J/ψ production in high multiplicity pp and pA collisions

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Introduction

- Consider process:

$\mu^+\mu^-$ or e^+e^-

$$\begin{matrix} pp \\ pA \end{matrix} \to J/\psi + X \to \; l^+l^- + X$$

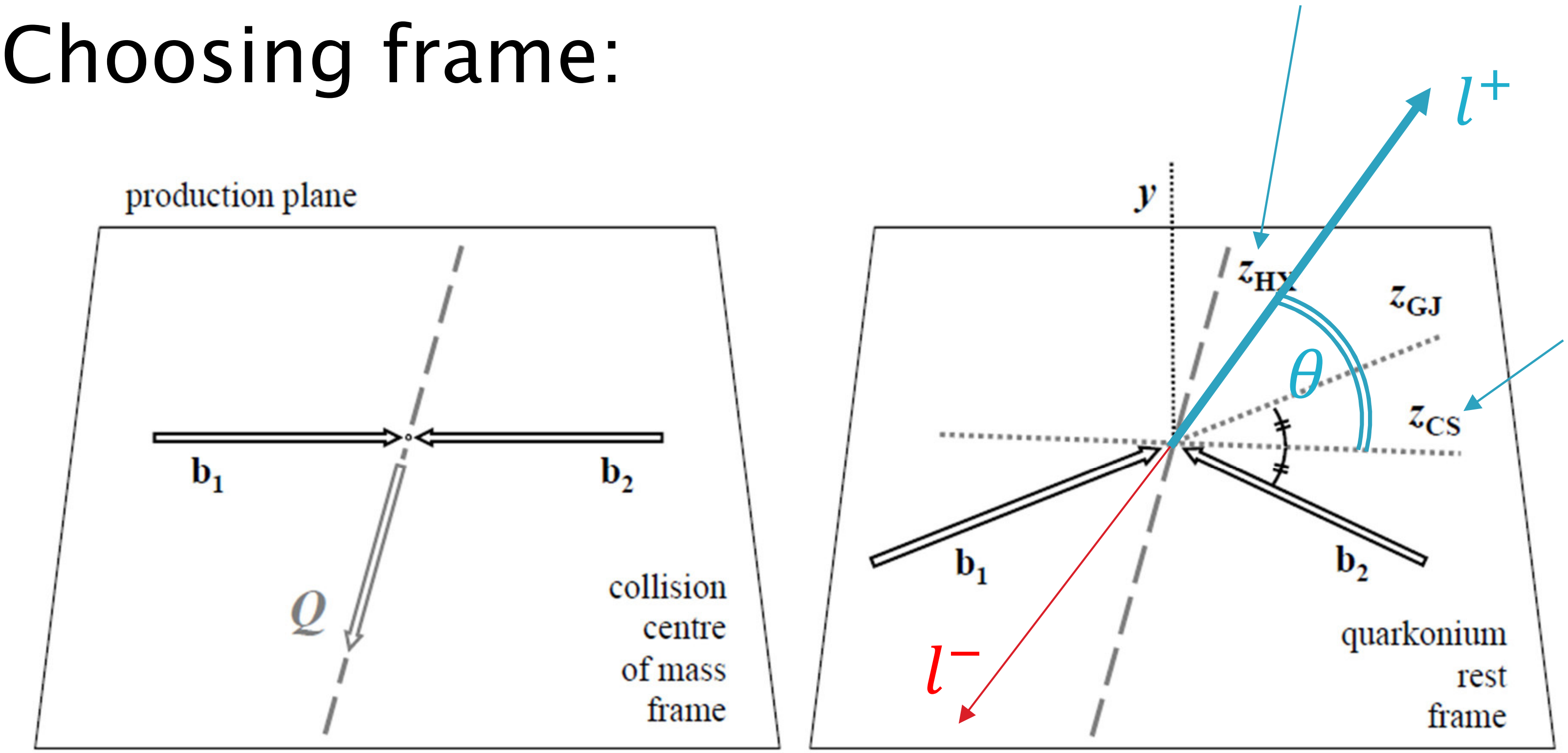
Light charged
hadrons
(high multiplicity)

- Nonrelativistic QCD (NRQCD) used to calculate cross-section.

- Short distance coefficients (SDC) of NRQCD calculated using Color Glass Condensate (CGC).

Polarization of J/ψ

- Choosing frame:



Helicity frame

Collins–Soper frame

P. Faccioli, C. Lourenco, J. Seixas and H. K. Wohri, Eur.Phys.J. C69 (2010) 657-673, [1006.2738]

- Angular distribution of one lepton (positive l^+):

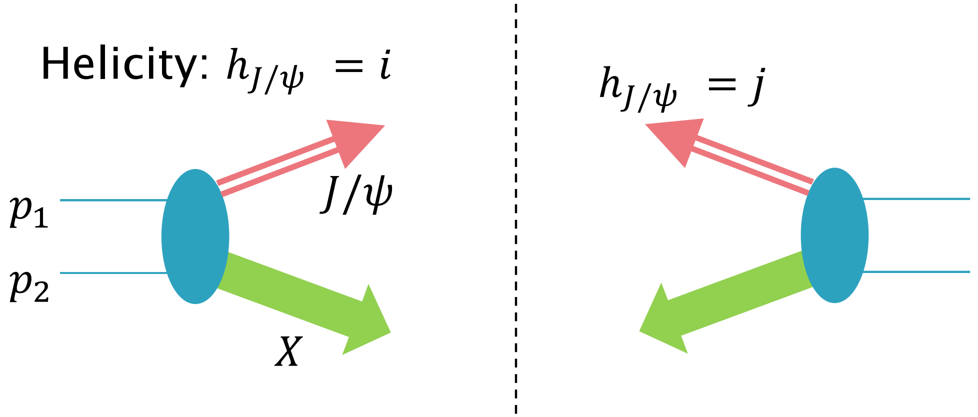
$$\boxed{\frac{d\sigma^{J/\psi(\to l^+ l^-)}}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi,}$$

Note: coefficients depend on the choice of frame

Polarization of J/ψ

Spin-1 particle: $i, j = -1, 0, +1$

$pp \to J/\psi + X$:



Amplitude $A^{(i)}$ Conjugated Amplitude $A^{*(j)}$

Spin density matrix:

$$\sigma_{ij} \sim A^{(i)} A^{*(j)}$$

Cross-section (yield): $\sigma = \sum_{i=1}^{3} \sigma_{ii}$

Polarization parameters are connected to the spin density matrix:

$$\lambda_\theta = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}, \qquad \lambda_\phi = \frac{d\sigma_{1,-1}}{d\sigma_{11} + d\sigma_{00}}, \qquad \lambda_{\theta\phi} = \frac{\sqrt{2}\,\mathrm{Re}(\mathrm{d}\sigma_{10})}{d\sigma_{11} + d\sigma_{00}}.$$

NRQCD

- In the NRQCD formalism $pp(pA) \rightarrow J/\psi + X$ is described by:

$$\mathrm{d}\sigma_{\mathrm{ij}} = \sum_{\kappa} \underbrace{\mathrm{d}\hat{\sigma}_{\mathrm{ij}}^{\kappa}}_{\text{Short distance coefficients (SDC)}} \underbrace{\langle \mathcal{O}_{\kappa} \rangle}_{\text{Long distance matrix elements (LDME)}},$$

Describe creation of $c\bar{c}$ pair, can be calculated using pQCD:

both color singlet and octet included

Non-perturbative quantities, describe hadronization of $c\bar{c}$ pair into J/ψ meson.

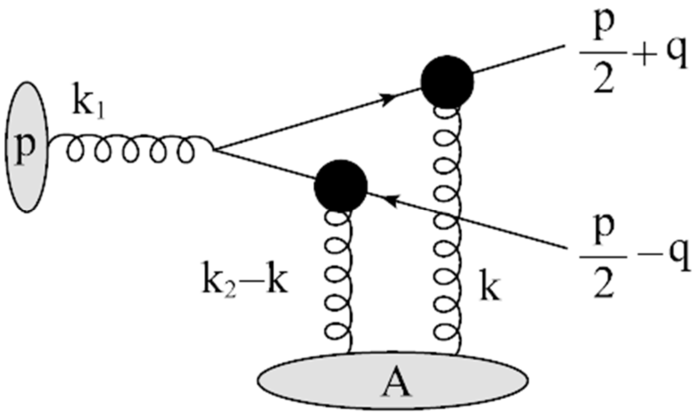
We use values fitted to Tevatron’s data using NLO collinear SDC
Chao et al. Phys.Rev.Lett. 108 (2012) 242004

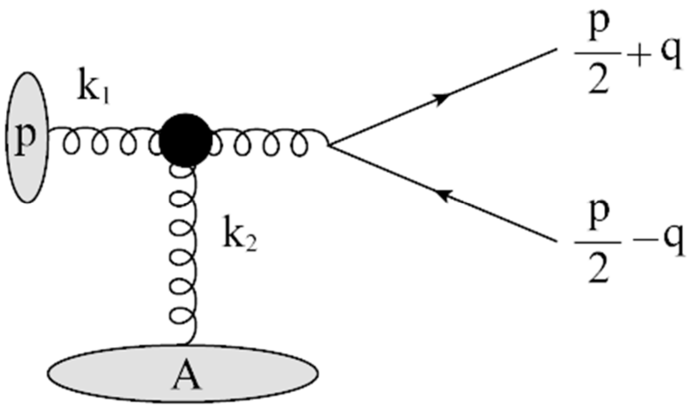
Color Glass Condensate (CGC)+ NRQCD

$$d\sigma_{ij} = \sum_{\kappa} d\hat{\sigma}_{ij}^{\kappa} \langle \mathcal{O}_{\kappa} \rangle,$$

Z.-B. Kang, Y.-Q. Ma and R. Venugopalan, JHEP 1401 (2014) 056
Y.-Q. Ma and R. Venugopalan, Phys.Rev.Lett. 113 (2014) 192301

We apply CGC to calculate short distance coefficients:





CGC+ NRQCD

Solution of running coupling Balitsky–Kovchegov eq.

Dipole forward scattering amplitude – Fourier tr. of

$$\frac{1}{N_c}\left\langle \mathrm{Tr}\left[V_F(\boldsymbol{x}_\perp)V_F^\dagger(\boldsymbol{x}'_\perp)\right]\right\rangle_{y_A}$$

SDC for color singlet ${}^3S_1^{[1]}$

$$\frac{d\hat{\sigma}^\kappa_{ij}}{d^2\boldsymbol{p}_\perp dy} \overset{\text{CS}}{=} \frac{\alpha_s(\pi R_p^2)}{(2\pi)^9(N_c^2-1)} \int_{\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp} \frac{\varphi_p(x_1,\boldsymbol{k}_{1\perp})}{k_{1\perp}^2} \mathcal{N}_Y(x_2,\boldsymbol{k}_\perp)\mathcal{N}_Y(x_2,\boldsymbol{k}'_\perp)$$
$$\times\,\mathcal{N}_Y(x_2,\boldsymbol{p}_\perp-\boldsymbol{k}_{1\perp}-\boldsymbol{k}_\perp-\boldsymbol{k}'_\perp)\,\mathcal{G}^\kappa_{ij}\left(x_1,x_2,p,\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp\right),$$

Unintegrated gluon distribution in the projectile

and for color octet: ${}^1S_0^{[8]},\ {}^3S_1^{[8]},\ {}^3P_J^{[8]}$ with $J=0,1,2$

$$\frac{d\hat{\sigma}^\kappa_{ij}}{d^2\boldsymbol{p}_\perp dy} \overset{\text{CO}}{=} \frac{\alpha_s(\pi R_p^2)}{(2\pi)^7(N_c^2-1)} \int_{\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp} \frac{\varphi_p(x_1,\boldsymbol{k}_{1\perp})}{k_{1\perp}^2} \mathcal{N}_Y(x_2,\boldsymbol{k}_\perp)$$
$$\times\ \mathcal{N}_Y(x_2,\boldsymbol{p}_\perp-\boldsymbol{k}_{1\perp}-\boldsymbol{k}_\perp)\,\Gamma^\kappa_{ij}\left(x_1,x_2,p,\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp\right),$$

Impact factors (contain projectors into given state κ)

Y.-Q. Ma, P. Tribedy, R. Venugopalan, K. Watanabe: Phys.Rev.D 98 (2018) 7, 074025

Charged hadrons multiplicity in CGC

Cross section for gluon emission:

Y. V. Kovchegov and K. Tuchin, Phys. Rev. D 65, 074026 (2002).
J. P. Blaizot, F. Gelis, and R. Venugopalan, Nucl. Phys. A743, 13 (2004)

Dipole forward scattering amplitude

$$\frac{d\sigma_g}{d^2\boldsymbol{p}_{g\perp}dy} \sim \int_{\boldsymbol{k}_{1\perp}} \frac{\boldsymbol{k}_{1\perp}^2(\boldsymbol{k}_{1\perp}-\boldsymbol{p}_{g\perp})^2}{\boldsymbol{p}_{g\perp}^2}\tilde{\mathcal{N}}_{x_1}(\boldsymbol{k}_{1\perp}) \tilde{\mathcal{N}}_{x_2}(\boldsymbol{k}_{1\perp}-\boldsymbol{p}_{g\perp})\theta(\boldsymbol{p}_{g\perp}^2-\boldsymbol{k}_{1\perp}^2).$$

and charged hadrons multiplicity:

$$\frac{dN_{\mathrm{ch}}}{d\eta} \sim \int_{z_{\mathrm{min}}}^{1} \frac{dz}{z^2} \int d^2\boldsymbol{p}_{h\perp} D_h(z) J(y_h \to \eta) \frac{d\sigma_g}{d^2\boldsymbol{p}_{g\perp}dy_g}, \qquad \boldsymbol{p}_{h\perp} = z\boldsymbol{p}_{g\perp}.$$

Fragmentation function for light hadrons

We use parametrization Kniehl, Kramer, Potter
Nucl. Phys. B582,514 (2000)

Y.-Q. Ma, P. Tribedy, R. Venugopalan, K. Watanabe: Phys.Rev.D 98 (2018) 7, 074025

Charged hadrons multiplicity in CGC

$$\frac{d\sigma_g}{d^2\boldsymbol{p}_{g\perp}dy} \sim \int_{\boldsymbol{k}_{1\perp}} \frac{\boldsymbol{k}_{1\perp}^2(\boldsymbol{k}_{1\perp}-\boldsymbol{p}_{g\perp})^2}{\boldsymbol{p}_{g\perp}^2} \tilde{\mathcal{N}}_{x_1}(\boldsymbol{k}_{1\perp}) \tilde{\mathcal{N}}_{x_2}(\boldsymbol{k}_{1\perp}-\boldsymbol{p}_{g\perp})\theta(\boldsymbol{p}_{g\perp}^2-\boldsymbol{k}_{1\perp}^2).$$

Solution of
running coupling
BK eq.

$$\frac{d\hat{\sigma}_{ij}^{\kappa}}{d^2\boldsymbol{p}_\perp dy} \overset{\mathrm{CO}}{=} \frac{\alpha_s(\pi R_p^2)}{(2\pi)^7(N_c^2-1)} \int_{\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp} \frac{\varphi_p(x_1,\boldsymbol{k}_{1\perp})}{k_{1\perp}^2} \mathcal{N}_Y(x_2,\boldsymbol{k}_\perp) \times \mathcal{N}_Y(x_2,\boldsymbol{p}_\perp-\boldsymbol{k}_{1\perp}-\boldsymbol{k}_\perp)\Gamma_{ij}^{\kappa}(x_1,x_2,p,\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp),$$

CGC:

High multiplicity events ↔ Colliding hadrons have high saturation scale

Y.-Q. Ma, P. Tribedy, R. Venugopalan, K. Watanabe: Phys.Rev.D 98 (2018) 7, 074025

Charged hadrons multiplicity in CGC

High multiplicity events ⟷ Intial hadrons have high saturation scale

$$\frac{dN_{\mathrm{ch}}}{d\eta} \sim \int_{z_{\mathrm{min}}}^{1} \frac{dz}{z^2} \int d^2\boldsymbol{p}_{h\perp} D_h(z) J(y_h \to \eta) \frac{d\sigma_g}{d^2\boldsymbol{p}_{g\perp} dy_g},$$

$$\frac{d\sigma_g}{d^2\boldsymbol{p}_{g\perp} dy} \sim \int_{\boldsymbol{k}_{1\perp}} \frac{\boldsymbol{k}_{1\perp}^2 (\boldsymbol{k}_{1\perp} - \boldsymbol{p}_{g\perp})^2}{\boldsymbol{p}_{g\perp}^2} \tilde{\mathcal{N}}_{x_1}(\boldsymbol{k}_{1\perp}) \tilde{\mathcal{N}}_{x_2}(\boldsymbol{k}_{1\perp} - \boldsymbol{p}_{g\perp}) \theta(\boldsymbol{p}_{g\perp}^2 - \boldsymbol{k}_{1\perp}^2).$$

Minimum bias events:

$$\left\langle \frac{dN_{\mathrm{ch}}^{pp}}{d\eta} \right\rangle \equiv \frac{dN_{\mathrm{ch}}}{d\eta}\bigg|_{Q^2_{s0,\mathrm{proton}} = Q_0^2},$$

Saturation scale in initial conditions for BK evolution

$= 0.168\ \mathrm{GeV}^2$

Value fitted to DIS data
J. L. Albacete et al.
PRD 80, 034031 (2009),
EPJC 71, 1705 (2011).

$$D_{x_0}(\boldsymbol{r}_\perp) = \exp\left[-\frac{(r_\perp^2 Q_{s0}^2)^\gamma}{4} \ln\left(\frac{1}{r_\perp \Lambda} + e\right)\right],$$

$$D_x(\boldsymbol{r}_\perp) = \int_{\boldsymbol{k}_\perp} e^{-i\boldsymbol{k}_\perp \cdot \boldsymbol{r}_\perp} \mathcal{N}_x(\boldsymbol{k}_\perp).$$

Y.-Q. Ma, P. Tribedy, R. Venugopalan, K. Watanabe: Phys.Rev.D 98 (2018) 7, 074025

Charged hadrons multiplicity in CGC

High multiplicity events ↔ Intial hadrons have high saturation scale

$$\frac{dN_{\rm ch}}{d\eta} \sim \int_{z_{\rm min}}^{1} \frac{dz}{z^2} \int d^2\boldsymbol{p}_{h\perp} D_h(z) J(y_h \to \eta) \frac{d\sigma_g}{d^2\boldsymbol{p}_{g\perp} dy_g},$$

Minimum bias events:

$$\left\langle \frac{dN_{\rm ch}^{pp}}{d\eta} \right\rangle \equiv \left. \frac{dN_{\rm ch}}{d\eta} \right|_{Q^2_{s0,\rm proton} = Q_0^2},$$

High multiplicity events:

$$\frac{dN_{\rm ch}^{pp}}{d\eta} \equiv \left. \frac{dN_{\rm ch}}{d\eta} \right|_{Q^2_{s0,\rm proton} = \xi Q_0^2}$$

$\xi > 1$

In what follows we calculate always ratio $\frac{dN_{pp}}{d\eta} / \left\langle \frac{dN_{pp}}{d\eta} \right\rangle$.

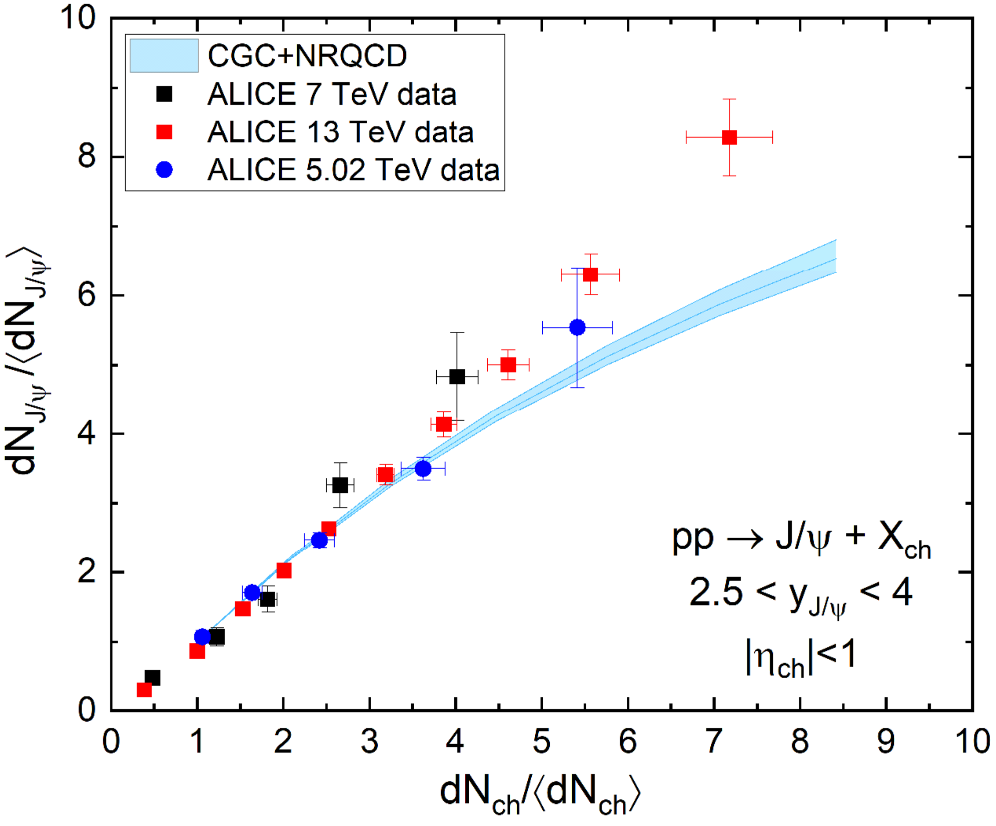
Numerical results

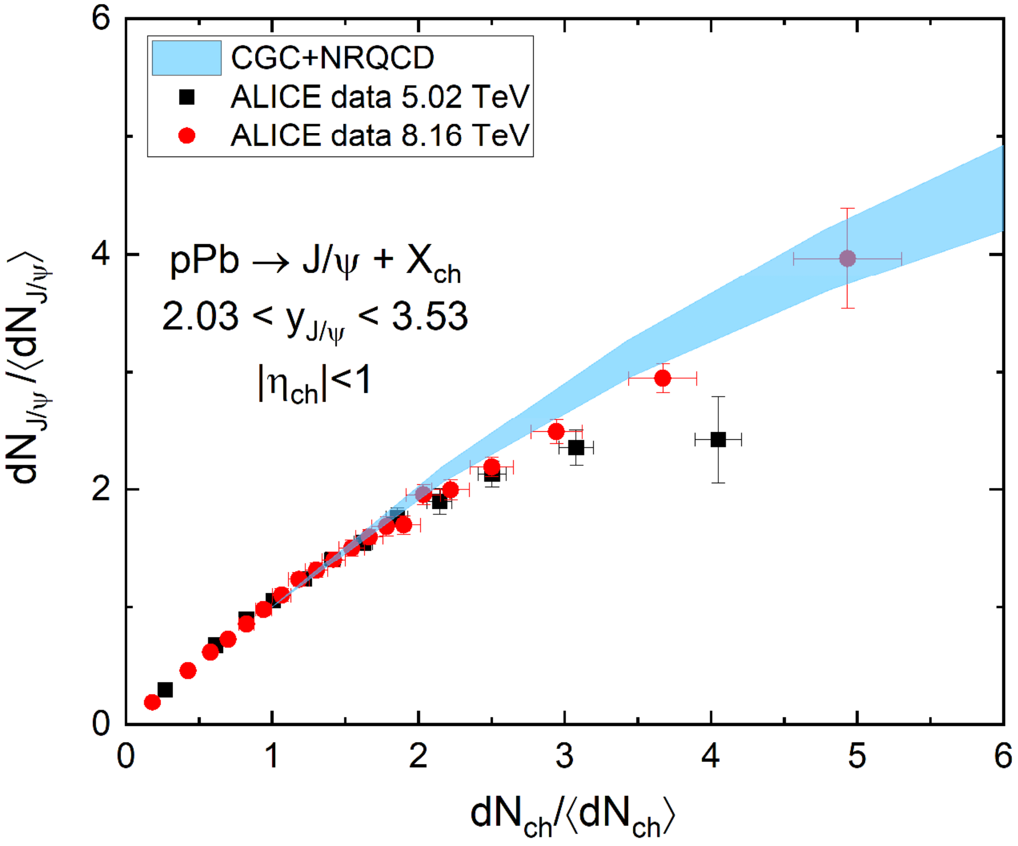
Preliminary

J/ψ yield vs. event multiplicity

pp

pA





pp

pPb

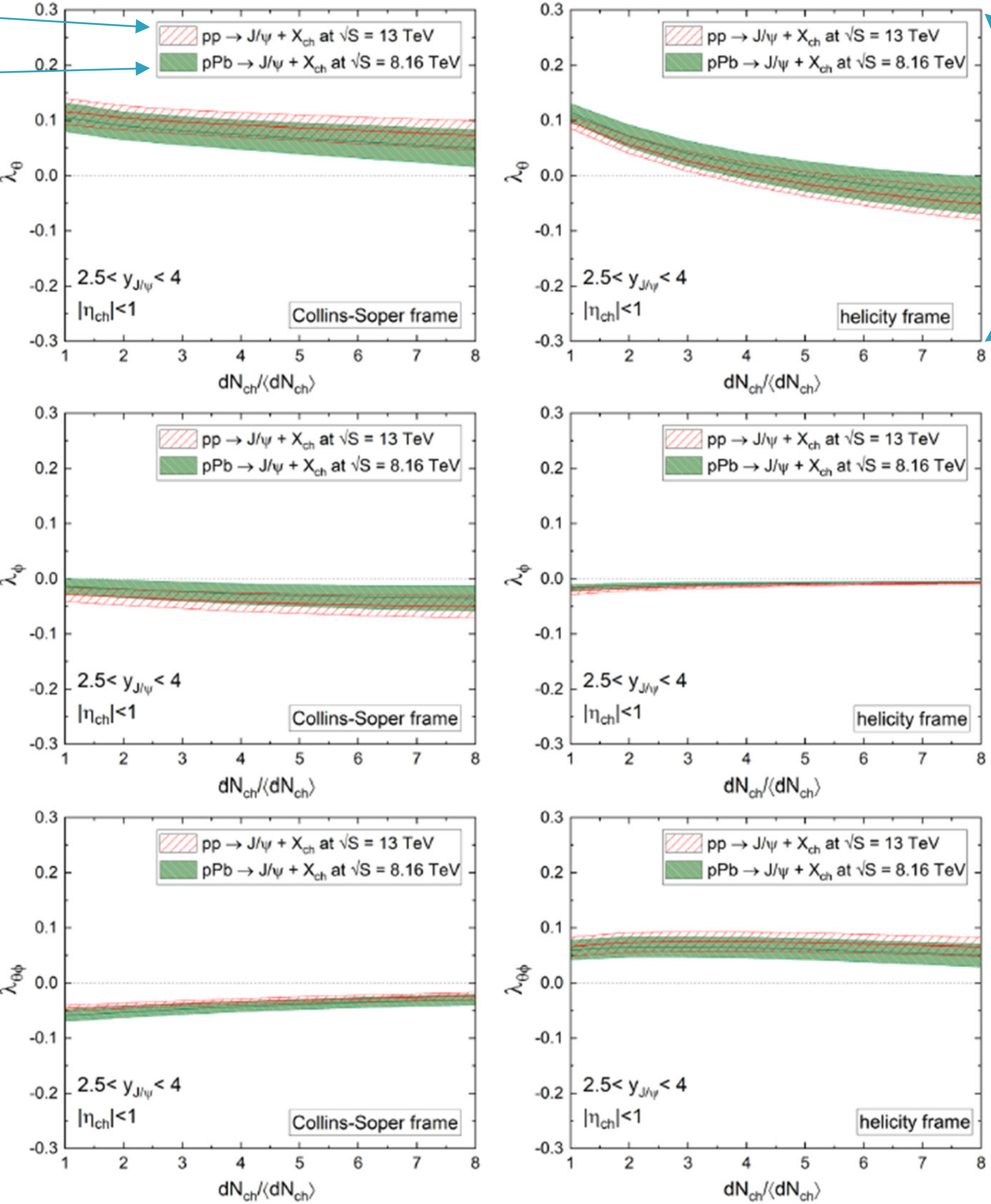
λ_θ

0.3

-0.3

λ_ϕ

$\lambda_{\theta\phi}$



Data not available

Collins-Soper

Helicity frame

Summary

- We discussed yield and polarization of J/ψ in high multiplicity events within CGC+NRQCD framework.
- Relative yield of J/ψ agrees with data (except high-multiplicity pp).
- Data for polarization not available. We predict small J/ψ polarization, decrease of polarization with multiplicity.

Thank you