Forward particle production in proton-nucleus collisions at the LHC

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Abstract. We present the current theory status on the particle production in the forward region in proton-nucleus (p+A) collisions based on the Color Glass Condensate framework. The cross-section expressed in a factorized form with the dipole amplitude which is related to the unintegrated gluon distribution. Energy dependence of the dipole amplitude is controlled by the nonlinear $x$-evolution equation and constrained by e+p scattering data at HERA. The transverse geometry of the target is modeled as an assembly of the nucleons distributed with the Woods-Saxon profile. We show our prediction for the nuclear modification factor of the hadron multiplicity in p+A reactions at the LHC energy.

1. Introduction — the CGC picture —
At the Large Hadron Collider (LHC) one can explore hadronic reactions in unprecedentedly wide range of kinematics. Vast majority of particles are produced there with transverse momentum $p_{\perp}$ at a few GeV/$c$, which corresponds to particle production from extremely small Bjorken’s $x = p^+/P^+$ components\(^1\) because $P^+ \propto \sqrt{s}$. The small-$x$ partons emerge from the short-time quantum fluctuations in light-cone perturbation theory. The higher the collision energy is, the shorter-lived fluctuations (partons) participate in the reaction according to the Lorentz time dilation (the BFKL cascade). Such a growth of the gluon distribution at small $x$ is observed in e+p scattering experiments at HERA. Moreover, at some point in the density growth, parton merging should become operative to make the dynamics nonlinear even in the small coupling framework.

The QCD effective theory for the dense small-$x$ degrees is formulated as Color Glass Condensate (CGC) [1], which describes a new universal aspect of QCD – emergence of a dynamic scale for the parton density per unit transverse area, so-called saturation scale, $Q_s^2(x)$. In e+p scatterings, the quark pair dissolved from the virtual photon, interacts coherently with the color field created by this dense gluon system of density $Q_s^2(x)$. This CGC picture involves

- multiple scatterings in the target (Cronin peak),
- gluon density depletion compared to the linear BFKL cascade.

In case of a nucleus of mass number $A$, the pair probes the color charge in the nucleons in the target as a whole. Dense valence charge density $xG(x,Q^2)/\pi R^2 \propto A^{1/3}$ enhances the nonlinearity of the dynamics, yielding stronger gluon depletion in the nuclear target even at moderate values of $x$.

\(^1\) Here $p^\pm$ are the light-cone momenta of the parton, $p^\pm = (p^0 \pm p^3)/\sqrt{2}$, and $P^\pm$ of the incident nucleon.
The significance of p+Pb collisions at the LHC is:
- the control experiment to A+A collisions for disentangling the initial from final state effects
- to check the relevance of the CGC by comparing p+A with p+p in wider kinematics.

2. CGC phenomenology
A current practical tool for the CGC analysis is the Balitsky-Kovchegov equation improved with running coupling corrections (rcBK equation) [2, 3]. The rcBK equation describes the $x$-evolution of the dipole amplitude $\tilde{N}_F(k, x)$ in the fundamental representation, resumming the $\alpha_s \ln(1/x)$ corrections and including the gluon recombination effects. The running coupling improvement gives rise to $x$-dependence of $Q^2_s(x)$ consistent with the empirical estimate[4, 5].

2.1. Constraining parameters
The amplitude $\tilde{N}_F(k, x)$ is confronted with the compiled e+p data at HERA within the dipole model in Ref. [6]. Setting the initial condition

$$1 - N(r, x_0 = 0.01) = \exp \left[ -\frac{(r^2 Q^2_{s0})^\gamma}{4} \ln \left( \frac{1}{r A_{QCD}} + e \right) \right]$$

(1)

with the transverse size $r$, they successfully fit the data with certain parameter sets. Here we use the modified sets as given in Table 1 which are obtained with a smooth regulator for the coupling constant, $\alpha_s(r) = 4\pi/(9 \ln[4C^2/(r^2 A^2_{QCD}) + a])$ (constant $a$ is adjusted by $\alpha_s(\infty) = \alpha_{tr}$). The result is insensitive to the infrared region as far as $Q^2_s \gg A^2_{QCD}$. The parameter $\gamma > 1$ is needed to fit the $p_{T}$ slope (Fig. 1).

We still need a model for a nuclear target. Following Ref. [7], we distribute the nucleons stochastically in the nucleus with the Woods-Saxon profile, and set locally the saturation scale as

$$Q^2_{s0,A} = N \times Q^2_{s0}$$

(2)

with $N$ the number of the nucleons along the trajectory of the projectile nucleon (Fig. 2).

Table 1. Fit parameters. Set “MV” is for comparison. $A_{QCD} = 0.241$ GeV.

| set  | $Q^2_{s0,A}$/GeV$^2$ | $\gamma$ | $\alpha_{tr}$ | $C$ |
|------|---------------------|---------|--------------|-----|
| MV   | 0.2                 | 1       | 0.5          | 1.0 |
| h    | 0.1597              | 1.118   | 1.0          | 2.47|
| h’   | 0.157               | 1.101   | 0.8          | 1.0 |

Figure 1. Tail of proton’s $\tilde{N}_F(k, x)$ at $\ln(x_0/x) = 0, 1.5, 3, 6$ for sets h’ and MV.

Figure 2. $k^2\tilde{N}_A(k, x)$ at $x = 3 \times 10^{-4}$ evolved from $x_0 = 0.01$ with $Q^2_{s0,A} = (1, 6, 12) \times Q^2_{s0}$. 
2.2. Forward particle production formula

The sets in Table 1 are examined with the LHC p+p data in the mid-rapidity region, using the $k_t$ factorization formula. The sets with $\gamma \sim 1.1$ result in a good description for the data [8, 9].

The forward particle production with rapidity $y > 0$, where $x_{1,2} = (p_{T}/z\sqrt{s})e^{\pm y}$ in $2 \to 1$ kinematics, has more sensitivity to the small-$x_2$ distribution. The cross-section is given in the factorized formula of Dumitru, Hayashigaki, and Jalilian-Marian (DHJ) [10]:

$$
\frac{dN}{dy_h d^2p_T} = \frac{K}{(2\pi)^2} \sum_{i=q,g} \int_{x_F}^{1} \frac{dz}{z} x_1 f_{i/p}(x_1, p_{T}^2) \tilde{N}_{i}(\frac{p_{T}}{z}, x_2) D_{h/i}(z, p_{T}^2),
$$

(3)

where $y_h$ and $p_{T}$ are the rapidity and transverse momentum of the produced hadron $h$, respectively. The $f_{i/p}(x_1, Q^2)$ is the collinear distribution function for the large-$x_1$ parton $i$, $\tilde{N}_{F,A}(k, x_2)$ the fundamental/adjoint dipole amplitude at small $x_2$, and $D_{h/i}$ the fragmentation function of a parton $i$ into a hadron $h$ with the momentum fraction $z$. This DHJ formula is obtained in the LO accuracy, and the constant parameter $K$ may absorb some part of higher order effects. We shall keep the parameters $x_0$ and $K$ be the same for $p$ and $A$, although we need $K$ dependent on the produced hadron species. Once we fix these in e+e and p+p collisions and $Q^2_{x0,A}$ by Eq. (2), we have no additional parameters.

3. Results

We use the parametrizations of CTEQ6M NLO [11] and DSS NLO [12] for $f_{i/p}$ and $D_{h/i}$, respectively, and choose the factorization scale to $\mu^2 = p_{T}^2$. We show in Fig. 3 our results on transverse momentum distributions of negatively charged hadrons $h^-$ at pseudo-rapidities $\eta = 2.2$ and $3.2$, and of neutral pions $\pi^0$ at $\eta = 4$ in pp and d+Au collisions at $\sqrt{s} = 200$ GeV [13, 9]. Data at $\eta = 2.2$ and $3.2$ (4) are taken from BRAHMS [14] (STAR [15]). The set $h'$ with $K = 1.0$ (0.4) describes the forward particle multiplicities of $h^-(\pi^0)$ in p+p and d+Au collisions at the same time without changing any parameters in the model.

![Figure 3](image-url) Hadron production in p+p (left) and d+Au (right) reactions at RHIC [14, 15].

![Figure 4](image-url) Nuclear modification factor $R_{p\bar{p}}$ at $y = 2, 4, 6$ at the LHC ($\sqrt{s} = 4.4$ TeV) with several parameter sets.
The nuclear modification factor is defined as the ratio of the cross-sections in p(d)+A and p+p collisions normalized by the number of nucleon collisions: $R_{p(d),A} = d\sigma_{p(d),A}/(N_{\text{coll}}d\sigma_{pp})$. The forward suppression of $R_{dA}$ was reported at RHIC in Refs. [14, 15]. Our calculation based on the CGC qualitatively reproduces this suppression at RHIC as a saturation effect [16, 13]. However, it is somewhat sensitive to the initial setup at $x = x_0$ because a subtle balance is needed between the Cronin-like enhancement due to multiple scattering and the saturation due to parton merging within the narrow evolution interval. At the LHC energy, one can expect a much wider evolution interval; $x_2$ can be as small as $x_2 \sim 10^{-6}$ at $y = 6$. In Fig. 4 we show our present expectation for $R_{ppb}(p_\perp)$ at $y = 2, 4$ and 6 at $\sqrt{s} = 4.4$ TeV. Despite ambiguities coming from the parameter uncertainty, we see that the saturation effect leads to systematically stronger suppression of $R_{ppb}(p_\perp)$ in forward rapidity region. This suppression is quantitatively different from the estimate based on nuclear parton distributions (see Ref. [9] for more discussions).

4. Summary

We have evaluated the $p_\perp$ spectrum of the single hadron production in the forward region at RHIC and the LHC energies, using the gluon distributions obtained by the rcBK equation with initial conditions constrained by the HERA e+p data. The $x$-evolution will manifest in the systematic suppression in the forward region in p+Pb reactions at the LHC energy.

To examine further the significance of the CGC approach, more exclusive observables such as e.g., the azimuthal correlations[16], and also heavy quark pair production and correlations[17, 18, 19], should be elaborated. Application to the cosmic ray events is also very intriguing. Furthermore, full NLO evaluations of the hadro-production cross-sections are necessary for theory consistency and for more quantitative investigations[20].

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