schwimmer model
Enhanced diagrams

\[ \sigma_{hA}^{Sch} = \sigma_{hN} \int d^2 b \frac{AT_A(b)}{1 + (A - 1)f(x, Q^2)T_A(b)} , \]

\[ f(x, Q^2) = 4\pi \int_x^{x_{IP}^{max}} dx_{IP} B(x_{IP}) \frac{F_{2D}^{(3)}(x_{IP}, Q^2, \beta)}{F_2(x, Q^2)} F_A^2(t_{min.}) \]

- similar to the B-K equation of dipole splitting
- OK for hA collisions at high energies
- exact solution of the Reggeon field theory
- parameterizations from diffractive HERA data and CTEQ

**Gluon shadowing - results**

Tywoniuk, Arsene, Bravina, Kaidalov, Zabrodin PLB 657 (2007) 170

- strong shadowing obtained
- no fitting or free parameters!
- shadowing is a “rescattering effect” - slow $Q^2$ behaviour
- in MC generator HYDJET


Brodsky et al. PRD 65 (2002) 114025
\( \alpha(x_F) \) dependence

... and what can we learn from it?

- change of behaviour of \( \alpha(x_F) \) going from low-energy to high-energy regime
- \( \alpha(x_F = 0) \) sensitive to the disappearance of low-energy effects and onset of shadowing
- no scaling of RHIC data (neither in \( x_F \) nor \( x_2 \))!

\[ \frac{d\sigma_{pA}}{dy} = \frac{d\sigma_{pp}}{dy} A^{\alpha(x_F)} \]

**\( \alpha(x_F) \) dependence**

... and what can we learn from it?


### Low energy absorption + em.

\[
\frac{1}{\xi(x_+) \sigma_{Q\overline{Q}}} \left( 1 - \exp \left\{ -\xi(x_+) \sigma_{Q\overline{Q}} T_A(b) \right\} \right)
\]

### High energy absorption + em.

\[
T_A(b) \exp \left\{ -\xi(x_+) \sigma_{Q\overline{Q}} T_A(b)/2 \right\}
\]

**Universal behaviour**:  
\[
\xi(x_+) = (1 - \epsilon) \exp \left\{ -(x_c/x_2)^2 \right\} + \epsilon x_+^\gamma
\]
$\alpha(x_F)$ dependence

... and what can we learn from it?

- scaling with $x_F$ for low energies due to energy-momentum conservation
- scaling with $x_2$ will appear for RHIC and higher energies
J/ψ production in pA @ RHIC and LHC


\[ \sigma_{abs} = 0 \] and shadowing reproduce the data at RHIC

→ first signal of coherent HQ production?

● at LHC - strong IS effect!
J/ψ production in pA @ RHIC and LHC


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K. Tywoniuk (UiO) Charmonium dynamics at RHIC and LHC
$p_\perp$-dependence of J/$\psi$ production in dAu @ RHIC

Discriminating between different models of anti-shadowing

Ferreiro, Fleuret, Rakotozafindrabe arXiv:0801.4949

CF shadowing is compared to EKS on MC generator level.

Stronger shadowing with CF!

Different behaviour at backward rapidities!
Comovers’ interaction model

Gain and loss equation that govern the final-state interactions with the co-moving medium - assuming only $J/\psi$ dissociation

\[
\tau \frac{dN_{J/\psi}}{dt}(b, s, y) = -\sigma_{co} N_{J/\psi}(b, s, y) N^{co}(b, s, y)
\]

\[
S^{co}(b, s, y) = \exp\left[-\sigma_{co} N^{co}(b, s, y) \ln \left(\frac{N^{co}(b, s, y)}{N_{pp}(0)}\right)\right]
\]

Gluon shadowing taken as before. Shadowing + comovers suppression with $\sigma = 0.65$ mb gives a too strong suppression. Recombination seems to be necessary at RHIC.


$\sigma$ – an effective cross section averaged over interaction time
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$\sigma$ – an effective cross section averaged over interaction time
Comovers’ suppression and recombination


We modify the rate equation to include effects of recombination of $c\bar{c}$ pairs in the comovers’ scenario.

$$\tau \frac{d N^{J/\psi}}{d\tau} (b, s, y) = -\sigma \left\{ N_{J/\psi} N^{\text{co}} - N_D N_{\bar{D}} \right\}$$

Cross sections are taken from pp measurements @ $\sqrt{s} = 200$ GeV → except $c\bar{c}$ at forward – from PYTHIA.

No free parameters in the model!
Comovers’ suppression and recombination


We modify the rate equation to include effects of recombination of $c\bar{c}$ pairs in the comovers’ scenario.

First approximation...

\[
S^{CR}(b, s, y) = \exp \left\{ -\sigma N^{co} \ln \left[ \frac{N^{co}}{N_{pp}} \right] \right\} \times \exp \left\{ \sigma Cn(b, s) \ln \left[ \frac{N^{co}}{N_{pp}} \right] \right\}
\]

\[
C = \frac{\left( \frac{d\sigma_{pp}}{dy} \right)^2}{\sigma_{pp}^{ND} \frac{d\sigma_{pp}^{J/\psi}}{dy}}
\]

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No free parameters in the model!
Charmonium suppression in a final state model

Comovers’ suppression and recombination
Comparison to data for Au+Au and Cu+Cu @ RHIC


CIM describes properly the rapidity dependence of the suppression!

\( \sqrt{s} = 200 \text{ GeV} \)

C = 0.59

C = 0.32
Comovers’ suppression and recombination
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Comovers’ suppression and recombination
Predictions for Pb+Pb @ LHC

- recombination a crucial effect
- strong dependence on the charm cross section
- theoretical extrapolations are very uncertain
- we assume \( \sigma^{c\bar{c}} \propto s^{0.3} \)

Comovers’ interaction model

\( \sqrt{s} = 5500 \text{ GeV} \)

Abreau et al. Heavy Ion Collisions at the LHC - Last Call for Predictions
Conclusions

- d+Au data at RHIC are consistent with $\sigma_{abs} = 0$ and gluon shadowing
  - → novel scaling in $x_2$ will appear at LHC
- strong shadowing effects are predicted for LHC, important in p+Pb collisions and as initial condition for Pb+Pb modeling of final-state effects
- combined effect of co-movers suppression and recombination at RHIC is consistent with Cu+Cu and Au+Au data
  - → rapidity dependence is reproduced
- density of charm grows mildly with energy
  - → recombination still weak in Pb+Pb at LHC
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Gribov inelastic shadowing

The contribution from $1, 2\ldots$ scatterings can be expanded in

$$\sigma_{pA} = \sigma_{pA}^{(1)} + \sigma_{pA}^{(2)} + \ldots$$

$$\sigma_{pA}^{(1)} = A \cdot \sigma_{NN},$$

$$\sigma_{pA}^{(2)} = -4\pi A(A - 1) \int d^2 b T_A^2(b) \int_{M_{min}^2}^{M_{max}^2} dM^2 \left[ \frac{d\sigma_{\gamma^* N}(Q^2, x_P, \beta)}{dM^2 dt} \right]_{t=0} F_A^2(t_{min})$$

Conclusions

BACKUP II

Hard diffraction @ HERA

\[
\frac{d\sigma^{D\gamma^\ast N}}{dM^2 dt} \bigg|_{t=0} = \frac{4\pi^2 \alpha_{em} B}{Q^2(Q^2 + M^2)} x_P F_{2D}^{(3)}
\]

FIT A and B

- two available fits, parameterized at low \(Q_0 = 1.75 - 2.5 \text{ GeV}^2\)
- maximal uncertainty in gluon dPDF due to mixing with quarks at \(\beta > 0.3\)
- can be further constrained by combined fit to additionally diffractive dijets and heavy flavor

K. Tywoniuk (UiO)
Why is $\sigma_{abs}$ suddenly decreasing?

- counterintuitive!
  - Kopeliovich et al.: energy loss grows
  - Kharzeev et al.: size of HQ grows
  - double counting of low and high energy effects?

- Capella, Ferreiro
  - field theoretical approach
  - asymptotic cross section exhibit self absorption
  - leads to $A^1$ dependence

Capella, Ferreiro, PRC 76 (2007) 064906
Boreskov, Capella, Kaidalov, Thanh Van, PRD 47 (1993) 919
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