J/ψ PRODUCTION IN HIGH-MULTIPLICITY pp AND pA COLLISIONS*

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Using the Color Glass Condensate (CGC) effective theory and non-relativi-tic QCD (NRQCD) factorization, we provide predictions of J/ψ polarization parameters in high-multiplicity proton–proton (pp) and proton–nucleus (pA) collisions. Energies and rapidity ranges are chosen to be accessible at the Large Hadron Collider (LHC). We predict a weak polarization of J/ψ that additionally decreases with growing event activities. Small difference between pp and pA collisions is observed.

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1. Introduction

At high energies, the Color Glass Condensate (CGC) effective field theory [1–5] allows to resum corrections from large logarithms of x variable and incorporate leading higher-twist contributions. In this approach, large-x degrees of freedom in the two hadrons are treated as static color sources that are coupled to dynamical gauge fields at small x. The requirement that the cross sections do not depend on this separation leads to the Jalilian-Marian–Iancu–McLerran–Weigert–Leonidov–Kovner (JIMWLK) equations [6–9]. This complicated system of equations is usually simplified by its mean field approximation: Balitsky–Kovchegov (BK) equation [10, 11].

The non-relativistic QCD (NRQCD) [12] effective field theory is currently the most rigorous and precise approach to heavy quarkonium production at high energy. It provides the factorization between heavy-quark pair production at a short distance and its hadronization into quarkonium at a long distance. The cross section for heavy-quark pair production in the CGC formalism was computed in Refs. [13–15]. This result was later used to combine the CGC framework with the NRQCD [16].

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In high-energy collisions, an inclusive J/ψ production is the best measured heavy quarkonium production process due to its relatively large cross section and dilepton decay signature. In recent years, the event activity dependence of J/ψ yield has been measured both at the LHC and the RHIC colliders [17–19]. Since the heavy-quark pair is produced at an early stage of collision, a J/ψ production mechanism can be dependent on event multiplicity due to the initial-state and/or final-state effects.

The application of the CGC+NRQCD framework to an inclusive J/ψ production led to successful description of the $p_\perp$ spectra in pp and pA collisions [20, 21] and also the polarization observables [22]. The event activity dependence of J/ψ production yield was explored in the CGC framework in Ref. [23].

2. Theoretical analysis

2.1. CGC+NRQCD framework

The NRQCD framework provides the factorization of the spin density matrix elements $\sigma_{ij}^{J/\psi}$ (indices i and j denote helicity of the meson)

$$\frac{\mathrm{d}\sigma_{ij}^{J/\psi}}{\mathrm{d}^2\boldsymbol{p}_\perp\,\mathrm{d}y} = \sum_\kappa \frac{\mathrm{d}\hat{\sigma}_{ij}^{\kappa}}{\mathrm{d}^2\boldsymbol{p}_\perp\,\mathrm{d}y} \left\langle \mathcal{O}_\kappa \right\rangle , \tag{1}$$

where it depends on the J/ψ's transverse momentum $\boldsymbol{p}_\perp$ and rapidity y. Short-distance coefficients (SDCs) $\mathrm{d}\hat{\sigma}_{ij}^{\kappa}$ describe heavy-quark pair production in a specific spin-color state denoted by κ. For explicit expressions for all relevant SDCs calculated in the CGC formalism, see Ref. [22].

Long-distance matrix elements (LDMEs) $\langle \mathcal{O}_\kappa \rangle$ represent a non-perturbative transition between the $c\bar{c}$ pair and J/ψ meson. They need to be determined by fitting to data. Leading intermediate states for J/ψ are $\kappa = {}^3S_1^{[1]},\ {}^1S_0^{[8]},\ {}^3S_1^{[8]},\ {}^3P_J^{[8]}$ with $J = 0,1,2$. Here, we will apply the LDME values obtained in Ref. [24] by fitting NLO collinear factorized pQCD+NRQCD results to the Tevatron high-$p_\perp$ prompt-J/ψ data. This set of LDMEs was also used in previous CGC+NRQCD studies [20–22, 25].

2.2. J/ψ polarization

The polarization of J/ψ meson is measured by considering the leptonic decay in its rest frame. By $\Omega = (\theta, \phi)$, we denote the solid angle of the positive lepton l^+ w.r.t. axes chosen according to the *e.g.* Collins–Soper [26] prescription. Then the lepton angular distribution is given by [27, 28]

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

Angular coefficients λ are directly connected to the spin density matrix elements (1)

$$\begin{aligned}\lambda_\theta &= \frac{\mathrm{d}\sigma_{11}^{J/\psi} - \mathrm{d}\sigma_{00}^{J/\psi}}{\mathrm{d}\sigma_{11}^{J/\psi} + \mathrm{d}\sigma_{00}^{J/\psi}}\,,\\ \lambda_\phi &= \frac{\mathrm{d}\sigma_{1,-1}^{J/\psi}}{\mathrm{d}\sigma_{11}^{J/\psi} + \mathrm{d}\sigma_{00}^{J/\psi}}\,,\\ \lambda_{\theta\phi} &= \frac{\sqrt{2}\,\mathrm{Re}\left(\mathrm{d}\sigma_{10}^{J/\psi}\right)}{\mathrm{d}\sigma_{11}^{J/\psi} + \mathrm{d}\sigma_{00}^{J/\psi}}\,.\end{aligned} \tag{3}$$

2.3. Inclusive hadron production in the CGC framework

The charged hadron multiplicity in the CGC framework at pseudorapidity η (we skip the overall constant which is irrelevant to our studies) is given by [23, 25]

$$\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta} \sim \int\limits_{z_{\min}}^{1} \frac{\mathrm{d}z}{z^2} \int \mathrm{d}^2\boldsymbol{p}_{h\perp}\, D_h(z) J(y_h \to \eta) \frac{\mathrm{d}\sigma_g}{\mathrm{d}^2\boldsymbol{p}_{g\perp}\mathrm{d}y_g}\,, \tag{4}$$

where $\mathrm{d}\sigma_g$ denotes the gluon production cross section calculated in the CGC framework [29, 30] and $D_h(z)$ is a fragmentation function for which we take the Kniehl–Kramer–Potter parametrization [31]. The hadrons carry z fraction of the gluon's transverse momentum, $\boldsymbol{p}_{h\perp} = z\boldsymbol{p}_{g\perp}$ and the integration over z is restricted from below by kinematics. The Jacobian $J(y_h \to \eta)$ accounts for the transformation between rapidity y_h and pseudorapidity η of the hadron.

The J/ψ's spin density matrix (1) and hadron's multiplicity (4) depend on the dipole correlators $\tilde{\mathcal{N}}_x(\boldsymbol{k}_\perp)$. In this paper, we use dipole correlators obtained by solving the running coupling BK equation [32] in momentum space [33]. Initial conditions at $x_0 = 0.01$ were chosen according to the McLerran–Venugopalan model [34, 35] and are parameterized by the saturation scale $Q^2_{\mathrm{s}0}$ in the hadron. In our approach, high multiplicities arise due to the hot spots where gluons are highly occupied, giving larger saturation scales. Therefore, we can use the value of $Q^2_{\mathrm{s}0}$ as a parameter controlling charged multiplicity of a given event. For the proton, it is equal to Q_0^2 for minimum-bias events and ξQ_0^2, $\xi > 1$ for high-multiplicity events. For pA collisions, the initial saturation scale in the nucleus is expected to be larger than in the proton, $Q^2_{\mathrm{s}0,\mathrm{nucleus}} = \nu Q^2_{\mathrm{s}0,\mathrm{proton}}$ with $\nu > 1$. The parameter ν is treated as an additional source of uncertainty, we vary it in the range of $\nu \in [2,3]$, as suggested by other studies [21, 36–38].

3. Numerical results

We present here predictions for polarization parameters in high-multiplicity events using kinematical conditions probed in the related measurements at the LHC (such as an inclusive J/ψ polarization or J/ψ yield in high-multiplicity events): center-of-mass energy is set to $\sqrt{S} = 13$ TeV for pp and $\sqrt{S} = 8.16$ TeV for pA collisions, light charged hadrons' pseudorapidity $|\eta_{\mathrm{ch}}| < 1$ and the J/ψ rapidity $2.5 < y_{J/\psi} < 4$. In order to estimate uncertainties of our predictions, we use errors of the LDMEs and the ν parameter variations in the case of pA.

In experimental studies, see *e.g.* [17–19], the J/ψ yield was measured as a function of the ratio between high-multiplicity pp (pA) collisions and that in minimum bias events

$$\frac{\mathrm{d}N_{\mathrm{ch}}^{pX}}{\left\langle \mathrm{d}N_{\mathrm{ch}}^{pX} \right\rangle}, \tag{5}$$

where $X = p$, A, and both multiplicities are integrated over the same pseudorapidity range. Here, we follow this setup and plot the polarization parameters as functions of ratio (5).

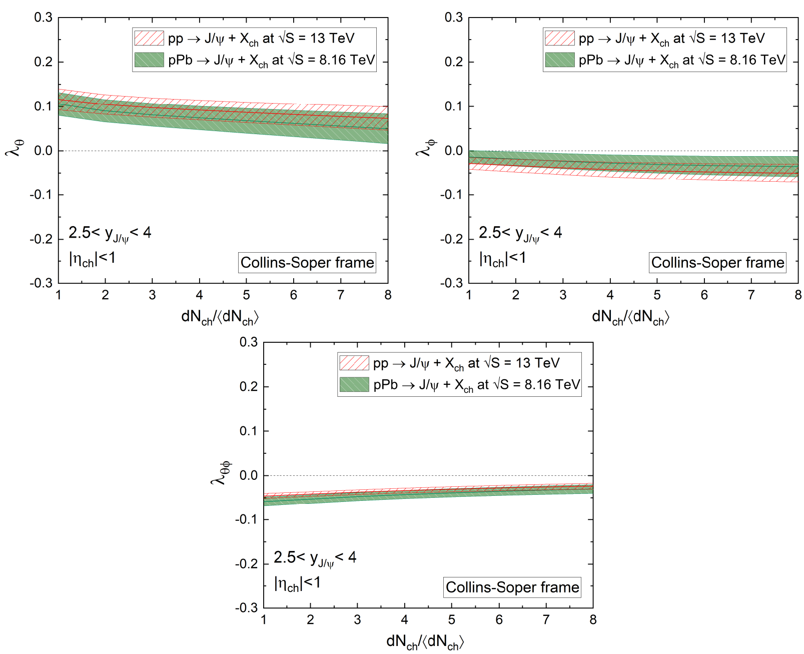

Fig. 1. Polarization parameters λ_θ (left), λ_ϕ (middle), and $\lambda_{\theta\phi}$ (right panel) of the forward J/ψ production as a function of relative multiplicity in pp collisions at 13 TeV (red hatched band) and pA collisions at 8.16 TeV (green full band).

In figure 1, we show three polarization parameters for pp (red hatched band) and pA (green filled band). We observe a small difference between pp and pA results (energy dependence is negligible). The polarization is small since all parameters are within the range $(-0.1, 0.15)$. The parameter λ_θ slightly decreases with the event activity.

4. Discussion and summary

The small difference in the J/ψ polarization between pp and pA collisions comes from the features of our model. At a short distance, where the saturation plays a role, the $c\bar{c}$ pair does not experience hadronization effects. Moreover, we are not including any final-state interaction of the J/ψ. Finally, pp and pA processes were assumed to have the same set of LDMEs. As the previous study [23] showed, the J/ψ's yield and its mean $p_\perp$ depend very strongly on the multiplicity of the event. This is because those observables are driven by the saturation scales, which are very different in the proton and nucleus. Therefore, the J/ψ's polarization measurement in high-multiplicity events is a complementary analysis to already existing measurements and provides a useful test of the CGC theory. Such observable should be accessible experimentally at the LHC.

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