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HIGH-ENERGY QCD: WHEN CGC MEETS EXPERIMENT*

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I present a brief review of recent phenomenological analyses of HERA, RHIC and LHC data based on the Color Glass Condensate, including the use of non-linear evolution equations with running coupling.

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1. Introduction

The Color Glass Condensate effective theory provides a consistent framework to study QCD scattering at high energies (for a review see *e.g.* [1, 2]). The main physical ingredient in the CGC is the inclusion of unitarity effects through the proper consideration of non-linear *recombination* effects, both at the level of particle production and also in the quantum evolution of hadronic wave functions. Such effects are expected to be relevant when nuclei (or hadrons, in full generality) are proven at small enough values of Bjorken-x. In that regime gluon occupation numbers are very large and gluon self-interactions become highly probable, thus taming, or *saturating*, further growth of the gluon densities. While the need for unitarity effects comprised in the CGC it is, at a theoretical level, clear, the real challenge from a phenomenological point of view is to assess to what extent they are present in available data. In that sense, the calculation of higher order corrections to the CGC formalism has supposed important leap forward in sharpening the CGC as an useful phenomenological tool.

The leading order BK–JIMWLK equations resums soft gluon emission in the leading logarithmic (LL) approximation in $\alpha_{\rm s} \ln 1/x$ to all orders, besides of including non-linear terms required by unitarity. At such degree of

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accuracy, the theory is incompatible with data. Such insufficiency of the theory has been partially fixed by the calculation of running coupling corrections to the BK–JIMWLK equations through the inclusion of quark loops to all orders [3,4]. Among other interesting dynamical effects, running coupling effects tame the growth of the saturation scale down to values compatible with experimental data [5]. Due to the complexity of the JIMWLK equations, in phenomenological works it is more feasible to solve the BK equation, more tractable numerically, which corresponds to their large-N_c limit. It reads

$$\begin{aligned}\frac{\partial\mathcal{N}(r,Y)}{\partial Y} &= \int d^2\boldsymbol{r}_1\, K^{\mathrm{run}}(\boldsymbol{r},\boldsymbol{r}_1,\boldsymbol{r}_2)[\mathcal{N}(r_1,Y)+\mathcal{N}(r_2,Y)\\ &\quad -\mathcal{N}(r,Y)-\mathcal{N}(r_1,Y)\,\mathcal{N}(r_2,Y)]\,,\end{aligned}\tag{1}$$

where $\mathcal{N}(r,Y)$ is the dipole scattering amplitude on a dense target, $Y = \ln x_0/x$ the rapidity, r the dipole transverse size and $r_2 = r - r_1$. It turns out that running coupling effects can be incorporated to the evolution equation through just a modification of the evolution kernel, referred to as K^{run} in Eq. (1) (see [5] for an extended discussion on the subject). Finally, Eq. (1) needs to be supplemented with initial conditions, that can be chosen to be of the McLerran–Venugopalan type [6]. This introduces two free parameters: The value x_0, where the evolution starts and the initial saturation scale Q_0. Finally, the unintegrated gluon distribution entering the different production processes discussed below is related to the dipole amplitude in Eq. (1) through a Fourier transform (see Eq. (5)). In all the phenomenological works described below those two parameters are fitted to experimental data.

2. Structure functions at HERA

Data on inclusive structure functions in $e+p$ collisions at small-x performed in HERA provide a good ground to test the CGC. According to the dipole model formulation of deep inelastic scattering, the γ^*–p cross-section can be written as

$$\sigma_{T,L}\left(x,Q^2\right) = 2\sum_f \int_0^1 dz \int d\boldsymbol{b}\, d\boldsymbol{r} \left|\Psi^f_{T,L}\left(e_f, m_f, z, Q^2, \boldsymbol{r}\right)\right|^2 \mathcal{N}(\boldsymbol{b},\boldsymbol{r},x)\,,\tag{2}$$

where Ψ describes the wave function for the virtual photon to split in a $q\bar{q}$ pair and $\mathcal{N}$ is the dipole scattering. Fig. 1 shows a fit [7] to data on the reduced cross-section measured at HERA using rcBK equation to describe the x-dependence of the dipole scattering amplitude in Eq. (2). Such good agreement with data suggests the possible presence of saturation effects as described in the rcBK equation.

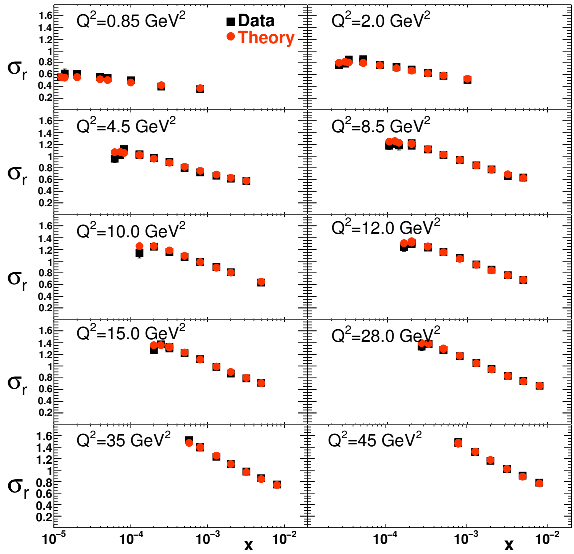

Fig. 1. Fits to data on the reduced cross-section σ_{r} measured in $e+p$ scattering at HERA.

3. Total multiplicities in heavy ion collisions

A main lesson learnt from experimental data collected in $\mathrm{Au}+\mathrm{Au}$ and $\mathrm{Pb}+\mathrm{Pb}$ collisions at RHIC and the LHC, respectively, is that bulk particle production in ion–ion collisions is very different from a simple superposition of nucleon–nucleon collisions. Such is evident in terms of the measured charged particle multiplicities, which exhibit a strong deviation from the scaling with the number of nucleon–nucleon collisions: $\frac{dN^{AA}}{d\eta}(\eta=0) \ll N_{\mathrm{coll}}\frac{dN^{AA}}{d\eta}(\eta=0)$. This observation leads to the conclusion that strong coherence effects among the constituent nucleons, or the relevant degrees of freedom at the nucleon level, must be present during the collisions process. The CGC offers a natural explanation of this observation: The total flux of scattering centers (gluons) entering the collisions is significantly reduced due to saturation effects in the wave function of the colliding nuclei. Such idea is realized in the phenomenological KLN model [8], which relies in the use of k_{t}-factorization. There the total multiplicities in central collisions rise proportional to the saturation scale of the colliding nuclei, $dN/d\eta \propto Q_{\mathrm{s}A}^2$. Even though the use of k_{t}-factorization in $A+A$ collisions is not justified, the good description of the energy, rapidity and centrality of multiplicity data yielded by the model lends support to the underlying physical picture. More realistic models resort to Monte Carlo methods in order to account for the fluctuations in the positions of nucleons in the transverse plane. The model in [9] relies also in the use of the rcBK equation to account for the local (in the transverse plane) energy evolution of the nuclear unintegrated gluon distributions. The analytic form of the initial conditions for the evolution are taken from the analysis of $e+p$ data described in the previous section. This set-up provides a very good description of total multiplicities in Au + Au collisions in RHIC and in Pb + Pb collisions at the LHC, as shown in Fig. 2.

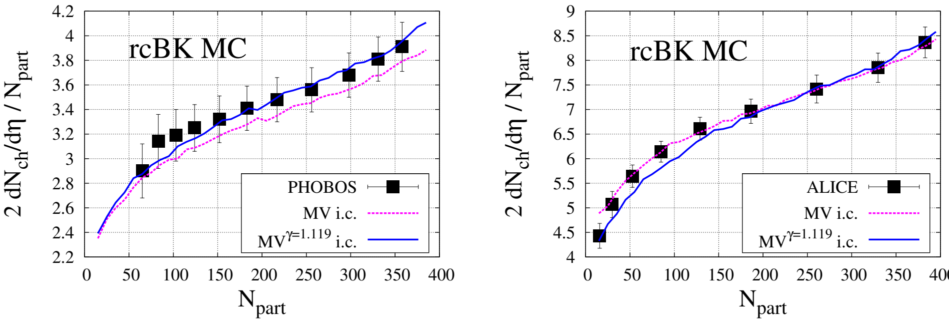

Fig. 2. Centrality dependence of mid-rapidity charged particle multiplicities measures at RHIC (left) and the LHC (right) compared to the rcBK Monte Carlo calculation of input with two different initial conditions.

4. Forward suppression phenomena at RHIC

Nuclear effects in $p+A$ or $A+A$ collisions are typically evaluated in terms of the nuclear modification factors

$$R_{pA} = \frac{\frac{dN^{pA}}{dyd^2p_{\rm t}}}{N_{\rm coll}\frac{dN^{pp}}{dyd^2p_{\rm t}}}\,, \tag{3}$$

where $N_{\rm coll}$ is the number of collisions. If high-energy nuclear reactions were a mere incoherent superposition of nucleon–nucleon collisions, then the observed R_{pA} should be equal to unity. However, RHIC measurements in $d+$Au collisions (or peripheral Au + Au collisions) [10, 11] in the forward rapidity region exhibit a clear suppression for all experimentally accessible values of $p_{\rm t}$. However, at more forward rapidities such Cronin enhancement disappears, turning into an almost homogeneous suppression for all the measured values of $p_{\rm t}$. According to $2 \to 1$ kinematics, the x-values probed in the projectile and target are $x_{1(2)} = (m_t/\sqrt{s})\,e^{\pm y}$. Thus, x-values are small for $y > 1$ at RHIC energies, offering a cleaner opportunity to explore CGC effects. There, the CGC formulation of single particle production takes on a relatively simple form [12]

$$\frac{dN_h}{dy_h\, d^2p_t} = \frac{K}{(2\pi)^2}\sum_q \int_{x_F}^{1} \frac{dz}{z^2}\left[x_1 f_{q/p}\left(x_1,p_t^2\right)\, \tilde{N}_F\left(x_2,\frac{p_t}{z}\right)\, D_{h/q}\left(z,p_t^2\right)\right.$$
$$\left. + x_1 f_{g/p}\left(x_1,p_t^2\right)\, \tilde{N}_A\left(x_2,\frac{p_t}{z}\right)\, D_{h/g}\left(z,p_t^2\right)\right], \qquad (4)$$

where p_t and y_h are the transverse momentum and rapidity of the produced hadron, and $f_{i/p}$ and $D_{h/i}$ refer to the parton distribution function of the incoming proton and to the final-state hadron fragmentation function, respectively. Thus, in the forward region the projectile is in the dilute regime and characterized by its parton distribution functions, while the nucleus is deep in the saturation region and characterized by unintegrated gluon distributions taken from the solutions of the rcBK equation

$$\tilde{N}_{F(A)}(x,k) = \int d^2\boldsymbol{r}\, e^{-i\boldsymbol{k}\boldsymbol{r}}\left[1-\mathcal{N}_{F(A)}\left(r, Y=\ln(x_0/x)\right)\right], \qquad (5)$$

where k refers to transverse momentum. With this set-up it is possible to obtain a very good description of forward neutral pions and negatively charged hadrons yields as measured by the STAR and BRAHMS collaborations, respectively, in $d+\mathrm{Au}$ minimum bias and in $p+p$ collisions [13].

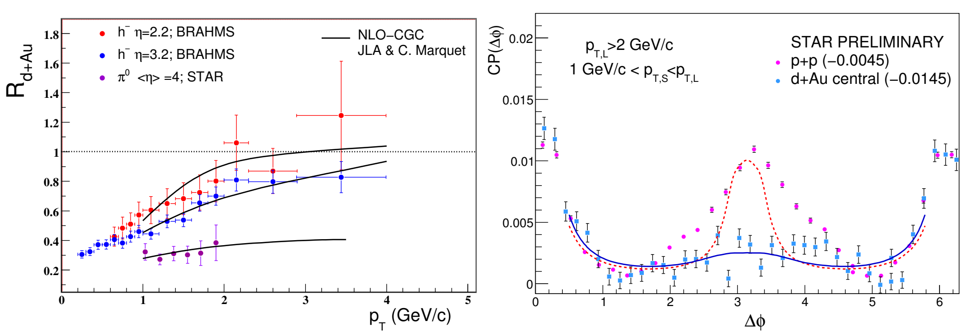

Fig. 3. Left: Nuclear modification factors at forward rapidities in minimum bias $d+\mathrm{Au}$ collisions in the CGC [13]. Right: Coincidence probability in forward di-hadron correlations measured in $p+p$ and $d+\mathrm{Au}$ correlations compared to the CGC calculation in [14].

By simply taking the ratios of the corresponding spectra, one gets a very good description of the nuclear modification factors at forward rapidities. It should be noted that we use the same normalization as the experimentalist do in their analyses of minimum bias $d+\mathrm{Au}$ collisions, *i.e.* we fix $N_{\mathrm{coll}} = 7.2$.

Physically, the observed suppression is due to the relative enhancement of non-linear terms in the small-x evolution of the nuclear wave function with respect to that of a proton.

Other important suppression phenomena observed at RHIC is the disappearance of the back-to-back azimuthal correlations in forward di-hadron measurements. Following [15], we calculate the coincidence probability, which is the experimental measured quantity. It has the meaning of the probability of, given a trigger hadron h1 in a certain momentum range, finding an associated hadron h2 in another predefined momentum range and with a difference between the azimuthal angles between the two equal to $\Delta\phi$. Our results [14], adapted to match the experimental cuts for trigger and associated particles, are shown in Fig. 3 (right) together with the corresponding preliminary data by the STAR Collaboration. The disappearance of the away-side peak around in $d+\mathrm{Au}$ collisions exhibited by data is quantitatively well described by our CGC calculation. In the CGC approach the physics of monojet production is due to the interplay between the transverse momenta of the produced hadrons and the one acquired during the interaction with the nucleus. In the CGC approach presented here the interaction with the nucleus is realized in a fully coherent way, and the momentum broadening is parametrically controlled by the x-dependent saturation scale of the nucleus.

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