

Net baryon production in the CGC formalism

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Abstract. In this work the net-baryon production at forward rapidities is investigated considering the CGC 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 LHC energies are presented. We also extend previous studies to pp and pA collisions and estimate for the first time 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, for leading baryon production.

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.

At higher energies new phenomena are expected to affect forward baryon production and at large rapidities, baryon production requires the interaction of valence quark with a relatively large momentum fraction (x_1) of the projectile with low fractional momentum (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. The CGC is characterized by a momentum scale (Q_s) which marks the onset of nonlinear (or saturation) effects and grows with the reaction energy. 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 (see [1] and references there in).



In the CGC formalism the differential cross section for the forward production of a hadron of transverse momentum p_T and mass m , at rapidity y , reads [1]:

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

where $D(z) \equiv D_{B/q}(z) - D_{\bar{B}/q}(z)$ is the net-baryon fragmentation function, $z = E_B/E_q$ is the fraction of the energy of the fragmenting quark (E_q) taken by the emerging baryon B , the variable q_T is the quark transverse momentum and x_F represents the Feynman- x momentum of the produced baryon.

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:

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

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 [2] by the BK equation [3]. This quantity encodes the information about the hadronic scattering and then about the non-linear and quantum effects in the hadron wave function. 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 HERA and RHIC data.

In general, it is assumed that it can be modelled through a simple Glauber-like formula, which reads

$$\mathcal{N}(x, r_T) = 1 - \exp \left[-\frac{1}{4} (r_T^2 Q_s^2)^{\gamma(x, r_T)} \right], \quad (3)$$

where $\gamma(x, r_T)$ 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 DGLAP regime.

In this paper we restrict our analyses to 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 [4]. Another feature of the BUW model which motivates this analysis is that it explicitly satisfies the property of geometric scaling [5], 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

$$\begin{aligned} \gamma(x, r_T) &= \gamma_s + \Delta\gamma(x, r_T) \\ &= \gamma_s + (1 - \gamma_s)(\omega^a - 1) [(\omega^a - 1) + b]^{-1}, \end{aligned} \quad (4)$$

where $\omega \equiv 1/(r_T Q_s(x))$, $\gamma_s = 0.628$ and the two free parameters $a = 2.82$ and $b = 168$ are fitted in such a way to describe the RHIC data on hadron production [4].

Besides, in comparison with other phenomenological parameterizations, 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. [6] the nonlinear effects were taken into account considering the model (called here the MTW model) proposed long ago by Golec-Biernat and Wusthoff [7], where the forward dipole scattering amplitude is given by

Eq. (3) with $\gamma = 1$. 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 model implies that the r_T integration in Eq. (2) can be carried out analytically and a simple expression for the unintegrated gluon distribution can be obtained:

$$\varphi(x_2, q_T) = 4\pi \frac{q_T^2}{Q_s^2(x_2)} \exp\left(-\frac{q_T^2}{Q_s^2(x_2)}\right). \quad (5)$$

The net-baryon rapidity distribution is obtained integrating Eq. (1) in p_T between $p_{T_{min}} = 0$ and $p_{T_{max}} = \sqrt{s} e^{-y}$. The upper limit $p_{T_{max}}$ comes from the kinematical condition $x_F < 1$. Following Ref. [6] we assume that the nuclear valence quark distribution is given by $x q_v^A(x, Q^2) = N_{part} x q_v^p(x, Q^2)$, with N_{part} being the number of participants. The proton valence quark distribution is described by the MRST01-LO parametrization [8]. For the fragmentation function we use the KKP parametrization [9].

Substituting (5) 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 (see references and discussions in [1]). 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 (the GBW curves below represent the predictions resulting from the substitution of the phenomenological model for the fragmentation function by the KKP parametrization).

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 $N_{part} = 315$ 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 that here the baryons are not produced by independent quark fragmentation.

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

$$R_{pA} = \frac{d^2 N_{pA}}{dy d^2 p_T} / A \frac{d^2 N_{pp}}{dy d^2 p_T}. \quad (6)$$

In Fig. 3 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. In contrast to the approach discussed in Ref. [10], which focus 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. [11]. As already emphasized in Ref. [10], both approaches are complementary. However, the behavior of R_{pA} in the latter approach is still an open issue.

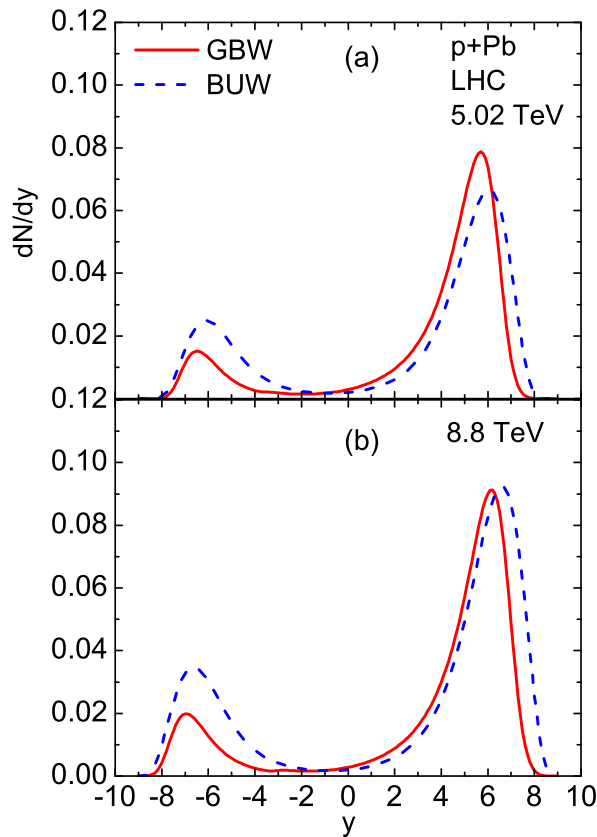


Figure 1. Net-baryon rapidity distributions in central $PbPb$ collisions at LHC energies.

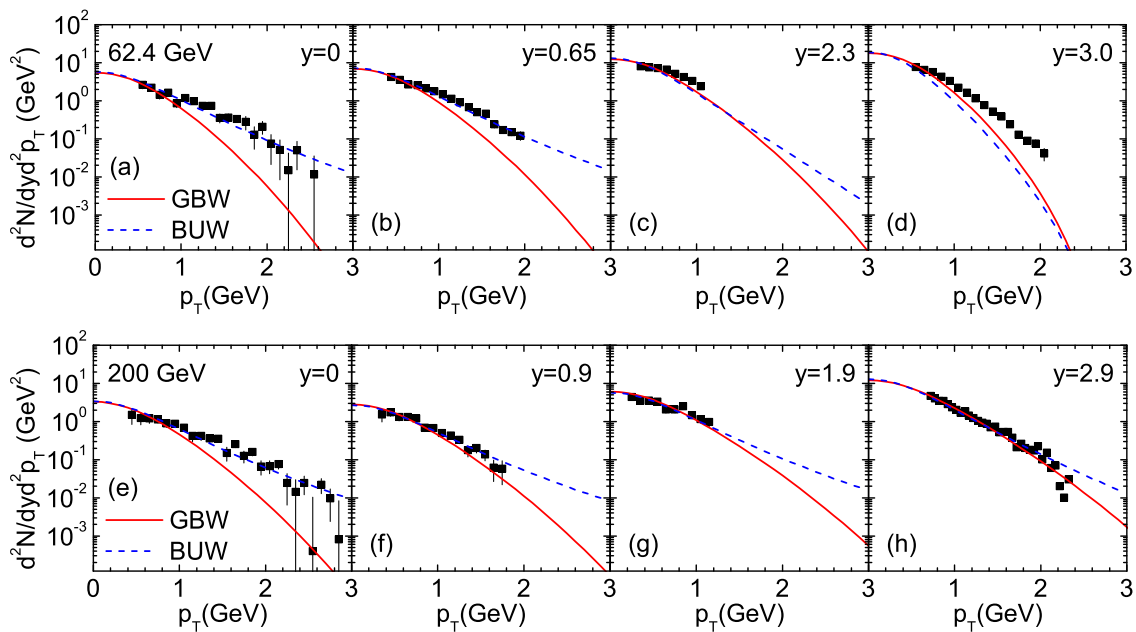


Figure 2. Net-baryon transverse momentum spectra in central $AuAu$ collisions at RHIC.

In this work we have improved the CGC formalism of forward particle production developed

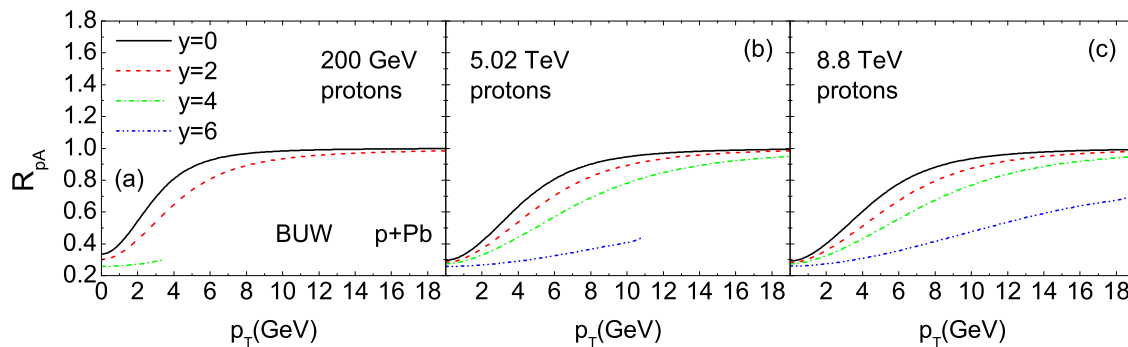


Figure 3. Nuclear modification ratio, R_{pA} , for net-proton production in pPb collisions at RHIC and LHC energies.

in [4, 6, 11] (the study of rapidity distributions, p_T and x_F spectra of forward protons and pions can be found in [1]). 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. A solid conclusion about this change of mechanism still requires further theoretical and experimental work.

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.

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