

CENTRALITY AND ENERGY DEPENDENCE OF CHARGED PARTICLES IN $p + A$ and $A + A$ COLLISIONS FROM RUNNING COUPLING k_T -FACTORIZATION*

ADRIAN DUMITRU

Department of Natural Sciences, Baruch College, CUNY
17 Lexington Avenue, New York, NY 10010, USA
and

The Graduate School and University Center, The City University of New York
365 Fifth Avenue, New York, NY 10016, USA

ANDRE V. GIANNINI, MATTHEW LUZUM

Instituto de Física, Universidade de São Paulo
Rua do Matão 1371, 05508-090 São Paulo-SP, Brazil

YASUSHI NARA

Akita International University, Yuwa, Akita-city 010-1292, Japan

(Received March 6, 2019)

We extend the numerical analysis of the energy and centrality dependence of particle multiplicities at midrapidity in high-energy $p + A$ and $A + A$ collisions from a running coupling k_T -factorization formula made in A. Dumitru, A.V. Giannini, M. Luzum, Y. Nara, *Phys. Lett. B* **784**, 417 (2018) by considering two unintegrated gluon distributions that were left out. While a good agreement with the experimental data in $A + A$ collisions is achieved, improving the description of those observables in $p + A$ collisions calls for a better understanding of the proton unintegrated gluon distribution at larger values of x and also the use of a realistic impact parameter dependence.

DOI:10.5506/APhysPolBSupp.12.973

1. Introduction

Over the past years, the Color Glass Condensate framework for particle production has been applied with success to understand the DIS data at

* Presented by A.V. Giannini at the Diffraction and Low- x 2018 Workshop, August 26–September 1, 2018, Reggio Calabria, Italy.

HERA energies and hadron production in a broad region of the phase space (from central to very forward rapidities) at the RHIC and LHC energies [1]. In particular, calculations of hadron production at midrapidity are based on the k_T -factorization approach, where the expression for inclusive (small- x) gluon production has originally been derived assuming a fixed coupling. Despite that, some studies [2–4] have included running coupling effects in their calculation by just replacing $\alpha_s \rightarrow \alpha_s(Q^2)$ in the relevant expressions and, then, fixing the momentum scale Q^2 later by hand. Since this is an arbitrary procedure, it comes as no surprise that distinct predictions found in the literature were obtained assuming different prescriptions for fixing Q^2 .

Although the results obtained following this procedure do not strongly depend on how Q^2 is fixed, here we follow Ref. [5] and employ the k_T -factorization formula for single-inclusive (small- x) gluon production in the scattering of two valence quarks derived in [6], which results from a resummation of the relevant one-loop corrections into the running of the coupling¹

$$\begin{aligned} \frac{d^3\sigma}{d^2k dy} = & N \frac{2C_F}{\pi^2} \frac{1}{k^2} \int d^2q d^2b d^2b' \bar{\phi}_{h_1}(\mathbf{q}, y, \mathbf{b}) \bar{\phi}_{h_2}(\mathbf{k} - \mathbf{q}, Y - y, \mathbf{b} - \mathbf{b}') \\ & \times \frac{\alpha_s(\Lambda_{\text{coll}}^2 e^{-5/3})}{\alpha_s(Q^2 e^{-5/3}) \alpha_s(Q^{*2} e^{-5/3})}. \end{aligned} \quad (1)$$

Equation (1) should be convoluted with a fragmentation function in order to yield results at a hadronic level (this procedure also fixes the collinear infrared cutoff Λ_{coll}^2 , which should match the momentum scale of the fragmentation function [7]). However, as p_T -integrated multiplicities are dominated by the soft region ($p_T \ll 1$ GeV), we keep the simple model for the fragmentation function used in [5]: $D(z, \mu_{\text{FF}}^2) \sim \delta(1 - z)$. A change in the fragmentation function would mainly change the normalization of our results and can be absorbed into the normalization factor N (which also accounts for “ K -factors” due to high-order corrections and will be determined by comparison with experimental data).

The unintegrated gluon distribution (UGD) is given by

$$\bar{\phi}(\mathbf{k}, y, \mathbf{b}) = \frac{C_F}{(2\pi)^3} \int d^2r e^{-i\mathbf{k} \cdot \mathbf{r}} \nabla_r^2 \mathcal{N}_A(\mathbf{r}, y, \mathbf{b}), \quad (2)$$

and does not involve a factor of $1/\alpha_s(k^2)$ as in the fixed coupling k_T -factorization formula; these factors appear explicitly in Eq. (1) with the

¹ Our notation follows Ref. [6]: $\mathbf{k}$ denotes the transverse momentum of the produced gluon, while $\mathbf{q}$ and $\mathbf{k} - \mathbf{q}$ are the “intrinsic” transverse momenta from the gluon distributions.

appropriate scale². $\mathcal{N}_A(\mathbf{r}, y, \mathbf{b})$ denotes the forward (adjoint) dipole scattering amplitude at impact parameter $\mathbf{b}$. As in previous works [8], a uniform gluon density within a proton was assumed.

As in [5, 8], $\mathcal{N}_A$ will be given by solutions of the running coupling Balitsky–Kovchegov (rcBK) equation provided by the AAMQS fits of the HERA data [9]. However, while Ref. [5] considered only the McLerran–Venugopalan (MV) UGD set, here we also consider the “g1.119” and “g1.101” UGD sets which are supposed to provide a better representation of the proton UGD³. Figure 1 shows the different UGDs considered here for a proton and for a target made of 12 nucleons after three units of rcBK rapidity evolution.

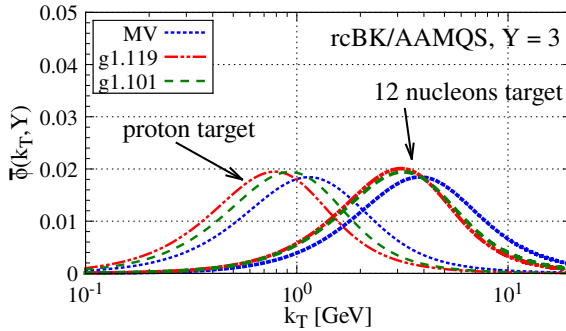


Fig. 1. UGDs from different initial conditions for rcBK equation at evolution rapidity $Y = 3$. The peak of this function defines the saturation scale, $Q_s(Y)$.

In what follows, we extend the analysis made in [5] by presenting results for the energy and centrality dependence of charged particle multiplicities produced in $p + A$ and $A + A$ collisions from different rcBK evolved UGDs. The references for all experimental data presented here can be found in [5].

2. Results, discussion and conclusions

Following previous phenomenological works [3, 4, 8, 10], we apply the k_T -factorization approach to compute the centrality and energy dependence of $dN_{\text{ch}}/d\eta$ in $A + A$ collisions. Figure 2 shows the results for the centrality dependence of the charged particle multiplicity in Au+Au and Pb+Pb/Xe+Xe collisions at the RHIC and at the LHC energies, respectively. The normalization figuring in Eq. (1) has been fixed (for each UGD) by matching the central Pb+Pb data at 2.76 TeV; the same normalization has been

² We refer to [6] for the full expression for the scale figuring in $\alpha_s(Q^2 e^{-5/3})$.

³ We note that all these UGDs have already been used to compute observables in hadronic collisions and detailed information about them can be found in the discussion around Eq. (3) of the second work listed in Ref. [8].

used across all collision systems, energies and centralities considered. One can see that while all UGDs present the well-known increase of $dN_{\text{ch}}/d\eta$ per participant towards more central collisions (which is related to the fact that the convolution of the UGDs in Eq. (1) increases as both transverse momentum arguments can be near the “saturation peak”, thanks to $A + A$ collisions becoming more symmetric), the results with the g1.119 UGD become worse as the collision energy increases; on the other hand, results with the g1.101 UGD compare well with the MV results from [5] and describe the data within the error bars.

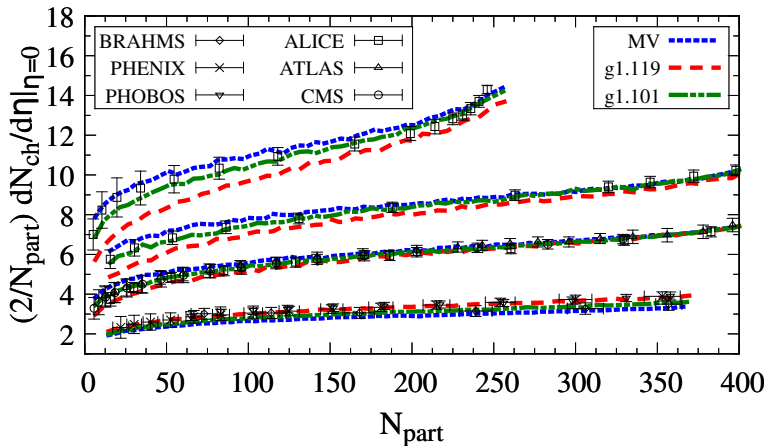


Fig. 2. Left: Centrality dependence of the multiplicity per participant pair in Au+Au/Pb+Pb/Xe+Xe collisions at $\sqrt{s} = 200$ GeV, 2.76 TeV, 5.02 TeV and 5.44 TeV. From bottom to top, curves and data points have been scaled by 1.0/0.85/1.0/1.35 to improve visibility.

While we checked that all UGDs provide a similar description of the energy evolution of the multiplicity per pair participant in central (0–6%) collisions⁴, the situation in $p + A$ collisions is more interesting. Figure 3 shows our results for the energy and centrality dependence of the charged particle multiplicity in $p + \text{Pb}$ collisions. While the results from the running coupling k_T -factorization formula for the energy dependence follow the same trend presented in Fig. 2 at the LHC energies, all UGDs fail to describe the data at the RHIC top energy. This should be expected since in this case, one is sensitive mainly to the rcBK initial conditions (given at $x_0 = 0.01$) rather than the small- x evolution. The inclusion of additional corrections to

⁴ This fact can also be inferred from Fig. 2 once all results presented are at least in near accordance with the experimental data for central collisions in all energy range considered.

Eq. (1), as well as extending the CGC framework to higher values of x [11], could help to achieve a better understanding of the proton UGD and lead to a better agreement with the data at the RHIC energies.

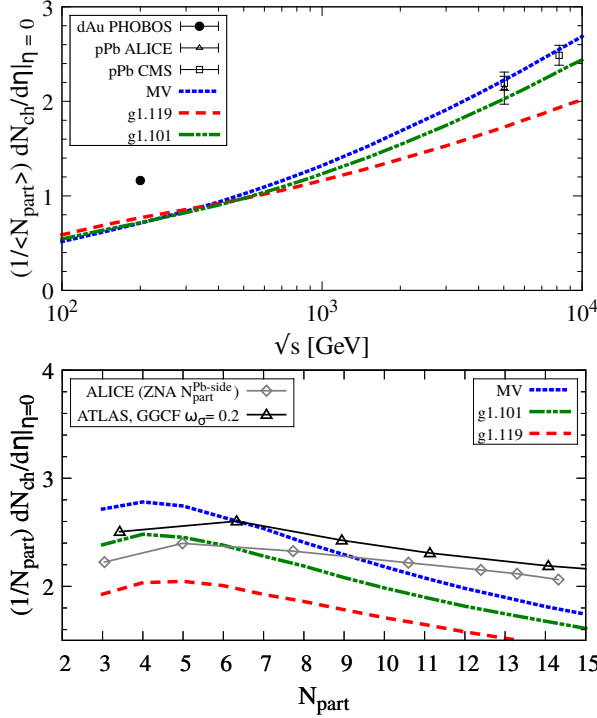


Fig. 3. Energy and N_{part} dependence of the charged particle multiplicity in $p + \text{Pb}$ collisions at $\eta = 0$.

The centrality dependence in $p + \text{Pb}$ collisions is also interesting. We find that at 5.02 TeV and beyond $N_{\text{part}} \simeq 4$, the multiplicity per participant actually slightly decreases with N_{part} , regardless the UGD considered. This is due to the fact that for increasingly *asymmetric* collisions (larger N_{part} for $p + A$), the convolution of the UGDs (in transverse momentum space) does not increase in proportion to N_{part} ; a fit of the MV result for $5 \leq N_{\text{part}} \leq 15$ gives $\sim \ln^{1.25}(N_{\text{part}})/N_{\text{part}}$. The same feature is also seen in the experimental data but with a somewhat flatter dependence on N_{part} . The origin of this difference can be related to the lack of a realistic impact parameter dependence of the proton-UGD in our computations and also due to the bias introduced in the experimental centrality selection. Results shown here can be improved by taking into account the bias on the configurations of the small- x gluon fields via the reweighting procedure developed in [12], since the UGDs employed here have been averaged over all BK gluon emissions without any bias.

Here, we extended the analysis of the energy and centrality dependence of the charged particle multiplicity produced at mid rapidities presented in [5] by considering two UGD sets that were left out in that first analysis. While two of them (MV and g1.101) provide a good description of the centrality and energy dependence in $A+A$ collisions, for $p+A$ collisions, all UGDs are only in qualitative agreement with the N_{part} dependence measured at the LHC energies and fail to describe the RHIC data for the energy evolution. Improving the agreement between theory and data in small collision systems and lower energies calls for a better understanding of the proton-UGD at higher values of x and the inclusion of a realistic impact parameter dependence.

A.D. acknowledges support by the DOE Office of Nuclear Physics through grant No. DE-FG02-09ER41620; and from The City University of New York through the PSC-CUNY research grant 60262-0048. A.V.G. acknowledges support by the Brazilian funding agency FAPESP through grant 17/14974-8. M.L. acknowledges support from FAPESP projects 2016/24029-6 and 2017/05685-2, and project INCT-FNA Proc. No. 464898/2014-5.

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