Suppression of charmonia in $pA$ and $AA$ collisions

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Partially based on:

PRC 95 (2017) 065203

PRC 91 (2015), 024911

NPA 931 (2014), 601
**J/ψ in pp collisions**

**Color Singlet Model (1980’s)**

Collinear factorization:
- Reasonable for $p_T$-integrated observables
- Incorrect $1/p_T$ behaviour for $p_T \gg m_{J/ψ}$

Large-$p_T$ description

- Phenomenological approaches (Color Octet, NRQCD)
- $k_T$-factorization instead of collinear

Co-production ($J/ψ + \bar{Q}Q$, ...)

(PRL 101 (2008) 152001)

Quark and gluon fragmentation
(S. Baranov, B. Kopeliovich, 2017 in preparation)

Multigluon contributions
(EPJC 75 (2015), 213)

**Sizeable contribution from other mechanisms**

**Collinear factorization**
Nuclear effects for $J/\psi$ in $pA$ collisions

Data & experiment for $J/\psi$

- Heavy quark limit: should vanish
- $R_{pA}$ increases when $x \to 1$ due to energy loss
- Compatible with E866, PHENIX and ALICE data

### $\psi(2S)$ suppression

- Why $\psi(2S)$ is more suppressed than $J/\psi$?

(Major challenge for many approaches which describe $J/\psi$, $\Upsilon$ suppression).
J/ψ in dipole approach

Same diagrams as in $k_T$ factorization, we just express everything in terms of dipole framework.

Large-$m_Q$ limit

- Dipole cross-section related to $k_\perp$ uPDF, e.g. for color singlet

$$
\sigma_d(x, r_\perp) = \int \frac{d^2 k_\perp}{(2\pi)^2} F(x, k_\perp) \left(1 - e^{i k_\perp \cdot r_\perp}\right).
$$

- Color octet dipole cross-section could be expressed as linear combinations of color singlets

- Major advantage: more convenient for description of nuclear absorption.

Reasonable description of $pp$ data

Same diagrams as in $k_T$ factorization, we just express everything in terms of dipole framework.
$J/\psi$ production cross-section in the dipole approach

$$
\frac{d\sigma_{pp}}{dy} = \frac{9}{8} g \left( x_1(y) \right) \int d\alpha G d\alpha_1 d^2 r_1 \ d\alpha_2 d^2 r_2 \ d^2 \rho \ \Psi^*_M (\alpha_1 r_1) \Psi_M (\alpha_2 r_2) \times

\times \sum_{n, n' = 1}^6 \eta_n \eta_{n'} \ \text{Tr} \left[ \Lambda_M \Phi_{g \rightarrow \bar{Q} Q} \left( \epsilon_n, \bar{r}_n \right) \Phi_{Q \rightarrow Q g} \left( \delta_n, \bar{\rho}_n \right) \right]

\times \text{Tr} \left[ \Lambda_M \Phi_{g \rightarrow \bar{Q} Q} \left( \epsilon_{n'}, \bar{r}_{n'} \right) \Phi_{Q \rightarrow Q g} \left( \delta_{n'}, \bar{\rho}_{n'} \right) \right]^*

\times \sigma \left( x_2, \bar{r}_n - \bar{r}_{n'} \right)

\text{Meson WFs}

\bullet \ \Lambda_M$-spin projector on meson WF
\bullet \ \Phi_{g \rightarrow \bar{Q} Q}, \Phi_{Q \rightarrow Q g} \ are \ evaluated \ perturbatively \ (m_c \rightarrow \infty \ \text{limit})
\bullet \ \bar{r}_{n(1,2)} \approx \bar{r}_{1,2} + \delta\bar{r}_n (\alpha, \alpha_G, r, \rho), \ \ \ \bar{\rho}_n \approx \bar{\rho} + \delta\bar{\rho}_n (\alpha, \alpha_G, r, \rho)
\bullet \ \text{Sum over 6 diagrams in amplitude and its conjugate is implied}

\bullet \ \text{For } p_T\text{-dependent cross-section, additional Fourier over difference of dipole impact parameter } \Delta \vec{b} = \vec{b}_1 - \vec{b}_2 \neq 0; \ \text{terms } \delta\bar{r}_n, \delta\bar{\rho}_n \ also \ depend \ on \ \vec{b}_{1,2}
Absorptive corrections

- Reduction of $g$ flux before $J/\psi$ production

$$\sim \exp \left( -\frac{\sigma_4(x, \vec{r}_1, \vec{r}_2, \vec{\rho})}{2} \int_{z}^{+\infty} \rho_A(b, \zeta) d\zeta \right)$$

$\vec{r}_1, \vec{r}_2$ is the dipole size, $\vec{\rho}$ is the transverse coord. of emitted gluon

- Attenuation of produced $\bar{Q}Q$ dipoles,

$$\sim \exp \left( -\frac{\sigma_{\bar{c}c}(x, r)}{2} \int_{z}^{+\infty} \rho_A(b) d\zeta \right)$$

Gluon shadowing

- Gluon fluctuation $g \rightarrow \bar{c}c$ is the dominant Fock state, yet there are contributions $\bar{c}cg, \bar{c}cgg, ...$

- Higher Fock states have shorter coherence time due to heavier mass

$$\Delta M_{ccg} \sim \frac{k_{g \perp}^2}{x_g}$$

- Attenuation of gluon densities & dipole cross-sections,

$$\sigma_d \rightarrow R_g(x_2) \sigma_d$$

Inelastic multiple pomeron exchanges

(see PRC 72, 054606 for more details)

- Due to differences in nuclear suppression of higher Fock states of proton

- Formally factorization breaking terms

- Similar to energy loss correction, suppresses gluon PDFs for $x_F \rightarrow 1$

All the mentioned corrections suppress $R_{pA}$ with increase of energy
J/ψ production in pA

2-nucleon contribution

- Opacity expansion:
  \[
  \langle T_A(b) \rangle \sigma(x, \langle r \rangle) \ll 1
  \]

  might reach 0.3-0.5 @LHC

- Most “dangerous” is the 2-nucleon correction

\[ \text{c̅c} \]

\[
\begin{array}{c}
\text{N} \quad \text{r} \\
\text{g} \quad \text{g}
\end{array}
\]

\[
\text{X} \quad \text{X}
\]

same order in \( \sim O(\alpha_s(m_c)) \)

\[
\frac{d\sigma^{(2N)}(pA \rightarrow J/ψX)}{dy} \sim \langle \rho_A(b, z_1) \rho_A(b, z_2) \rangle
\]

\[
\times \sum_{g \rightarrow \{8-\}} \sum_{\{8-\} \rightarrow \{1+\}} \sum_{S_A^{(2N)}(\cdots)} \text{suppression}
\]

\[
R_{pA}^{(2N)} \sim \frac{d\sigma^{(2N)}}{d\sigma(pp)}
\]

mildly grows with energy

\[
\sum_{g \rightarrow \{8-\}} \approx \frac{5}{8} \left[ \sigma_{\bar{c}c} \left( \frac{r_1 + r_2}{2} \right) - \sigma_{\bar{c}c} \left( \frac{r_1 - r_2}{2} \right) \right]
\]

\[
\sum_{g \rightarrow \{8-\}} \approx \frac{1}{8} \left[ \sigma_{\bar{c}c} \left( \frac{r_1 + r_2}{2} \right) - \sigma_{\bar{c}c} \left( \frac{r_1 - r_2}{2} \right) \right]
\]

\[
S_A^{(2N)} = \exp \left( -\frac{\sigma_3(r_1) + \sigma_3(r_2)}{2} \int_{z_1}^{z_2} d\zeta \rho_A(b, \zeta) \right)
\]

\[
- \frac{\sum_{\{8-\}}(r_1, r_2)}{2} \int_{z_1}^{z_2} d\zeta \rho_A(b, \zeta)
\]

\[
- \frac{\sigma_{\bar{c}c}(r_1) + \sigma_{\bar{c}c}(r_2)}{2} \int_{z_2}^{\infty} d\zeta \rho_A(b, \zeta)
\]
Absorption (dotted) determines energy dependence of $R_{pA}$, $2N$-term: 20-40% contribution

- Inclusion of gluon shadowing (dashed) slightly decreases $R_{pA}$ at forward rapidities

- Inclusion of soft multiple pomerons/energy loss (solid) decreases cross-section at RHIC, almost no effect at LHC
\( J/\psi \) in \( pA \): theory vs experiment

**Rapidity dependence**

PHENIX: PRL 107, 142301

![Graph showing Rapidity dependence for PHENIX data.]

ALICE: JHEP 1402, 073

![Graph showing Rapidity dependence for ALICE data.]

- Reasonable agreement with experiment in a wide kinematic range
- \( R_{pA} \sim 1 \) due to partial compensation of absorption and 2-nucleon term

**\( p_T \)-dependence**

(Experimental points: ALICE, JHEP 1506 (2015), 055)

![Graph showing \( p_T \)-dependence for PHENIX data.]

![Graph showing \( p_T \)-dependence for ALICE data.]

\( p_T \) dependence

\( R(1N) + R(2N) \)

\( R(1N) \)

\( R(2N) \)
Other quarkonia in $pA$: theory vs experiment

**ψ(2S) suppression**

**PHENIX: PRL 111, 202301**

- Reasonable agreement with experiment in a wide kinematic range
- 2S suppression due to node in meson WF
- No free parameters

**ALICE: JHEP 1412, 073**

**Τ(1S), Τ(2S) suppression**

**PHENIX: PRC 87, 044909**

- Reasonable agreement with experiment in a wide kinematic range
- 2S suppression due to node in meson WF
- No free parameters

(dipole energy in nucleus rest frame)
Suppression of quarkonia in AA: theory vs experiment

- Attenuation inside the cold nuclear phase is stronger than for pA due to higher nuclear densities.
- Inside hot phase (QGP), there are two complementary mechanisms: “melting” (modification of potential $V_{c\bar{c}}(r, T)$) and absorption:
  \[ \text{Im} V \sim - \frac{\nu_\psi \hat{q}(\ldots) r^2}{4} \]
- Equations of state of QGP: $\hat{q} \Rightarrow$”local temperature” $T$ for melting.
- We do not consider the so-called coalescence contributions, when $\bar{c}c$ start recombine in the QGP phase.

- Reasonable agreement
- Transport coefficient $\hat{q}_0 = 2 \pm 1$ GeV$^2$/fm is the main source of uncertainty.
Summary

**$pA$ collisions**
- We found that two-nucleon mechanism gives a sizeable contribution both at RHIC and LHC and explains why $R_{pA} \sim 1$ despite of the fact that mere absorption is sizeable.
- We described suppression of $J/\psi$, $\psi(2S)$, $\Upsilon(1S)$, and $\Upsilon(2S)$ in $pA$ collisions in the dipole framework.

**$AA$ collisions**
- For $AA$, we found reasonable agreement with ALICE data on $p_T$-dependence