Inclusive J/ψ production in forward proton-proton and proton-lead collisions at high energy

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arXiv:2409.01791 (2024)

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Outline

Based on *Gimeno-Estivill, Lappi, Mäntysaari (2024) arXiv:2409.01791*

- J/ψ production in Color Glass Condensate(CGC) + Non-relativistic QCD(NRQCD)

  → Correlators of Wilson Lines
  → Target parametrization constrained by DIS HERA data

- Results compared to LHCb and ALICE data + previous J/ψ phenomenology in CGC+NRQCD

  → J/ψ cross section in p+p and p+Pb
  → Nuclear modification factor R_{pPb}

Gluon saturation

- High-energy (small-x) regime $\rightarrow$ strong increase in gluon density

- Forward rapidity ($y \gg 1$) in pA and pp collisions

$$x_p \propto e^{y} \lesssim 1 \longrightarrow \text{dilute projectile}$$
$$x_A \propto e^{-y} \ll 1 \longrightarrow \text{dense gluon target}$$

- Massive quarks $\mathrm{c\bar{c}}$: J/ψ

$M_{\mathrm{J}/\psi} \sim Q_{\mathrm{s}} \longrightarrow$ sensitive to saturation

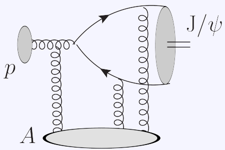
$v \ll 1,\ \alpha_{\mathrm{s}}(M_{\mathrm{J}/\psi}) \ll 1 \longrightarrow$ perturbative expansion in non-relativistic QCD

Inclusive J/ψ production

Color Glass Condensate (CGC) + Non-Relativistic QCD (NRQCD)

$$\frac{\mathrm{d}\sigma_{\mathrm{J}/\psi}}{\mathrm{d}^2\boldsymbol{p}\mathrm{d}y} = \sum_{\kappa} \frac{d\hat{\sigma}^{\kappa}_{c\bar{c}}}{\mathrm{d}^2\boldsymbol{p}\mathrm{d}y} \langle \mathcal{O}^{\mathrm{J}/\psi}_{\kappa} \rangle$$

short-distance cross sections $\otimes$ long-distance matrix elements (LDME)



LDME

- Values from cross section/polarization fit to Tevatron J/ψ data *Chao et al. (2012)*
- Ordered in powers of velocity

$$\langle \mathcal{O}^{\mathrm{J}/\psi}(^3\mathrm{S}_1^{[1]}) \rangle \sim 1$$
$$\langle \mathcal{O}^{\mathrm{J}/\psi}(^1\mathrm{S}_0^{[8]}) \rangle \sim v^3$$
$$\langle \mathcal{O}^{\mathrm{J}/\psi}(^3\mathrm{S}_1^{[8]}) \rangle \sim v^4$$
$$\langle \mathcal{O}^{\mathrm{J}/\psi}(^3\mathrm{P}_0^{[8]}) \rangle \sim v^4$$

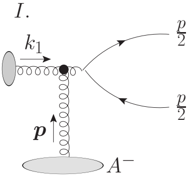
$$\kappa = {}^{2s+1}L_J^{[c]}$$

s: spin
L: orbital angular momentum
J: total angular momentum
c: color

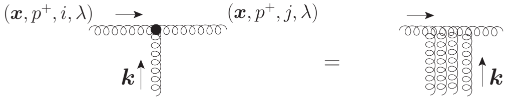
Bodwin, Braaten, Lepage (1994)

CGC

- Dilute-dense collision in the proton collinear limit ($\boldsymbol{k}_1 \to 0$)
- Target: classical gluon field A^-



- Eikonal interaction parton-nucleus: Wilson Line $V(\boldsymbol{x})$

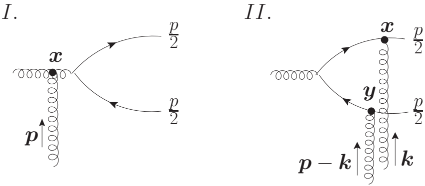


λ: polarization, i, j: color

Wilson Line

$$V_{\mathrm{F,A}}(\boldsymbol{x}) = \mathcal{P} \exp\left(-ig \int dx^+ A_a^-(x^+, \boldsymbol{x}) t^a\right)$$

Short-distance coefficients in CGC



Color octet states: *I* & *II*

$$\frac{d\hat{\sigma}}{d^2\boldsymbol{p}\,dy} \propto \alpha_s x_p f_{p/g}(x_p,\mu^2) \int_{\boldsymbol{b}} \int_{\boldsymbol{k}} \mathcal{N}(\boldsymbol{k})\mathcal{N}(\boldsymbol{p}-\boldsymbol{k})\tilde{\Gamma}_8^{\kappa}(p,k)$$

$\mathcal{N}(\boldsymbol{k}) = \int_{\boldsymbol{r}} e^{i\boldsymbol{k}\boldsymbol{r}} D_{\boldsymbol{r}}$

Color singlet states: *II*

$$\frac{d\hat{\sigma}}{d^2\boldsymbol{p}\,dy} \propto \alpha_s x_p f_{p/g}(x_p,\mu^2) \int_{\boldsymbol{x},\boldsymbol{x}',\boldsymbol{y}',\boldsymbol{y}} e^{-i\boldsymbol{p}\boldsymbol{\Delta}}\left(Q_{\boldsymbol{x},\boldsymbol{x}',\boldsymbol{y}',\boldsymbol{y}} - D_{\boldsymbol{r}}D_{\boldsymbol{r}'}\right)\tilde{\Gamma}_1^{\kappa}(r,r')$$

$D_{\boldsymbol{r}} \sim \left\langle \mathrm{Tr}[V_F(\boldsymbol{0})V_F^{\dagger}(\boldsymbol{r})]\right\rangle$

$Q_{\boldsymbol{x},\boldsymbol{x}',\boldsymbol{y}',\boldsymbol{y}} \sim \left\langle \mathrm{Tr}\left[V_F(\boldsymbol{x})V_F^{\dagger}(\boldsymbol{x}')V_F(\boldsymbol{y}')V_F^{\dagger}(\boldsymbol{y})\right]\right\rangle$

Dipole size: $\boldsymbol{r} = \boldsymbol{x} - \boldsymbol{y}$ (conjugate amplitude: $\boldsymbol{r}' = \boldsymbol{x}' - \boldsymbol{y}'$)
Impact parameter: $\boldsymbol{b} = (\boldsymbol{x} + \boldsymbol{y})/2$
Shift center of dipoles: $\boldsymbol{\Delta} = (\boldsymbol{x}' + \boldsymbol{y}' - \boldsymbol{x} - \boldsymbol{y})/2$

Kang, Ma, Venugopalan (2014)

Color Structure

Dipole

$$D_{\boldsymbol{x}-\boldsymbol{y}} = \frac{1}{N_{\mathrm{c}}} \left\langle \mathrm{Tr}[V_{\mathrm{F}}(\boldsymbol{x}) V_{\mathrm{F}}^{\dagger}(\boldsymbol{y})] \right\rangle$$

- Proton target: rcBK with initial condition: MV model parametrization fit to HERA DIS data
- Nuclear target: $\boldsymbol{b}$-dependent initial condition from the optical Glauber model

Lappi, Mäntysaari (2014)

- rcBK evolution for each $\boldsymbol{b}$

$\longrightarrow$ For nucleus target no free parameters besides Woods-Saxon nuclear density

Quadrupole

$$Q_{\boldsymbol{x},\boldsymbol{x}',\boldsymbol{y}',\boldsymbol{y}} = \frac{1}{N_{\mathrm{c}}} \left\langle \mathrm{Tr}\left[V_{\mathrm{F}}(\boldsymbol{x}) V_{\mathrm{F}}^{\dagger}(\boldsymbol{x}') V_{\mathrm{F}}(\boldsymbol{y}') V_{\mathrm{F}}^{\dagger}(\boldsymbol{y}) \right] \right\rangle$$

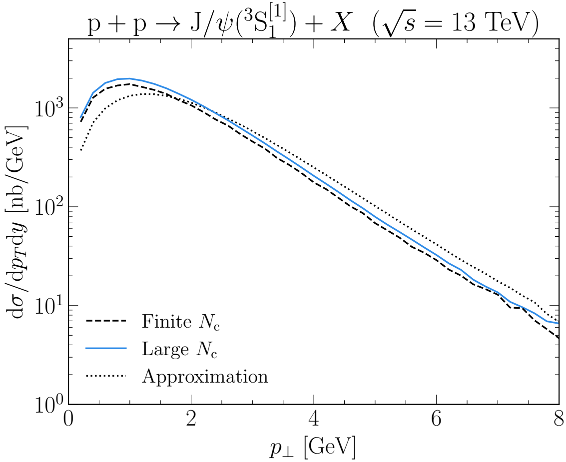
- Explicit expression in the Gaussian approximation for finite and large N_c

Dominguez, Marquet, Xiao, Yuan (2011)

$\longrightarrow$ Quantification of finite-$\mathrm{N_c}$ corrections + J/ψ phenomenology with explicit Q

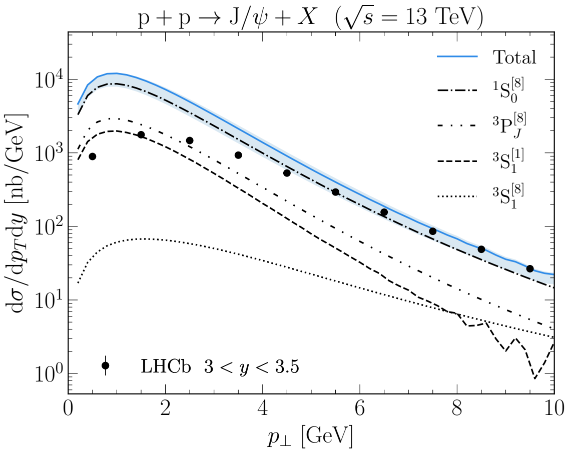
Results: finite-N_c corrections quadrupole

Color singlet state in proton-proton collisions at $y = 3.25$



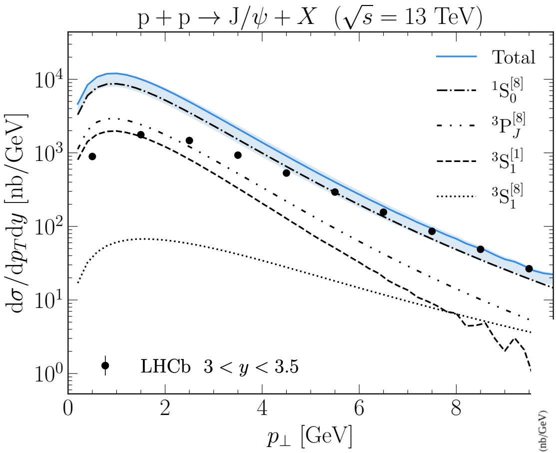
- Finite-N_c corrections are small $\mathcal{O}(1/N_c^2) \sim 12\%$
- Approximated quadrupole (*Ma, Venugopalan*) different by a factor of 2

J/ψ production in proton-proton collisions



- Correct description at high-$p_\perp$
- Low-$p_\perp$
  $\to$ Need Sudakov correction
- Dominant octet state $^1\mathrm{S}_0^{[8]}$
- Color singlet state $^3\mathrm{S}_1^{[1]} \sim 15\%$

J/ψ production in proton-proton collisions



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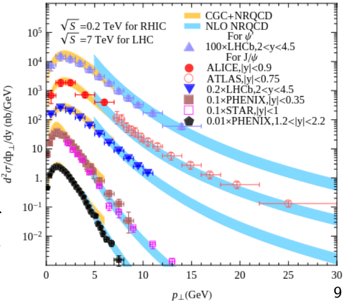
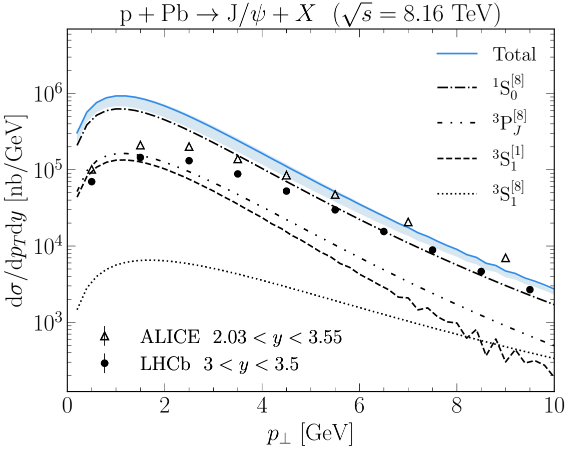


Ma, Venugopalan (2014)

- Some parameters from interpolation between PDF and uGD

J/ψ production in proton-nucleus collisions



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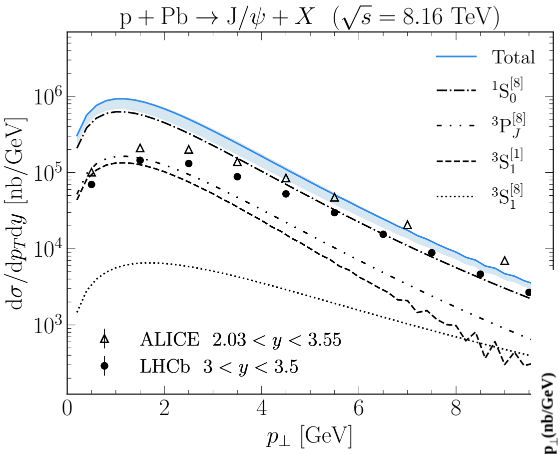

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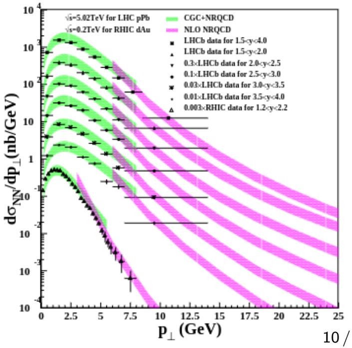

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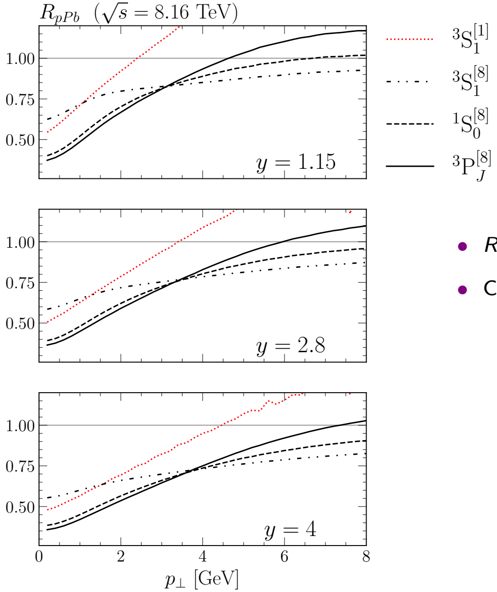
Nuclear modification ratio individual channels



$$R_{pPb} = \frac{d\sigma_{pPb}}{A d\sigma_{pp}}$$

- $R_{pPb} \to 1$ by construction at high-$p_\perp$
- Cronin enhancement color singlet $^3S_1^{[1]}$

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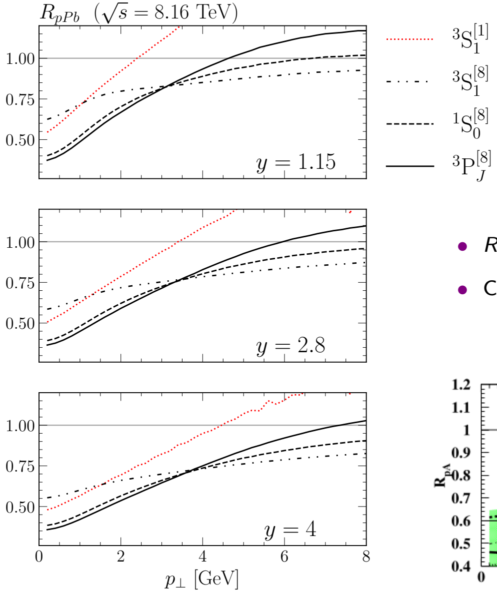

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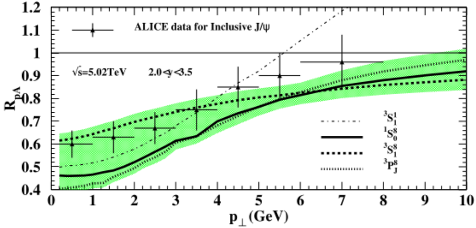
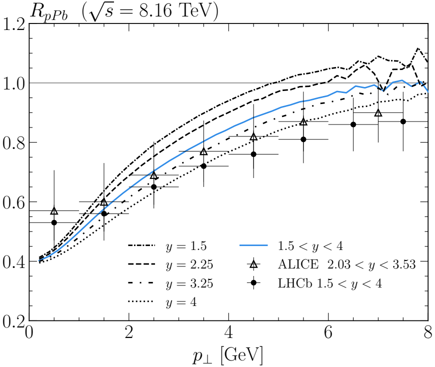
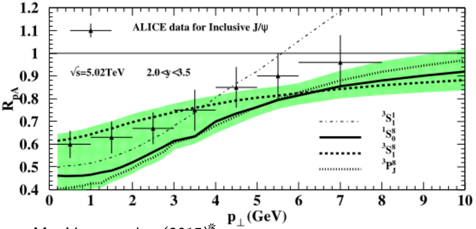


Nuclear modification ratio vs $p_\perp$ and y





Ma, Venugopalan (2015)

- Strong suppression at low $p_\perp$
- Steeper $p_\perp$-dependence → need NLO correction

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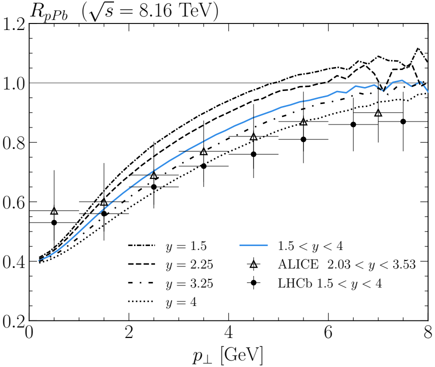

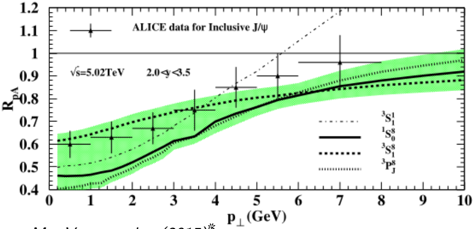

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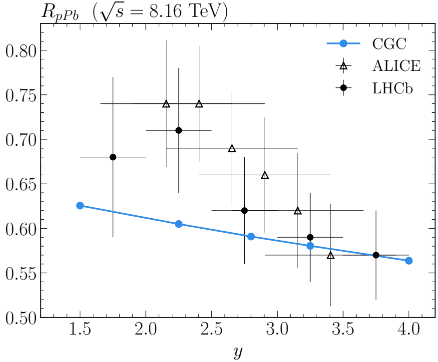

Summary

- J/ψ production in forward p+p and p+A in CGC+NRQCD

  → Explicit expression of the quadrupole
  → Description of the dense target in CGC constrained by DIS HERA data

- R_{pPb} compatible with data, with a similar trend as the CGC+CEM calculation

  Ducloué, Lappi, Mäntysaari (2015)

- Possible improvements

  → Sudakov correction at NLO
  → Fit initial conditions for BK equation including heavy quarks