Baryon stopping in the color glass condensate formalism: A phenomenological study

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(Received 30 January 2014; revised manuscript received 3 March 2014; published 24 March 2014)

The net-baryon production at forward rapidities is investigated considering the color glass condensate formalism. We assume that at large energies the coherence of the projectile quarks is lost and that the leading baryon production mechanism changes from recombination to independent fragmentation. The phenomenological implications for net-baryon production in $pp/pA/AA$ collisions are analyzed and predictions for Large Hadron Collider energies are presented.

DOI: 10.1103/PhysRevC.89.035205 PACS number(s): 24.85.+p, 12.38.Mh, 25.75.Dw

I. INTRODUCTION

In high energy hadronic collisions, baryons are produced both in the central and in the forward rapidity region. In the first case baryons are produced together with antibaryons and the net-baryon number (baryons minus antibaryons) is small. In contrast, in the large rapidity region there are almost only baryons and no antibaryons. These experimental facts suggest that the forward baryons are produced from the valence quarks of the projectile, whereas low rapidity baryons are produced mainly from gluons and sea quarks. How valence quarks are converted into forward (or leading) baryons remains to be clarified. In lower [($\sqrt{s} \simeq 20$ to 100 GeV) where s = center-of-mass energy squared] energies proton-proton collisions, leading baryon production can be well understood in terms of the recombination of the three valence quarks after the collision with the target [1] or, equally well, in terms of diquark fragmentation [2]. At higher energies new phenomena are expected to affect forward baryon production. At high energies and at large rapidities, baryon production requires the interaction of a valence quark with a relatively large momentum fraction x_1 of the projectile with low fractional momentum (small x_2) partons in the target. In the low x regime the target is a dense system of partons (predominantly gluons) which may form the color glass condensate (CGC), a state of very high partonic densities in which the nonlinear effects of QCD change the parton distributions and hence the cross sections (for reviews see Ref. [3]). The CGC is characterized by a momentum scale which marks the onset of nonlinear (or saturation) effects. This so-called saturation scale Q_s grows with the reaction energy. In Ref. [4] it was conjectured that at increasing projectile energies the valence quarks receive a transverse momentum kick of the order of Q_s and hence above a certain energy the coherence of the projectile quarks is lost and the leading baryon production mechanism changes from recombination to independent fragmentation. In this work we shall explore the phenomenological implications of this assumption for the leading baryon production in $pp/pA/AA$ collisions at LHC energies. Our goal is to improve the previous studies using the CGC formalism that have been performed in Refs. [5–8] (called here the MTW model), where the nonlinear evolution of the target was accounted for. In particular, we would like to improve the calculation of Ref. [6] by computing the p_T distribution of the produced leading baryons, which was missing in that work. Furthermore we also improve the treatment of the nonlinear effects, considering the forward dipole scattering amplitude proposed in Ref. [9], which captures the main properties of the solution of the Balitsky-Kovchegov (BK) equation, which determines the QCD evolution of the CGC, and describes the RHIC and LHC data for hadron production. We also extend these previous studies [5,6] to pp and pA collisions and estimate for the first time the ratio $R_{pA} = \frac{d^2N_{pA}}{dyd^2p_T}/A\frac{d^2N_{pp}}{dyd^2p_T}$ for leading baryon production. Finally, the proton and pion production at forward rapidities are compared. Our study is strongly motivated by the recent results presented in Ref. [10], which have demonstrated that the LHCf experimental data [11] for neutral pion production at very low p_T can be quite well described within the framework of the CGC formalism, indicating the emergence of the saturation scale as a hard momentum scale at very forward rapidities.

This paper is organized as follows. In the next section we present a brief review of the CGC formalism and its main formulas. In particular we present the models for the forward dipole scattering amplitude used in our calculations. In Sec. III we present our results for the p_T and y dependences of the leading baryon cross section. A comparison with the RHIC data is performed and predictions for baryon production in pPb and PbPb collisions at LHC energies are presented. Moreover, we present our predictions for the ratio R_{pA}. Finally, in Sec. IV, we summarize our main conclusions.

II. NET-BARYON PRODUCTION IN THE CGC FORMALISM

In the CGC formalism the differential cross section for the forward production of a hadron of transverse momentum p_T at rapidity y reads [12–14]

$$\frac{dN}{d^2p_Tdy} = \frac{1}{(2\pi)^2}\int_{x_F}^{1}\frac{dz}{z^2}D(z)\frac{1}{q_T^2}\,x_1q_v(x_1)\,\varphi(x_2,q_T)\,, \quad (1)$$

where the net-baryon fragmentation function is defined as

$$D(z) \equiv D_{\Delta B/q}(z) = D_{B/q}(z) - D_{\bar{B}/q}(z), \quad (2)$$

with $z = E_B/E_q$ being the fraction of the energy of the fragmenting quark, E_q, taken by the emerging baryon B. The fractional momenta of the projectile quark and of the target gluon are $x_1 = q_T\, e^{y}/\sqrt{s}$ and $x_2 = q_T\, e^{-y}/\sqrt{s}$, respectively. The variable $q_T = \sqrt{p_T^2 + m^2}/z$ is the quark transverse momentum and the Feynman x variable is given by $x_F = \sqrt{p_T^2 + m^2}\, e^{y}/\sqrt{s}$. Moreover, $x_1\, q_v(x_1)$ is the valence quark distribution of the projectile hadron, and the function $\varphi(x_2,q_T)$ is the unintegrated gluon distribution of the hadron target which is given by

$$\varphi(x_2,q_T) = 2\pi q_T^2 \int r_T dr_T \mathcal{N}(x_2,r_T) J_0(r_T q_T)\,, \tag{3}$$

where J_0 is a Bessel function and $\mathcal{N}(x_2,r_T)$ is the forward scattering amplitude of a color dipole of radius r_T off a hadron target.

The evolution of $\mathcal{N}(x_2,r_T)$ is described in the mean field approximation of the CGC formalism [15] by the BK equation [16]. This quantity encodes the information about the hadronic scattering and then about the nonlinear and quantum effects in the hadron wave function (for reviews, see, e.g., [3]). In the last years, several groups have constructed phenomenological models which satisfy the asymptotic behavior of the leading order BK equation in order to fit the Hadron-Electron Ring Accelerator at DESY (HERA) and RHIC data [9,13,14,17,18]. In general, it is assumed that it can be modeled through a simple Glauber-like formula, which reads

$$\mathcal{N}(x,r_T) = 1 - \exp\left[-\tfrac{1}{4}\left(r_T^2 Q_s^2\right)^{\gamma(x,r_T^2)}\right], \tag{4}$$

where γ is the anomalous dimension of the target gluon distribution. The main difference among the distinct phenomenological models comes from the behavior predicted for the anomalous dimension, which determines the transition from the nonlinear to the extended geometric scaling regime, as well as from the extended geometric scaling to the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) regime. In this paper we restrict our analyses to the model proposed in Ref. [9], the so-called BUW model, which is able to describe the ep HERA data for the proton structure function and the hadron spectra measured in pp and dAu collisions at RHIC energies [9,19]. Another feature of the BUW model which motivates this analysis is that it explicitly satisfies the property of geometric scaling [20], which is predicted for the solutions of the BK equation in the asymptotic regime of large energies. In the BUW model, the anomalous dimension is given by $\gamma(x,r_T) = \gamma_s + \Delta\gamma(x,r_T)$, where $\gamma_s = 0.628$ and [9]

$$\Delta\gamma(x,r_T) = \Delta\gamma_{\rm BUW} = (1-\gamma_s)\frac{(\omega^a - 1)}{(\omega^a - 1) + b}. \tag{5}$$

In the expression above, $\omega \equiv 1/[r_T Q_s(x)]$ and the two free parameters $a = 2.82$ and $b = 168$ are fitted in such a way as to describe the RHIC data on hadron production. It is clear, from Eq. (5), that this model satisfies the property of geometric scaling [20–22], since $\Delta\gamma$ depends on x and r_T only through the variable $1/r_T Q_s(x)$. Besides, in comparison with other phenomenological parametrizations, in the BUW model, the behavior expected for the unintegrated gluon distribution in the large p_T limit (linear regime) is recovered: $\varphi(x_2,q_T) \propto 1/q_T^4$ at large q_T. In contrast, in Ref. [5] the nonlinear effects were taken into account considering the model proposed long ago by Golec-Biernat and Wusthoff [17], where the forward dipole scattering amplitude is given by Eq. (4) with $\gamma = 1$. This model implies that the r_T integration in Eq. (3) can be carried out analytically and a simple expression for the unintegrated gluon distribution can be obtained:

$$\varphi(x_2,q_T) = 4\pi \frac{q_T^2}{Q_s^2(x_2)} \exp\left(-\frac{q_T^2}{Q_s^2(x_2)}\right). \tag{6}$$

Although this model satisfactorily describes the nonlinear regime (small q_T), it clearly does not contain the expected behavior for large q_T. Consequently, the resulting predictions are not valid at large values of the transverse momentum of the hadron. This explains the behavior observed in Figs. 3 and 4 of the Ref. [6] for the net-proton spectra.

III. RESULTS

The net-baryon rapidity distribution is obtained integrating Eq. (1) in p_T between $p_{T_{\rm min}} = 0$ and $p_{T_{\rm max}} = \sqrt{s}\, e^{-y}$. The upper limit $p_{T_{\rm max}}$ comes from the kinematical condition $x_F < 1$. Following Ref. [5] we assume that the nuclear valence quark distribution is given by $x\, q_v^A(x,Q^2) = N_{\rm part} x\, q_v^{\rm proton}(x,Q^2)$, with $N_{\rm part}$ being the number of participants. The proton valence quark distribution is described by the Martin-Roberts-Stirling-Thorne leading order (MRST01-LO) parametrization [23]. For the fragmentation function we use the phenomenological model (already used in [5,6]):

$$D_{p-\bar{p}}(z) = N\, z^a\, (1-z)^b, \tag{7}$$

with $N = 520\,142$, $a = 11.6$, $b = 6.74$, and also the KKP parametrization [24]. As already demonstrated in Refs. [5,6],

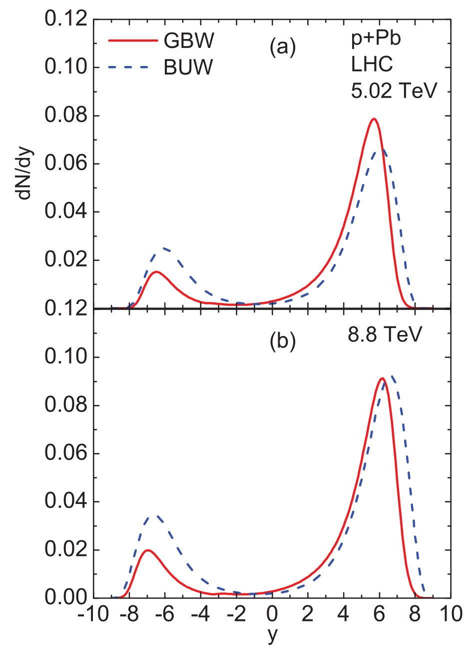

FIG. 1. (Color online) Net-baryon rapidity distributions in pPb collisions at LHC energies.

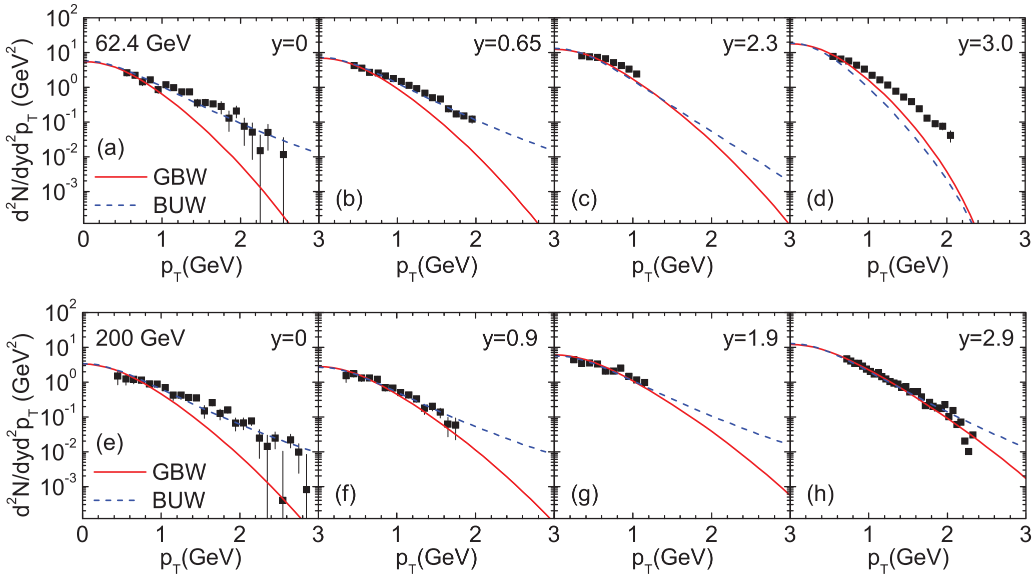

FIG. 2. (Color online) Net-baryon transverse momentum spectra in central AuAu collisions at RHIC. Data from [25–30].

the MTW model describes quite well the experimental data for the net-baryon rapidity distribution for $\sqrt{s} = 17.3$ and 62.4 GeV and slightly overestimates the data for $\sqrt{s} = 200$ GeV and forward rapidities. We have checked that substituting (7) by the KKP fragmentation function changes the resulting rapidity distributions only at very low energies. At higher energies the predictions become similar and less sensitive to the fragmentation functions. Substituting (6) by the unintegrated gluon distribution derived from the BUW model does not lead to significant changes in the final rapidity distributions, except at the lowest energies. In this energy region the rapidity distribution obtained with the BUW model does not show a dip at $y = 0$, in contradiction with the data [25–30]. This disagreement is an indication of the limitation of this approach at lower energies. On the other hand, at increasing energies, the MTW and BUW predictions for the net-baryon rapidity distributions in nucleus-nucleus collisions are essentially equivalent, even for central PbPb collisions at LHC energies. The same is true for proton-nucleus collisions. As an illustration, in Fig. 1 we present the predictions for pPb collisions at LHC energies. In the figure, GBW represents the MTW model with KKP fragmentation functions. The choice of the same fragmentation function allows us to observe the differences introduced by changing only the unintegrated gluon distribution.

In Fig. 2 we present our predictions for the net-baryon transverse momentum spectra in central AuAu collisions at RHIC energies. As in Ref. [6] we have assumed $N_{\rm part} = 315$ and 357 for $\sqrt{s} = 62.4$ and 200 GeV, respectively. These plots show two striking features. First, we observe a very good agreement between data and the spectra obtained with Eq. (1) and the BUW dipole amplitude and, at the same time, a disagreement between data points and the spectra obtained with the GBW dipole amplitude, specially when $p_T > 1$ GeV. This happens because the GBW dipole amplitude has no DGLAP evolution and should not be able to reproduce data with large p_T. The BUW amplitude has the correct behavior at larger p_T and is able to describe the data in this region. Another interesting feature of these plots is the failure of the formalism at the largest rapidity and lowest energy. This may be an indication

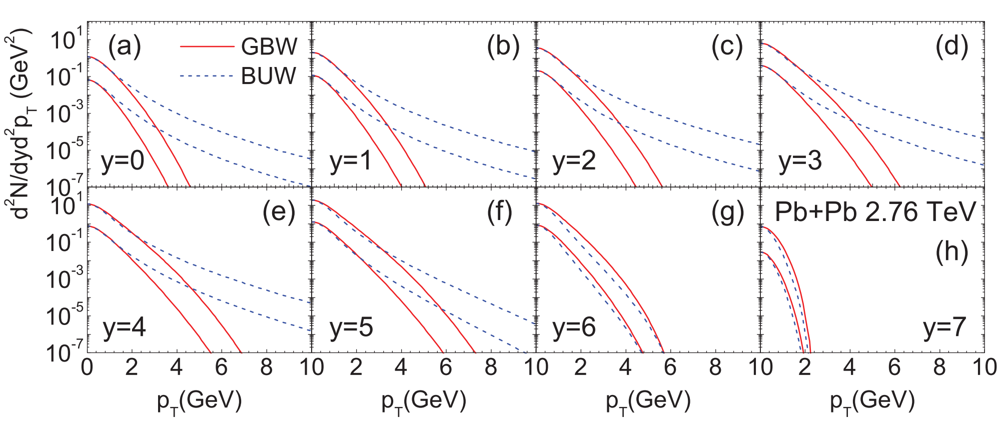

FIG. 3. (Color online) Transverse momentum spectra in PbPb collisions at $\sqrt{s} = 2.76$ TeV and different rapidities. Upper and lower lines represent pions and protons, respectively.

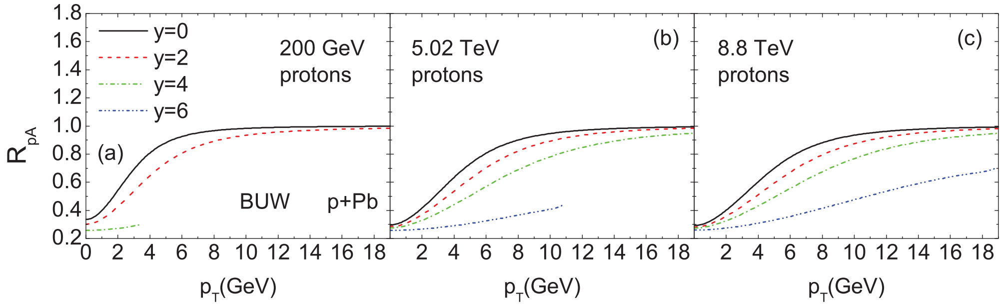

FIG. 4. (Color online) Nuclear modification ratio R_{pA} for net-proton production in pPb collisions at RHIC and LHC energies.

that here the baryons are not produced by independent quark fragmentation. They are more likely to be produced by the coalescence of the incoming valence quarks. In Fig. 3 we present our predictions for the proton and pion transverse momentum spectra at $\sqrt{s} = 2.76$ TeV and different rapidities. As already verified for RHIC energies, the GBW and BUW predictions are very distinct at large transverse momentum, in particular at $y \leqslant 5$. At larger values of rapidities, both predictions are similar, which is directly associated to the limitation in the phase space available for the considered energy. Moreover, it is important to emphasize the similarity between the p_T behavior of proton and pion production.

In order to quantify the magnitude of the nuclear effects in the net-proton production we introduce the nuclear modification ratio, equal to the ratio of the net-proton production cross section in pA collisions over the one in pp collisions scaled by the number of binary collisions and defined by

$$R_{pA} = \frac{\frac{d^2N_{pA}}{dyd^2p_T}}{A\frac{d^2N_{pp}}{dyd^2p_T}}\,. \tag{8}$$

The behavior of this ratio for valence quark production, i.e., not including quark fragmentation, has been studied in Ref. [31] in the quasiclassical approximation of the McLerran-Venugopalan model [32] taking into account quantum corrections through the nonlinear evolution derived in Ref. [33]. The authors predict the presence of a Cronin enhancement in the quasiclassical regime and a suppression in the nuclear modification factor when the nonlinear effects are considered. In contrast to the approach discussed in Ref. [31], which focuses on the production of soft valence quarks far away (in rapidity) from the fragmentation region, here we consider the production of hard valence quarks which experience no recoil and are produced in the fragmentation region as proposed in Ref. [12]. As already emphasized in Ref. [31], both approaches are complementary. However, the behavior of R_{pA} in the latter approach is still an open issue. In Fig. 4 we present our predictions. We observe a suppression at small values of p_T which increases at larger energies and rapidities, as expected from nonlinear effects.

The CGC formalism of forward particle production is appropriate to study the difference between the net-proton and net-pion production at forward rapidities. In what follows we analyze the behavior of the ratio between the cross sections for net-proton and net-pion production in PbPb collisions. Until some years ago the proton to pion ratio was expected to be always smaller than 1. However, in some experiments [34], this ratio was found to be much larger and in the range $2 < p_T < 6$ GeV, being even compatible with 1. This has been called "the baryon anomaly." Some explanations for this effect have been proposed in [35–37]. The interest in the subject will grow again now in view of the appearance of very recent data from ALICE [38], which confirm the observation of the anomaly in pPb collisions. In Fig. 5 we show the proton-to-pion ratio as a function of the transverse momentum considering the CGC formalism. As it can be seen,

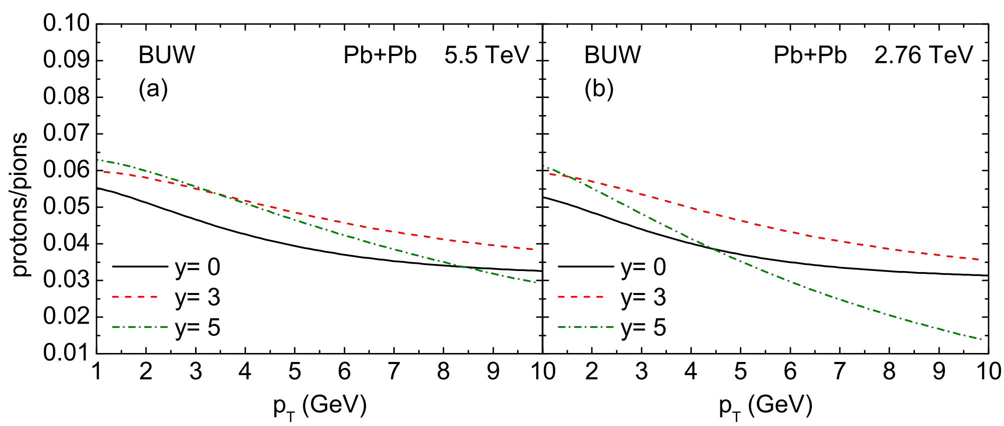

FIG. 5. (Color online) Transverse momentum dependence of the ratio between the cross sections for net-proton and net-pion production in PbPb collisions at different values of rapidity and LHC energies.

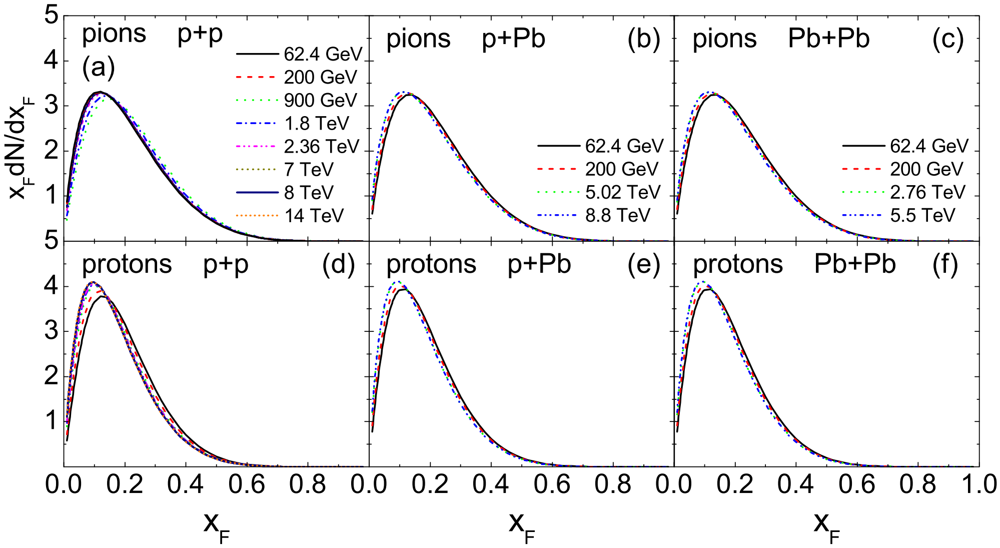

FIG. 6. (Color online) Energy dependence of the x_F distributions of pions and protons produced in pp, pPb, and PbPb collisions.

the p/π ratio is small; depends very weakly on the rapidity, on the collision energy; and decreases with p_T. This is in sharp contrast with experimental data [36–38], which show a ratio p/π increasing with the transverse momentum and reaching large values, close to 1. Consequently, we conclude that in the CGC formalism there is no baryon anomaly and pions are always more abundant. Therefore the anomaly must come from the protons and pions produced from gluons and sea quarks in the central rapidity region.

Forward nucleon production is very important for cosmic ray physics, where highly energetic protons reach the top of the atmosphere and undergo successive high energy scatterings on the light nuclei in the air. In each of these collisions, a projectile proton (the leading baryon) looses energy, creating showers of particles, and goes to the next scattering. The interpretation of cosmic data depends on the accurate knowledge of the leading baryon momentum spectrum and its energy dependence. The crucial question of practical importance is the existence or nonexistence of the Feynman scaling, which says that x_F spectra of secondaries are energy independent. In cosmic ray applications we are sensitive essentially to the large x_F region (the fragmentation region) and hence we can try to answer this question using the CGC formalism and the expressions derived in the preceding sections. An additional motivation for this calculation is the fact that, in the near future, Feynman scaling (or its violation) will be investigated experimentally at the LHC by the LHCf Collaboration [39,40].

Changing variables from y to x_F and integrating (1) over p_T we obtain the x_F spectra of leading protons and pions in pp, pPb, and PbPb collisions at several energies, which are shown in Fig. 6. In all panels we can clearly see a shift to smaller values of x_F, indicating a softening of the leading particle spectrum. This Feynman scaling violation is compatible with the one obtained in Ref. [1] and Ref. [41], where different mechanisms are responsible for the violating behavior.

IV. CONCLUSIONS

In this work we have improved the CGC formalism of forward particle production developed in [5], [6], [12], and [14] and applied it to the study of rapidity distributions, p_T, and x_F spectra of forward protons and pions. We obtain a good agreement with existing data and show predictions for the forthcoming LHC data.

Concerning forward proton production, our results suggest that at energies around $\sqrt{s} = 62.4$ GeV, there is a transition from quark recombination to independent quark fragmentation. The independent fragmentation dynamics underpredicts the data at large rapidities and lower energies but starts to describe the data very well at higher energies. This effect can be seen in Fig. 2 at the largest rapidities. A solid conclusion about this change of mechanism still requires further theoretical and experimental work. We observe a violation of Feynman scaling in leading particle spectra which is compatible with other approaches. Finally, in the CGC formalism we do not observe any baryon anomaly. This suggests that this phenomenon is related to the central region dynamics of gluons and sea quarks.

ACKNOWLEDGMENTS

This work was partially financed by the Brazilian funding agencies CAPES, CNPq, FAPESP, and FAPERGS. We thank S. J. Brodsky for very instructive discussions.

[1] F. O. Duraes, F. S. Navarra, and G. Wilk, Braz. J. Phys. **35**, 3 (2005); Phys. Rev. D **47**, 3049 (1993).

[2] A. Berera, M. Strikman, W. S. Toothacker, W. D. Walker, and J. J. Whitmore, Phys. Lett. B **403**, 1 (1997).

[3] F. Gelis, E. Iancu, J. Jalilian-Marian, and R. Venugopalan, Ann. Rev. Nucl. Part. Sci. **60**, 463 (2010); E. Iancu and R. Venugopalan, in *Quark-Gluon Plasma 3*, edited by R. C. Hwa and X.-N. Wang (World Scientific, Singapore, 2004), p. 249; H. Weigert, Prog. Part. Nucl. Phys. **55**, 461 (2005); J. Jalilian-Marian and Y. V. Kovchegov, *ibid.* **56**, 104 (2006).

[4] A. Dumitru, L. Gerland, and M. Strikman, Phys. Rev. Lett. **90**, 092301 (2003); **91**, 259901(E) (2003).

[5] Y. Mehtar-Tani and G. Wolschin, Phys. Rev. Lett. **102**, 182301 (2009).

[6] Y. Mehtar-Tani and G. Wolschin, Phys. Rev. C **80**, 054905 (2009).

[7] Y. Mehtar-Tani and G. Wolschin, Phys. Lett. B **688**, 174 (2010).

[8] Y. Mehtar-Tani and G. Wolschin, Europhys. Lett. **94**, 62003 (2011).

[9] D. Boer, A. Utermann, and E. Wessels, Phys. Rev. D **77**, 054014 (2008).

[10] V. P. Goncalves and M. L. L. da Silva, Nucl. Phys. A **906**, 28 (2013).

[11] O. Adriani *et al.* (LHCf Collaboration), Phys. Rev. D **86**, 092001 (2012).

[12] A. Dumitru and J. Jalilian-Marian, Phys. Rev. Lett. **89**, 022301 (2002).

[13] D. Kharzeev, Y. V. Kovchegov, and K. Tuchin, Phys. Lett. B **599**, 23 (2004).

[14] A. Dumitru, A. Hayashigaki, and J. Jalilian-Marian, Nucl. Phys. A **765**, 464 (2006); **770**, 57 (2006).

[15] E. Iancu, A. Leonidov, and L. McLerran, Nucl. Phys. A **692**, 583 (2001); E. Ferreiro, E. Iancu, A. Leonidov, and L. McLerran, *ibid.* **703**, 489 (2002); J. Jalilian-Marian, A. Kovner, L. McLerran, and H. Weigert, Phys. Rev. D **55**, 5414 (1997); J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, *ibid.* **59**, 014014 (1998); J. Jalilian-Marian, A. Kovner, and H. Weigert, *ibid.* **59**, 014015 (1998); J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, *ibid.* **59**, 034007 (1999); A. Kovner, J. G. Milhano, and H. Weigert, *ibid.* **62**, 114005 (2000); H. Weigert, Nucl. Phys. A **703**, 823 (2002).

[16] I. Balitsky, Nucl. Phys. B **463**, 99 (1996); Y. V. Kovchegov, Phys. Rev. D **60**, 034008 (1999); **61**, 074018 (2000).

[17] K. Golec-Biernat and M. Wusthoff, Phys. Rev. D **59**, 014017 (1998); **60**, 114023 (1999).

[18] J. Bartels, K. Golec-Biernat, and H. Kowalski, Phys. Rev. D **66**, 014001 (2002); H. Kowalski and D. Teaney, *ibid.* **68**, 114005 (2003); E. Iancu, K. Itakura, and S. Munier, Phys. Lett. B **590**, 199 (2004); H. Kowalski, L. Motyka, and G. Watt, Phys. Rev. D **74**, 074016 (2006); V. P. Goncalves, M. S. Kugeratski, M. V. T. Machado, and F. S. Navarra, Phys. Lett. B **643**, 273 (2006); C. Marquet, R. Peschanski, and G. Soyez, Phys. Rev. D **76**, 034011 (2007); G. Soyez, Phys. Lett. B **655**, 32 (2007); G. Watt and H. Kowalski, Phys. Rev. D **78**, 014016 (2008).

[19] M. A. Betemps and V. P. Goncalves, J. High Energy Phys. 09 (2008) 019.

[20] A. M. Staśto, K. Golec-Biernat, and J. Kwieciński, Phys. Rev. Lett. **86**, 596 (2001).

[21] C. Marquet and L. Schoeffel, Phys. Lett. B **639**, 471 (2006).

[22] V. P. Goncalves and M. V. T. Machado, Phys. Rev. Lett. **91**, 202002 (2003); J. High Energy Phys. 04 (2007) 028.

[23] A. D. Martin, W. J. Stirling, and R. S. Thorne, Phys. Lett. B **636**, 259 (2006).

[24] B. A. Kniehl, G. Kramer, and B. Pötter, Nucl. Phys. B **582**, 514 (2000).

[25] I. G. Bearden *et al.* (BRAHMS Collaboration), Phys. Rev. Lett. **93**, 102301 (2004).

[26] H. H. Dalsgaard, Int. J. Mod. Phys. E **16**, 1813 (2007).

[27] I. C. Arsene *et al.* (BRAHMS Collaboration), Phys. Lett. B **677**, 267 (2009).

[28] H. Appelshauser *et al.* (NA49 Collaboration), Phys. Rev. Lett. **82**, 2471 (1999).

[29] R. Debbe (BRAHMS Collaboration), J. Phys. G **35**, 104004 (2008).

[30] F. Videbaek and O. Hansen, Phys. Rev. C **52**, 2684 (1995); L. Ahle *et al.* (E802 Collaboration), *ibid.* **60**, 064901 (1999); B. B. Back *et al.* (E917 Collaboration), Phys. Rev. Lett. **86**, 1970 (2001).

[31] J. L. Albacete and Y. V. Kovchegov, Nucl. Phys. A **781**, 122 (2007).

[32] L. McLerran and R. Venugopalan, Phys. Rev. D **49**, 2233 (1994).

[33] K. Itakura, Y. V. Kovchegov, L. McLerran, and D. Teaney, Nucl. Phys. A **730**, 160 (2004).

[34] B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. Lett. **97**, 152301 (2006); B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. C **79**, 034909 (2009); B. I. Abelev *et al.* (STAR Collaboration), Phys. Lett. B **655**, 104 (2007); S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **91**, 172301 (2003); J. Adams *et al.* (STAR Collaboration), *ibid.* **92**, 052302 (2004).

[35] R. C. Hwa and C. B. Yang, Phys. Rev. C **67**, 034902 (2003); V. Greco, C. M. Ko, and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003); R. J. Fries, B. Muller, C. Nonaka, and S. A. Bass, Phys. Rev. C **68**, 044902 (2003).

[36] S. J. Brodsky and A. Sickles, Phys. Lett. B **668**, 111 (2008).

[37] V. Topor Pop, M. Gyulassy, J. Barrette, and C. Gale, Phys. Rev. C **84**, 044909 (2011).

[38] B. B. Abelev *et al.* (ALICE Collaboration), arXiv:1307.6796 [nucl-ex].

[39] T. Sako *et al.* (LHCf Collaboration), invited talk at XVI International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2010), Batavia, IL, USA, 28 June 2 July 2010, http://www.slac.stanford.edu/econf/C1006284.

[40] O. Adriani, L. Bonechi, M. Bongi, G. Castellini, R. D'Alessandro, A. Faus, K. Fukatsu, M. Haguenauer, Y. Itow, and K. Kasahara *et al.* (LHCf Collaboration), Nucl. Phys. B, Proc. Suppl. **212–213**, 270 (2011).

[41] G. H. Arakelyan, C. Merino, C. Pajares, and Y. M. Shabelski, Phys. Atom. Nucl. **76**, 316 (2013).