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Unified framework for heavy flavor and quarkonium production in high multiplicity $p+p$ and $p+A$ collisions at RHIC and LHC

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Abstract

We discuss the production of D -mesons and J/ψ in high multiplicity proton-proton and proton-nucleus collisions within the Color-Glass-Condensate (CGC) framework. We demonstrate that the modification of the LHC data on D and J/ψ yields in high multiplicity events relative to minimum bias events arise from a significant enhancement of the gluon saturation scales of the corresponding rare parton configurations in the colliding protons and nuclei. For a given event multiplicity, we predict these relative yields to be energy independent from $\sqrt{s} = 200$ GeV at RHIC to the highest LHC energies.

Keywords: Heavy Flavor; Quarkonium; Color Glass Condensate; proton-nucleus collision; High multiplicity events

1. Introduction

Heavy flavor (D) and quarkonium (J/ψ) production in minimum bias proton-proton ($p+p$) and proton-nucleus ($p+A$) collisions at RHIC and LHC have been studied extensively in the Color-Glass-Condensate (CGC) effective field theory over the last several years [1, 2, 3, 4, 5, 6, 7]. These works demonstrated that quantitative descriptions of the transverse momentum and rapidity distributions could be achieved in these collisions. The study of rare high multiplicity events in $p+p$ and $p+A$ collisions at RHIC and the LHC have opened up a new window in the dynamics of atypical parton configurations in QCD. A striking result in such events are the ridge-like structures of azimuthally collimated and long range in rapidity hadron correlations leading to an interesting debate on the relative importance of initial or final state effects. Systematic studies of heavy quarks— a so-called “event engineering” can play an important role in clarifying the underlying mechanisms of high multiplicity events. In this proceedings, we will present a brief perspective on the comparison of currently available experimental data on high multiplicity D meson and J/ψ production in $p+p$ and $p+A$ collisions [8, 9, 10, 11, 12] with our recent results [13] obtained within the CGC EFT.

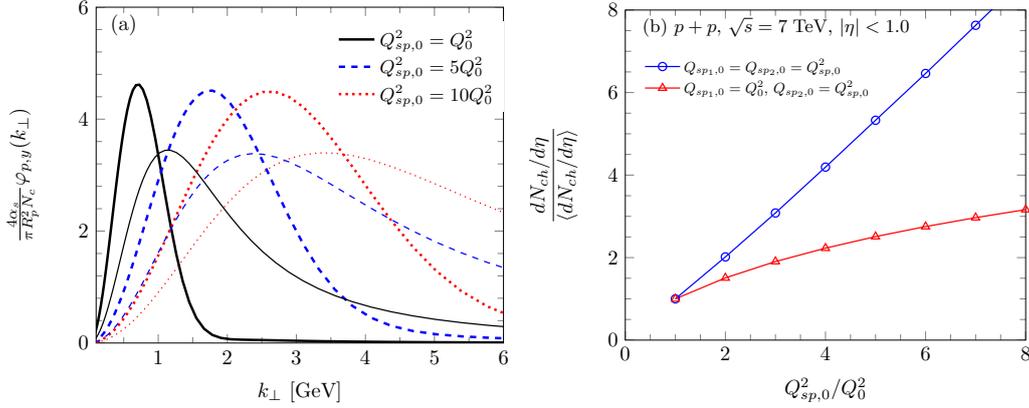


Fig. 1. (a): k_{\perp} distribution of φ_p at $x = 0.01$ (thick) and $x = 10^{-4}$ (thin) by varying the initial saturation scale $Q_{sp,0}^2$. (b): $Q_{sp,0}^2$ vs normalized charged hadron multiplicity $dN_{ch}/\langle dN_{ch} \rangle$ in $p + p$ collisions at the LHC. The circular points (in blue) are results for the normalized charged particle multiplicity obtained by equating the saturation scales for the projectile and target: $Q_{sp1,0} = Q_{sp2,0}$. The triangular points (in red) are obtained by varying $Q_{sp2,0}^2$ while $Q_{sp1,0}^2$ is fixed as Q_0^2 .

2. CGC Framework

We shall focus on the charged hadron multiplicity N_{ch} dependence of D and J/ψ production in this paper. In our calculations, the charged hadron production in $p + p(A)$ collisions is computed by convoluting inclusive gluon production cross-section [14]

$$\frac{d\sigma_g}{d^2\mathbf{p}_{g\perp} dy} = \frac{\alpha_s}{(2\pi)^3 \pi^3 C_F} \frac{1}{p_{g\perp}^2} \int d^2\mathbf{k}_{\perp} \varphi_{p,y_p}(\mathbf{k}_{\perp}) \varphi_{A,Y}(\mathbf{p}_{g\perp} - \mathbf{k}_{\perp}), \quad (1)$$

with the KKP fragmentation function (FF) [15]. Here $y_p = \ln 1/x_1$ and $Y = \ln 1/x_2$ with $x_{1,2}$ being incoming gluon's longitudinal momentum fraction. Information on impact parameter is encoded in the unintegrated gluon distribution function (UGDF) φ through the saturation scales of the proton and nucleus.

The differential cross-section for $c\bar{c}$ production in $p + p(A)$ collisions in the large N_c limit can be expressed as [16]

$$\frac{d\sigma_{c\bar{c}}}{d^2\mathbf{p}_{c\perp} d^2\mathbf{q}_{\bar{c}\perp} dy_c dy_{\bar{c}}} = \frac{\alpha_s N_c^2 \pi R_A^2}{2(2\pi)^{10} (N_c^2 - 1)} \int d^2\mathbf{k}_{2\perp} d^2\mathbf{k}_{\perp} \frac{\varphi_{p,y_p}(\mathbf{k}_{1\perp})}{k_{1\perp}^2} \mathcal{N}_Y(\mathbf{k}_{\perp}) \mathcal{N}_Y(\mathbf{k}_{2\perp} - \mathbf{k}_{\perp}) \Xi, \quad (2)$$

where Ξ is hard part and \mathcal{N}_Y is the fundamental dipole amplitude. Single D meson production is straightforwardly calculated by using heavy quark FF which is set to be the QCD evolved BCFY FF [17]. In computing the J/ψ cross-section, we will employ the CGC + NRQCD formalism [19], wherein the hard matrix elements differ from Ξ , as well as the CGC + ICEM model, whereby the latter is the improved color evaporation model [20].

The rapidity dependence of the cross-sections is computed by solving the running coupling BK equation [21] for \mathcal{N}_Y . All input parameters in the initial dipole amplitude at $x_0 = 0.01$ are determined by DIS global fits to HERA data. In our numerical computations, we take the initial saturation scale $Q_{sp,0}^2 = 0.168 \text{ GeV}^2$ for the proton and $Q_{sA,0}^2 = 2 Q_{sp,0}^2$ for nuclei as discussed in [2, 3].

High values of N_{ch} are achieved by allowing the initial saturation scales of both the projectile and target to fluctuate to large values, corresponding to a fluctuation of large x parton configurations in these rare events. Figure 1 (a) shows the φ_p distribution in such events at both the initial saturation scale of $x = 0.01$ and after evolution to $x = 10^{-4}$. We observe that QCD evolution in the rare events leads to very broad distributions peaked at values of transverse momenta that are ~ 3 GeV. If the saturation scales of the projectile and target are similar, φ_{p_1} and φ_{p_2} will have a large overlapping weight in the integrand of Eq. 1 leading to a rapid increase of N_{ch} as shown in Fig. 1 (b).

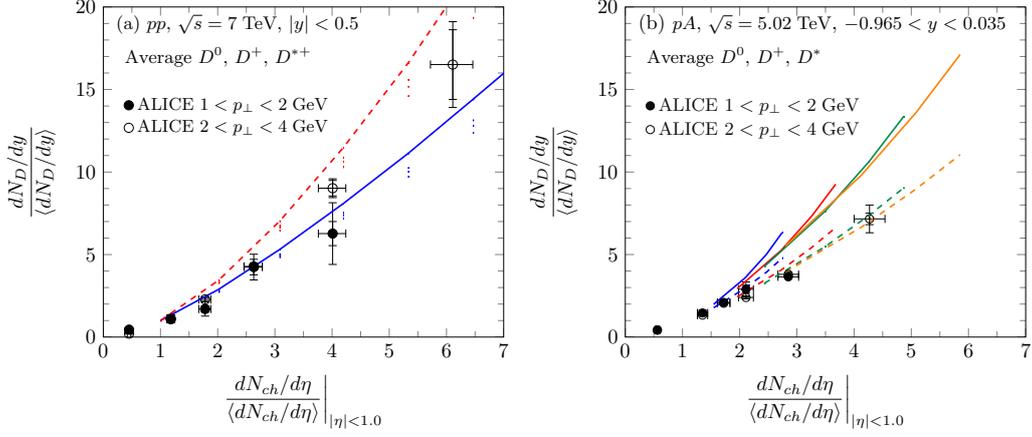


Fig. 2. (a): Relative yields of average D (D^0 , D^+ , D^{*+}) as a function of relative multiplicity in $p + p$ collisions at the LHC. The solid (dashed) line is the result at $1 < p_{\perp} < 2$ GeV ($2 < p_{\perp} < 4$ GeV). Data are from Ref. [8]. (b): Results in $p + A$ collisions. The solid (dashed) lines are the results at $1 < p_{\perp} < 2$ GeV ($2 < p_{\perp} < 4$ GeV). The blue, red, green and orange curves all show model results for variations in the range $Q_{s,p,0}^2 = 1 - 4Q_0^2$ for $Q_{sA,0}^2 = 4, 6, 9, 12Q_0^2$ respectively. Data are from Ref. [9].

3. Results

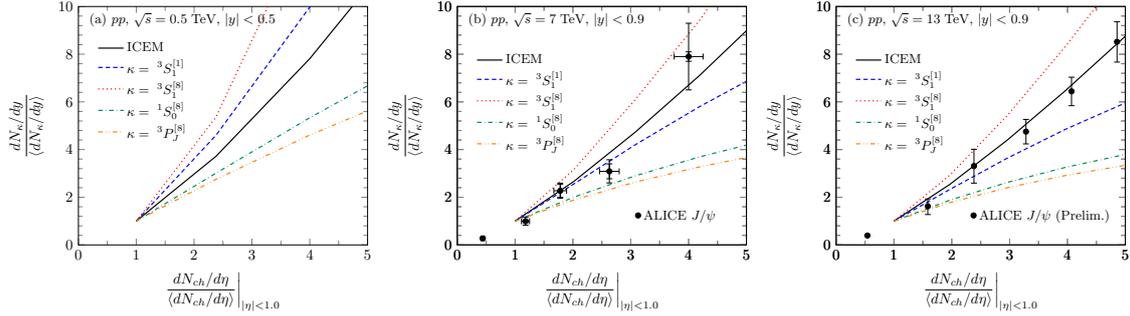


Fig. 3. N_{ch} dependence of J/ψ production in $p + p$ collisions in the CGC+ICEM (solid curve) and the CGC+NRQCD (other curves) at RHIC (a) and the LHC (b)(c). Data points are from Refs. [10, 11, 12].

In Fig. 2, we present our results on the N_{ch} dependence of D production in both $p + p$ and $p + A$ collisions at the LHC. The CGC EFT shows a nice agreement with the data within the systematic uncertainties with respect to the FFs and the initial saturation scales. These are however quite small for the double ratios presented. A similar trend of the p_{\perp} dependence of the double ratios is seen in both $p + p$ and $p + A$ collisions [13].

The N_{ch} dependence of J/ψ production in $p + p$ collisions is shown in Fig. 3. The relative contribution of different intermediate channels $\kappa = {}^{2S+1}L_J^{[c]}$ is examined in the CGC+NRQCD framework. We find that the ${}^3S_1^{[8]}$ intermediate state has a larger relative weight than the other channels for all $dN_{ch}/d\eta$. This suggests that J/ψ production with high event activity is dominated by the ${}^3S_1^{[8]}$ channel but has only small contributions from ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ channels. This result is consistent with the universality requirement for LDMEs employed in hadron-hadron collisions to be consistent with those extracted from BELLE e^+e^- data [22]. In Fig. 3, we also put the ICEM curves which have trends similar to the ${}^3S_1^{[8]}$ channel. Comparisons of the CGC+ICEM computations to available data at the LHC indicate that the event activity dependence of the ratios for J/ψ production is insensitive to \sqrt{s} . We therefore predict that results for the relative yields as a function of event activity will be identical (within systematic uncertainties) as those from the LHC.

However, the relative weight of different κ can be changed at RHIC energy. We have also checked that J/ψ production in $p + A$ collisions in the CGC+ICEM provides a nice agreement with data on the ratio [13].

It will be interesting in future to address event activity dependence of $\psi(2S)$ and Υ in $p + p$ and $p + A$ collisions. However this will require including additional effects such as comover partons and soft gluons emission (Sudakov factor) [3, 4] that become increasingly important with increasing heavy quark masses.

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