Gluon saturation and energy dependence of hadron multiplicity in pp and AA collisions at the LHC

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The recent results in $\sqrt{s} = 2.76$ TeV Pb + Pb collisions at the Large Hadron Collider (LHC) reported by the ALICE collaboration shows that the power-law energy-dependence of charged hadron multiplicity in Pb + Pb collisions is significantly different from p + p collisions. We show that this different energy-dependence can be explained by inclusion of a strong angular-ordering in the gluon-decay cascade within the color glass condensate (or gluon saturation) approach. This effect is more important in nucleus-nucleus collisions where the saturation scale is larger than 1 GeV. Our prescription gives a good description of the LHC data both in p + p and Pb + Pb collisions.

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I. INTRODUCTION

The recent LHC data on hadron production in proton-proton (pp) and nucleus-nucleus (AA) scattering [1–5] shows that gluon saturation that follows both from the BFKL Pomeron calculus [6] and from the color glass condensate (CGC) approach [7–10], gives an adequate description of the high energy scattering in QCD. The model based on the gluon saturation was able to predict the hadron production at $\sqrt{s} = 7$ TeV [11] (see also Ref. [12]) and the experimental data both for pp [1] and AA collisions [4,5] confirmed the basic qualitative predictions of this approach [13,14]. However, the recently reported data from the ALICE collaboration [4] on hadron production in AA collisions also demonstrated that we are far away from the high precision quantitative description. For example, the model that predicted 7 TeV data for pp scatterings and which also describes HERA and RHIC data, failed to describe the multiplicity in AA collisions [15] with the same accuracy. This fact cannot be considered as discouraging since AA collisions are more complicated QCD problem and moreover the other model calculations, based on the same ideas, were somehow able to describe the data [13,14,16]. Nevertheless, this gives rise to a question that whether despite of considerable progress in theory during the past two decades we are ready to give a reliable prediction in the framework of the high-density QCD.

In practice, our theoretical description of hadron-hadron and nucleus-nucleus scatterings is based on two main ingredients: Balitsky-Kovchegov (BK) nonlinear equation [10] and k_t factorization [17,18]. However, the BK equation is not complete since it does not take into account the correct (nonperturbative) behavior at large impact parameters and, because of this, it leads to the violation of the Froissart theorem, see Ref. [19] where this problem discussed in detail. A practical consequence of this is the fact that we may not be able to guarantee the accuracy better than $\pm 20\%$ (if not worse) [20–22] from the application of the BK equation. Having said that, the recent application of the BK equation to the description of HERA data looks promising indeed [23]. On the other hand, the k_t factorization is not reliable for dense-dense system scatterings [24–26] and, strictly speaking, we cannot apply this factorization neither to proton-proton nor to nucleus-nucleus scatterings at midrapidity. Therefore, we are doomed to build models trying to get a feedback from the experimental data for a theoretical breakthrough.

As a first attempt toward understanding of the new LHC data on nucleus-nucleus collisions, one may compare the experimental data with the principal qualitative predictions of the gluon saturation. The cornerstone of such predictions is the fact that the multiplicity in pp and AA collisions are proportional to $Q_s^2 \propto s^{\lambda/2}$ [6,15,17,18,27], where Q_s is the saturation scale, s is the center-of-mass energy squared per nucleon pair and λ is free parameter to be fixed with other experiments like DIS at HERA. This indicates that the energy dependence of multiplicity in both pp and AA collisions should be the same, assuming that the atomic number or A dependence of the saturation scale is factorizable from energy. This simple property is in accordance with RHIC data [15,27,28]. However, the new ALICE data shows that multiplicities in pp and AA collisions have a different energy power-law behavior (see Fig. 1). Thus, at first sight, it looks as if that one of the principal feature of high-density QCD is violated. In this paper, we will argue that indeed the recent LHC data on AA collisions at $\sqrt{s} = 2.76$ TeV has already opened up a new QCD regime which requires further theoretical understanding than previously thought. Here, we shall give a simple explanation of the different energy behavior of the hadron multiplicity in AA and pp data at high energy based on the gluon saturation (or the CGC) scenario.

In the CGC approach, the hadron production goes in two stages: production of gluons and subsequently the decay of gluon-jet (or mini-jet) into hadrons. Therefore,

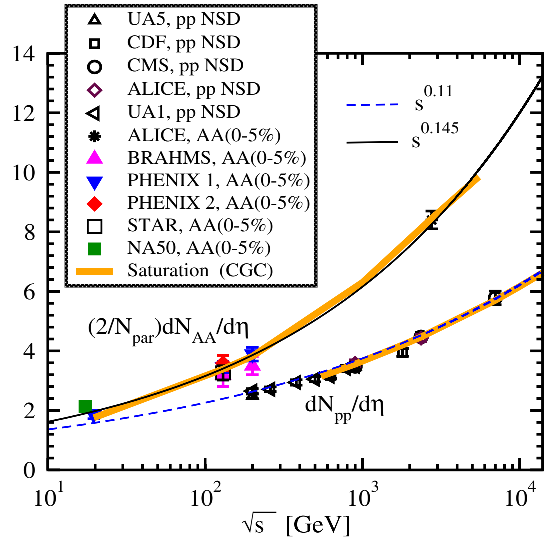

FIG. 1 (color online). The energy behavior of charged particle pseudorapidity per participant pair for central AA and nonsinglet diffractive pp collisions. The energy dependence can be described based on the saturation picture by $s^{0.11}$ for pp and $s^{0.145}$ for AA collisions. The saturation (CGC) curve for pp collisions is taken from Ref. [11]. The saturation curve for the AA collisions was calculated from Eq. (9), having incorporated the effects of gluon jet angular ordering which is important when the saturation scale $Q_s > 1$ GeV; see the text for the details. The total theoretical uncertainties in the saturation model calculation is about 7% (not shown here). The experimental data are from Refs. [1,3,4,35,29–34]. The data from the PHENIX collaboration denoted by PHENIX 1 and 2 can be found in Ref. [34].

the multiplicity of the produced hadrons at pseudorapidity η can be calculated as a convolution of these two stages,

$$\frac{dN_h}{d\eta d^2p_T} \propto \frac{dN^{\rm Gluon}}{dyd^2p_T} \otimes N_h^{\rm Gluon}(E_{\rm jet}), \tag{1}$$

$$\frac{dN_h}{d\eta} \propto \sigma_s Q_s^2 \times N_h^{\rm Gluon}(Q_s), \tag{2}$$

where the first part $\frac{dN^{\rm Gluon}}{dyd^2p_T}$ gives the gluon jet production yield at rapidity y (in pp or AA collisions) computable in the k_T factorization scheme [17,18], and the second term $N_h^{\rm Gluon}$ is the average multiplicity of hadrons in the gluon jet with a jet energy $E_{\rm jet}$ (see Secs. II and III). The symbol $\otimes$ indicates a convolution, that is, integrals over variables with possible weight factors included.

The kinematics look simpler in the center-of-mass of the produced gluon in which two gluons with the mean transverse momenta of the order of Q_s and the fraction of energy $x_1 = x_2 = Q_s/\sqrt{s}$ collide, producing the gluon which moves in the transverse plane with the value of its momentum of the order of Q_s. Equation (2) up to a possible logarithmic correction, can be simply obtained by a dimensionality argument based on the CGC picture in which the multiplicity of the gluon jets is proportional to $\sigma_s Q_s^2$ where σ_s is the effective area of interaction [27]. Notice that the typical transverse momentum in Eq. (1) is of the order of the saturation scale Q_s.

The crucial ingredient which is essential to explain the different energy dependence of the multiplicity in pp from AA collisions originates from the experimental data for jet production in e^+e^- annihilation [35–38], namely $N_h^{\rm Gluon}$ is

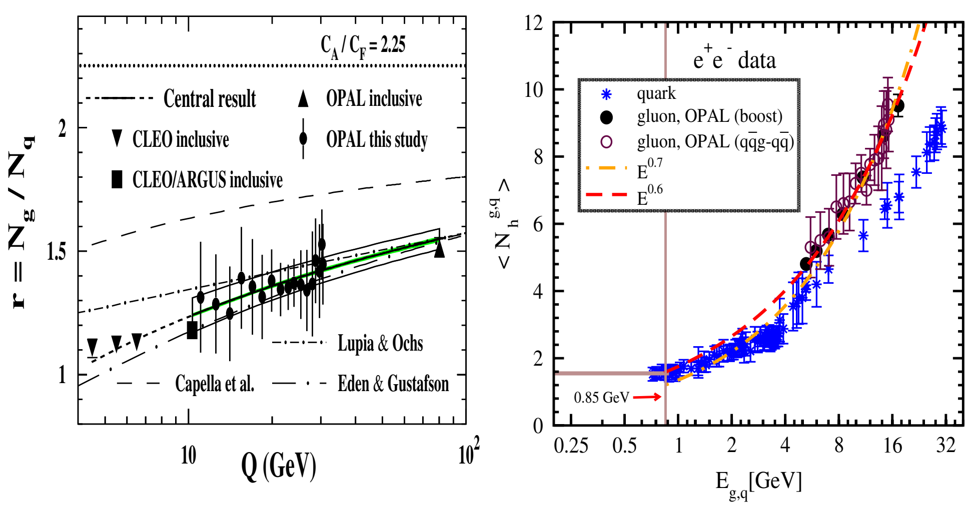

FIG. 2 (color online). Right: The mean charged hadron multiplicity of unbiased gluon N_h^g and quark N_h^q jets in e^+e^- annihilation, as a function of the jet energy. For gluon jet, we show experimental data obtained by two different methods, jet boost algorithm and subtracting multiplicities in two-jet $q\bar{q}$ events from three-jet $q\bar{q}g$ events [36,37]. The experimental data for quark jet production in e^+e^- annihilation are taken from Ref. [35]. The energy behavior of N_h^g can be described by $E_g^{0.6\div0.7}$ for $E_g \geq 0.85$ GeV. Left: The ratio of the mean charged particle multiplicities between unbiased gluon and quark jets as a function of scale. Various theoretical predictions [45] based on perturbative QCD (pQCD) are also shown in the plot. The plot in the left panel is taken from Ref. [37].

almost constant at energies of the gluon jet less than about 1 GeV but starts to increase with the energy of the gluon jet larger than 1 GeV, see Fig. 2 and Sec. III. For proton-proton collisions, the value of the saturation scale is smaller than 1 GeV and consequently $N_h^{\rm Gluon}$ does not give an additional energy dependence, while for nucleus-nucleus scatterings at high energies the saturation scale $Q_s(A) \propto A^{1/3} Q_s(p)$ (A is the atomic number) is larger than 1 GeV and $N_h^{\rm Gluon}$ increases leading to an additional non-negligible power-law energy dependence. This extra contribution accounts for the gluon-decay effect before hadronization and is missing in the k_T factorization.

The paper is organized as follows: In Sec. II, we introduce the missing gluon-decay cascade effect in the k_t factorization. We also show that the observed power-law energy dependence of multiplicity in pp and AA collisions at the LHC is fully consistent with the saturation picture by inclusion of the gluon cascade angular-ordering effect. In Sec. III, we generalize the k_t factorization in order to incorporate this effect, and present our numerical results for the charged hadron multiplicity both in pp and pA collisions. As a conclusion, in Sec. IV we highlight our main results.

II. THE ENERGY-DEPENDENCE OF CHARGED HADRON MULTIPLICITY

The k_T factorization [17,18,39–42] includes gluon emissions between the projectile and target, and also gluon radiation in the *final* initial-state from the produced gluons. The k_T factorization accounts for the BFKL type gluon emissions, namely, the parent gluon emits a cascade of gluons with their longitudinal momenta k_i^+ being progressively smaller while the transverse momenta k_{Ti} of the parent and emitted gluons are the same. This leads to an angular ordering in the cascade shown in Fig. 3

$$\begin{aligned} &p^+ > k_1^+ > k_2^+ > \ldots > k_n^+, \\ &p_T \sim k_{T1} \sim k_{T2} \ldots \sim k_{Tn}, \\ &\theta_1 < \theta_2 < \theta_3 < \ldots < \theta_n. \end{aligned} \tag{3}$$

However, the other contribution of the gluon decay, in the final initial-state, before hadronization, stems from the kinematic region outside the BFKL emission regime where

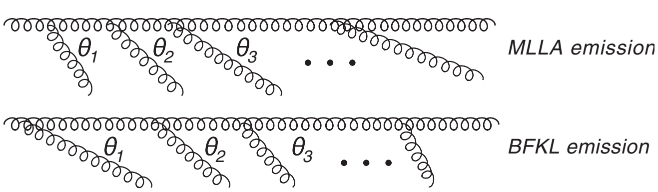

FIG. 3. Angular ordering in the gluon cascade in the MLLA ($\theta_1 > \theta_2 > \theta_3 > \ldots > \theta_n$) and the BFKL ($\theta_1 < \theta_2 < \theta_3 < \ldots < \theta_n$) regime.

both emitted gluons are collinear to the emitter. In this kinematic region, the angle between the gluon (quark) and the decay gluon θ_i is small and the main contribution of gluon-decay has an opposite angular ordering to the BFKL type gluon emissions given in Eq. (3), see Fig. 3,

$$\begin{aligned} &p^+ > k_1^+ > k_2^+ > \ldots > k_n^+, \\ &p_T \gg k_{T1} \gg k_{T2} \ldots \gg k_{Tn}, \\ &\theta_1 > \theta_2 > \theta_3 > \ldots > \theta_n. \end{aligned} \tag{4}$$

This angular ordering means that a gluon in a fully developed cascade can only emit inside a cone defined by the momenta of its first two immediate predecessors, similar to the well-known Chudakov effect in QED [43]. It is a well-established fact from jet observables (especially at small momentum fractions $z = P_{\rm hadron}/E_{\rm jet}$) that soft and collinear logarithms summed by the modified leading logarithmic approximation (MLLA), together with angular ordering reproduces the most important features of QCD cascade [36–38,44]. This combined with the local parton-hadron duality (LPHD) also gives quantitative predictions for hadron multiplicity and spectra in e^+e^- and ep collisions over the whole momentum range down to momenta of a few hundred MeV [38,44]. The MLLA contains systematically next-to-leading logarithmic corrections and incorporates single and double-logarithmic effects in the development of parton cascades [38,44].

One should note that although the MLLA angular-ordering kinematic region is quite important at the gluon (quark) decay stage, but it does not lead to the large double log contribution in the total cross-section and it contributes to the self-energy of the quark and, therefore, to the running QCD coupling in the case that we integrate over all produced gluons. Therefore, this kinematic region is not included in the k_T factorization formula and has to be considered separately, namely, summing of these double log for the gluon jet decay leads to the extra term $N_h^{\rm Gluon}$ in Eq. (1) which can be calculated within the MLLA approach. On the other hand, the effect of propagation and interaction of the produced jet in the gluonic medium with the BFKL angular ordering and its saturation effect have been already taken into account in the k_T factorization. It is well known that the gluon decay probability can be factorized from the rest of cross section in $e^+e^- \to q\bar{q}g$ reaction [44]. This is the essence of the factorization given in Eq. (1). Therefore, one may extract information about the gluon-decay stage in the MLLA region from gluon jet data in e^+e^- collisions.

In order to verify Eq. (2), we need to know $N_h^{\rm Gluon}$. As we already mentioned, one may calculate the charged hadron multiplicities in the gluon jet $N_h^{\rm Gluon}(E_{\rm jet})$ in pQCD within the MLLA scheme [38,44]. In order to obtain the energy dependence of the function $N_h^{\rm Gluon}$, we use directly experimental data for $N_h^{\rm Gluon}(E_{\rm jet})$ in the e^+e^- annihilation.

Unfortunately, such data are limited to high gluon jet energy $E_{\rm jet} > 5$ GeV [36,37], see Fig. 2. For lower energy $E_{\rm jet} < 5$ GeV, we construct the hadron multiplicity of gluon jet from the corresponding multiplicity of quark-jet $N_h^{\rm Quark}$ where we have experimental data [35]. It is well known that in the double log approximation, the ratio of the multiplicities in quark and gluon jets is equal to $N_h^{\rm Gluon}/N_h^{\rm Quark} = C_A/C_F = 9/2$ [38,44]. However, the higher order perturbative corrections significantly suppress this ratio at low energies of the jet making it close to one [37,45–47], see Fig. 2 (left panel). One can see from Fig. 2 that $N_h^{\rm Gluon}$ is constant at about $E_{\rm jet} < 1$ GeV and it grows as a power of $E_{\rm jet}$ at higher energies. From the available e^+e^- collisions data shown in Fig. 2, we found that the energy dependence of the mean charged particle multiplicity of gluon jet can be approximately described by

$$\langle N_h^{\rm Gluon}\rangle \propto E_{\rm jet}^{\delta}, \quad \text{with} \quad \delta = 0.6 \div 0.7 \quad \text{for } E_{\rm jet} \geq 0.85 \div 1 \text{ GeV}. \tag{5}$$

It is essential to stress again that such behavior also follows from the theoretical estimates in the next-to-next-to-next-to-leading order (3NLO) pQCD [45–47] in the MLLA scheme [38,44].

It is well known that the saturation scale has the following energy (or x) behavior [6–8,10,48–51]:

$$Q_s^2(x) = Q_0^2\left(\frac{x_0}{x}\right)^{\lambda} \propto s^{\lambda/2}, \tag{6}$$

where the saturation scale Q_0 is fixed at an initial value x_0. We assume that the typical energy of the gluon jet $E_{\rm jet}$ is of the order of average saturation scale. Now, using Eq. (2) and Eqs. (5) and (6) we obtain

$$\frac{dN_h}{d\eta}(pp) \propto Q_s^2 \propto s^{\lambda/2} = s^{0.11}, \tag{7}$$

$$\frac{dN_h}{d\eta}(AA) \propto Q_s^2 \times (E_{\rm jet} \propto Q_s)^{0.65} \propto s^{\lambda/2+0.65\times\lambda/4} = s^{0.145}, \tag{8}$$

where we assumed that the saturation scale for pp collisions is $Q_s < 1$ GeV and for AA collisions we have $Q_s > 1$ GeV. In the above and the following we take for the parameter δ, the average value $\bar{\delta} = 0.65$ from Eq. (5) and Fig. 2. In Eq. (7), the average value of $\lambda = 0.11$ in the effective saturation scale for pp collisions can be obtained from k_t factorization results given in Ref. [11] or by a fit to the available data for nonsinglet diffractive inclusive hadron production in pp collisions shown in Fig. 1. Then, the power-law behavior given in Eq. (8) for AA collisions comes naturally without any extra freedom. In Fig. 1, we show that the energy power-law scaling given in Eqs. (7) and (8) leads to a very good description of experimental data both in pp and AA collisions, including the recent ALICE data in AA collisions at 2.76 TeV.

III. CHARGED HADRON MULTIPLICITY IN THE IMPROVED k_t FACTORIZATION

In this section, we shall investigate how the saturation model predictions based on the k_t factorization [17,18] will change by the inclusion of the angular ordering effect in the gluon jet decay cascade. Motivated by previous sections, we postulate that the missing effect of gluon jet decay cascade can be effectively incorporated into the k_t factorization in the following way,:

$$\frac{dN_h}{d\eta}(AA \quad \text{or} \quad pp) = \frac{\mathcal{C}}{\sigma_s}\int d^2p_T h[\eta]\frac{d\sigma^{\rm Gluon}}{dyd^2p_T}(AA \quad \text{or} \quad pp)\mathcal{N}_h^{\rm Gluon}(\bar{Q}_s), \tag{9}$$

where $h[\eta]$ is the Jacobin transformation between y and η [27]. The impact-parameter dependence of the formulation allows us to calculate the average area of interaction σ_s via the geometrical scaling property [11]. The gluon jet cross section in AA (or pp) collisions can be obtained from [17]

$$\frac{d\sigma^{\rm Gluon}(y;p_T;\bar{B})}{dyd^2p_T} = \frac{2C_F\alpha_s(p_T)}{(2\pi)^4}\int_{B_1}^{B2} d^2\vec{B}\int d^2\vec{b}d^2\vec{r}_Te^{i\vec{p}_T\cdot\vec{r}_T}\frac{\nabla_T^2 N_{A,p}^G(x_1;r_T;b)\nabla_T^2 N_{A,p}^G(x_2;r_T;b_-)}{p_T^2\alpha_s(Q_{A,p}(x_1;b))\alpha_s(Q_{A,p}(x_2;b_-))}, \tag{10}$$

where $x_{1,2} = (p_T/\sqrt{s})e^{\pm y}$, p_T and y are the transverse-momentum and rapidity of the produced gluon jet. The vector $\vec{B}$ is the impact parameter between the center of two nuclei (or two hadrons in the case of pp collisions), $\vec{b}$ and $\vec{b}_- = \vec{b} - \vec{B}$ are the impact parameter between the interacting nucleons with respect to the center of two nuclei (or hadrons). A given centrality bin corresponds to a range of the impact-parameter $\bar{B} \in [B_1, B_2]$ of the collisions. We extended the k_T-factorization by introducing a running strong-coupling α_s [11]. In the above, the amplitude $N_{A,p}^G$ is defined as [17]

$$N_{A,p}^G(x_i;r_T;b) = 2N_{A,p}(x_i;r_T;b) - N_{A,p}^2(x_i;r_T;b), \tag{11}$$

where $N_{A,p}(x_i;r_T;b)$ is the dipole-nucleus (for index A) or dipole-proton (for index p) forward scattering amplitude with r_T and $\vec{b}$ being the transverse dipole size and the impact parameter of the scattering, respectively.

In Eq. (9), $\mathcal{N}_h^{\rm Gluon}$ is the average hadron multiplicity in the gluon-jet decay in the MLLA region and can be obtained from experimental data in e^+e^- reactions [35–37]. Using Eq. (5) and assuming that typical transverse momentum of the gluon jet is approximately equal to the average saturation scale $\bar{Q}_{A,p}$ at a given centrality and kinematics, we define

$$\mathcal{N}_h^{\rm Gluon}(\bar{Q}_{A,p}) = C_0 \begin{cases} \left(\frac{\bar{Q}_{A,p}}{0.85}\right)^{0.65} & \text{for } \bar{Q}_{A,p} \geq 0.85 \text{ GeV;} \\ 1 & \text{for } \bar{Q}_{A,p} < 0.85, \end{cases} \tag{12}$$

with a notation,

$$\bar{Q}_{A,p} = \left(\frac{Q^2_{A,p}(x_1, b) + Q^2_{A,p}(x_2, b_-)}{2}\right)^{1/2}. \tag{13}$$

The normalization factor C_0 in Eq. (12) can be absorbed into the parameter $\mathcal{C}$ in Eq. (9) which relates the produced gluons to the final-state hadrons based on the Local Patron-Hadron Duality principle [38], assuming that the final-state hadronization is a soft process and cannot change the direction of the emitted gluon jet further.

The impact-parameter dependence in the k_t factorization is not trivial and a prior is not obvious if it can be factorized. Here, we are interested to study the effect of new $\mathcal{N}_h^{\rm Gluon}$ term in the k_t factorization Eq. (9). To this end, we employ the b-CGC saturation model [52] which gives a good description of inclusive hadron production in pp collisions at the LHC [11]. In this model, the size of proton naturally changes with energy [11]. This model effectively incorporates all known saturation properties driven by the small-x nonlinear evolution equations [51] including the impact-parameter dependence of the dipole amplitude [53]. This model describes very well the HERA DIS data at small-x [51,52,54] and direct-photon production [55]. The extension of this model for the case of nuclear target was introduced in Ref. [15] which also gives a good description of RHIC multiplicity data. The dipole-nucleon forward scattering amplitude in the b-CGC model [52] is defined as

$$N_p(x; r; b) = \begin{cases} N_0\left(\frac{\mathcal{Z}}{2}\right)^{2(\gamma_s + (1/\kappa\lambda Y)\ln(2/\mathcal{Z}))} & \text{for } \mathcal{Z} \leq 2; \\ 1 - \exp(-\mathcal{A}\ln^2(\mathcal{B}\mathcal{Z})) & \text{for } \mathcal{Z} > 2, \end{cases} \tag{14}$$

where we defined $\mathcal{Z} = rQ_p(x; b)$, $Y = \ln(1/x)$ and $\kappa = \chi''(\gamma_s)/\chi'(\gamma_s)$ where χ is the LO BFKL characteristic function. The parameters $\mathcal{A}$ and $\mathcal{B}$ are determined uniquely from the matching of N_p and its logarithmic derivatives at $\mathcal{Z} = 2$. The proton saturation scale is given by

$$Q_p(x; b') = \left(\frac{x_0}{x}\right)^{\lambda/2} \exp\left\{-\frac{b'^2}{4(1-\gamma_{\rm cr})B_{\rm CGC}}\right\}. \tag{15}$$

Based on the universality of the saturation in the CGC framework, the corresponding dipole-nucleus dipole amplitude N_A can be obtained from Eq. (14) by only replacing the proton saturation scale by that of the nucleus,

$$Q_A^2(x; b) = \int d^2\vec{b}' T_A(\vec{b} - \vec{b}') Q_p^2(x; b'), \tag{16}$$

where $T_A(B)$ denotes the nuclear thickness. The above definition leads to $Q_A^2 \approx Q_p^2 A^{1/3}$ which is consistent with basic idea of saturation [6,7,56]. We use for the nuclear thickness the Wood-Saxon parametrization [57]. The parameters λ, $\gamma_{\rm cr}$, N_0, x_0 and $B_{\rm CGC}$ are obtained from a fit to the DIS data at low Bjorken-x $x < 0.01$ with a very good χ^2/d.o.f. $= 0.92$ [52].

Numerical results and discussion

The number and density of participant at different centralities are calculated based on the Glauber formalism [58], assuming $\sigma_{nn}^{inel} = 64.8$, 58.5 and 42 mb for $\sqrt{s} = 5.5$, 2.76 and 0.2 TeV, respectively [59]. Following Refs. [11,15] in order to regularize the divergence of the k_t factorization, we introduce a gluon-jet-mass $m_{\rm jet}$. We are now ready to confront the improved k_t factorization Eq. (9) with experimental data. First, notice that the nuclear saturation scale defined via Eq. (16) can be in principle different with exact one up to a factor of the order of one. A change of $Q_A \to 1 \div 1.5 Q_A$ brings about 0–7% increase in the hadron multiplicity obtained from Eq. (9) at high energies. We have only two free parameters, the prefactor $\mathcal{C}$ and the gluon jet mass $m_{\rm jet}$, which are determined at low-energy for a fixed centrality. The main source of uncertainties in our approach is due to the assumption that gluon jet mass $m_{\rm jet}$ and the normalization prefactor $\mathcal{C}$ do not change with energy, rapidity and centrality. Unfortunately, due to limited available data in AA collisions at various high energies, we cannot verify if this assumption is correct and therefore we should take into account possible uncertainties associated with this assumption. We use RHIC data at $\sqrt{s} = 200$ GeV around midrapidity to fix our only free parameters $m_{\rm jet}$ and $\mathcal{C}$. Unfortunately, as it is obvious from Figs. 1 and 4, the experimental errors in the data points taken for fixing these unknown parameters is rather large. We checked that in the case of AA collisions, $m_{\rm jet} \approx 0.12 \div 0.14$ GeV is consistent with RHIC data within error bars. The experimental errors in the charged hadron multiplicity in Au + Au collisions at $\sqrt{s} = 200$ GeV (shown in Fig. 1) may induce an uncertainty as large as $7 \div 9\%$ in the value of the parameter $\mathcal{C}$.

In Fig. 1, we show the energy dependence of the charged hadron multiplicity at midrapidity (labeled with saturation) obtained from Eq. (9) both for pp and AA collisions.

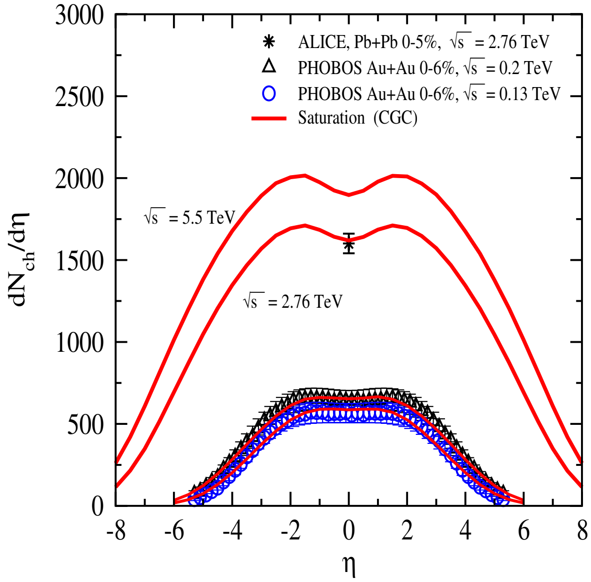

FIG. 4 (color online). Pseudorapidity distribution of charged particles produced in Au-Au and Pb-Pb central collisions at RHIC $\sqrt{s} = 130$, 200 GeV and the LHC energies $\sqrt{s} = 2.75$, 5.5 TeV. The experimental data are from the PHOBOS [31] and the ALICE collaboration [4].

The proton saturation scale Q_p in the b-CGC model Eq. (15) is rather small and varies very slowly with energy, e. g. for central collisions and midrapidity at $\sqrt{s} = 14$ TeV and $p_T = 1$ GeV, we have $Q_p = 0.8$ GeV. Therefore, in the case of pp collisions for our interested range of energy considered in this paper, the contribution of $\mathcal{N}_h^{\text{Gluon}}$ term in the improved k_t factorization Eq. (9) is negligible and the charge hadron multiplicity obtained via Eq. (9), shown in Fig. 1, coincides with the results given in Ref. [11] without the presence of $\mathcal{N}_h^{\text{Gluon}}$ term. However, in the case of AA collisions, the nuclear saturation scale defined by Eq. (16) can be $Q_A > 0.85$ GeV and consequently $\mathcal{N}_h^{\text{Gluon}}$ term in the improved k_t factorization Eq. (9) is important. The inclusion of gluon-decay angular-ordering effect via $\mathcal{N}_h^{\text{Gluon}}$ in Eq. (9) does not noticeably affect our prescription at RHIC due to our freedom in fitting m_{jet} and $\mathcal{C}$ parameters to the same data (at $\sqrt{s} = 200$ GeV) while it increases the charged hadron multiplicity about 20–25% at the LHC energies in AA collisions. Notice that the impact-parameter dependence of condition given in Eq. (12) limits the contribution of $\mathcal{N}_h^{\text{Gluon}}$ term at various energies and centralities. Overall, the improved k_t factorization results of Eq. (9) shown in Fig. 1 agree very well with both pp and AA data at the LHC and also RHIC, including the recent ALICE data for AA collisions at 2.76 TeV.

In Fig. 4, we show pseudorapidity dependence at RHIC energies $\sqrt{s} = 130$ and 200 GeV in 0–6% Au + Au collisions, and also for the LHC energies $\sqrt{s} = 2.76$ and 5.5 TeV in 0–5% Pb + Pb collisions. In our calculation, the number of participant at 5.5 TeV for 0–5% centrality is approximately $N_{\text{par}} = 385$. Our prediction for $dN_{AA}/d\eta$ obtained from Eq. (9) at midrapidity for 0–5% Pb + Pb collisions at 5.5 TeV is 1897 ± 133. It is seen in Fig. 4 that as the energy increases the peak of rapidity distribution at forward (backward) becomes more pronounced due to the saturation effect. This effect has been also observed in Refs. [11,60] in the case of pp collisions.

In Fig. 5 (right), we show the scaled pseudorapidity density $(2/N_{\text{par}})(dN_{AA}/d\eta)$ at midrapidity where N_{par} is the number of participant for a given centrality. The recent

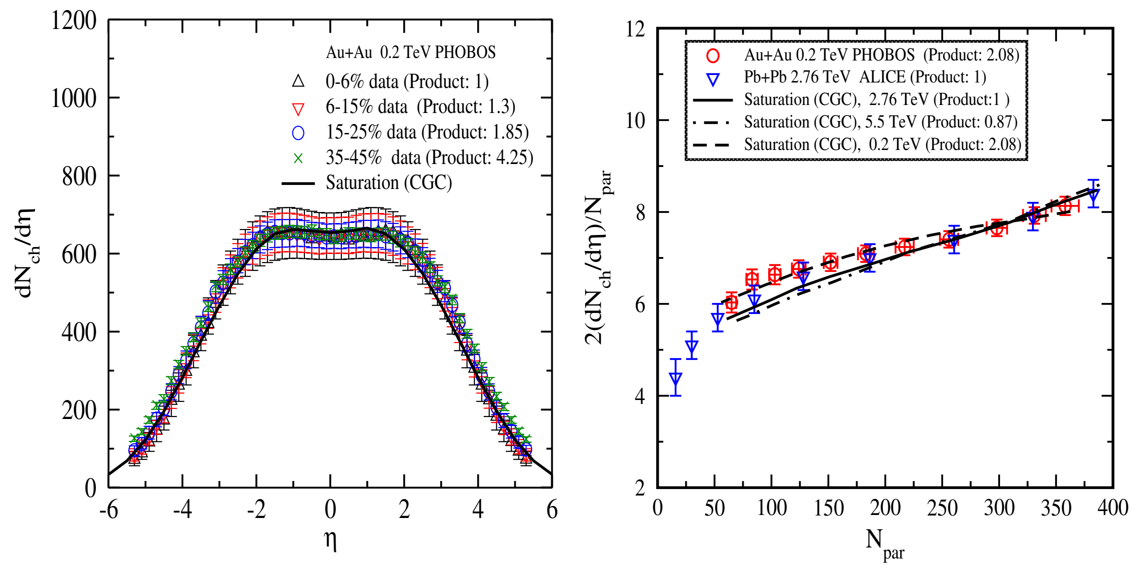

FIG. 5 (color online). Right: The scaled pseudorapidity density as a function of number of participant at midrapidity for AA collisions at 0.2, 2.76 and 5.5 TeV. Left: The pseudorapidity distribution at RHIC 0.2 TeV at different centralities. Both theoretical predictions and experimental data show gluon saturation-driven scaling property. We also show in the plots the corresponding normalization product factors. The experimental data are from the PHOBOS [61,31] and ALICE [5] collaborations.

ALICE data [5] at 2.76 TeV AA collisions reveals interesting scaling property, namely $(2/N_{\rm par})(dN_{AA}/d\eta)$ at different energies have the same $N_{\rm par}$ dependence up to a normalization factor. In Fig. 5 (right), we show that the saturation results obtained via Eq. (9) for $\sqrt{s} = 0.2$, 2.76 and 5.5 TeV, indeed follow this scaling behavior. One can observe similar scaling property already at RHIC [61], namely $dN_{AA}/d\eta$ at fixed energy but different centralities falls into a single curve up to a normalization factor, see Fig. 5 (left). Both scaling properties shown in Fig. 5 can be easily understood within the CGC picture and follows from simple Eq. (2). We expect that the centrality scaling for $dN_{AA}/d\eta$ at a fixed energy will be also valid at the LHC. Notice that the logarithmic correction due to the running strong-coupling in the k_t factorization is not shown in the simple Eq. (2) and is important. The curves shown in Fig. 5 are results of full calculation and includes this effect. We predict that $(2/N_{\rm par})(dN_{AA}/d\eta)$ for 5.5 TeV AA collisions at midrapidity to be about $\frac{1}{0.87\pm0.06}$ times bigger than the corresponding one at 2.76 TeV, see Fig. 5 (right).

Finally, one may wonder if a convolution of the fragmentation function in Eq. (9), can have the same effect as incorporating the gluon-decay cascade effect via $\mathcal{N}_h^{\rm Gluon}$. First, 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. On the same line, the fragmentation function is based on a different factorization and QCD evolution equation and its universality is also questionable in the k_t factorization approach. Moreover, here we were mostly interested to understand the role of initial-state effects in the hadron productions in pp and AA collisions. Therefore, we generalized the factorization Eq. (9) in order to incorporate the missing initial-state effect due to the gluon-decay cascade. We then assumed that the final hadronization is a soft process and will not change the direction of gluon decays. This was also motivated by the fact that the MLLA scheme [38,44] combined with the LPHD principle provides a good description of data in e^+e^- and ep collisions up to very small p_T [38].

IV. CONCLUSION

We showed that the basic energy power-law behavior given in Eqs. (7) and (8) for pp and AA collisions is in accordance with the saturation/CGC picture. We showed that the gluon-jet angular-ordering at the decay stage induces extra energy dependence in the case that the saturation scale is large. This contribution has been neglected in previous k_t factorization-based studies. This effect is important for AA collisions where the saturation scale is larger and gives rise to an extra contribution about 20–25% to the multiplicity in AA collisions at the LHC. This explains the observed different energy power-law behavior of charged hadron multiplicity in AA and pp collisions at the LHC. The scaling properties of multiplicity at different energies and centralities shown in Fig. 5 and also the energy power-law behavior of the multiplicity in pp and AA collisions shown in Fig. 1, all indicate that the saturation picture and the CGC scenario provides a unique and efficient way of describing various experimental data.

After our paper, there has been recently an interesting paper by Lappi [62] on the same line. It is argued by the author of Ref. [62] that the ratio of $\langle p_T\rangle/\sqrt{(dN/d\eta)/S_T}$ in our approach is in conflict with the observed experimental data at RHIC. Here, we would like to point out that this is not the case indeed.

It is constructive first to recall the argument of Ref. [62]. Let us assume that based on the LPHD picture one gluon produces n-charged hadrons after fragmentation. Then based on only the dimensionality argument, we have

$$\langle p_T\rangle \sim Q_s/n, \tag{17}$$

$$\frac{1}{S_T}\frac{dN}{d\eta} \sim nQ_s^2, \tag{18}$$

where $\langle p_T\rangle$ is the average transverse momentum and S_T is the overlap area between the colliding nuclei in the transverse plane. From above, we have $\langle p_T\rangle/\sqrt{(dN/d\eta)/\sigma_s} \sim \frac{1}{n\sqrt{n}}$. Therefore in our approach, the ratio $\langle p_T\rangle/\sqrt{(dN/d\eta)/\sigma_s}$ decreases for more central collisions in contrast to the KLN type approach [27,62]. First, notice that in our approach we have $n \sim N_h^{\rm Gluon}$ for $Q_s > 0.85 \div 1$ GeV corresponding to the excess of charged hadron production in the presence of jet-decay effects, see Eqs. (2) and (12) and Fig. 2. In Fig. 6 (right) we show the experimental data from the STAR collaboration [63] for $\langle p_T\rangle/\sqrt{(dN^\pi/d\eta)/\sigma_s}$ as a function of centrality. It is seen from Fig. 6 that the ratio $\langle p_T\rangle/\sqrt{(dN/d\eta)/S_T}$ at $\sqrt{s} = 0.2$ TeV Au + Au collisions decreases for more central collisions. We expect that based on our model, this ratio should further suppresses at the LHC in the central AA collisions.

In the KLN-type approaches [27], we have $\langle p_T\rangle \sim x$ where $x = \sqrt{(dN/d\eta)/S_T}$ while in our approach we have $\langle p_T\rangle \sim x^{0.264}$ for the case that the saturation scale is $Q_s > 0.85 \div 1$ GeV. This follows from the fact we have $x \sim Q_s\sqrt{N_h^{\rm Gluon}(Q_s)}$ and $\langle p_T\rangle \sim Q_s/N_h^{\rm Gluon}(Q_s)$ at large saturation scale, see Eqs. (2), (5), and (12). In Fig. 6 (left), we show the average transverse momenta as a function of $\sqrt{(dN/d\eta)/S_T}$. The STAR collaboration [63] has found that the experimental data for the charged pion at different centralities can be described by $\langle p_T\rangle \approx p_0 + 0.07x$ where the constant $p_0 = 0.29$ GeV was obtained from a fit and may be interpreted as primordial transverse momentum. It seems, however, that the obtained value of p_0 is rather large (and the coefficient behind x is abnormally small).

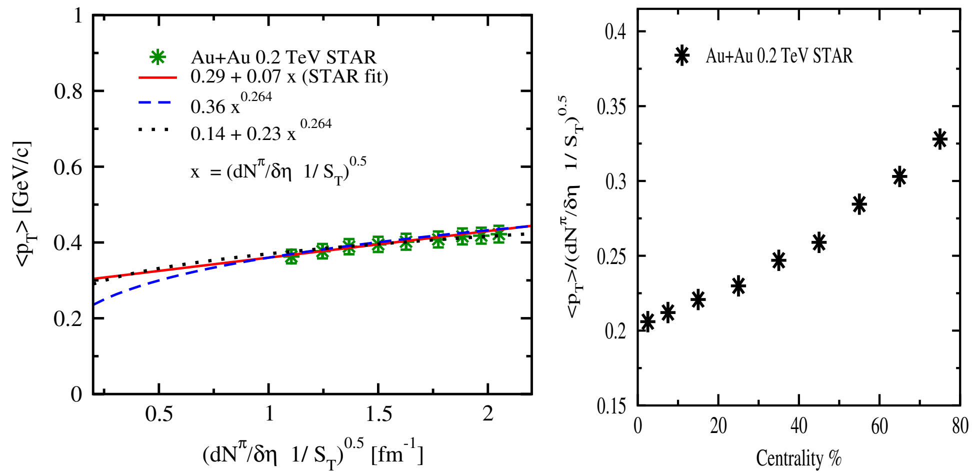

FIG. 6 (color online). Right: The ratio $\langle p_T \rangle / \sqrt{(dN^{\pi}/d\eta)/S_T}$ at various centralities for Au + Au collisions at 0.2 TeV. The data was constructed from three experimental measurements, the average transverse momentum $\langle p_T \rangle$ of π^-, $dN^{\pi}/d\eta$ and S_T [63]. Left: Average transverse momenta as a function of $\sqrt{(dN^{\pi}/d\eta)/\sigma_s}$ for Au + Au collisions at 0.2 TeV. The experimental data are from the STAR collaboration [63].

Such a rather large value for p_0 may be in contradiction with the notion of asymptotic deconfinement for a dense system, namely, the confinement radius increases with density [15,64]. In Fig. 6, we show that a fit driven by our approach prefers a smaller primordial transverse momentum of about pion mass $p_0 \sim 0.14$ GeV (or even $p_0 \sim 0$) and it reasonably describes the same data within the error bars. Notice that at small multiplicity for very peripheral collisions our fit and entire saturation formulation is questionable.

Finally, we should stress that the jet-decay effects bring a rather small extra contribution which requires a more careful analysis than only a naive dimensionality argument. We showed in this paper this extra contribution is important when the saturation scale is large and that is in accordance with the existing experimental data in various reactions. Our main concern in this paper was the combine description of proton-proton and nuclear data in a contrast to the KLN-type approaches that deal mostly with nuclear reactions.

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