Charged particle multiplicities in pA interactions at the LHC from the Color Glass Condensate

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The forthcoming LHC measurement of hadron multiplicity in proton-nucleus collisions is a crucial test of the $k_t$ factorization and gluon saturation based models. Here, we provide quantitative predictions for the pseudorapidity distribution of charged particles produced in minimum bias proton-nucleus collisions at the LHC based on the idea of gluon saturation in the color-glass condensate framework. Our formulation gives good descriptions of the LHC and RHIC data for the charged-hadron multiplicities in both proton-proton and nucleus-nucleus collisions, and also the deep inelastic scattering at HERA at small Bjorken-$x$.

I. INTRODUCTION

The Color Glass Condensate (CGC) formalism is a self-consistent effective QCD theory at high energy (or small $x$) in which one systematically re-sums quantum corrections which are enhanced by large logarithms of $1/x$ and also incorporates non-linear high gluon density effects which are important where the physics of gluon saturation is dominant, for a review see Ref. [1] and references therein.

In the CGC approach, the hadron production in proton-nucleus collisions goes in two stages: production of gluons and subsequently the decay of gluon-jet or mini-jet into hadrons, namely hadronization (or fragmentation in the standard pQCD language) [3]. The first stage of this process is under theoretical control and can be calculated via the $k_t$ factorization. The jet decay, unfortunately, can be treated mostly phenomenologically. However, one may hope that the phenomenological uncertainties would be reduced to few constants whose values will be extracted from the experiment in other reactions and energy. Notice that the inclusive gluon-production in the $k_t$ factorization has been proven at the leading log(1/x) approximation for scatterings of a dilute partonic system on a dense one such as p+$A$ collisions at high energy\(^1\). In nucleus-nucleus collisions at around midrapidity, one has to deal with a dense-dense scatterings, therefore the $k_t$ factorization and as a consequence all saturation based predictions are less reliable. Therefore, the upcoming data from p+A run at the LHC is very crucial in order to test the $k_t$ factorization and discriminate between various saturation models.

Already the first LHC data on hadron multiplicity in nucleus-nucleus collisions call for a theoretical understanding of these data based on QCD. One of the unexpected new feature of the LHC data has been the very different power-law energy behavior of charged hadron multiplicities in $A+A$ compared to $p+p$ collisions [5, 6]. Although this is still open problem, there have been some different approaches to accommodate this feature of data within the saturation picture [7, 8]. We will show below that the first-day experimental p+A data on charged hadron multiplicity can also discriminate between these approaches.

In this letter, we provide quantitative predictions for the pseudorapidity distribution of charged particles produced in minimum bias proton-nucleus collisions at the LHC based on the $k_t$ factorization within the CGC framework. This approach has been also successful to describe the charged hadron multiplicity in both p+p and A+A collisions at the LHC [3, 8], see also [9–11]. We refer the reader to Refs. [3, 8, 12] for the technical details. Here we shortly introduce the main formalism in Sec. II and then show our results in Sec III.

II. MAIN FORMULATION

The gluon jet production in A+B collisions can be described by $k_T$-factorization given by [2],

$$\frac{d\sigma}{dy d^2p_T} = \frac{2\alpha_s}{C_F} \frac{1}{p_T^2} \int d^2k_T \phi^G_A(x_1; \vec{k}_T) \phi^G_B(x_2; \vec{p}_T - \vec{k}_T),$$

where $C_F = (N_c^2 - 1)/2N_c$ with $N_c$ being the number of colors, $x_{1,2} = (p_T/\sqrt{s})e^{\pm y}$, $p_T$ and $y$ are the transverse-momentum and rapidity of the produced gluon jet. $\phi^G_A(x; \vec{k}_T)$ denotes the unintegrated gluon density and is the

\(^1\) For the recent theoretical development on this line including the effect of the running coupling corrections to the $k_t$ factorization, see Ref. [3].
probability to find a gluon that carries $x_i$ fraction of energy with $k_T$ transverse momentum in the projectile A (or target B). The unintegrated gluon density is related to the color dipole forward scattering amplitude,

$$\phi^G_A(x_i; \vec{k}_T) = \frac{1}{\alpha_s} \int \frac{C_F}{(2\pi)^3} d^2\vec{b} d^2\vec{r}_T e^{i\vec{k}_T \cdot \vec{r}_T} \nabla^2 N^G_A(x_i; r_T; b),$$

with notation

$$N^G_A(x_i; r_T; b) = 2N_A(x_i; r_T; b) - N^2_A(x_i; r_T; b),$$

where $r_T$ denotes the dipole transverse size and $\vec{b}$ is the impact parameter of the scattering. For the value of strong-coupling $\alpha_s$ we employ the running coupling prescription used in Ref. [12].

The most important ingredient of the single inclusive hadron production cross section which captures the saturation dynamics is the fundamental (or adjoint) dipole cross section, the imaginary part of the forward quark anti-quark scattering amplitude on a proton or nucleus target $N_{A,\pi} (x_i; r_T; b)$. In principle, the dipole cross-section can be computed via the JIMWLK/BK evolution equations [13, 14]. For the recent progress in obtaining the impact-parameter dependent solution of the BK equation, see Ref. [15]. It has been shown that the impact-parameter dependence of the dipole amplitude is important for phenomenological studies [3, 7, 8, 10, 12], including for describing the diffractive data at HERA [16]. Following Refs. [3, 8, 12] we use the b-CGC saturation model [16] which explicitly depends on impact-parameter. This model approximately incorporates all known properties of the exact solution to the BK equation including the impact-parameter dependence of the scattering amplitude [3] and it also describes the small-$x$ data at HERA [16]. For comparison, we will confront the predictions coming from the b-CGC with the MCRegBK [7]. The MCRegBK model effectively incorporates the impact-parameter dependence into the BK equation solution via the Monte Carlo implementation of the $k_t$ factorization by taking into account fluctuations of the position of nucleon inside a nucleus [3]. Notice that both the b-CGC and the MCRegBK model have been quite successful to describe various experimental data in different reactions. However, we will show here that these two models give rather different predictions for the charged hadron multiplicity in p+ A collisions at the LHC.

The $k_t$ factorization has infrared divergence. By introducing a new parameter $m_{\text{jet}}$ as mini-jet mass which mimics the pre-hadronization effect, one can also regularize the cross-section. Unfortunately, we do not know how mini-jet mass changes with medium and kinematics. Therefore, one may model or chose the value of mini-jet at lower energy and hope that it should be still valid at higher energy for different rapidities and centralities. This is the approach that all previous saturation based studies have adopted, although, in different models, different values for $m_{\text{jet}}$ has been taken [3, 7, 8, 10, 12, 17]. Therefore, the uncertainties associated with our freedom in choosing the mini-jet mass should be considered and will be quantified here. In order to take account of the difference between rapidity $y$ and the measured pseudo-rapidity $\eta$, we employ the Jacobian transformation between $y$ and $\eta$ [3]. The final-state hadronization effects are incorporated via the Local Parton-Hadron Duality principle [3, 7, 8, 10, 12], namely the hadronization is a soft process and cannot change the direction of the emitted radiation. This introduces only one extra parameter which can be absorbed into the over-all normalization of the cross-section. Therefore, we have only two unknown parameters in our model, the overall normalization factor and the mini-jet mass which are fixed at lower energy at midrapidity for central collisions. Then our results at higher energies, different rapidities and centralities can be considered as free-parameter predictions.

### III. DISCUSSION AND PREDICTIONS

First, in Fig. 1 we show our description of the existing experimental data in p+p inelastic non-singlet diffractive (NSD) collisions and predictions for higher energies. Note that our curve at 7 TeV was prediction and it is seen that it is in good agreement with the recent LHC data [18]. In Fig. 4 (right), we also show our predictions for charged hadron multiplicity distribution in p+p collisions at $\sqrt{s} = 4.4, 14$ TeV ($s$ is the center-of-mass energy squared per nucleon).

In the case of scatterings on a nucleus target, one should also know the atomic number (A) and impact-parameter dependence of the saturation scale. In our approach, the saturation scale of proton and nucleus both depend on the impact-parameter, see Refs. [8, 12]. However, we assume that the atomic number or A (size of nuclei) dependence of

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2 One should note that the main contribution of the $k_t$ factorization for the multiplicity comes from small $p_T < 1.5$ GeV where the fragmentation functions are not reliable. We recall that it is still an open problem how to incorporate the fragmentation processes into the CGC/saturation formalism.
FIG. 1: Pseudo-rapidity distribution of charged particles production in p+p (right panel) and A+A (left panel) collisions at various energies. Right: the theoretical curves from top to bottom are at $\sqrt{s} = 14$, 7 and 4.4 TeV. The band in the right panel indicates about 2% theoretical error. The total theoretical uncertainties is less than 6% mainly due to our freedom in fixing the overall normalization and mini-jet mass with the experimental data at lower energy, see Ref. [3]. The experimental data are from [5, 6, 18].

As we already pointed out, one of the most interesting new feature of the LHC multiplicity data is the fact that the energy growth of multiplicities in A+A collisions is different from p+p ones [5, 6]. Notice that the $k_t$ factorization at the leading log approximation accounts for most of hadron multiplicity while still some contributions due to gluon decay cascade in the so-called MLLA (Modified Leading Logarithmic Approximation) [19] kinematics may be missing [8]. The latter effect requires the inclusion of higher order corrections and has been traditionally studied within a different resummation scheme in which one systematically incorporates next-to-leading logarithmic corrections, namely single and double-logarithmic effects in the development of parton cascades [19]. In Ref. [8] we extracted the energy-dependence of the gluon-jet decay cascade from $e^+e^-$ annihilation data and we showed that the energy-dependence of about $s^{0.036}$ due to the enhanced gluon-decay cascade is exactly what explains the different power-law energy-dependence of hadron multiplicities in A+A compared to p+p collisions at the LHC. This effect is more important for A+A collisions at high energy where the saturation scale is larger and consequently the average transverse momentum of the jet becomes about or bigger than 1 GeV. The MLLA gluon decay cascade gives rise to an extra contribution about 20−25% to the multiplicity in A+A collisions at the LHC. This picture is fully consistent with all existing experimental data including RHIC data [8]. We will show below that this picture can be further tested in p+A run at the LHC.

In Fig. 1 (left), we show the charged hadron pseudorapidity distribution at the LHC in A+A central (∼ 0 − 5%) collisions at various energies. The effect of the gluon-decay cascade are incorporated in our results. Again, we have only two parameters which was fixed with the lower energy data points at the RHIC. Although, the midrapidity experimental data point at $\sqrt{s} = 2.76$ TeV for A+A 0 − 5% central collisions was available [5] at the time that we published our results [8], the pseudorapidity distribution was prediction and its agreement with the recently released data from the CMS collaboration [6] is striking.

Having described both p+p and A+A multiplicities experimental data for large range of energies/rapidities, the multiplicity in p+A collisions can be considered as an important check of consistence. The normalization again (similar to Fig. 1) is fixed with RHIC data. Unfortunately the error bars of RHIC data is rather large (see Fig. 2) and this induces uncertainties upto ∼ 15% in our results. It was shown in Refs. [3, 8] that assuming a different mini-jet...
PHOBOS, 0.2 TeV
BRAHMS, 0.2 TeV
CGC-R1, 4.4 TeV
CGC-R2, 4.4 TeV
MCrcBK, 4.4 TeV

**FIG. 2:** Pseudo-rapidity distribution of the charged particles production in p+A minimum (Mini) bias collisions at the LHC $\sqrt{s} = 4.4$ TeV. The theoretical curves labeled by CGC-R1 and MCrcBK are based on the leading log $k_t$-factorization formalism but two different saturation models. The curve labeled by CGC-R2 is based on the modified $k_t$-factorization formalism incorporating the gluon-decay cascade effects from the Modified Leading Logarithmic Approximation scheme, see the text for the details. The experimental data are from [20].

$m_{jet}$ for the cases of A+A and p+p collisions will be in favor of data. Here, in order to reduce the model dependence associated with the choice of mini-jet mass, we take a fixed value for $m_{jet}$ for all rapidities, in the both fragmentation region of nucleus and proton. We estimated that uncertainties due to various value for $m_{jet}$ brings about 10% errors in our calculation. We focus only on a pseudorapidity region where the effect of valence quarks can be ignored. In Fig. 2, we show our prediction for the pseudorapidity distribution of charged hadron multiplicity at the LHC energy $\sqrt{s} = 4.4$ TeV in minimum-bias p+Pb collisions. We show our results both based on the $k_t$ factorization (labeled by CGC-R1) and also the modified $k_t$ factorization incorporating the effect of the MLLA gluon-decay cascade (labeled by CGC-R2). Notice that the contribution of the MLLA gluon-decay cascade may be also important in p+A collisions at the LHC energy since the average saturation scale of the system can be bigger than 1 GeV. This effect enhances the multiplicity about 20%, in accordance with our results for A+A collisions [8].

Notice that in the case of p+p and A+A collisions where the interacting system is symmetric in the rapidity, the corresponding multiplicity distribution is also symmetric (see Fig. 1). The position of two peaks in pseudorapidity corresponds to the fragmentation region of the projectile and the target. It has been shown that the peak in the multiplicity distribution at forward and backward rapidity is enhanced at higher energies due to the fact that the saturation scale increases with energy (and density) [8, 10, 12, 17, 21]. The exact shape of multiplicity distribution (position of the peaks, the local minimum and the width of the peak) depends on the unintegrated gluon density and the Jacobian transformation which relates the rapidity and pseudorapidity. In the case of p+A collisions, the interacting system is not symmetric namely the saturation scale in the nuclear fragmentation region is bigger than the projectile (proton) side and consequently the multiplicity distribution in pseudorapidity is not symmetric. In Fig. 2 we see rather strong forward-backward asymmetry for p+Pb compared to the symmetric collisions. The shape and position of maximum in backward and forward rapidity distribution are intricately related to the saturation scale in nucleus and proton. A bigger saturation scale in the nucleus washes away the maximum of the multiplicity distribution in the proton fragmentation region.

For comparison, in Fig. 2 we also show the predictions coming from the MCrcBK of Ref. [7]. Assuming that both predictions have about 15% errors due to the uncertainties associated with fixing the normalization with the RHIC data, it is seen that two approaches give rather different predictions for the multiplicity distribution in p+A collisions. Using the $k_t$ factorization at the leading log approximation, our prediction for charged hadron multiplicity at $\sqrt{s} = 4.4$ TeV at midrapidity $\eta = 0$ in p+A mini-bias collisions is $dN/d\eta = 19.67 \pm 1.5$ (CGC-R1) while prediction coming from the MCrcBK approach [7] is $dN/d\eta = 16.71 \pm 1.3$ (MCrcBK). The main difference between these two approaches is due to different employed saturation model. On the other hand, including the MLLA gluon decay cascade effect into the $k_t$ factorization increases our multiplicity results and at midrapidity we have $dN/d\eta = 21.88 \pm 1.7$ (CGC-R2), see
Fig. 2. To conclude, in this letter, we provided quantitative predictions for charged hadron multiplicity in p+Pb collisions at the LHC. We showed that the LHC p+Pb data on the charged particles pseudo-rapidity multiplicity distribution can discriminate between saturation models and also examine the $k_t$ factorization at an unprecedented level. In general, the measurement of inclusive hadron production in p+A collisions at the LHC can be a very good probe of the small-x physics, see also Ref. [22].

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[1] F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, Ann. Rev. Nucl. Part. Sci. 60, 463 (2010) [arXiv:1002.0333]. J. Jalilian-Marian, Y. V. Kovchegov, Prog. Part. Nucl. Phys. 56, 104 (2006) [hep-ph/0505052].

[2] Y. V. Kovchegov and K. Tuchin, Phys. Rev. D65, 074026 (2002) [hep-ph/0111362].

[3] E. Levin and A. H. Rezaeian, Phys. Rev. D82, 014022 (2010). [arXiv:1005.0631].

[4] W. A. Horowitz and Y. V. Kovchegov, Nucl. Phys. A849, 72 (2011) [arXiv:1009.0545].

[5] ALICE Collaboration, Phys. Rev. Lett. 105, 252301 (2010) [arXiv:1011.3916].

[6] CMS Collaboration, J. High Energy Phys. 08, 141 (2011) [arXiv:1107.4800]; ATLAS Collaboration, [arXiv:1108.6027].

[7] J. L. Albacete and A. Dumitru, [arXiv:1011.5161].

[8] E. Levin and A. H. Rezaeian, Phys. Rev. D83, 114001 (2011) [arXiv:1102.2385].

[9] E. Levin and A. H. Rezaeian, [arXiv:1011.3591].

[10] P. Tribedy and R. Venugopalan; Nucl. Phys. A850, 136 (2010); Erratum-ibid. A859, 185 (2011).

[11] L. McLerran and M. Praszalowicz, Acta Physica Polon. B41, 1917 (2010).

[12] E. Levin and A. H. Rezaeian, Phys. Rev. D82, 054003 (2010) [arXiv:1007.2430].

[13] I. Balitsky, Nucl. Phys. B463, 99 (1996); J. Jalilian-Marian, A. Kovner, A. Leonidov and H. Weigert, Nucl. Phys. B504, 415 (1997); J. Jalilian-Marian, A. Kovner, A. Leonidov and H. Weigert, Phys. Rev. D59, 014014 (1999); E. Iancu, A. Leonidov and L. D. McLerran, Nucl. Phys. A692, 583 (2001); Y. V. Kovchegov, Phys. Rev. D60, 034008 (1999); Phys. Rev. D61, 074018 (2000); A. H. Mueller, Phys. Lett. B523, 243 (2001); E. Ferreiro, E. Iancu, A. Leonidov and L. McLerran, Nucl. Phys. A703, 489 (2002).

[14] A. Dumitru, J. Jalilian-Marian, T. Lappi, B. Schenke and R. Venugopalan, [arXiv:1108.4764]; E. Iancu and D. N. Triantafyllopoulos, JHEP 1111, 105 (2011) [arXiv:1109.0302]; [arXiv:1112.1104]; E. Avsar, A. M. Stasto, D. N. Triantafyllopoulos and D. Zaslavsky, [arXiv:1107.1252].

[15] K. Golec-Biernat and A. M. Stasto, Nucl. Phys. B668, 345 (2003); J. Berger and A. Stasto, Phys. Rev. D83, 034015 (2011); [arXiv:1106.5740]; J. Kuokkanen, K. Rummukainen and H. Weigert, [arXiv:1108.1867].

[16] G. Watt and H. Kowalski, Phys. Rev. D78, 014016 (2008); E. Iancu, K. Itakura and S. Munier, Phys. Lett. B590, 199 (2004).

[17] D. Kharzeev, E. Levin and M. Nardi, Nucl. Phys. A730, 448 (2004); Erratum-ibid. A743, 329 (2004).

[18] CMS Collaboration, Phys. Rev. Lett. 105, 022002 (2010); ALICE Collaboration, Eur. Phys. J. C65, 111 (2010); CMS Collaboration, JHEP 1002, 041 (2010); S. Eidelman et al. [Particle Data Group Collaboration], “Review of particle physics”, Phys. Lett. B592, 1 (2004).

[19] For a review see: V. A. Khoze and W. Ochs, Int. J. Mod. Phys. A12, 2949 (1997); A. Bassetto, M. Ciafaloni and G. Marchesini, Phys. Rep. 100, 201 (1983); Yu. L. Dokshitzer, V. A. Khoze, A. H. Mueller and S. I. Troyan, Basics of Perturbative QCD (Editions Frontieres, Gif-sur-Yvette, 1991).

[20] PHOBOS Collaboration, Phys. Rev. Lett. 93, 082301 (2004); BRAHMS Collaboration, Phys. Rev. Lett. 94, 032301 (2005).

[21] J. H. Rezaeian and A. Schaefer, Phys. Rev. D81, 114032 (2010) [arXiv:0908.3695].

[22] J. Jalilian-Marian and A. H. Rezaeian; [arXiv:1110.2810].