Forward particle production in the CGC formalism: average transverse momentum and τ scaling

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Abstract. In this work we have used the Color Glass Condensate (CGC) formalism of forward particle production to describe the transverse momentum spectra of charged particles in proton-lead collisions at the LHC. We have also investigated the rapidity dependence of the average transverse momentum, \( < p_T > \), and the so called scaling variable, \( \tau = p_T^2/Q_s^2 \), where \( Q_s \) represents the saturation scale of these processes. We have computed the ratios of the first quantity at a given rapidity \( y \) to the value at \( y = 0 \) (going from \( y = 0 \) towards the proton fragmentation region) at the LHC energies. The ratios of the second quantity have been computed to the normalized \( \tau \) distributions. Our analysis, based on gluon saturation and geometrical scaling, shows that these ratios decrease strongly with \( y \) above midrapidities and increase slightly with the energy. We briefly discuss the implications of our results and present predictions for the forthcoming LHC data.

Recent experiments at the LHC have measured charged hadron rapidity and transverse momentum distributions in proton-proton (\( pp \)), proton-lead (\( pPb \)) and lead-lead (\( PbPb \)) collisions in a new domain of collision energy. The quantities measured in these collisions are very sensitive to the underlying dynamics, to the initial conditions of the created system and to the hadronic final state interactions.

Many questions about the dynamics of interaction between partons in these processes remain still open. It is expected that a system of gluons at high energy (or small Bjorken-\( x \)) forms a new state of matter, the Color Glass Condensate (CGC), where the gluon density increases inside the hadron wave function and becomes very large in comparison to all other parton species (valence and sea quarks). This growth eventually saturates and reaches the regime of “parton saturation”, characterized by a momentum scale \( (Q_s) \), the so called saturation scale, which marks the onset of nonlinear (gluon recombination) effects and grows with the reaction energy. In fact, the CGC has now become an effective theory which describes the gluon content of a high energy hadron or nucleus in the saturation regime and many saturation models have been proposed (see [1] and references therein).

It is important to emphasize that the data from the LHC will allow to probe the nuclear gluon distribution at very small Bjorken-\( x \) (\( \approx 10^{-6} \)) and, therefore, to test the nature and the properties of the CGC. Of course, many models will also be put to the test.
In this work we adopt the hybrid formalism of the CGC \[2, 3, 4\] to compute the cross section of inclusive charged hadron production at the LHC energies. In this formalism the large-x degrees of freedom of the proton are described in terms of usual parton distribution functions (PDF) of collinear factorization with a scale dependence given by the DGLAP evolution equations. The small-x glue of the nucleus is described in terms of its unintegrated gluon distribution (UGD).

At leading order, the cross section for single-inclusive forward hadron production (with rapidity \(y\) and transverse momentum \(p_T\)) in high-energy nucleon-nucleus collisions is described in terms of the dipole scattering amplitude in the following way:

\[
\frac{dN^{pA-hX}}{dydp_T^2} = \frac{K}{(2\pi)^2} \int_0^1 \frac{dz}{z^2} \sum_q x_1 f_q(x_1, Q^2) \tilde{N}_F(x_2, \frac{p_T}{z}) D_q(z, Q^2) + x_1 f_g(x_1, Q^2) \tilde{N}_A(x_2, \frac{p_T}{z}) D_g(z, Q^2),
\]

where the \(K\)-factor effectively accounts for NLO corrections, \(x_{1,2} = e^{\pm y} p_T/z/\sqrt{s}\) and \(z \equiv x_F/x_1\).

In order to compare our results to the final state distributions of measured charged particles one has to translate the rapidity distributions into pseudo-rapidity distributions through the corresponding Jacobian transformation, \(y \rightarrow \eta, (, x_F = e^\eta \sqrt{p_T^2 + m^2/\sqrt{s}}, where \(m\) represents an average mass of the produced particles). The parton distribution functions \(f_{q(g)}\) and the fragmentation functions \(D_{q(g)}\) are considered at the scale \(Q^2\), and \(\tilde{N}_{F(A)}\) describes a quark (gluon) scattering off the nucleus, in the fundamental (adjoint) representation and encodes the information about the hadronic scattering and thus about the non-linear and quantum effects in the hadron wave function.

In the hybrid formalism, the forward scattering amplitude of a color dipole of radius \(r_T\) off a nucleus target, \(\tilde{N}_A\), is given by

\[
\tilde{N}_A(x_2, q_T) = \int d^2 r_T e^{i\vec{q}_T \cdot \vec{r}_T} N_A(r_T, x_2, q_T),
\]

\[
N_A(r_T, x_2, q_T) = 1 - \exp\left\{-\frac{1}{4} q_T^2 Q_s^2(x_2) \gamma^{(x_2, q_T)}\right\}
\]

The corresponding expression for quarks, \(\tilde{N}_F\), is easily obtained from \(N_A\) by the replacement \((r_T^2 Q_s^2) \gamma \rightarrow ((C_F/C_A)r_T^2 Q_s^2)\gamma\), with \(C_F/C_A = 4/9\).

The main difference among the distinct phenomenological models comes from the behavior of the “anomalous dimension” of the target gluon distribution, \(\gamma(x_2, q_T)\), which determines the transition from the nonlinear to the extended “geometric scaling” regime (it is well known that the small-x Deep Inelastic Scattering data show geometric scaling \[5\]), as well as from the extended geometric scaling to the DGLAP regime. This means that the cross sections depend on \(Q^2/Q_s^2(x)\) only, instead of \(Q^2\) and \(x\) independently. In such a regime, of course, the geometric scaling arises as a feature of saturation from nonlinear evolution equations.

In this work we restrict our analysis to the so-called BUW model \[4\], 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. Another feature of the BUW model which motivates this analysis is that it explicitly satisfies the property of geometric scaling, 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 \(\gamma(x, q_T) = \gamma_s + \Delta\gamma_{BUW}(x, q_T)\), with

\[
\Delta\gamma_{BUW}(x, q_T) = (1 - \gamma_s)(\omega^a - 1) \left[ (\omega^a - 1) + b \right]^{-1},
\]

where \(\omega \equiv q_T/Q_s(x), \gamma_s, a\) and \(b\) are free parameters of the model.
Moreover in the BUW model the behavior expected for the unintegrated gluon distribution in the large $p_T$ limit (linear regime) is recovered: $\varphi(x_2, q_T) \propto 1/q_T^2$ at large $q_T$ (or, equivalently, for small $r_T$). For larger $\omega$ the exponent in Eq. (2) can be expanded and the dipole scattering amplitude simplifies to:

$$N_A(q_T) \approx \frac{2\pi 2^{2\gamma(w)-1} Q_{*}^{2\gamma(w)+2}}{q_T^{2\gamma(w)+2}} \frac{\Gamma(1 + \gamma(w))}{\Gamma(-\gamma(w))}$$

$$\gamma(w) \rightarrow 4\pi Q_s^2 \frac{1 - \gamma(w)}{q_T^2} \ll 1 \propto Q_s^2 + a_s q_T^4 + a_T$$

if possible $y$ dependencies are suppressed.

In what follows we assume that the saturation scales in adjoint and fundamental representations are given, respectively, by $Q_{s,A}^2 = A^{1/3} Q_0^2 (x_0/x_2)^\lambda$ and $Q_{s,F}^2 = 4/9 Q_{s,A}^2$, with $Q_0^2 = 1 \text{GeV}^2$, $x_0 = 3 \times 10^{-4}$, $\lambda = 0.288$ and $A \equiv A_{Pb} = 208$. We also assume the CTEQ5-LO [6] and KKP [7] parameterizations for the parton distribution and fragmentation functions, respectively, at the scale $Q^2 \equiv m^2 + p_T^2$ and a $y$-dependent $K$-factor for NLO corrections.

In Figure 1 we present our results (in the large $\omega$ limit) for charged particle distributions in $pPb$ collisions, at LHC with energy $\sqrt{s} = 5.02 \text{TeV}$ [8], for three different windows of pseudo-rapidity: a) $|\eta| < 0.3$, b) $0.3 < \eta < 0.8$ and c) $0.8 < \eta < 1.3$. In these calculations we have adopted, respectively, $<\eta> = 0$ ($K = 2.0$), $<\eta> = 0.525$ ($K = 2.1$) and $<\eta> = 1.05$ ($K = 2.2$). In all cases, the (free) parameters of the model are $\gamma_s = 0.80$, $a = 2.73$, $b = 470$ and $m = m_\pi$. As can be seen our results exhibit a reasonable agreement with data.

![Figure 1. Charged particle distributions in $pPb$ collisions at LHC.](image-url)
Inspired by Ref. [9], we shall investigate the rapidity dependence of the average transverse momentum ($<p_T>$) and the scaling variable ($<\tau = p_T^2/Q_s^2>$). To this end we have computed the following ratios:

$$R_1(y,s) = \frac{<p_T>(y,s)}{<p_T>(y,s)} |_{y=0}; \quad <p_T>(y,s) = \int d^2p_T \frac{dN}{dyd^2p_T}$$

$$R_2(y,s) = \frac{<\tau>(y,s)}{<\tau>(y,s)} |_{y=0}; \quad <\tau>(y,s) = \int \frac{d\tau}{d^2p_T} \frac{dN}{dyd\tau}$$

With the same parameters fixed before, in Figure 2 we present the ratios above at the LHC energies. As can be seen our analysis, based on gluon saturation and geometrical scaling, shows that these ratios decrease strongly with $y$ (above midrapidities) and increase slightly with the energy. It is important to note that our first result is compatible with that predicted by the collective expansion picture in the hydrodynamic framework. Our second result tells us that the geometrical scaling violation increase with $y$ but is slightly smaller for higher energies.

![Figure 2.](image-url) Rapidity dependence of the average transverse momentum (a) and the geometrical scaling variable (b).

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