Baryon stopping and Feynman scaling in the color glass condensate approach

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Abstract. In this work baryon stopping and leading baryon production are investigated in the context of the color glass condensate (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 find that at very high energies the leading baryon $x_F$ spectra become nearly energy independent and we reach the approximate Feynman scaling regime.

1. 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.

1.1. Leading baryons

The outgoing baryons which have large longitudinal momentum ($x_F \geq 0.2$) and the same valence quarks (or at least one of them) as the incoming particles are called leading particles (LP).

The momentum spectra of leading particles have been measured already some time ago [1]. Recently, data on leading protons and neutrons produced in electron-proton reactions at HERA with a c.m.s. energy one order of magnitude higher became available [2]. In the case of photoproduction data can be interpreted in terms of the Vector Dominance Model and can...
therefore be considered as data on LP production in vector meson-proton collisions. These measurements of LP spectra both in hadron-hadron and in electron-proton collisions have renewed the interest on the subject, specially because the latter are measured at higher energies and therefore the energy dependence of the LP spectra can now be determined. It is important to have a very good understanding of these spectra for a number of reasons. They are the input for calculations of the LP spectra in hadron-nucleus collisions, which are a fundamental tool in the description of atmospheric cascades initiated by cosmic radiation. The precise knowledge of energy flow (LP spectra and inelasticity distributions) is necessary to interpret the results obtained in cosmic ray experiments, such as the Pierre Auger Collaboration.

In high energy heavy ion collisions at RHIC and LHC, the expression leading baryon spectrum is less used. Instead, we speak of baryon stopping to talk about essentially the same concept, namely the momentum (or rapidity) distribution of baryons emerging from valence quarks after the collision. As expected, the valence quarks are found at rapidities lower than the beam rapidities, and we say that they have been partially stopped. It is very important to know where the outgoing (leading) baryons are located in momentum space. If the stopping is large they will stay in the central rapidity region and affect the dynamics there, generating, for example, a baryon rich equation of state. The composition of dense matter is therefore relevant for the study of quark gluon plasma formation. In any case, before modelling p-A or A-A collisions one has to understand properly hadron-hadron processes. The LP spectra are also interesting for the study of diffractive reactions, which dominate the large $x_F$ region. Since LP spectra are measured in reactions with low momentum transfer and go up to large $x_F$ values, it is clear that the processes in question happen, at least partially, in the non-perturbative domain of QCD.

1.2. Perturbative QCD and gluon saturation

In the framework of the QCD parton model of high energy collisions, leading particles originate from the emerging fast partons of the collision debris. There is a large rapidity separation between fast partons and sea partons. Fast partons interact rarely with the surrounding wee partons. The interaction between the hadron projectile and the target is primarily through wee parton clouds. Fast partons might therefore filter through essentially unaltered. Based on these observations and aiming to study p-A collisions, the authors of Ref. [3] proposed a mechanism for LP production in which the LP spectrum is given by the convolution of the parton momentum distribution in the projectile hadron with its corresponding fragmentation function into a final leading hadron. This independent fragmentation scheme was, however, not supported by the then existing leading baryon spectra measurements [1]. It was shown that the essential ingredient to correctly reproduce the data was valence quark recombination [4]. Indeed, at lower energies ($\sqrt{s} \approx 10 - 60$ GeV) what happens is rather a coalescence of valence quarks to form the LP and not an independent fragmentation of a quark or diquark to a nucleon. At higher energies this situation may change. Due to quantum evolution, the colliding systems become extremely dense and the average momentum transfer also increases. The incident proton constituents scatter, experience a large momentum transfer, the coherence of the projectile is destroyed completely and the scattered quarks and gluons fragment independently. As a consequence, the proton decays predominantly into a beam of “fast” mesons, with the baryon number shifted to small momentum fraction ($x_F \leq 0.1$). This mechanism of LP production implies a strong energy loss by the valence quarks and the consequent strong enhancement of the energy used to produce secondary particles, the so called inelasticity. In [5] this possibility was considered with the inclusion of gluon saturation effects. The authors pointed out that, while the change from valence quark recombination to independent fragmentation is a natural consequence of the hardening of the collisions, the precise energy at which this transition happens is determined by the saturation scale. In [6] it was shown that, assuming that valence quark recombination
would still dominate LP production at very high energies, the role played by gluon saturation would be just to slow down the softening trend of LP spectra with increasing energies. It is however a very modest effect. The final conclusion was that, as long as quarks recombination (a non-perturbative phenomenon) remains the dominant mechanism of LP production, the LP spectrum will not be a good place to search for gluon saturation effects.

A few years later, after the publication of the net-baryon rapidity distribution data by the BRAHMS Collaboration, the authors of [7] carried out an analysis of these data using a color glass condensate model in which valence quarks traverse the nuclear target, interacting and fragmenting independently into baryons. In a nuclear target the saturation scale is considerably larger than in a nucleon, even when the latter has much higher energies. They computed the rapidity distributions and transverse momentum spectra, obtaining an overall good agreement with data. At lower energies and larger rapidities they were not able to reproduce the $p_T$ spectra. This could be an indication of the breakdown of independent fragmentation at lower energies. In [8] we repeated their calculation introducing a more reliable dipole scattering cross section. As a result we obtained a better fit of the spectra, but the discrepancy between the model predictions and the low energy data persisted. In this contribution we discuss these calculations giving special attention to the LP spectra obtained with the same model and their behavior at very high energies.

2. Net-baryon production and the color glass condensate

As mentioned above, at higher energies new phenomena are expected to affect forward baryon production. This process requires the interaction of valence quarks with a relatively large momentum fraction ($x_1$) of the projectile with low 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 [8] and references therein).

In the CGC formalism the differential cross section of forward production of a hadron with transverse momentum $p_T$ and mass $m$, at rapidity $y$, reads [8]:

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

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. Furthermore, $x_1 q_v(x_1)$ 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 [9] by the BK equation [10]. This quantity encodes the information about the hadronic scattering and hence about the non-linear and quantum effects in the hadron wave function.
In general, it is assumed that it can be modelled through a simple Glauber-like formula, which reads
\[ N(x, r_T) = 1 - \exp \left[-\frac{1}{4} (r_T^2 Q_s^2) \gamma(x, r_T) \right], \tag{3} \]
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 contribution we restrict our analysis 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 [11]. In the BUW model, the anomalous dimension is given by
\[ \gamma(x, r_T) = \gamma_s + \Delta \gamma(x, r_T) \]
\[ = \gamma_s + (1 - \gamma_s)(\omega^a - 1) [ (\omega^a - 1) + b ]^{-1}, \tag{4} \]
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 [11]. 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:
\[ \varphi(x_2, q_T) \propto 1/ q_T^4 \]
In contrast, in Ref. [7] (called here the MTW model) the nonlinear effects were taken into account considering the model proposed long ago by Golec-Biernat and Wusthoff [12], where the forward dipole scattering amplitude is given by Eq. (3) with \( \gamma = 1 \). In this model the \( r_T \) integration in Eq. (2) can be carried out analytically and a simple expression for the unintegrated gluon distribution can be obtained:
\[ \varphi(x_2, q_T) = 4\pi q_T^2 \frac{Q_s^2(x_2)}{Q_s^2(x_2)} \exp \left(-\frac{q_T^2}{Q_s^2(x_2)} \right). \tag{5} \]

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.

3. Results

3.1. Net-baryon production

The net-baryon rapidity distribution is obtained integrating Eq. (1) in \( p_T \) between \( p_{T_{\text{min}}} = 0 \) and \( p_{T_{\text{max}}} = \sqrt{\epsilon e^{-y}} \). The upper limit \( p_{T_{\text{max}}} \) comes from the kinematical condition \( x_F < 1 \). Following Ref. [7] we assume that the nuclear valence quark distribution is given by \( x q^A_v(x, Q^2) = N_{\text{part}} x q^p_v(x, Q^2) \), with \( N_{\text{part}} \) being the number of participants. The proton valence quark distribution is described by the MRST01-LO parametrization [13]. For the fragmentation function we use the KKP parametrization [14].

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 [8]). 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 [8].

As an illustration, in Fig.1 we present the results for nucleus-nucleus collisions at RHIC and LHC energies (the GBW curves below represent the predictions resulting from the substitution of the phenomenological model for the fragmentation function used in [7] by the KKP parametrization).

![Figure 1](image_url)

**Figure 1.** Net-baryon rapidity distributions in PbPb collisions at SPS energies and in AuAu collisions at RHIC energies. Data from [15, 16, 17, 18, 19, 20].

In Fig.2 we present our predictions for the net-baryon transverse momentum spectra in central AuAu collisions at RHIC energies. As in Ref. [7] we have assumed \(N_{\text{part}} = 315\) 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.

3.2. Leading particle spectra and Feynman scaling

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 off light nuclei in the air. In each of these collisions, a projectile proton (the leading baryon) loses 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 non-existence 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 [21, 22].

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.3. In all panels we can clearly see a shift to smaller values of $x_F$, indicating a very slow softening of the leading particle spectrum. This approximate Feynman scaling is quite different from the behavior found in [6], where a much stronger softening of the LP spectra was observed. The difference between the two results can be traced back to difference between valence quark recombination and independent fragmentation. Whereas in the former energy loss is a complex phenomenon, which involves the whole baryon and changes more rapidly with the energy, in the latter a single valence quark interacts with the target and the LP spectrum changes only until the target reaches its high density limit. From this point on LP is approximately frozen.

The study of leading particle spectra will gain a new interest in view of the proposals of upgrades of the existing experimental facilities. In [23], the authors proposed an experiment...
for the precise measurements of very forward particle production at RHIC. The proposal is to install a LHCf-like calorimeter in the ZDC installation slot at one of the RHIC interaction points. By installing a high-resolution electromagnetic calorimeter at this location it would be possible to measure the spectra of photons, neutrons and $\pi^0$ at pseudo rapidities above 6. The new measurements at 500 GeV p-p collisions would contribute to improve the hadronic interaction models used in the cosmic-ray air shower simulations. Using a similar kinematic coverage at RHIC to that of the measurements at LHC, it would be possible to test the Feynman scaling with a wide energy range and make the extrapolation of models into cosmic-ray energy more reliable.

4. Summary

In this work we have improved the CGC formalism of net-baryon production developed in [7] (a more detailed study of rapidity distributions, $p_T$ and $x_F$ spectra of forward protons and pions can be found in [8]). 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 with independent valence quark fragmentation we observe an approximate Feynman scaling at very high energies.
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