$J/\psi$ production and saturation effects

Breakdown of factorization at high energies

Kirill Tuchin

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

"QUANTIFYING THE PROPERTIES OF HOT QCD MATTER", INT, JULY 6, 2010
Factorization?

**Hard pQCD:**

- Factorization is broken if the hard amplitude involves *simultaneous* interactions with more than two partons at a time.

- Coherent scattering: \( l_c > R_A \) (coherence effects start at \( l_c \sim R_p \))
Coherence

Landau-Lifshitz, II §80: “Scattering of waves with large frequencies”

\[ d\sigma = \left( \frac{e^2}{mc^2} \right)^2 \left| \sum e^{-iqr} \right|^2 \sin^2 \theta \, d\omega. \quad q \sim 1/\lambda \quad l_c = \lambda \]

Coherent scattering: \( \lambda \gg R \Rightarrow qr \ll 1 \Rightarrow e^{iqr} = 1 \)

Incoherent scattering: \( \lambda \ll R \Rightarrow qr \gg 1 \Rightarrow e^{iq(r_a - r_b)} = \delta_{ab} \)  Raman (combinational) light scattering

\[ l_c = \frac{1}{k_- + (q - k)_- - q_-} \approx \frac{1}{Mx} \]

Coherent scattering: \( l_c \gg R_A \Rightarrow x \ll \frac{1}{MR_A} \)

Inelastic qN cross section

Coherence \( \Leftrightarrow \) Higher twists \( \propto \rho \sigma L \propto r^2 xG(x) A^{1/3} \) nuclear density
Sources of higher twist enhancement

**CGC/saturation = implementing the coherence.**

Quasi-classical approximation (MV model): \( \rho \sigma L \sim \alpha_s^2 A^{1/3} \sim 1 \)

Low x evolution enhances the higher twist contributions that break the factorization
Inclusive gluons in pA or DIS

\[
\frac{d\sigma^{pA}}{d^2k \ dy} = \frac{C_F}{\alpha_s \pi} \frac{1}{(2\pi)^3} \int d^2 B \ d^2 b \ d^2 z \ \nabla_z^2 n_G(z, b - B, 0) e^{-ik \cdot z} \nabla_z^2 N_G(z, b, 0)
\]

There is a \( k_T \) - factorization at the Leading Log Approximation.

\[ k_T \text{- factorization from: } \frac{d\sigma^{pA}}{d^2k \ dy} = \frac{2 \alpha_s}{C_F} \frac{1}{k^2} \int d^2 q \ \phi_p(q) \ \phi_A(k - q), \]

One can trace the origin of this (approximate) factorization in that there is no restriction on the quantum numbers of the product (Spin, Color etc.)
Two distribution functions

Conventional unintegrated gluon distribution

\[ \phi(x, k^2) = \frac{C_F}{\alpha_s (2\pi)^3} \int d^2 b d^2 r e^{-i k \cdot r} \nabla_r^2 N_G(r, b, y = \ln 1/x), \]

Unintegrated gluon distribution in MV model

\[ \phi^{WW}(x, k^2) = \frac{1}{2\pi^2} \int d^2 b d^2 r e^{-i k \cdot r} \text{Tr} \langle A^{WW}(0) \cdot A^{WW}(r) \rangle \]

\[ = \frac{4 C_F}{\alpha_s (2\pi)^3} \int d^2 b d^2 r e^{-i k \cdot r} \frac{1}{r^2} N_G(r, b, y = \ln 1/x) \]

Both have the same “dilute” limit

\[ \phi_A(x, k^2) = \phi_A^{WW}(x, k^2) = A \phi_N(x, k^2) = A \frac{\alpha_s C_F}{\pi} \frac{1}{k^2}, \quad k_T \to \infty, \]

but are quite different at finite \( k_T \)...
Inclusive gluon in AA

Does it follow from the $k_T$-factorization in pA/DIS that there is a factorization in AA? **NO!**

This type of diagrams brakes the factorization. Kovchegov, 2000

Similar diagrams in pA vanish for not completely understood reasons. **Assume** that they vanish in AA as well.

$$\frac{dN^{AA}}{d^2k \, d^2b \, dy} = 2 C_F \frac{1}{\alpha_s \pi^2} \left\{ - \int \frac{d^2z}{(2\pi)^2} e^{i k \cdot z} \frac{1}{z^2} \left( 1 - e^{-z^2 Q_{s1}^2/4} \right) \left( 1 - e^{-z^2 Q_{s2}^2/4} \right) + \int \frac{d^2x \, d^2y}{(2\pi)^3} e^{i z \cdot (x-y)} \frac{x}{x^2} \cdot \frac{y}{y^2} \left[ \frac{1}{x^2 \ln \frac{1}{|x|} \left( 1 - e^{-x^2 Q_{s1}^2/4} \right) \left( 1 - e^{-x^2 Q_{s2}^2/4} \right)} + \frac{1}{y^2 \ln \frac{1}{|y|} \left( 1 - e^{-y^2 Q_{s1}^2/4} \right) \left( 1 - e^{-y^2 Q_{s2}^2/4} \right)} \right] \right\}.$$
Phenomenology of light hadrons

Due to factorization we can infer the magnitude of the cold nuclear matter effect in AA from that in DA

This is true only if there is a factorization between the nuclei!
Inclusive heavy quark

Valence quark of p or D

Valence quarks of different nucleons

Since \( t_{int} << t_p \), there are three distinct classes of diagrams, depending on when the interaction happens: before/after gluon emission and before/after q-anti-q production.

Neglecting interaction of valence quarks of proton (∼collinear factorization)

\[
\frac{d\sigma_{pA}}{d^2k dy d^2b} = \frac{\alpha_s m^2}{8\pi^4} \left\{ \frac{1}{2} \frac{r \cdot r'}{rr'} K_1(m) K_1(m') + K_0(m)K_0(m') \right\} \\
\times \left\{ e^{-\frac{1}{4}(x-x')^2 Q_s^2} + 1 - e^{-\frac{1}{8}x^2 Q_s^2} - e^{-\frac{1}{8}Q_s^2 r'^2} \right\}
\]
Inclusive heavy quark (cont.)

Quasi-classical approximation (MV model):
\[ \rho \sigma L \sim \alpha_s^2 A^{1/3} \sim 1 \]

Probability of no inelastic scattering of a dipole of size \( r \) is
\[ e^{-\rho \sigma(r)L} \]
where \( \sigma(r) \propto r^2 \), \( \rho \) is nuclear matter density, \( L \) - length of dipole trajectory.

Elastic dipole scattering:
\[ \left( 1 - e^{-\rho \sigma(r)L} \right) \left( 1 - e^{-\rho \sigma(r')L} \right) \]

Inelastic dipole scattering:
\[ e^{-\rho \sigma(r)L} e^{-\rho \sigma(r')L} \left( e^{e \sigma(r,r')L} \rho L - 1 \right) \]

One inelastic dipole scattering:
\[ \hat{\sigma}(r, r') \propto \vec{r} \cdot \vec{r}' \]
Open charm $R_{pA}$ vs PHENIX data


![Graph showing Open charm $R_{pA}$ vs PHENIX data](attachment:graph.png)

- **$R_{pA}$** vs $p_T$ (GeV)
- **Open charm (Min. bias)**
- $y_{RHIC} = 0$
- $y_{RHIC} = 2$
- $y_{LHC} = 0$
- $y_{LHC} = 2$
- $y_{LHC} = 4$

**R$_{dAu}$ (Prompt $\mu^-$)**

- **South:** $\mu^-$
- **North:** $\mu^-$
- $1.4 < |\eta| < 1.8$
- Systematic Error

**PHENIX Preliminary**

Wednesday, July 7, 2010
In this figure

\[ \sqrt{s} = 5500 \text{ GeV}, \ y = 2, \ k_t = 0.5 \text{ GeV} \]

\[ R_{PA} \]

\[ p_T \ (\text{GeV}) \]

\[ m \ (\text{GeV}) \]

Open beauty (Min. bias)

- \( y_{RHIC} = 0 \)
- \( y_{RHIC} = 2 \)
- \( y_{LHC} = 0 \)
- \( y_{LHC} = 2 \)
- \( y_{LHC} = 4 \)

In this figure

\[ x < 0.01 \]
Inclusive c-quark: approx. factorization

\[
\frac{d\sigma_{pA}}{d^2k \ dy \ d^2b} = \frac{\alpha_s m^2}{8\pi^4} \int d^2r \int d^2r' \ e^{-i \frac{1}{2} k \cdot (x-x')} G(x_1, m_c^2) \left\{ \frac{1}{2} \frac{r \cdot r'}{rr'} K_1(rm) K_1(r'm) + K_0(rm) K_0(r'm) \right\} \\
\times \left\{ e^{-\frac{1}{8} (x-x')^2 Q_s^2} + 1 - e^{-\frac{1}{8} r^2 Q_s^2} - e^{-\frac{1}{8} r' Q_s^2} \right\}
\]

There is an apparent factorization between the proton and the nucleus, but this is NOT a k_T-factorization.
How good/bad is the factorization for $J/\psi$?

Can we infer the cold nuclear matter effect in AA from DA?
Assuming factorization...

The effective absorption cross sections from fits of Ramona's calculations to PHENIX d+Au $R_{CP}$ data are shown for each shadowing model.

This is **not** an attempt to extract physics from the d+Au $R_{CP}$! This is just a parameterization of the data that is independent at each rapidity.

The red points are the data points. $y = -1.7$ and $y = 1.7$.

This does not look like a reasonable behavior.
Assuming factorization...

Similarly, according to Ferreiro, Fleuret, Lansberg and Rakotozafindrabe, 2010:

(a) EKS98  
(b) EPS08  
(c) nDSg
Production of $J/\psi$: momentum scales

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>1.5 – 4.5 MeV</td>
</tr>
<tr>
<td>$d$</td>
<td>5.0 – 8.5 MeV</td>
</tr>
<tr>
<td>$s$</td>
<td>80 – 155 MeV</td>
</tr>
<tr>
<td>$c$</td>
<td>1.0 – 1.4 GeV</td>
</tr>
<tr>
<td>$b$</td>
<td>4.0 – 4.5 GeV</td>
</tr>
<tr>
<td>$t$</td>
<td>174.3 ± 5.1 GeV</td>
</tr>
</tbody>
</table>

`Heavy’ and `light’ are determined by the ratio $m^2/Q_s^2$

- $\Lambda_{QCD}$
- $Q_s$

• Heavy quarks are produced at short distances $\sim 1/2m \sim 0.1$ fm (charm) $\Rightarrow \alpha_s << 1$

• However, quarkonium binding is not perturbative:

$$\frac{M^2 - 4m^2}{4m^2} \ll 1$$

Therefore, $cc \rightarrow J/\psi$ is non-perturbative
**J/ψ in hot medium**

Immersing J/ψ in a hot chirally-symmetric de-confined medium modifies

- J/ψ binding potential \( V(r,T) \)
- J/ψ wave function \( \Phi(r,T) \)
- J/ψ formation rate \( \propto |\Phi(r,T)|^2 \)

and turns on new production mechanisms such as recombination etc.

If we have a good theoretical control of these processes we will be able to extract medium properties from the J/ψ production cross sections.

First, we need to understand J/ψ production in pp and in pA collisions.
**J/ψ production mechanisms**

- Color singlet model

  $qar{q}$ must have the same quantum numbers as the final quarkonia.

The wave function parameter $\psi(0)$ is uniquely fixed using the J/ψ decay rate.

![Graph of J/ψ production at the Tevatron](image)

Artoisenet, Landsberg, Maltoni, 2007

- Far from data
- Strong scale dependance
- Poor convergence
J/ψ production mechanisms (cont.)

- Color evaporation model

\( q \bar{q} \) can have any quantum numbers, but invariant mass less than open charm threshold. Conversion rate is described by one overall constant for each quarkonium state.

- Predicts that J/ψ is not polarized due to multiple soft gluon emission.
J/ψ production mechanisms (cont.)

- Non-relativistic QCD model

Gives the best fit to Tevatron p_T spectra, but has a lot of free parameters (non-perturbative matrix elements).

![Graph showing the function \( \alpha = \frac{\sigma_T - \sigma_L}{\sigma_T + \sigma_L} \) against p_T (GeV/c) with data points and theoretical curves.]

- Misses polarization.
- Fails for associated production
J/ψ production mechanisms (cont.)

Do we have a chance to understand the J/ψ production in pA if we don’t fully understand it in pp?

Possibly yes, because we have an additional parameter $A>>1$ that allows to resum parametrically large higher twists contributions.

The resumation parameter is $\alpha_s^2 A^{1/3}$ (quasi-classical approximation). We still need to specify the production mechanism.

We assume that $q\bar{q}$

- has the same global quantum numbers as J/ψ, i.e. $I^-$
- but carries any color
Production of $J/\psi$ at high energies: time sequence

Pre-hadron cc production time $\tau_P = \frac{l_c}{c} = 7 \, e^y \, \text{fm}$

$J/\psi$ wave function formation time $\tau_F = \frac{2 M_\psi}{M_\psi' - M_\psi} l_c = 42 \, e^y \, \text{fm}$

Hierarchy of time scales: $\tau_F \gg \tau_P \gg \tau_{\text{int}}$

$Y = \ln(1/x)$

Pre-hadron cc production time: Way outside the nucleus

$J/\psi$ wave function formation time: Way outside the nucleus
Production of J/ψ: pp vs pA

This mechanism is dominant for central collisions.

\[ \alpha_s^3 A^{1/3} = \alpha_s (\alpha_s^2 A^{1/3}) \sim \alpha_s \]

\[ \alpha_s^4 A^{2/3} = (\alpha_s^2 A^{1/3})^2 \sim 1 \]

Note that the factorization is broken already at the lowest order.
Production of $J/\psi$ in pA

Inclusive cross section

$$\frac{d\sigma_{pA \rightarrow JX}}{dy \, d^2b} = 8\pi \, xG(x, a^2) \int_0^1 dz \int_0^1 dz' \int \frac{d^2k}{16\pi^3} \int \frac{d^2k'}{16\pi^3} \int \frac{d^2l}{(2\pi)^2} \times \Delta\psi_{\lambda_1\lambda_2}^g(k, l, z)\psi_{\lambda_1\lambda_2}^J(k, z) \Delta\psi_{\lambda_1\lambda_2}^{g*}(k', l', z')\psi_{\lambda_1\lambda_2}^{J*}(k', z') \, T_{gA \rightarrow JX}$$

where $pA$ pair $q$ We assume that the color bleaching is a soft process described by one overall constant which manifests itself in weaker dependence of the scattering amplitudes on the nuclear collisions.

Thus, in the quasipclassical approximation, we simultaneously interact with any pair of nucleons. Therefore, in the quasipclassical regime – which is parametrically enhanced contribution in the quasipclassical regime – which is

$${\int_0^1 dz \int_0^1 dz' \int \frac{d^2k}{16\pi^3} \int \frac{d^2k'}{16\pi^3} \int \frac{d^2l}{(2\pi)^2} \times \Delta\psi_{\lambda_1\lambda_2}^g(k, l, z)\psi_{\lambda_1\lambda_2}^J(k, z) \Delta\psi_{\lambda_1\lambda_2}^{g*}(k', l', z')\psi_{\lambda_1\lambda_2}^{J*}(k', z') \, T_{gA \rightarrow JX}$$

has not been able to generalize to a non-local (in transverse space) evolution equation.

If the averaging procedure is local (but not Gaussian) we shall obtain

$$\int_0^1 dz \int_0^1 dz' \int \frac{d^2k}{16\pi^3} \int \frac{d^2k'}{16\pi^3} \int \frac{d^2l}{(2\pi)^2} \times \Delta\psi_{\lambda_1\lambda_2}^g(k, l, z)\psi_{\lambda_1\lambda_2}^J(k, z) \Delta\psi_{\lambda_1\lambda_2}^{g*}(k', l', z')\psi_{\lambda_1\lambda_2}^{J*}(k', z') \, T_{gA \rightarrow JX}$$

denoting the photon's polarization, we start with transverse coordinate space. Performing a Fourier transform of the dipole fluctuation, we obtain

$$\psi_{\lambda\alpha r r'}(k, z) = ef \frac{\sqrt{z(1-z)}}{k^2 + m_f^2 + Q^2 z(1-z)} \bar{u}_r(q - k) e^{i\lambda} \cdot \gamma u_{r'}(k)$$

where $f$ is the forward elastic scattering amplitude

$$\psi_{\lambda\alpha r r'}(k, z) = 2\psi_{\lambda_1\lambda_2}^g(k, z) - \psi_{\lambda_1\lambda_2}^g(k + l, z) - \psi_{\lambda_1\lambda_2}^g(k - l, z)$$

$\Delta\psi_{\lambda_1\lambda_2}^g(k, l, z) = 2\psi_{\lambda_1\lambda_2}^g(k, z) - \psi_{\lambda_1\lambda_2}^g(k + l, z) - \psi_{\lambda_1\lambda_2}^g(k - l, z)$

$\gamma$-A scattering amplitude

Brody, Frankfurt, Gunion, Mueller, Strikman, 1994
Production of J/ψ in pA (cont.)

In coordinate space

\[ \psi_{rr'}^{\lambda}(x, z) = \frac{e_f}{2\pi} (\delta_{rr'} i e^\lambda \cdot \nabla_x [r(1-2z) + \lambda] + r \delta_{rr'} m_f (1 + r \lambda)) K_0(xa). \]

\[ a^2 = Q^2 z (1 - z) + m_f^2 \]

We use the non-relativistic wave function

\[ \psi_k^{\lambda_1 \lambda_2}(k, z) = \sqrt{\frac{2}{M}} \psi^{J*}(0)(-2g^2) \delta(z - 1/2) \]

\[ \frac{d\sigma_{pA \to JX}}{dy d^2b} = 8\pi xG(x, Q^2) \int \frac{d^2r}{4\pi} \int \frac{d^2r'}{4\pi} \sum_{\lambda, \lambda'} \Phi_{\lambda\lambda'}(r) \Phi_{\lambda\lambda'}^*(r') T_{gA \to JX}(r, r') \]

\[ \sum_{\lambda, \lambda'} \Phi_{\lambda\lambda'}(r) \Phi_{\lambda\lambda'}^*(r') = \frac{1}{4} \frac{2}{M} |\psi^{J*}(0)|^2 4g^2 \frac{\alpha_s}{\pi} \left\{ \frac{a^2}{4} \frac{r r'}{r r'} K_1(ar) K_1(ar') + m^2 K_0(ar) K_0(ar') \right\}, \text{ trans.} \]

\[ 4Q^2 \frac{1}{16} K_0(ar) K_0(ar'), \text{ long.} \]

For \( r << 1/|l| \) this can be approximated:

\[ \sum_{\lambda, \lambda'} \Phi_{\lambda\lambda'}(r) \Phi_{\lambda\lambda'}^*(r') \propto \frac{m^2 r^2}{4} K_2(m_cr) \]

We used this approximation before, but in what follows I will use the full wave functions.
Production of J/ψ in pA (cont.)

• Elastic amplitude for cū production: 
\[ T_{gA\rightarrow c\bar{c}A}(r, r') = \left( 1 - e^{-r^2Q_s^2/8} \right) \left( 1 - e^{-r'^2Q_s^2/8} \right) \]
Elastic contribution to J/ψ is the same!

• Inelastic amplitude for cū production: 
\[ T_{gA\rightarrow c\bar{c}X}(r, r') = e^{-(r-r')^2Q_s^2/8} - e^{-r'^2Q_s^2/8}e^{-r^2Q_s^2/8} \]
For J/ψ we need to select only even number of interactions with the nucleus.

Recall: one inelastic dipole scattering 
\[ \hat{\sigma}(r, r') \propto \vec{r} \cdot \vec{r}' \]

\[ T_{gA\rightarrow JX'}(r, r') = e^{-r^2Q_s^2/8}e^{-r'^2Q_s^2/8}(\cosh[2r \cdot r' Q_s^2/8] - 1) \]

• We calculate J/ψ production in pp in a usual color octet model
\[
\frac{1}{S_p} \frac{d\sigma_{pp\rightarrow JX}}{dy \, d^2b} = \frac{4N_c}{\alpha_s \pi^2} \frac{\alpha_s G_2^2}{\pi} P \int d^2r \int d^2r' \left[ \frac{a^2}{2} \frac{r \cdot r'}{rr'} K_1(mr)K_1(mr') + m^2 K_0(ar)K_0(ar') \right] \\
\times 2r \cdot r' \frac{1}{8} Q_{s1}^2 \frac{1}{8} Q_{s2}^2.
\]
Breakdown of $x_F$-scaling

Kharzeev, KT, 2005

$\sigma_{pA} = A^\alpha \sigma_{pp}$

$\alpha = 2/3$ plateau: black disk regime.

Additional assumptions:

- $J/\psi$ is non-relativistic. Relativistic correction depends on $m$ but not on energy - included in prefactor.
- Parametrically small corrections due to the real part and off-diagonal matrix elements are neglected.
Production of J/ψ: from pA to AA

Inclusive cross section

\[
\frac{1}{S_A} \frac{d\sigma_{AA\rightarrow J/X}}{dy \, d^2b} = 8\pi \int \frac{d^2r}{4\pi} \int \frac{d^2r'}{4\pi} \sum_{\lambda,\lambda'} \Phi_{\lambda\lambda'}(r) \Phi_{\lambda\lambda'}^*(r') T_{AA\rightarrow J/X}(r, r')
\]

\[
\frac{\alpha_s \pi^2}{4N_c} x G(x, Q^2) \rightarrow \frac{d^2b}{r^2} \left( 1 - e^{-\frac{1}{8} r^2 Q_s^2} \right)
\]

If we wanted to calculate in the color octet model we would have replaced

\[
T_{gA\rightarrow c\bar{c}A}(r, r') = 1 - e^{-r^2 Q_s^2/8} - e^{-r'^2 Q_s^2/8} + e^{-(r-r')^2 Q_s^2/8}
\]

with

\[
T_{AA\rightarrow c\bar{c}A}(r, r') = \frac{1}{r'^2} \left( 1 - e^{-\frac{1}{8} r^2 Q_s^2} \right) \left( 1 - e^{-\frac{1}{8} r'^2 Q_s^2} \right) + \frac{1}{r'^2} \left( 1 - e^{-\frac{1}{8} r'^2 Q_s^2} \right) \left( 1 - e^{-\frac{1}{8} r'^2 Q_s^2} \right)
\]

\[
- \frac{1}{(r - r')^2} \left( 1 - e^{-\frac{1}{8} (r-r')^2 Q_s^2} \right) \left( 1 - e^{-\frac{1}{8} (r-r')^2 Q_s^2} \right).
\]

However, in a new mechanism we restrict the number of inelastic interactions.
Production of J/ψ: from pA to AA

Inelastic interactions are only in this term:

\[
\frac{1}{(r - r')^2} \left( 1 - e^{-\frac{1}{8}(r-r')^2 Q_{s1}^2} \right) \left( 1 - e^{-\frac{1}{8}(r-r')^2 Q_{s2}^2} \right)
= \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{1}{n! m!} \left( -\frac{1}{8} Q_{s1}^2 \right)^{n-1} \left( -\frac{1}{8} Q_{s2}^2 \right)^m (r - r')^{2(n+m-1)}
\]

Two attached gluons \( \propto r \cdot r' \) three attached gluons \( \propto (r \cdot r')^2 \) etc.

Therefore, we have to re-sum even number of interactions:

\[
(r - r')^{2(n+m-1)} = \sum_{k=0}^{n+m-1} \binom{n + m - 1}{k} (r^2 + r'^2)^{n+m-k-1} (-2r \cdot r')^k
\Rightarrow \sum_{s=0}^{(n+m-1)/2} \binom{n + m - 1}{2s} (r^2 + r'^2)^{n+m-2s-1} (-2r \cdot r')^{2s}
= \frac{1}{2} \left[ (r - r')^{2(n+m-1)} + (r + r')^{2(n+m-1)} \right].
\]

Finally,

\[
\frac{1}{(r - r')^2} \left( 1 - e^{-\frac{1}{8}(r-r')^2 Q_{s1}^2} \right) \left( 1 - e^{-\frac{1}{8}(r-r')^2 Q_{s2}^2} \right) \Rightarrow
\frac{1}{2} \left\{ \frac{1}{(r - r')^2} \left( 1 - e^{-\frac{1}{8}(r-r')^2 Q_{s1}^2} \right) \left( 1 - e^{-\frac{1}{8}(r-r')^2 Q_{s2}^2} \right) + \frac{1}{(r + r')^2} \left( 1 - e^{-\frac{1}{8}(r+r')^2 Q_{s1}^2} \right) \left( 1 - e^{-\frac{1}{8}(r+r')^2 Q_{s2}^2} \right) \right\}
\]
Inclusion of low-x evolution

A phenomenological approach is to replace the initial condition for BK equation

\[ N(r, b, y_0) = 1 - e^{-\frac{1}{8} r^2 Q_s^2(y_0)} \]

with the full solution.

We use the model of Kowalski-Motyka-Watt that is fitted to DIS data

\[
N(r, 0, y) = \begin{cases} 
  N_0 \left( \frac{r^2 Q_s^2}{4} \right)^\gamma, & r Q_s \leq 2; \\
  1 - \exp[-A \ln^2(B r Q_s)], & r Q_s \geq 2,
\end{cases}
\]

\[
Q_s^2 = A^{1/3} x_0^\gamma e^{\lambda y} s^{\lambda/2} \text{GeV}^2 \\
\gamma = \gamma_s + \frac{1}{\kappa \lambda (\ln \sqrt{s} + y)} \ln \left( \frac{2}{r Q_s} \right)
\]

There is one free parameter: the probability P of an additional soft gluon radiation in traditional color octet model. We fixed it P=0.69
Numerical results

- We obtained similar results with the KKT model.
- Rapidity dependence in AA case in the 0<y<1.7 interval is very small.

   Anomalous suppression in AA is probably due to hot medium effects.
Summary

I discussed hadron production in nuclear collisions at high energies: Generally, traditional factorization schemes are broken, although sometimes they approximately hold.

I showed that $J/\psi$ production mechanism in pp and pA/AA collisions is different due to strong coherence effects. Factorization is violated already at the lowest order.

We calculated the $J/\psi$ production in pA and AA and found a good agreement with data in pA. In AA there is an additional suppression that is due to interactions with the hot nuclear medium.