COLOR GLASS CONDENSATE APPROACH TO p+Pb COLLISIONS AT THE LHC*

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Single inclusive particle production in high-energy p+Pb collisions is computed with factorization formulas. We use the unintegrated gluon distribution obtained by solving the running-coupling Balitsky–Kovchegov equation and constrained by $e + p$ scattering data, and model the nuclear target as an assembly of the nucleons with fluctuations. We show our prediction for single inclusive particle spectra and nuclear modification factor in p+Pb collisions at the LHC [J.L. Albacete *et al.*, *Nucl. Phys.* **A897**, 1 (2013)].

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1. Introduction — the CGC picture and pA collisions

The Large Hadron Collider (LHC) provides us the opportunity to explore the highest-energy hadronic interactions in p+p and hottest QCD medium in Pb+Pb collisions ever in laboratory. In these reactions, majority of particles are produced from the processes initiated by the gluons with small Bjorken x, which are the short-time, but longitudinally-extended fluctuations in the incoming hadrons. With lowering x, number of gluons in the projectile grows by cascading, and such a growth is indeed hinted in $e + p$ scattering data at HERA. At sufficiently small x, the gluon concentration becomes so large that the gluon merging starts to slow down the growth, leading to a universal saturation regime, called Color Glass Condensate (CGC), characterized with the dynamic scale, so-called *saturation scale* $Q_{\rm s}(x)$.

In the CGC picture, a heavy nucleus at small x is not a simple sum of nucleons, but a dense gluon system generated from the color fluctuations of many nucleons coherently, where the color charge density per transverse area is enhanced by the nuclear thickness $\propto A^{1/3}$ with A the atomic mass

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number. In this respect, significance of the p+Pb run at the LHC is twofold: *(i)* a crucial reference to disentangle the initial from the final state effects in $A+A$ collisions and *(ii)* assessing the CGC effects by comparing $p+A$ and $p+p$ collisions with wide kinematics at top laboratory energies.

2. CGC approach

2.1. Nuclear unintegrated gluon distribution

The unintegrated gluon distribution (UGD) in a hadron is related to the forward dipole amplitude $\mathcal{N}(r,x)$. The x dependence of the amplitude is controlled by the Balitsky–Kovchegov equation

$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int\limits_{\boldsymbol{r}_1} \mathcal{K}^{\rm run} \left[\mathcal{N}(r_1,x) + \mathcal{N}(r_2,x) - \mathcal{N}(r,x) - \mathcal{N}(r_1,x)\mathcal{N}(r_2,x)\right] , \tag{1}$$

where the dipole size is assigned as $\boldsymbol{r} = \boldsymbol{r}_1 + \boldsymbol{r}_2$. The quadratic term represents the gluon merging in the evolution. The kernel $\mathcal{K}^{\rm run}$ includes running coupling corrections in Balitsky's prescription, which gives x-dependence of $Q_{\rm s}^2(x)$ consistent with the empirical estimate [1].

In Ref. [2], performing the global fit of the compiled $e+p$ data at HERA, they constrained the amplitude $\mathcal{N}(r,x)$ $(x < x_0 = 0.01)$ with the initial condition

$$1 - \mathcal{N}(r, x_0 = 0.01) = \exp\left[-\frac{\left(r^2 Q_{\rm s0}^2\right)^\gamma}{4} \ln\left(\frac{1}{r\Lambda_{\rm QCD}} + e\right)\right] . \tag{2}$$

In the work [3], we consider the two parameter set obtained assuming the running coupling constant $\alpha_{\rm s}(r) = 4\pi/(9\ln[4C^2/(r^2\Lambda^2)+a])$ with $\Lambda = 0.241$ GeV (constant a is adjusted by $\alpha_{\rm s}(\infty) = \alpha_{\rm fr}$); $(\gamma, Q_{\rm s0}^2/{\rm GeV}^2, \alpha_{\rm fr}, C) = (1.119, 0.168, 1.0, 2.47)$, (1.101, 0.101, 0.8, 1), in addition to the McLerran–Venugopalan (MV) model with (1, 0.2, 0.5, 1). The value $\gamma > 1$ may have its origin in non-Gaussian valence color correlations in the proton [4]. The dipole amplitude in the adjoint representation is obtained by $1 - \mathcal{N}_{\rm A} = (1-\mathcal{N})^2$ in the large-N_c limit.

For a nuclear target, we assume the same functional form of $\mathcal{N}(r, x = x_0)$ as that for a proton, and nuclear effects show up through the initial saturation scale $Q_{\rm s0}^2$. Following Ref. [5], we distribute the nucleons stochastically in the nucleus, and set at each transverse position the saturation scale as $Q_{{\rm s0},A}^2 = N \times Q_{\rm s0}^2$ with N being the number of the nucleons along the trajectory of the projectile nucleon. We evolve the dipole amplitude with rcBK equation locally ignoring transverse-position dependence. See Fig. 1, left and right.

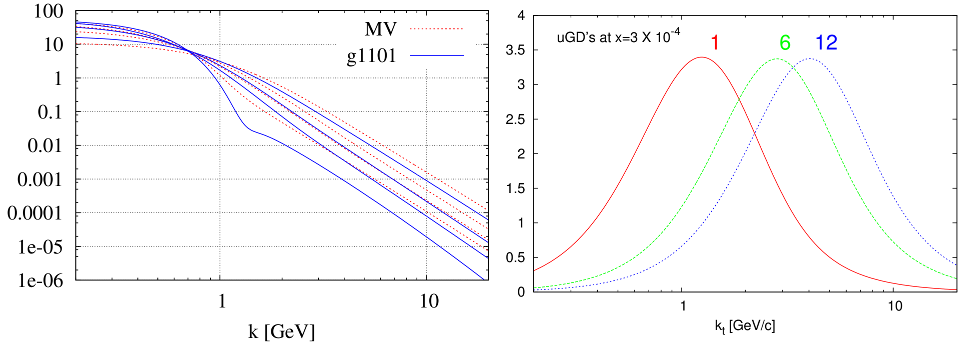

Fig. 1. Left: Tail of proton's $\widetilde{\mathcal{N}}_{\mathrm{F}}(k,x)$ at $\ln(x_0/x) = 0, 1.5, 3, 6$. Right: $k^2\widetilde{\mathcal{N}}_{\mathrm{A}}(k,x)$ at $x = 3 \times 10^{-4}$ evolved from $x_0 = 0.01$ with $Q^2_{\mathrm{s0,A}} = (1, 6, 12) \times Q^2_{\mathrm{s0}}$ (MV).

2.2. Particle production formula

In Fig. 2, we show the kinematic coverage in $x_{1,2}$ for hadrons produced at transverse momentum $p_\perp$ with rapidity y, in the $2 \to 1$ parton process. At RHIC energy, one can probe smaller x_2 part of the gluon distribution as going forward to $y = 2.2, 3.2, 4$, but the process becomes sensitive to the larger x_1 near the kinematic boundary. At the LHC, on the other hand, wide phase space opens up to probe the small x_2 distribution. The x_1 can become also small in mid-rapidity particle production.

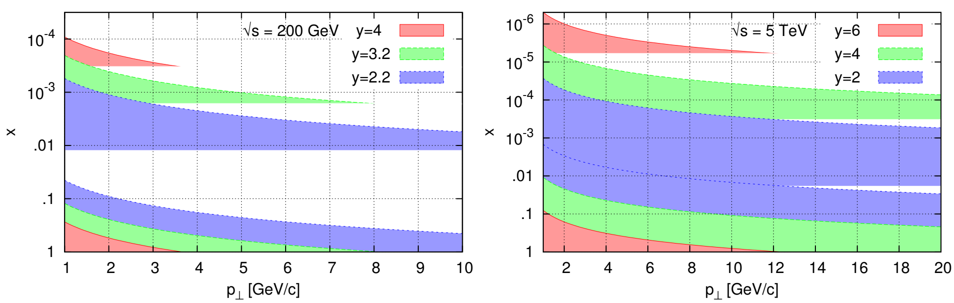

Fig. 2. Left: $x_{1,2}$ coverage at $y = 2.2$, 3.2 and 4 at RHIC energy $\sqrt{s} = 200$ GeV. Right: $x_{1,2}$ coverage at $y = 2$, 4 and 6 at LHC energy.

We use the k_{t}-factorization formula to compute the particle production at mid-rapidity in p+Pb collisions at the LHC [6], where both the $x_{1,2}$ are small

$$\frac{d\sigma^{A+B\to g}}{dyd^2p_{\mathrm{t}}d^2R} = K^k \frac{2}{C_{\mathrm{F}}} \frac{1}{p_{\mathrm{t}}^2} \int^{p_{\mathrm{t}}} \frac{d^2k_{\mathrm{t}}}{4} \int d^2\boldsymbol{b}\, \alpha_{\mathrm{s}}(Q)\, \varphi_{\mathrm{P}}(k_1, x_1; \boldsymbol{b})\, \varphi_{\mathrm{T}}(k_2, x_2; \boldsymbol{R} - \boldsymbol{b}) \tag{3}$$

with the UGD introduced as $\varphi(k,x,\boldsymbol{R}) = \frac{C_{\rm F}}{\alpha_{\rm s}(k)\,(2\pi)^3} k^2 \widetilde{\mathcal{N}}_{\rm A}(k,x,\boldsymbol{R})$. Here, y and $p_{\rm t}$ are the rapidity and transverse momentum of the produced gluon, respectively, while $x_{1,2} = (p_{\rm t}/\sqrt{s})\exp(\pm y)$, $k_{1,2} = |p_{\rm t} \pm k_{\rm t}|/2$ and $C_{\rm F} = (N_c^2-1)/2N_c$. We let $\alpha_{\rm s}(Q)$ run with $Q = \max\{k_1,k_2\}$. $K^k \sim 1.5$–3 is a normalization factor. The hadron multiplicity is simply evaluated by multiplying an effective constant κ_g, while high-$p_{\rm t}$ spectrum is obtained by including the standard fragmentation function [3, 6].

In the forward region with large x_1 and small x_2, another factorized formula should be more appropriate [7]

$$\frac{dN}{dy_h d^2p_\perp} = \frac{K}{(2\pi)^2} \sum_{i=q,g} \int_{x_{\rm F}}^{1} \frac{dz}{z^2}\, x_1 f_{i/p}\left(x_1, p_\perp^2\right) \widetilde{\mathcal{N}}_i\left(\frac{p_\perp}{z}, x_2\right) D_{h/i}\left(z, p_\perp^2\right), \quad (4)$$

where the $f_{i/p}(x_1,\mu^2)$ is the collinear distribution function of the parton i, $\widetilde{\mathcal{N}}_{\rm F,A}(k,x_2)$ the Fourier transform of the dipole amplitudes, and $D_{h/i}(z,\mu^2)$ the fragmentation function of the parton i into the hadron h with the momentum fraction z. The normalization constant K may account for some higher-order effects. Once we fix parameters in $e+p$ and $p+p$ collisions and scale $Q^2_{\rm s0,A}$ by counting the overlap nucleons, we can predict the forward particle production in $p+A$ collisions.

3. Results

First, we check our formula using existing data. In Fig. 3, shown is the $p_{\rm t}$ spectrum of the charged hadron in $p+p(\bar{p})$ collisions at $\sqrt{s} = 1.96$ and 7 TeV. The K^k is adjusted at $p_{\rm t} = 1$ GeV. We see that the UGD parameter sets with $\gamma \sim 1.1$ fit the data after convolution with the fragmentation functions. The MV model yields too hard spectrum. In Fig. 4, we show the

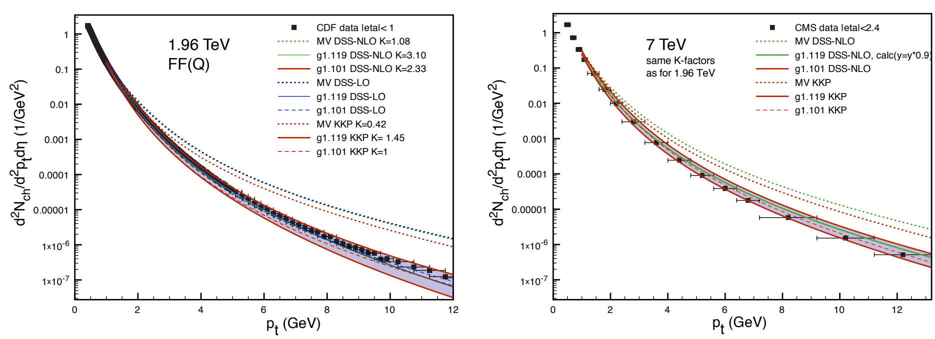

Fig. 3. $p_{\rm t}$ distribution of charged hadrons in the central region of $p+\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV (left), and $p+p$ collisions at $\sqrt{s} = 7$ TeV (right). Data from CDF and CMS.

hadron spectrum in the forward region in $p+p$ and d+Au collisions at RHIC energy [3, 8]. We used here CTEQ6M NLO and DSS NLO, respectively, for $f_{i/p}$ and $D_{h/i}$ in Eq. (4) and chose the factorization scale to $\mu^2 = p_\perp^2$. We set the same $K = 1.0$ (0.4) for $h^-(\pi^0)$ in $p+p$ and d+Au collisions. The result at RHIC energy is rather sensitive to the initial condition at $x = x_0$, and there seems a room for some additional tuning to fit.

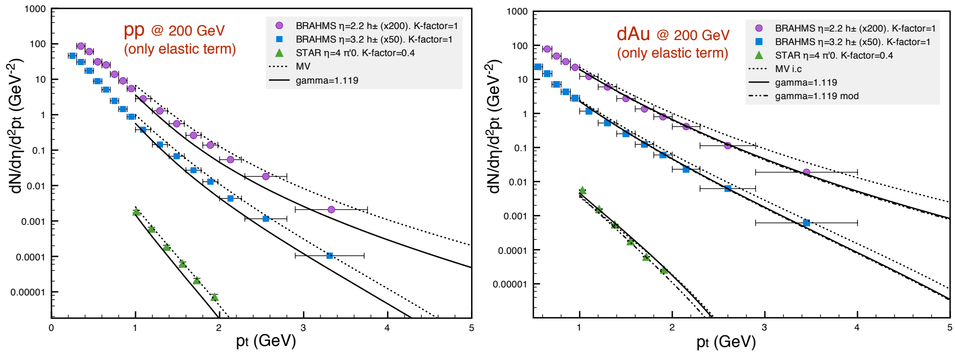

Fig. 4. p_{t} distribution of negatively charge hadrons at $\eta = 2.2, 3.2$ and π^0 at $\eta = 4$ in $p+p$ (left) and d+Au (right) collisions at $\sqrt{s} = 200$ GeV. Data from BRAHMS and STAR.

Next, we present our predictions for p+Pb run at the LHC. In Fig. 5, left, there is the pseudo-rapidity distribution of charged particles for two different UGDs. Recent LHC data [9] showed that the predicted multiplicity at mid-rapidity was almost right, but the rapidity dependence was slightly steeper than data (given our specific $\partial y/\partial\eta$). Finally, we present the nuclear modification factor in the forward rapidity region at the LHC. It is the ratio

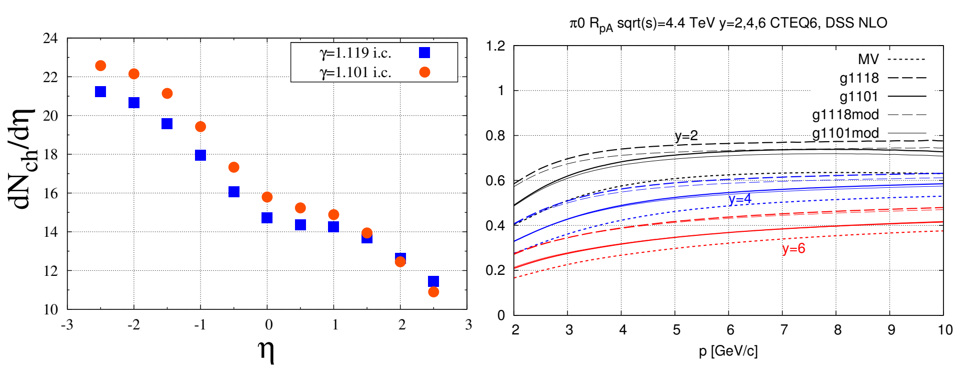

Fig. 5. Left: η distribution of charged particles in p+Pb collisions at $\sqrt{s} = 5$ TeV. Right: Nuclear modification factor $R_{p\mathrm{Pb}}$ at $y = 2, 4, 6$ at $\sqrt{s} = 4.4$ TeV.

of the cross-sections in p+Pb and $p+p$ collisions normalized by the number of nucleon collisions; $R_{p\text{Pb}} = d\sigma_{p\text{Pb}}/(\langle N_{\text{coll}}\rangle d\sigma_{pp})$. We evaluated $\langle N_{\text{coll}}\rangle$ in our simulation code. One can expect here a much wide evolution interval in x_2 down to $\sim 10^{-6}$ at $y = 6$. In Fig. 5, right, we show our expectation for $R_{p\text{Pb}}(p_\perp)$ at $y = 2$, 4 and 6 at $\sqrt{s} = 4.4$ TeV. Despite parameter ambiguities, we see that the saturation effect leads to systematically stronger suppression of $R_{p\text{Pb}}(p_\perp)$ as going to $y = 2, 4, 6$. This systematic suppression is qualitatively different from other model estimates (see Ref. [3] for more discussions).

4. Summary

We have reviewed the CGC approach to the particle productions high-energy $p + A$ collisions. The key building block is the dipole amplitude governed by the rcBK evolution equation and constrained by the HERA $e + p$ data. We have shown the existing data are reasonably described by the CGC approach, and have presented some predictions for the LHC p+Pb run. To assess further the relevance of the CGC approach, more exclusive observables [10] should be elaborated and critically compared with data and other models. Full NLO evaluation is also necessary for theory consistency and for more quantitative studies [11].

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