Nuclear Effects In The Inclusive Production of Vectorial Mesons at Proton-Nucleus Collisions

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August/2021
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- Introduction and motivation;
- Discuss the color dipole approach;
- Define dipole cross section amplitude models for our analysis;
- Present the quarkonium production cross section;
- Show the results and conclusions;
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- In the 80's, the \( J/\psi \) suppression was proposed as ultimate test of quark-gluon plasma (QGP)\(^1\);
  - Although useful for study the QGP, it remains as open topic;
- The cold nuclear effects is similar to \( J/\psi \) suppression and affects his production;
- Therefore, a better understanding of this picture enhance the knowledge of QGP impact in this meson production\(^2\);
- One way of estimate such effects is through Nuclear Modification Factors \( (R_{AB}) \)\(^3\), that is cross section's dependent;
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The QGP evolution takes place in several steps which we can’t observe directly\cite{4, 5};
- The observation is done through experimental observables;

The increasing of hadron production with quantum numbers not present in the colliding matter is one of oldest signal of QGP medium\cite{6, 7}.

- One expects that in a hot and dense medium occurs $S\bar{S}$ pair production\cite{6, 7};
  - Experiments at RHIC and LHC energies shows an increasing in the strange particles production\cite{8, 9};
- Experimental observations indicates that the collective behaviour of matter of medium produced by RHIC and LHC are similar\cite{10};
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The color dipole formalism considers the **photons and gluons** as a **superposition of Fock states**, where the $q\bar{q}$ pairs are the dominant Fock states\(^{[11]}\);

\[\Rightarrow \text{For instance, we can consider the fluctuation } \gamma^* \rightarrow q\bar{q};\]

\[\Rightarrow \text{Fluctuation } q\bar{q} \text{ lifetime } \gg \text{ target lifetime interaction;}\]

\[\Rightarrow \text{Therefore, this approach allow us to factorize the QED } (\gamma^* \rightarrow q\bar{q}) \text{ from QCD } (q\bar{q}\text{-target interaction}) \text{ part, acting like separated process;}\]

\[\text{Color dipole cross section}^{[11]}\]

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\sigma_{\text{tot}}^{\gamma^* p}(x, Q^2) = \int \frac{d^2 x_\perp}{4\pi} \int_0^1 \frac{dz}{z(1-z)} |\Psi^{\gamma^* \rightarrow q\bar{q}}(x_\perp, z)|^2 \sigma_{\text{tot}}^{q\bar{q} p}(x_\perp, Y); \tag{1}
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![Color dipole](image)

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The Glauber formalism can be used for taking into account nuclear corrections in the dipole-nuclei interaction\cite{12};

- It considers multiple scattering, including nuclear shadowing effects;
- The extension of such formalism results in the Glauber-Muller expression:

\[ \sigma_{GM}^{\text{dip}} = 2 \int d^2 \vec{b} \left[ 1 - e^{-\frac{1}{2} \sigma_{\bar{q}q \text{nucleon}} S(\vec{b})} \right] ; \] (2)

where:
- $\sigma_{\bar{q}q \text{nucleon}}$ is the $\bar{q}q$-nucleon cross section;
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In this work, we consider the quarkonium production cross section in the **quasi-classical QCD dipole model**[15–17]:

- The quasi-classical approach takes the nuclei as being described by a classic color field, i.e., that obey Yang-Mills equations;
  - It’s possible to use it if $\alpha_s^2 A^{1/3} \sim 1$; in this condition one have a high parton density in the process;
- This approach is a multiple scattering approximation similar to the Glauber-Mueller one;
- Basically, the cross section is obtained from the **contributions that takes place before and after the last inelastic gluon-nuclei interaction**:  

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\frac{d\sigma_{pA \to J/\psi X}}{dy \, d^2b} = x_1 G(x_1, m_c^2) \int_0^1 dz \int \frac{d^2r}{4\pi} \Phi(r, z) \int_0^1 dz' \int \frac{d^2r'}{4\pi} \Phi(r', z') \times \frac{4\vec{r} \cdot \vec{r}'}{(\vec{r} + \vec{r}')^2} \left[ \left[ 1 - N_A((\vec{r} - \vec{r}')/2, y) \right] - \left[ 1 - N_F(\vec{r}, y) \right]\left[ 1 - N_F(\vec{r}', y) \right] \right];
$$

where:

1. $x_1$: Parton distribution function.
2. $G(x_1, m_c^2)$: The gluon distribution function.
3. $\Phi(r, z)$: The color field.
4. $N_A$ and $N_F$: The number of partons in the nucleus and in the free space, respectively.
In this work, we consider the quarkonium production cross section in the **quasi-classical QCD dipole model**[15–17]:

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where:

$$
\begin{align*}
\Phi(r, z) & = \frac{1}{2\pi} e^{-|r|^2} \\
N_A & = \int d^2r \Phi(r, z) \\
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Differential cross section for $J/\psi$ production in $pA$ collisions[18]
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Dipole amplitude models

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where:

- \( z \) is the momentum fraction, \( r \) the dipole transverse size;
- \( b \) is the impact parameter, \( Q_s \) is the saturation scale;
- \( \Phi(r, z) \) the meson wave function;
- \( G(x_1, m_c^2) \) the distribution function of gluons in the projectile proton;
- ★ The \( N_A \) and \( N_F \) are the dipole-quark elastic scattering amplitude in the **Adj**oint and **Fund**amental representations, respectively;
The Golec-Biernat-Wustoff (GBW) phenomenological amplitude model

The GBW amplitude model [19, 20] propose a parametrization of the dipole cross section from the Deep Inelastic Scattering data, due the difficulties of modelling the non-integrated gluon function;

- In this model, we have:

\[
N_A(r, 0, y) = 2N_F(r, b, y) - N_F^2(r, b, y)
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N_F(r, 0, y) = 1 - e^{-\frac{r^2 Q_s^2}{4}};
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- where \( r \) is the transverse distance; \( Q_s \) is the saturation scale given by

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Q_s^2 = \frac{9}{4} \left\{ A^{1/3} \left( \frac{x_0}{x_2} \right)^{\lambda} \right\};
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- with \( x_0 = 3 \times 10^{-4} \) and \( \lambda = 0.288 \) [21];

★ we use the equation (4) through our entire work;
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The Dumitru-Hayashigaki-Jalilian (DHJ) model

The DHJ model [22] suggests improvements in the profile parametrization of dipole regarding the Kharzeev-Kovchegov-Tuchin (KKT) model[23, 24], in order to provide a better data description in central rapidity. Such agreement keeps the Color Glass Condensate formalism predictions;

- In this model, we have:
  \[ N_A(r, 0, y) = 1 - e^{-\frac{1}{4}(r^2Q_s^2)\gamma} \]
  \[ N_F(r, 0, y) = 1 - \sqrt{1 - N_A(r, 0, y)} \]
  \[ \text{with } \gamma = \gamma_s + (1 - \gamma_s)\frac{\ln(m^2/Q_s^2)}{\lambda Y + \ln(m^2/Q_s^2) + d\sqrt{Y}}; \]

- where \( Y = \ln(1/x), x = x_2 = me^{-y}/\sqrt{S}, \gamma_s = 0.628 \) and \( d = 1.2 \) [22];
The bCGC model

The bCGC model [25] gives the density properties of gluons in the hadrons, both in the longitudinal and transversal dimensions, including the dependency of impact parameter in the saturation scale;

- In this model, we have:

\[
N_A(r, 0, y) = \begin{cases} 
N_0 \left( \frac{r^2 Q_s^2}{4} \right)^\lambda, \quad rQ_s \leq 2, & \text{with} \\
1 - e^{-\mathcal{A} \ln^2 (B r Q_s)}, \quad rQ_s > 2
\end{cases}
\]

\[
\gamma = \gamma_s + \frac{\ln(2/r Q_s)}{k \lambda \ln(1/x)},
\]

\[
\mathcal{A} = -\frac{N_0^2 \gamma_s^2}{(1 - N_0)^2 \ln(1 - N_0)},
\]

\[
B = \frac{1}{2} (1 - N_0)^{-(1 - N_0)/N_0 \gamma_s},
\]

- where \( Y = \ln(1/x), \gamma_s = 0.649, N_0 = 0.7, \lambda = 0.2023, x_0 = 0.00069 \) [26] and \( k = 9.9 \) [25];
The main goal of the present work is to evaluate **nuclear modifications factors** $R_{pA}$ in the rapidity spectrum;

In particular, we are going to analyze the factors in terms of the differential cross sections [27]:

$$R_{pA}(y) = \frac{d\sigma_{pA}(y)/dy}{Ad\sigma_{pp}/dy}$$

This allow us to analyze the quarkonium suppression as long as $R_{pA}(y)$ differs from the unit;
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Numerical results

- In the following, are shown the numerical result from our analyzes for RHIC and LHC;
- We compare it with experimental data from several collaborations
  - LHCb [28–31], ALICE [32, 33, 33], CMS [34], ATLAS [35];
  - PHENIX [36];
Nuclear modification ratios as function of energy for (a) 5.02 TeV, (b) 8.16 TeV and (c) 8.8 TeV, with LHC data at pPb collision for J/ψ production;

The results shows suppression higher than the experimental data: (a) $\sim 25\%$ and (b) $\sim 20\%$ at $y \sim 0$; the prediction at (c) shows strong suppression across the entire spectrum ($\sim 75\%$ at forward rapidity);
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**J/ψ results with RHIC energies**

- **Numerical results**  

  - **Nuclear modification ratios as function of energy for (a) 200 GeV, with RHIC data at dAu collision for J/ψ production;**
  
  - **Good agreement with experimental data, but strong suppression for bCGC model;**
  
  - **$R_{dAu} > 1$ only for GBW amplitude;**
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Results and conclusion

Numerical results

Nuclear modification ratios as function of energy for (a) 5.02 TeV, (b) 8.16 TeV and (c) 8.8 TeV, with LHC data at pPb collision for $\gamma$ production;

The results shows enhancement and suppression up to $\sim 70\%$ and $\sim 50\%$, respectively; the prediction (c) also shows enhancement and suppression up to $\sim 70\%$ and $\sim 50\%$, respectively;
Nuclear modification ratios as function of energy for (a) 5.02 TeV, (b) 8.16 TeV and (c) 8.8 TeV, with LHC data at pPb collision for $\Upsilon$ production;

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Conclusions

- In general, the nuclear modification factors for $J/\psi$ production have been shown more suppression than $\Upsilon$ case;
- In particular, the bCGC model overestimated the suppression more than other models;
- Further, the evaluation are very sensitive to the saturation scale and another approaches should be analyzed;
- Also, an enhanced study can be made taking into account another theoretical approaches, beyond quasi-classical one.
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Thank you!
References


Results and conclusion

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References IV


[34] CMS Collaboration. Nuclear modification of $\Upsilon$ states in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. 2019.
