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

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Partially based on:

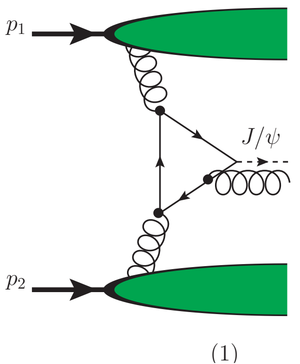
PRC 95 (2017) 065203

PRC 91 (2015), 024911

NPA 931 (2014), 601

J/ψ in pp collisions

Color Singlet Model (1980's)



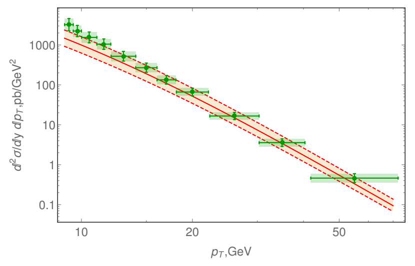
Collinear factorization:

- Reasonable for p_T-integrated observables
- Incorrect $1/p_T$ behaviour for $p_T \gg m_{J/\psi}$

Large-p_T description

(see QWG review, Eur.Phys.J. C71 (2011) 1534)

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



Sizeable contribution from other mechanisms

- Co-production ($J/\psi + \bar{Q}Q$, ...)

(PRL 101 (2008) 152001)

- Quark and gluon fragmentation

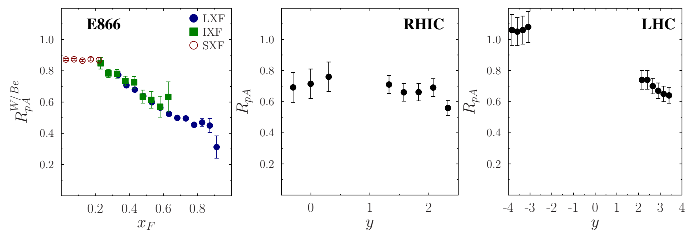
(S. Baranov, B. Kopeliovich, 2017 in preparation)

- Multigluon contributions (EPJC 75 (2015), 213)

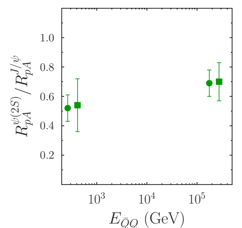
Nuclear effects for J/ψ in pA collisions

Data & experiment for J/ψ

- 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

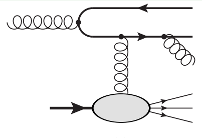


- Why $\psi(2S)$ is more suppressed than J/ψ ?

(Major challenge for many approaches which describe J/ψ, Υ suppression).

J/ψ in dipole approach

CSM in dipole approach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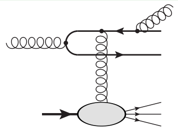
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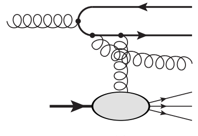
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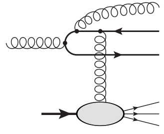
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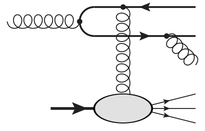
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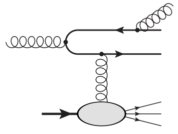

(6)

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

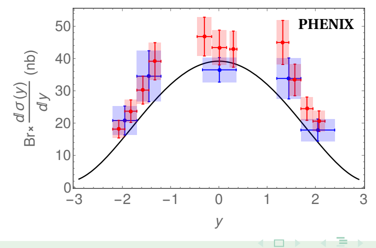
Large-m_Q limit

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

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

- Color octet dipole cross-section could be expressed as linear combinations of color singlets
- Major advantage: more convenient for description of nuclear absorption.

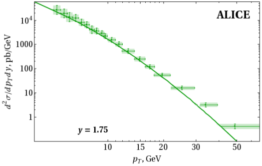
Reasonable description of *pp* data



J/ψ production cross-section in the dipole approach

$$\begin{aligned}
\frac{d\sigma_{pp}}{dy} &= \frac{9}{8}\, g\left(x_1(y)\right) \int d\alpha_G\, d\alpha_1\, d^2 r_1\, d\alpha_2\, d^2 r_2\, d^2\rho\, \overbrace{\Psi_M^*\left(\alpha_1\, r_1\right)\Psi_M\left(\alpha_2\, r_2\right)}^{\text{Meson WFs}} \times \\
&\times \sum_{n,n'=1}^{6} \underbrace{\eta_n \eta_{n'}}_{\text{numerical factor}} \mathrm{Tr}\left[\Lambda_M \Phi_{g\to\bar{Q}Q}\left(\epsilon_n,\, \vec{r}_n^{(1)}\right)\Phi_{Q\to Q\,g}\left(\delta_n,\, \vec{\rho}_n\right)\right] \\
&\times \mathrm{Tr}\left[\Lambda_M \Phi_{g\to\bar{Q}Q}\left(\epsilon_{n'},\, \vec{r}_{n'}^{(2)}\right)\Phi_{Q\to Q\,g}\left(\delta_{n'},\, \vec{\rho}_{n'}\right)\right]^* \\
&\times \underbrace{\sigma\left(x_2,\, \vec{r}_n - \vec{r}_{n'}\right)}_{\text{dipole cross}-\text{section}}
\end{aligned}$$

- Λ_M-spin projector on meson WF
- $\Phi_{g\to\bar{Q}Q}$, $\Phi_{Q\to Q\,g}$ are evaluated perturbatively ($m_c \to \infty$ limit)
- $\vec{r}_n^{(1,2)} \approx \vec{r}_{1,2} + \delta\vec{r}_n\left(\alpha,\, \alpha_G,\, r,\, \rho\right), \qquad \vec{\rho}_n \approx \vec{\rho} + \delta\vec{\rho}_n\left(\alpha,\, \alpha_G,\, r,\, \rho\right)$
- Sum over 6 diagrams in amplitude and its conjugate is implied



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

J/ψ production in pA

Absorptive corrections

- Reduction of g flux before J/ψ production

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

$\vec{r}_{1,2}$ is the dipole size, $\vec{\rho}$ is the transverse coord. of emitted gluon

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

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

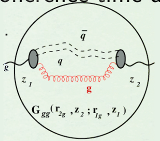
Inelastic multiple pomeron exchanges

(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 $x_F \to 1$

Gluon shadowing

- Gluon fluctuation $g \to \bar{c}c$ is the dominant Fock state, yet there are contributions $\bar{c}cg$, $\bar{c}cgg, \ldots$
- Higher Fock states have shorter coherence time due to heavier mass



$$\Delta M_{c\bar{c}g} \sim \frac{k^2_{g\perp}}{x_g}$$

- Attenuation of gluon densities & dipole cross-sections,

$$\sigma_d \to R_g\left(x_2\right)\sigma_d$$

- Coherence length $l_c \sim \mathrm{const}/x_2$, sizeable at LHC

All the mentioned corrections suppress R_{pA} with increase of energy

J/ψ production in pA

2-nucleon contribution

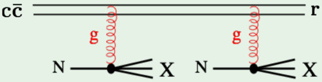
- Opacity expansion:

$$\langle T_A(b)\rangle \sigma\left(x, \langle r\rangle\right) \ll 1$$

might reach 0.3-0.5 @LHC

- Most "dangerous" is the

2-nucleon correction



same order in $\sim \mathcal{O}\left(\alpha_s\left(m_c\right)\right)$

$$\frac{d\sigma^{(2N)}(pA\to J/\psi X)}{dy} \sim$$

$$\sim \Big\langle \rho_A\left(b,\, z_1\right)\rho_A\left(b,\, z_2\right) \times \Sigma_{g\to\{8^-\}}\Sigma_{\{8^-\}\to\{1^+\}} \times \underbrace{S_A^{(2N)}\left(\ldots\right)}_{\text{suppression}} \Big\rangle_{r_{1,2},\,\alpha_{1,2},\,z_1<z_2,\,b}$$

$$\Sigma_{g\to\{8^-\}} \approx \frac{5}{8}\left[\sigma_{\bar{c}c}\left(\frac{\vec{r}_1+\vec{r}_2}{2}\right) - \sigma_{\bar{c}c}\left(\frac{\vec{r}_1-\vec{r}_2}{2}\right)\right]$$

$$\Sigma_{g\to\{8^-\}} \approx \frac{1}{8}\left[\sigma_{\bar{c}c}\left(\frac{\vec{r}_1+\vec{r}_2}{2}\right) - \sigma_{\bar{c}c}\left(\frac{\vec{r}_1-\vec{r}_2}{2}\right)\right]$$

$$S_A^{(2N)} = \exp\left(-\frac{\sigma_3\left(\vec{r}_1\right)+\sigma_3\left(\vec{r}_2\right)}{2}\int_{-\infty}^{z_1} d\zeta\,\rho_A\left(b,\zeta\right) - \frac{\Sigma_{(8-)}\left(\vec{r}_1,\,\vec{r}_2\right)}{2}\int_{z_1}^{z_2} d\zeta\,\rho_A\left(b,\zeta\right) - \frac{\sigma_{c\bar{c}}\left(r_1\right)+\sigma_{c\bar{c}}\left(r_2\right)}{2}\int_{z_2}^{\infty} d\zeta\,\rho_A\left(b,\zeta\right)\right)$$

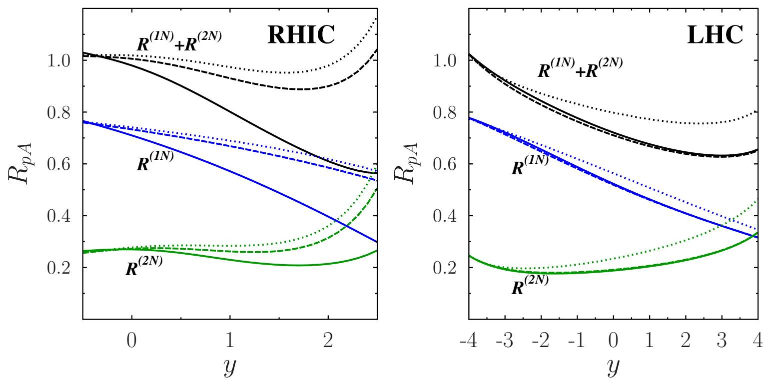
- $\Sigma_{g\to\{8^-\}}$, $\Sigma_{\{8^-\}\to\{1^+\}}$ grow with energy $\sim \sigma_{c\bar{c}}$
- $S_A^{(2N)}\left(\ldots\right)$ decreases
-

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

mildly grows with energy

J/ψ in pA: suppression vs. enhancement

How large are different contributions ?

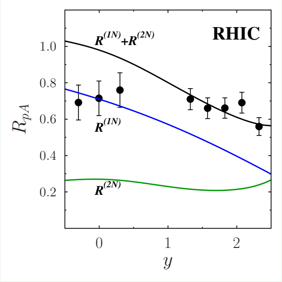


- Absorption (dotted) determines energy dependence of R_{pA}, 2N-term: 20-40% contribution
- Inclusion of gluon shadowing (dashed) slightly decreases R_{pA} at forward rapidities
- Inclusion of soft multiple pomerons/energy loss (solid) decreases cross-section at RHIC, almost no effect at LHC

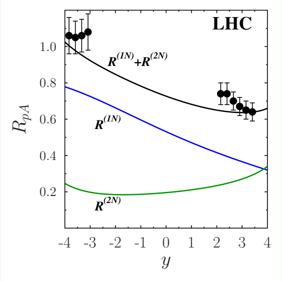
J/ψ in pA: theory vs experiment

Rapidity dependence

PHENIX: PRL 107, 142301

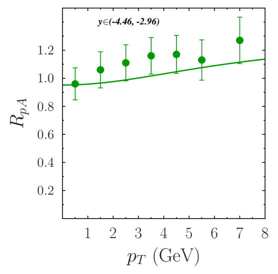


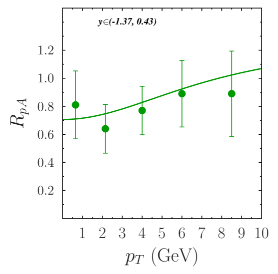
ALICE: JHEP 1402, 073



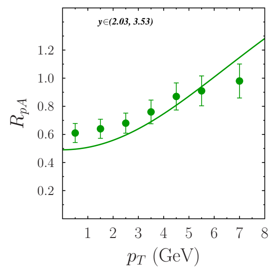
p_T-dependence

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





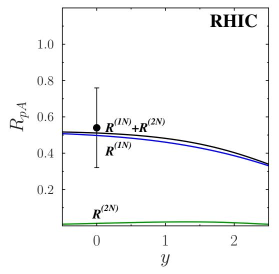
- Reasonable agreement with experiment in a wide kinematic range
- $R_{pA} \sim 1$ due to partial compensation of absorption and 2-nucleon term



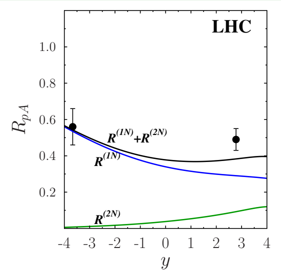
Other quarkonia in *pA*: theory vs experiment

$\Psi(2S)$ suppression

PHENIX: PRL 111, 202301

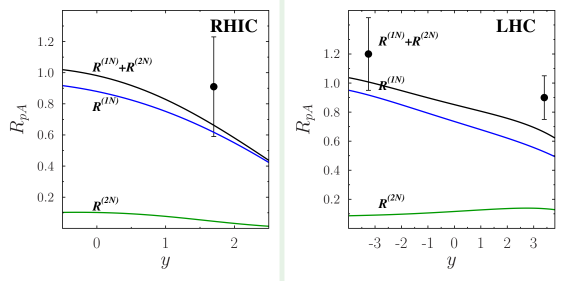


ALICE: JHEP 1412, 073



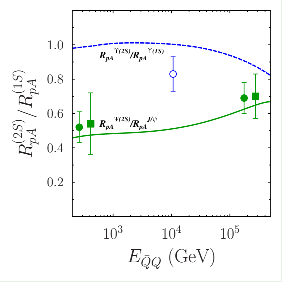
$\Upsilon(1S),\Upsilon(2S)$ suppression

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

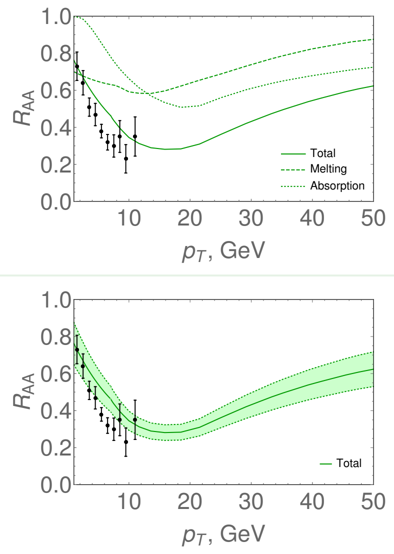
- Attenuation inside the cold nuclear phase is stronger than for *pA* due to higher nuclear densities
- Inside hot phase (QGP), there are two complementary mechanisms: "melting" (modification of potential $V_{c\bar{c}}(r, T)$) and absorption

$$\mathrm{Im}\, V \sim -\frac{v_\psi\, \hat{q}(\ldots)\, r^2}{4}$$

- 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 $\hat{q}_0 = 2 \pm 1\,\mathrm{GeV}^2/\mathrm{fm}$ is the main source of uncertainty.

Results for R_{AA} suppression



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/ψ, $\psi(2S)$, $\Upsilon(1S)$, 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