Physics Letters B 784 (2018) 417–422

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Particle multiplicities in the central region of high-energy collisions from k_T-factorization with running coupling corrections

Adrian Dumitru [a,b,c], Andre V. Giannini [d,*], Matthew Luzum [d], Yasushi Nara [e]

[a] Department of Natural Sciences, Baruch College, CUNY, 17 Lexington Avenue, New York, NY 10010, USA
[b] The Graduate School and University Center, The City University of New York, 365 Fifth Avenue, New York, NY 10016, USA
[c] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[d] Instituto de Física, Universidade de São Paulo, Rua do Matão 1371, 05508-090 São Paulo-SP, Brazil
[e] Akita International University, Yuwa, Akita-city 010-1292, Japan

ARTICLE INFO

Article history:
Received 26 May 2018
Received in revised form 5 July 2018
Accepted 19 August 2018
Available online 23 August 2018
Editor: J.-P. Blaizot

Keywords:
Particle production
Color Glass Condensate
k_T-Factorization
Heavy-ion collisions
Proton nucleus collisions

ABSTRACT

Horowitz and Kovchegov have derived a k_T-factorization formula for particle production at small x which includes running coupling corrections. We perform a first numerical analysis to confront the theory with data on the energy and centrality dependence of particle multiplicities at midrapidity in high-energy p+A (and A+A) collisions. Moreover, we point out a strikingly different dependence of the multiplicity per participant on N_{part} in p+Pb vs. Pb+Pb collisions at LHC energies, and argue that the observed behavior follows rather naturally from the convolution of the gluon distributions of an asymmetric vs. symmetric projectile and target.

The Color Glass Condensate (CGC) approach to particle production in high-energy collisions conjectures that the energy and system size dependence of the p_T-integrated multiplicity can be computed in weak coupling. The qualitative argument for this conjecture is that the running coupling at the particle production vertex would be effectively evaluated at a scale of order the semi-hard "saturation scale" $Q_s \gg \Lambda_{\text{QCD}}$, even at low p_T.

McLerran and Venugopalan have shown that such a semi-hard scale indeed emerges for a large nucleus due to the high density of valence color charge per unit transverse area [1]. Furthermore, the running coupling Balitsky–Kovchegov (rcBK) equation [2] for the unintegrated gluon distribution (UGD) shows that the saturation scale grows with energy. Most gluons "in the wave function" of a hadron or nucleus have transverse momentum $k_T \sim Q_s$, suppressing the sensitivity to the infrared, $k_T \sim \Lambda_{\text{QCD}}$ [3]; cf. Fig. 1 below.

There have been many studies of the energy and centrality dependence of particle production in p+A and A+A collisions within the k_T-factorization approach [4], using UGDs which exhibit "saturation" at $k_T < Q_s$ [5–9]. Whenever running of the coupling has been considered, an ad-hoc choice for the scale of $\alpha_s(Q)$ in the k_T-factorization formula had to be made.[1] For example, Ref. [9] assumed that the coupling is evaluated at $\max |\vec{p}_T \pm \vec{k}_T|/2$ so as to avoid the infrared regime (thanks to $k_T \sim Q_s$, as mentioned above). While in practice the sensitivity to such ad-hoc running coupling prescriptions may not be very large, it is clearly worthwhile to assess running coupling corrections from a more solid theoretical basis. Previous computations of particle production in the central region relied on expressions derived for fixed coupling, and running was implemented *a posteriori* by hand.

Horowitz and Kovchegov have derived a k_T-factorization formula beyond LO to include running coupling corrections [11] (also see Ref. [12]) to single-inclusive (small-x) gluon production in the scattering of two valence quarks. Their expression results from a resummation of the relevant one-loop corrections into the running of the coupling. They propose the following generalization to hadron–hadron or hadron–nucleus collisions:

* Corresponding author.
E-mail address: avgiannini@usp.br (A.V. Giannini).

[1] The issue of running coupling corrections also arises in fully numerical "dense-dense" computations [10] which do not employ k_T-factorization.

https://doi.org/10.1016/j.physletb.2018.08.028

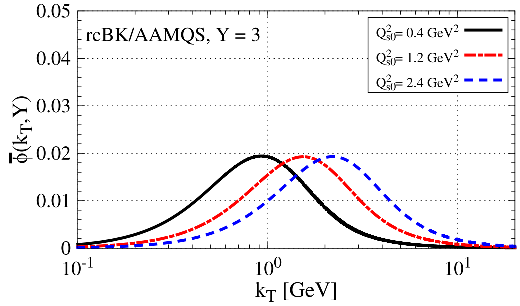

Fig. 1. Impact parameter averaged, unbiased unintegrated gluon distribution $\overline{\phi}(k)$ at evolution rapidity $Y = 3$ for a target with a thickness of one, three, and six nucleons, respectively. The peak of this function defines the saturation scale $Q_s(Y)$. (The quoted values of Q_{s0}^2 refer to the saturation scale squared for an adjoint dipole at $x_0 = 0.01$.)

$$\frac{d^3\sigma}{d^2k\,dy} = N\,\frac{2\,C_F}{\pi^2}\,\frac{1}{\boldsymbol{k}^2}\int d^2q\int d^2b\,d^2b'\,\overline{\phi}_{h_1}(\boldsymbol{q},y,\boldsymbol{b})\,\overline{\phi}_{h_2}(\boldsymbol{k}-\boldsymbol{q},Y-y,\boldsymbol{b}-\boldsymbol{b}')\,\frac{\alpha_s\left(\Lambda^2_{\rm coll}\,e^{-5/3}\right)}{\alpha_s\left(Q^2\,e^{-5/3}\right)\,\alpha_s\left(Q^{*\,2}\,e^{-5/3}\right)}\,. \tag{1}$$

(Our notation follows Ref. [11]; $\boldsymbol{k}$ now denotes the transverse momentum of the produced gluon while $\boldsymbol{q}$ and $\boldsymbol{k}-\boldsymbol{q}$ are the "intrinsic" transverse momenta from the gluon distributions.) This distribution of gluons in transverse momentum and rapidity has to be convoluted with a fragmentation function in order to obtain the p_T-distribution of produced hadrons. Eq. (1) implicitly assumes that collinear factorization applies in fragmentation. $\Lambda^2_{\rm coll}$ is a collinear infrared cutoff which should match the scale of the fragmentation function typically chosen as $\mu^2_{\rm FF} \simeq p_T^2$. We have computed hadron transverse momentum distributions in p+A collisions in this way and shall report our findings elsewhere. Here, we are primarily concerned with the p_T-integrated multiplicity where the most relevant regime is that around the average p_T. For this regime we employ a simple model fragmentation function $D(z,\mu^2_{\rm FF}) \sim \delta(1-z)$. For the observables considered here slight modifications of this fragmentation function mainly affect the normalization in Eq. (1) and can be absorbed into N. The normalization also absorbs "K-factors" due to higher order corrections and will be fixed by matching to data.

The unintegrated gluon distribution is given by

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

Note that these functions do not involve a factor of $1/\alpha_s(k^2)$; instead, the factors of the inverse coupling with the appropriate scale appear explicitly in Eq. (1). $\mathcal{N}_A(\boldsymbol{r},y,\boldsymbol{b})$ denotes the forward (adjoint) dipole scattering amplitude at impact parameter $\boldsymbol{b}$. We assume a uniform gluon density within a proton.[2] $\mathcal{N}_A(r)$ approaches a constant as $r\to\infty$ and so $\overline{\phi}(\boldsymbol{k}) \sim k^2$ vanishes at low transverse momentum. For $k^2 \gg Q_s^2$, on the other hand, $\overline{\phi}(k) \sim 1/k^2$. In the absence of the non-linear corrections to small-x evolution present in the BK equation this behavior would extend down to low k_T.

The numerical form of $\mathcal{N}_A$ employed here is identical to that used previously in Ref. [9]; it has been obtained in Ref. [13] by solving the rcBK equation.[3] Here, we restrict to using their solution for MV model initial condition since p_T-integrated observables for their other UGD sets are not much different at small x. Finally, we stress that the dipole forward scattering amplitude obtained in Ref. [9] has been averaged over all BK gluon emissions without bias. A plot of $\overline{\phi}(k)$ is shown in Fig. 1. This corresponds to the unintegrated gluon distribution after 3 units of rcBK rapidity evolution.

The factors of the inverse coupling in Eq. (1) are determined by the coefficient of the one-loop β-function (with $N_c = N_f = 3$), and we set $\Lambda_{\overline{\rm MS}} = 0.24$ GeV. The Q^2-dependence of the coupling is given by

$$\begin{aligned}
\ln\frac{Q^2}{\mu^2_{\overline{\rm MS}}} = \frac{1}{2}\ln\frac{\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2}{\mu^4_{\overline{\rm MS}}} - \frac{1}{4\,\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^6}\Bigg\{&\boldsymbol{k}^2\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^3 \\
\times\Bigg\{\left[\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2-\left(\boldsymbol{q}^2\right)^2\right]\left[\left(\boldsymbol{k}^2\right)^2+\left((\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right)^2\right]&+2\,\boldsymbol{k}^2\left[\left(\boldsymbol{q}^2\right)^3-\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^3\right] \\
-\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2\left[2\left(\boldsymbol{k}^2\right)^2+3\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^2-3\,\boldsymbol{k}^2\left[(\boldsymbol{k}-\boldsymbol{q})^2+\boldsymbol{q}^2\right]\right]&\ln\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{\boldsymbol{q}^2}\right)\Bigg\} \\
+\,i\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^3\Bigg\{\boldsymbol{k}^2\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]&\left[\boldsymbol{k}^2\left[(\boldsymbol{k}-\boldsymbol{q})^2+\boldsymbol{q}^2\right]-\left(\boldsymbol{q}^2\right)^2-\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2\right] \\
+\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2\left(\boldsymbol{k}^2\left[(\boldsymbol{k}-\boldsymbol{q})^2+\boldsymbol{q}^2\right]-2\left(\boldsymbol{k}^2\right)^2-2\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^2\right)&\ln\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{\boldsymbol{q}^2}\right)\Bigg\} \\
\times\sqrt{2\,\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2+2\,\boldsymbol{k}^2\,(\boldsymbol{k}-\boldsymbol{q})^2+2\,\boldsymbol{q}^2\,\boldsymbol{k}^2-\left(\boldsymbol{k}^2\right)^2-\left(\boldsymbol{q}^2\right)^2-\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2}&\Bigg\}\,,
\end{aligned} \tag{3}$$

[2] For p+p collisions, not considered here, a more detailed model of the impact parameter dependence of $\mathcal{N}_A$ is required [7,8]. Computing the impact parameter dependence of the gluon distribution of a proton directly from small-x evolution is still an unresolved problem [14].

[3] The BK equation actually provides the forward scattering amplitude for a fundamental dipole, averaged over configurations. At large N_c, from group theory, one obtains the average scattering amplitude for an adjoint dipole as $\mathcal{N}_A = 2\mathcal{N}_F - \mathcal{N}_F^2 + \mathcal{O}(N_c^{-2})$.

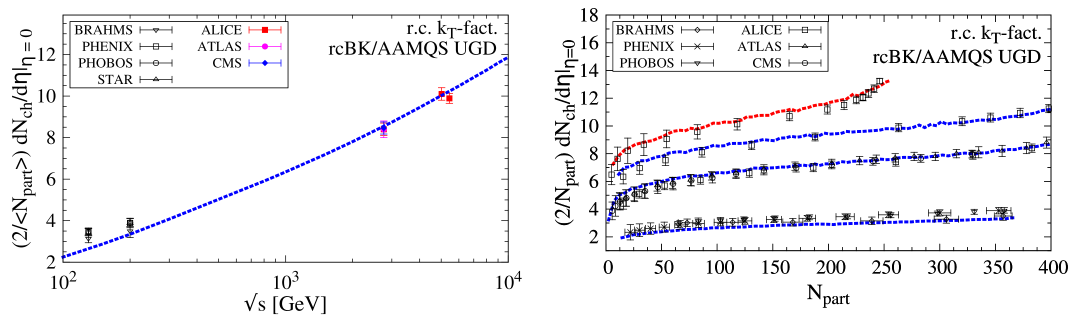

Fig. 2. Left: Energy dependence of the multiplicity per participant pair in central (0–6%) Xe+Xe/Au+Au/Pb+Pb collisions at $\sqrt{s} = 200$ GeV, 2.76 TeV and 5.02 TeV, respectively. Right: same as a function of N_{part}. The curve and data points for 5.02 TeV have been scaled by 1.1 to improve visibility; moreover, our prediction and the new data for Xe+Xe at $\sqrt{s} = 5.44$ TeV have been scaled by 1.25 in order to not overlap with the curves for Pb+Pb collisions.

$\ln \frac{Q^{*2}}{\mu^2_{\overline{\text{MS}}}}$ is given by the complex conjugate of this expression so that the product $\ln \frac{Q^2}{\mu^2_{\overline{\text{MS}}}} \ln \frac{Q^{*2}}{\mu^2_{\overline{\text{MS}}}}$ is real, as it should be. In the limit $q \ll k$ this simplifies to[4]

$$\ln \frac{Q^2}{\mu^2_{\overline{\text{MS}}}}\Big|_{q\to 0} = \ln \frac{k^2}{\mu^2_{\overline{\text{MS}}}} + \frac{1}{2} - \frac{(\boldsymbol{k}\cdot\boldsymbol{q})^2}{k^2 q^2} - i\,\frac{\boldsymbol{k}\cdot\boldsymbol{q}}{k^2 q^2}\sqrt{k^2 q^2 - (\boldsymbol{k}\cdot\boldsymbol{q})^2}\,, \tag{4}$$

so that

$$\int \frac{d\phi_q}{2\pi}\left[\ln \frac{Q^2}{\mu^2_{\overline{\text{MS}}}} \ln \frac{Q^{*2}}{\mu^2_{\overline{\text{MS}}}}\right]_{q\to 0} = \ln^2 \frac{k^2}{\mu^2_{\overline{\text{MS}}}} + \frac{1}{4}\,. \tag{5}$$

Therefore, at high transverse momentum, and choosing the collinear cutoff scale $\Lambda^2_{\text{coll}} = k^2$, the spectrum of produced gluons is proportional to $\alpha_s(k^2)\,k^{-4}\ln^2 k^2$.

For $k \ll q$ we have

$$\ln \frac{Q^2}{\mu^2_{\overline{\text{MS}}}}\Big|_{k\to 0} = \ln \frac{q^2}{\mu^2_{\overline{\text{MS}}}}\,, \tag{6}$$

Here, the dominant contribution to Eq. (1) is from $q \sim Q_s$ since $\overline{\phi}(q)$ quickly decays when q is far from Q_s. Eq. (6) shows that the distribution of produced gluons is well defined at low transverse momentum, $k \to \Lambda_{\overline{\text{MS}}}$. The spectrum can be integrated over $k > \Lambda_{\overline{\text{MS}}}$ without encountering a divergence. (It is not sensible to address the spectrum of "gluons" with $k < \Lambda_{\overline{\text{MS}}}$.)

Physically, $d\sigma/d^2k dy \sim \alpha_s(\Lambda^2_{\text{coll}} \sim k^2)/k^2$ should rather level off when both collision partners are dense; k_T-factorization fails here. For proton–nucleus collisions with $Q_{s,A} \gg Q_{s,p}$ the actual contribution to dN/dy from $k < Q_{s,p}$ is small and we can therefore simply apply Eq. (1) down to $k = \Lambda_{\overline{\text{MS}}}$. For nucleus–nucleus collisions this is not justified since there are many particles at $\Lambda_{\overline{\text{MS}}} < k < Q_s$. Here, the correct spectrum below Q_s can only be obtained from a "dense-dense" computation which does not rely on k_T-factorization. (To date, such calculations, for example, refs. [10,15], have been performed only for fixed coupling, or with ad-hoc running.) On the other hand, phenomenological applications of k_T-factorization have been rather successful in reproducing the dependence of the multiplicity in A+A collisions on energy and centrality [5,8,9]. This is presumably due to the fact that for large nuclei and high energies this dependence is entirely determined by the single scale Q_s. In any case, given those previous applications of k_T-factorization with ad-hoc scale choice to the centrality dependence of the multiplicity in A+A collisions it is certainly interesting to also see the result obtained from Eq. (1). Hence, we integrate Eq. (1) from $k_{\min}$ of order $\Lambda_{\overline{\text{MS}}}$. We have checked the dependence of $dN/d\eta$ in Pb+Pb collisions at LHC energies on N_{part} for $k_{\min} = \Lambda_{\overline{\text{MS}}} \ldots 2\Lambda_{\overline{\text{MS}}}$ and obtained virtually identical curves.

To compute produced particle multiplicities in p+A and A+A collisions we convolute Eq. (1) with a Monte-Carlo Glauber simulation, which has been described in more detail in refs. [9]. This allows us to compute the dependence of the multiplicity on the number of participants. First results using Eq. (1) were obtained in Ref. [16] for minimum bias collisions with KLN model [5,6] gluon distributions.

Fig. 2 shows our results for the multiplicity per participant pair in A+A collisions at RHIC and LHC energies. We have fixed the normalization factor in Eq. (1) to match to central Pb+Pb collisions at 2.76 TeV; the same normalization has been used for all other energies, centralities, and collision systems. The data shown in Fig. 2 is from refs. [17–23]. Our curves are very close to those published in Ref. [9] using ad-hoc scale setting. The data at $\sqrt{s} = 200$ GeV mainly probes the MV model gluon distribution at the initial $x_0 = 0.01$ rather than small-x rcBK evolution. The multiplicity as a function of N_{part} shows the well known increase of $dN/d\eta$ per participant towards more central collisions. It is driven by the increasing overlap in transverse coordinate space of the 2d projections of the nuclear Woods–Saxon distributions. This leads to increasingly *symmetric* collision partners at any given point in the transverse plane so that the convolution integral of the gluon distributions in Eq. (1) increases as both transverse momentum arguments can be near the "saturation peak".

We also show our prediction for Xe+Xe collisions at 5.44 TeV in Fig. 2. We have updated the figure to include new data for Xe+Xe collisions released by the ALICE collaboration [24].

---

[4] The r.h.s. of Eq. (4) differs from the expression given in eq. (3.33) of Ref. [11]; the correct result, which we verified independently, was first communicated to us in private by Yu. Kovchegov.

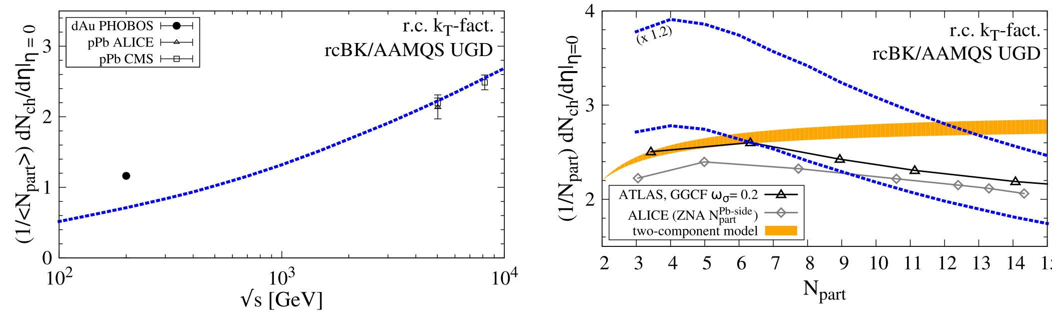

Fig. 3. Energy and N_{part} dependence of the multiplicity in p+Pb collisions at $\eta = 0$. In the figure on the right the two short dashed lines correspond to our results for 5.02 TeV and 8.16 TeV, respectively; the latter have been rescaled by a factor of 1.2 for better visibility. The band corresponds to the "soft+hard" two-component model in Eq. (11).

Fig. 3 shows the multiplicity in p+A collisions as a function of energy and of N_{part}; midrapidity ($\eta = 0$) corresponds to the CM frame. The data points are from refs. [25–27]. The energy dependence of the multiplicity obtained from the r.c. k_T-factorization formula with rcBK UGDs compares well to the measurements at LHC energies. The extrapolation to RHIC energy of $\sqrt{s} = 200$ GeV, however, is significantly too low. This is not unexpected since at such energies one is sensitive mainly to the MV model initial condition imposed at $x_0 = 0.01$ rather than to small-x evolution. This should in fact fail, in particular for small systems, since the MV model assumes a large nucleus. Improving results for p/d+A collisions at RHIC energy (and $\eta \sim 0$) will require an improved theoretical understanding of the unintegrated gluon distribution of a proton at $x = 0.01$ and greater, as well as possibly additional corrections to Eq. (1).

The dependence of the multiplicity at LHC energies on N_{part} is rather interesting. Somewhat surprisingly perhaps, we find that beyond $N_{\text{part}} \simeq 4$ the multiplicity *per participant* decreases slightly with N_{part}. This is due to the fact that for increasingly asymmetric collisions the convolution in transverse momentum space of the gluon distributions does not increase in proportion to N_{part}. Simple considerations suggest that it grows logarithmically (also see the discussion in refs. [6]). A numerical fit to the 5.02 TeV curve shown in Fig. 3 (right), for $15 \geq N_{\text{part}} \geq 5$, gives $\sim \ln^{1.25}(N_{\text{part}})/N_{\text{part}}$. In contrast, A+A collisions become more symmetric as the impact parameter decreases and the multiplicity per participant increases with N_{part}.

Such a feature is also seen in data, as shown in Fig. 3 (right), where we show ALICE [28] and ATLAS [29] data for $(1/N_{\text{part}})\, dN_{\text{ch}}/d\eta$ vs. N_{part} in p+Pb collisions at 5 TeV. In fact, in Ref. [26] the ALICE collaboration already noted that the multiplicity per participant in NSD p+Pb collisions at 5 TeV (averaged over N_{part} !) is 16% *lower* than in NSD p+p collisions interpolated to the same collision energy. Remarkably, this trend appears to continue beyond $N_{\text{part}}^{\text{mb}} \simeq 8$.

While the distribution of multiplicity is a quantity that can be measured in a fairly direct way, the number of participants is not, and in principle depends on the method of centrality selection. We refer to the above-mentioned publications for more detailed discussions of the experimental centrality selections and their determination of N_{part}, but here show the ALICE "ZNA $N_{\text{part}}^{\text{Pb-side}}$" and the ATLAS "GGCF $\omega_\sigma = 0.2$" results [29,30], which are believed to be less model dependent and may be the most suitable to compare to N_{part} as used in our model.

These data exhibit a trend similar to the calculation, but with somewhat flatter dependence on N_{part}. This could be due to the lack of a realistic impact parameter dependence of the proton-UGD in our computations, and due to a bias on the gluon distribution introduced by the experimental centrality selection. A more accurate matching of $(1/N_{\text{part}})\, dN_{\text{ch}}/d\eta$ to the measurements would entail accounting for such bias on the configurations of small-x gluon fields through reweighting [31].

It is interesting to compare the prediction from Eq. (1) to a k_T-factorization formula derived at fixed coupling, with running of α_s implemented by hand, and with rcBK gluon distributions. The latter corresponds to replacing in eq. (1):

$$\alpha_s\left(\Lambda^2_{\text{coll}}\, e^{-5/3}\right) \to \alpha_s\left(k^2\right) , \tag{7}$$

$$\alpha_s\left(Q^2\, e^{-5/3}\right) \to \alpha_s\left(q^2\right) , \tag{8}$$

$$\alpha_s\left(Q^{*2}\, e^{-5/3}\right) \to \alpha_s\left((\boldsymbol{k} - \boldsymbol{q})^2\right) . \tag{9}$$

(Other prescriptions for running of α_s "by hand" exist, as already mentioned in the introduction.) The replacements (8), (9), in particular, are inspired by the fact that at fixed coupling the unintegrated gluon distributions about Q_s are of order $1/\alpha_s$. Note that in the $\boldsymbol{q} \to 0$ limit at high $\boldsymbol{k}$ the ratio of coupling constants in Eq. (1) now approaches a $\boldsymbol{k}$-independent constant as opposed to Eqs. (4), (5). To obtain the particle multiplicity we integrated over $\boldsymbol{k}$ from $k_{\text{min}} = 0.25$ GeV. Also, we again adjusted the normalization factor $N_{\text{f.c.}}$ to the multiplicity in central Pb+Pb collisions at 2.76 TeV.

The resulting ratio is shown in Fig. 4. Overall, the f.c. formula with ad-hoc running of the coupling provides a fairly satisfactory description of the dependence of the multiplicity on N_{part}, so that the discrepancy to the r.c. formula is fairly moderate. However, a systematically steeper rise of $dN_{\text{ch}}/d\eta$ with N_{part} is clearly visible.

Fig. 5 shows our result for the dependence of the transverse energy divided by the number of charged particles, in p+Pb collisions, on the number of participants. This ratio is independent of the normalization factor N in Eq. (1) and has instead been normalized to the CMS measurement [32] of $dE_T/d\eta$ in minimum bias p+Pb collisions at 5 TeV. The dependence on N_{part} and on energy is then a prediction. As before, the number of participants should be determined in the fragmentation region of the nucleus with a method that smoothly approaches the p+p limit as $N_{\text{part}} \to 2$. This omits the bias on E_T due to fluctuations of the multiplicity at midrapidity which p+A collisions inherit from p+p [33].

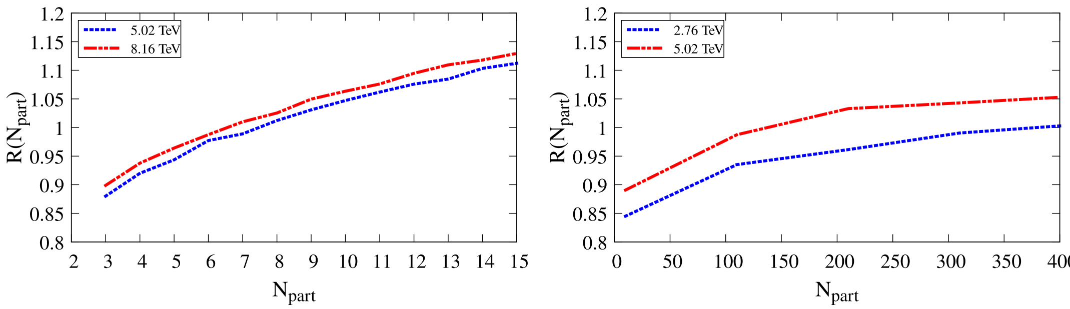

Fig. 4. Ratios of charged particle multiplicities in p+Pb (left) and Pb+Pb (right) collisions obtained from a fixed-coupling k_T-factorization formula with running of α_s implemented by hand (see text) divided by eq. (1).

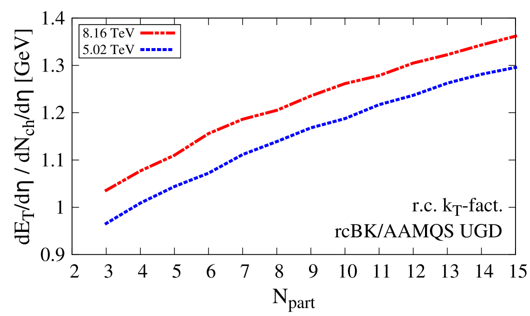

Fig. 5. Transverse energy per charged particle vs. N_{part} in the central region of p+Pb collisions at 5 TeV and 8 TeV.

Our computation predicts an increase of E_T per particle for increasingly asymmetric collisions. Such "broadening" of the transverse momentum distributions of produced gluons is expected due to the increase of the saturation scale of the target nucleus [5]. We should point out that $dE_T/d\eta$ is, however, sensitive to final state interactions which may reduce its magnitude [34].

One may attempt to interpret the decrease of the particle multiplicity per participant with N_{part} noted above in a simple two-component "soft+hard" model [35]. However we can see that this is not possible.

Let $f(\sqrt{s}) \geq 0$ denote the fractional contribution from the hard component which is proportional to the number of binary collisions. $1 - f(\sqrt{s})$ then corresponds to the soft contribution, proportional to N_{part}:

$$\frac{dN_{AB}}{d\eta} = \left[\frac{1-f}{2} N_{\text{part}} + f N_{\text{coll}}\right] \frac{dN_{pp}}{d\eta} . \tag{10}$$

In Ref. [35] Kharzeev and Nardi obtained $f(\sqrt{s} = 56 \text{ GeV}) = 0.22$ and $f(\sqrt{s} = 130 \text{ GeV}) = 0.37$. For $\sqrt{s} = 5$ TeV we find that a universal fit from p+p to central Pb+Pb with Eq. (10) is impossible. Fitting to very peripheral Pb+Pb collisions only ($N_{\text{part}} \leq 34$ corresponding to ≤ 17 participants per nucleus, on average) we estimate $f \approx 0.26 \pm 0.01$. A similar fit of the new Xe+Xe data by ALICE [24], again for $N_{\text{part}} \leq 34$, gives $f \approx 0.34 \pm 0.01$. We consider this a lower bound on the value of f appropriate for p+A collisions since leading-twist perturbative processes may already experience slight "shadowing" even in rather peripheral heavy-ion collisions.

For p+A collisions we can rearrange the above equation as follows:

$$\frac{1}{N_{\text{part}}} \frac{dN_{pA}}{d\eta} = \left[\frac{1+f}{2} - \frac{f}{N_{\text{part}}}\right] \frac{dN_{pp}}{d\eta} . \tag{11}$$

The r.h.s. is an increasing function of N_{part} for any $f > 0$. The curve corresponding to the r.h.s. of Eq. (11) with $f = 0.26 \to 0.34$ and $dN_{pp}/d\eta = 4.4$ is shown as a band in Fig. 3(right). The formula describes the data *below* the average $\langle N_{\text{part}} \rangle \simeq 8$ for minimum bias collisions fairly well. However, the trend for more central p+Pb collisions appears different from the data shown. Furthermore, since N_{coll} is linear in N_{part} for p+A collisions, this simple model would not predict an increase of the transverse energy per particle like in Fig. 5.

Let us summarize the main points of this paper. We have performed the first analysis of the energy and centrality dependence of particle multiplicities in the central region of high energy p+A collisions predicted by k_T-factorization with running coupling corrections, and rcBK gluon distributions. We point out that the formula derived by Horowitz and Kovchegov [11] results in a well-defined gluon transverse momentum distribution[5] down to $p_T \sim \Lambda_{\overline{\text{MS}}}$. Since this is conceptually the lowest scale where a computation in perturbation theory at running coupling level applies, this framework does not require an ad-hoc cutoff on the transverse momentum spectrum of produced gluons. A contribution from $p_T \sim \Lambda_{\overline{\text{MS}}}$ and below would be genuinely non-perturbative.

Our numerical results show that the r.c. k_T-factorization formula with rcBK gluon densities provides a good description of the energy and centrality dependence of the multiplicity in p+A collisions at LHC energies, $\sqrt{s} > 1$ TeV. For p+A collisions at RHIC energies, on the other hand, a better understanding of the unintegrated gluon distribution of a proton at $x \sim 0.01$ is required. It may be worth pointing out

[5] k_T-Factorization, of course, does not correctly describe the gluon p_T-distribution below the saturation scale of the proton. However, the contribution from the region $p_T < Q_{s,p}$ to the p_T-integrated multiplicity is small when $Q_{s,p} \ll Q_{s,A}$.

that we have attempted to introduce as few model parameters as reasonably possible in order to exhibit where the current theory fails. In our analysis of particle multiplicities we fitted a single energy, centrality, and system independent constant: the normalization factor N in Eq. (1).

Our main observation relevant for phenomenology is to note that the convolution of the unintegrated gluon densities of a proton and of a nucleus increases more slowly than linear with the asymmetry of the gluon densities set by the number of participants. The asymmetry of the gluon distributions in p+A collisions results from the coherence of the interaction with the dense target. As a consequence, the multiplicity per participant in increasingly asymmetric p+A collisions is found to decrease slowly. (This may flatten out somewhat if a bias on the small-x gluon distribution is taken into account.) Such behavior is markedly different from that for more and more central, and increasingly symmetric A+A collisions, as well as from expectations based on a simple two-component "soft+hard" particle production model with only energy dependent shares.

Acknowledgements

We thank Yu. Kovchegov, L. McLerran and V. Skokov for useful comments. 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. thanks Sergio Korogui for helping with programming related issues and gratefully acknowledges the Brazilian funding agency FAPESP for financial support 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.

References

[1] L.D. McLerran, R. Venugopalan, Phys. Rev. D 49 (1994) 2233, Phys. Rev. D 49 (1994) 3352.
[2] Y. Kovchegov, H. Weigert, Nucl. Phys. A 784 (2007) 188;
I.I. Balitsky, Phys. Rev. D 75 (2007) 014001;
E. Gardi, J. Kuokkanen, K. Rummukainen, H. Weigert, Nucl. Phys. A 784 (2007) 282;
I. Balitsky, G.A. Chirilli, Phys. Rev. D 77 (2008) 014019.
[3] A.H. Mueller, Nucl. Phys. B 558 (1999) 285.
[4] L.V. Gribov, E.M. Levin, M.G. Ryskin, Phys. Rep. 100 (1983) 1.
[5] D. Kharzeev, E. Levin, Phys. Lett. B 523 (2001) 79;
D. Kharzeev, E. Levin, M. Nardi, Nucl. Phys. A 730 (2004) 448, Erratum: Nucl. Phys. A 743 (2004) 329;
A. Dumitru, D.E. Kharzeev, E.M. Levin, Y. Nara, Phys. Rev. C 85 (2012) 044920.
[6] D. Kharzeev, E. Levin, M. Nardi, Nucl. Phys. A 747 (2005) 609.
[7] E. Levin, A.H. Rezaeian, Phys. Rev. D 82 (2010) 014022, Phys. Rev. D 82 (2010) 054003.
[8] P. Tribedy, R. Venugopalan, Nucl. Phys. A 850 (2011) 136, Erratum: Nucl. Phys. A 859 (2011) 185;
P. Tribedy, R. Venugopalan, Phys. Lett. B 710 (2012) 125, Erratum: Phys. Lett. B 718 (2013) 1154.
[9] J.L. Albacete, A. Dumitru, arXiv:1011.5161 [hep-ph];
J.L. Albacete, A. Dumitru, H. Fujii, Y. Nara, Nucl. Phys. A 897 (2013) 1.
[10] B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. C 86 (2012) 034908.
[11] W.A. Horowitz, Y.V. Kovchegov, Nucl. Phys. A 849 (2011) 72.
[12] Y.V. Kovchegov, H. Weigert, Nucl. Phys. A 807 (2008) 158.
[13] J.L. Albacete, N. Armesto, J.G. Milhano, C.A. Salgado, Phys. Rev. D 80 (2009) 034031;
J.L. Albacete, N. Armesto, J.G. Milhano, P. Quiroga Arias, C.A. Salgado, Eur. Phys. J. C 71 (2011) 1705.
[14] K.J. Golec-Biernat, A.M. Stasto, Nucl. Phys. B 668 (2003) 345;
J. Berger, A. Stasto, Phys. Rev. D 83 (2011) 034015.
[15] J.-P. Blaizot, T. Lappi, Y. Mehtar-Tani, Nucl. Phys. A 846 (2010) 63.
[16] F.O. Duraes, A.V. Giannini, V.P. Goncalves, F.S. Navarra, Phys. Rev. D 94 (5) (2016) 054023.
[17] I.G. Bearden, et al., BRAHMS Collaboration, Phys. Lett. B 523 (2001) 227, Phys. Rev. Lett. 88 (2002) 202301.
[18] S.S. Adler, et al., PHENIX Collaboration, Phys. Rev. C 71 (2005) 034908.
[19] B.B. Back, et al., PHOBOS Collaboration, Phys. Rev. C 65 (2002) 061901.
[20] B.I. Abelev, et al., STAR Collaboration, Phys. Rev. C 79 (2009) 034909.
[21] S. Chatrchyan, et al., CMS Collaboration, J. High Energy Phys. 1108 (2011) 141.
[22] G. Aad, et al., ATLAS Collaboration, Phys. Lett. B 710 (2012) 363.
[23] K. Aamodt, et al., ALICE Collaboration, Phys. Rev. Lett. 106 (2011) 032301, Phys. Rev. Lett. 116 (22) (2016) 222302.
[24] S. Acharya, et al., ALICE Collaboration, arXiv:1805.04432 [nucl-ex].
[25] B.B. Back, et al., PHOBOS Collaboration, Phys. Rev. Lett. 93 (2004) 082301.
[26] B. Abelev, et al., ALICE Collaboration, Phys. Rev. Lett. 110 (3) (2013) 032301.
[27] A.M. Sirunyan, et al., CMS Collaboration, J. High Energy Phys. 1801 (2018) 045.
[28] J. Adam, et al., ALICE Collaboration, Phys. Rev. C 91 (6) (2015) 064905.
[29] G. Aad, et al., ATLAS Collaboration, Eur. Phys. J. C 76 (4) (2016) 199.
[30] V. Guzey, M. Strikman, Phys. Lett. B 633 (2006) 245, Erratum: Phys. Lett. B 663 (2008) 456.
[31] A. Dumitru, G. Kapilevich, V. Skokov, Nucl. Phys. A 974 (2018) 106.
[32] CMS Collaboration [CMS Collaboration], CMS-PAS-HIN-14-014.
[33] A. Bzdak, V. Skokov, Phys. Lett. B 726 (2013) 408.
[34] M. Gyulassy, T. Matsui, Phys. Rev. D 29 (1984) 419;
M. Gyulassy, Y. Pang, B. Zhang, Nucl. Phys. A 626 (1997) 999;
K.J. Eskola, K. Kajantie, P.V. Ruuskanen, K. Tuominen, Nucl. Phys. B 570 (2000) 379;
A. Dumitru, M. Gyulassy, Phys. Lett. B 494 (2000) 215.
[35] X.N. Wang, M. Gyulassy, Phys. Rev. Lett. 86 (2001) 3496;
D. Kharzeev, M. Nardi, Phys. Lett. B 507 (2001) 121.