Manifestations of gluon saturation at RHIC

Javier L. Albacete
The Ohio State University

Abstract

The experimental results from RHIC provide accumulated evidence for the discovery of the Color Glass Condensate. I present a brief review of the saturation-based phenomenological works aimed at describing various aspects of heavy ion collisions. I discuss the success of such models in describing bulk features of multiparticle production in Au-Au collisions as well as the rapidity dependence of the nuclear modification factor in d-Au collisions as the most compelling indication for the presence of gluon saturation effects at RHIC.

1 Introduction

During the last years, the Relativistic Heavy Ion Collider (RHIC) has carried out an extensive experimental program in Au-Au, Cu-Cu, d-Au and p-p collisions over an broad range of collision energies, from 19.2 to 200 GeV per nucleon, with the ultimate goal of forming and studying the Quark Gluon Plasma (QGP). Besides the success of the RHIC program in this line of research [1–3], its discovery potential has reached other areas of QCD. Thus, the analyses of experimental data strongly suggest that RHIC collisions probe a novel regime of QCD governed by coherent non-linear phenomena and gluon saturation: the Color Glass Condensate (CGC). The CGC physics (for a review see, e.g. [4]) describes hadronic and nuclear wave functions at small values of the Bjorken-x variable. In such regime the gluon occupation numbers reach the maximal values allowed by unitarity i.e. they *saturate*. Further growth of the gluon densities is suppressed by gluon-gluon repulsive interactions. Very succinctly, the CGC comprises classical (the McLerran-Venugopalan model [5] and Glauber-Mueller rescatterings [6]) and quantum evolution (nonlinear JIMWLK [7] and BK [8] equations) effects both in small-x hadronic wave functions and in scattering process, leading to a universal description of high energy QCD scattering.

The presence of saturation effects in RHIC collisions could be argued a priori: At high energies, the colliding nuclei are highly Lorentz contracted along their direction of motion, leading to the spatial superposition of the gluon fields associated to their constituent nucleons or, equivalently, to large transverse gluon densities. Alternatively, the coherence length at small enough values of Bjorken-x is eventually larger than the nuclear radius, $l_c \sim 1/2m_N x > R_A$, so coherent phenomena may play an important role in the collision dynamics. Actually, the theoretical estimations for the saturation scale of the gold nucleus at RHIC were $Q_{sA}^2 \sim 1 \div 2$ GeV^2, in principle large enough for saturation effects to be important. However, the complicated dynamics of Au-Au collisions at the highest RHIC energies, including the QGP formation and its subsequent expansion, raises the question of whether such effects would have a clear experimental manifestation or whether they would be blurred by the strong final state effects induced by the presence of the QGP. It turns out that some of the bulk features of multiparticle production in Au-Au collisions, such as the collision energy, rapidity and centrality dependence of particle multiplicities, seem to be mostly controlled by the initial state of the collision and, therefore, describable in terms of CGC physics.

The RHIC program also includes d-Au reactions at collision energy $\sqrt{s} = 200$ GeV. The d-Au program can be considered as an control experiment: the smaller energy densities involved in d-Au reactions do not suffice for the formation of a QGP. This reduces significantly the role of final state effects, allowing a clearer exploration of the initial state saturation effects. The situation is also more favourable on the theoretical side. The problem of calculating the evolution equations and production processes is better understood for dilute-dense scattering processes (i.e. proton-nucleus) than for dense-dense (nucleus-nucleus) scattering. Actually, one of the clearest signals of the presence of saturation effects at RHIC is given by suppression of the nuclear modification factor with increasing rapidity in d-Au collisions, which was predicted by CGC based calculations [9, 10].

2 Collision energy, rapidity and centrality dependence of hadron yields in d-Au and Au-Au collisions

CGC physics offers a natural explanation to the lower-than-predicted multiplicities measured at RHIC, namely the reduced flux of scattering centers, i.e. gluons, participating in the collision (for a review of predictions in the pre-RHIC era see, e.g. [11]). Thus, theoretical investigations [12] suggest a proportionality between the number of produced particles in A-A collisions and the number of partons in the wave function of the colliding nuclei, mostly dominated by semi-hard gluons with transverse momenta of the order of the saturation scale $k \sim Q_s$. Besides, the largeness of the saturation scale $Q_s >> \Lambda_{QCD}$ allows the use of weak coupling methods. The phenomenological implementation of these ideas was pioneered by Kharzeev, Levin and Nardi (KLN) [13–15], who extended the k_t-factorization formalism of [16] to describe multiparticle production at RHIC. In this approach primary gluon production in A-B collisions is given by the convolution of the unintegrated gluon distributions (udg's) of the projectile and target, $\varphi_{A(B)}$, according to

$$\frac{dN^{AB}}{d\eta\, d^2p_t\, d^2b} = \frac{4\pi N_c\, \alpha_s}{N_c^2 - 1} \int d^2k_t\, d^2s\, \varphi_A(x_1, \underline{k}, \underline{s})\, \varphi_B(x_2, \underline{p} - \underline{k}, \underline{b} - \underline{s})\,, \tag{1}$$

where $\underline{p}$ and η are the transverse momentum and pseudo-rapidity of the produced gluon and $\underline{b}$ is the impact parameter of the collision. The $\underline{s}$ integral in Eq. (1) extends over the collision area and $x_{1(2)} = |\underline{p}|/\sqrt{s}\, e^{\pm\eta}$, according to the $2 \to 1$ kinematics. Importantly, an analogous factorized formula holds exactly for p-A collisions. The udg's entering Eq. (1) present, at least, two distinct regimes: a *saturated* one and a dilute or perturbative one. Very schematically:

$$\varphi(x, k) \sim \begin{cases} Cte & \text{for} \quad k < Q_s(x) \\ \frac{Q_s^2(x)}{k^2} & \text{for} \quad k > Q_s(x) \end{cases} \tag{2}$$

The most important parameter in these calculations is the saturation scale, $Q_s(x)$, which provides the separation between the two regimes. Its energy/rapidity dependence is modelled as

$$Q_s^2(x) = Q_0^2\, (x_0/x)^\lambda\ , \tag{3}$$

where λ is often adjusted to the empirical value $\lambda = 0.288$ extracted from fits to small-x HERA data on deep inelastic lepton-hadron processes in the framework of saturation models [17, 18]. The phenomenological connection between HERA and RHIC is motivated by the property of *geometric scaling* displayed by small-x DIS data [19] and also exhibited by the solutions of the BK equation [20]. Additionally, local parton-hadron duality is assumed in order to compare Eq. (1), which describes primary gluon production, with the hadron spectra measured experimentally. Such assumption relies on the expectation that final state effects, including hadronization, do not modify substantially the angular distribution, and therefore the rapidity distribution of produced particles. This approach provides an excellent description of the collision energy and pseudo-rapidity dependence of the charged particle multiplicity data in d-Au and Au-Au collisions at energies $\sqrt{s} = 130$ and 200 GeV, as shown in Fig 1. Importantly, the recent calculation of running coupling corrections to the BK-JIMWLK kernel [21] allow to obtain a description of the nuclear udg's directly in terms of solutions of the BK equation which is in perfect agreement with the energy and rapidity dependence of RHIC data [22], thereby reducing the uncertainties associated to the parametrization of the nuclear udg's. Moreover, the combination of CGC calculations with subsequent hydrodynamic evolution of the system as carried out in [23] yields an equally successful comparison with RHIC multiplicity data, confirming the dominance of the initial state effects in this aspect of the collision.

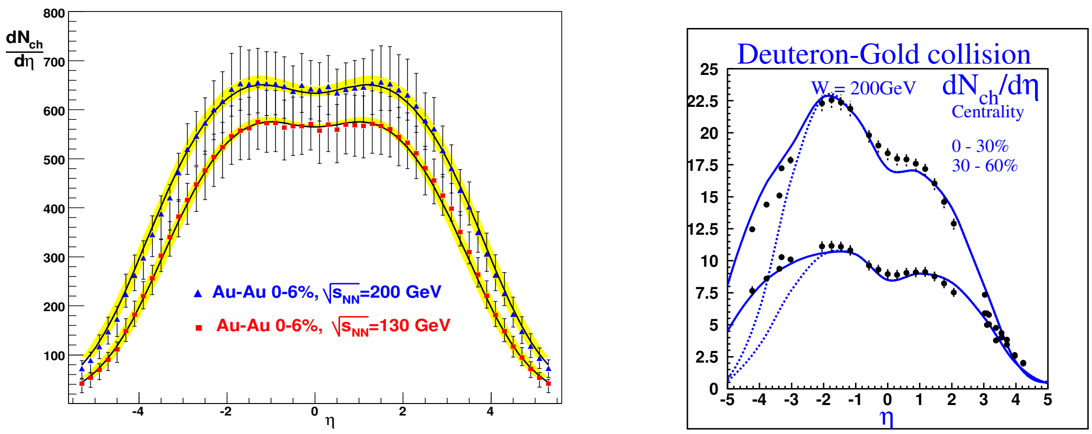

Fig. 1: Charged particle multiplicities in central Au-Au collisions at $\sqrt{s} = 130$ and 200 GeV (left plot, figure from [22], data from [2]) and in d-Au collision at $\sqrt{s} = 200$ GeV for two centrality classes: 0-30 % and 30-60 % (right plot, figure taken from [24], Data from [25]).

The centrality dependence of RHIC multiplicities, normally discussed in terms of the number of participant nucleons in the collision area, N_{part}, is also naturally explained in saturation-based calculations [14], as seen in Fig 2. Under the assumption of *geometric scaling* of the nuclear udg's, the mid-rapidity multiplicity resulting from Eq. (1) rises proportional to the saturation scale which, as indicated by fits to DIS nuclear data, is roughly proportional to the number of participants, yielding, from [26]:

$$\frac{1}{N_{part}} \frac{dN^{AA}}{d^2b\, d\eta}\bigg|_{\eta=0} \propto \sqrt{s}^{\lambda}\, N_{part}^{\frac{1-\delta}{3\delta}}\,, \tag{4}$$

with $\delta \approx 0.8$. Eq. (4) shows two important features: First, it yields an exact factorization of the energy and centrality dependence of the mid-rapidity multiplicity. Second, it predicts an approximate scaling of the multiplicity densities with respect to N_{part}. This is a distinctive feature of saturation-based calculations with respect to the standard pQCD collinear approaches, which predict scaling with the number of binary collisions. In the original KLN approach the small violations of the N_{part} scaling rise as a consequence of running coupling corrections to Eq (1). Both features of Eq (1) are exhibited by experimental data, as seen in Fig 2.

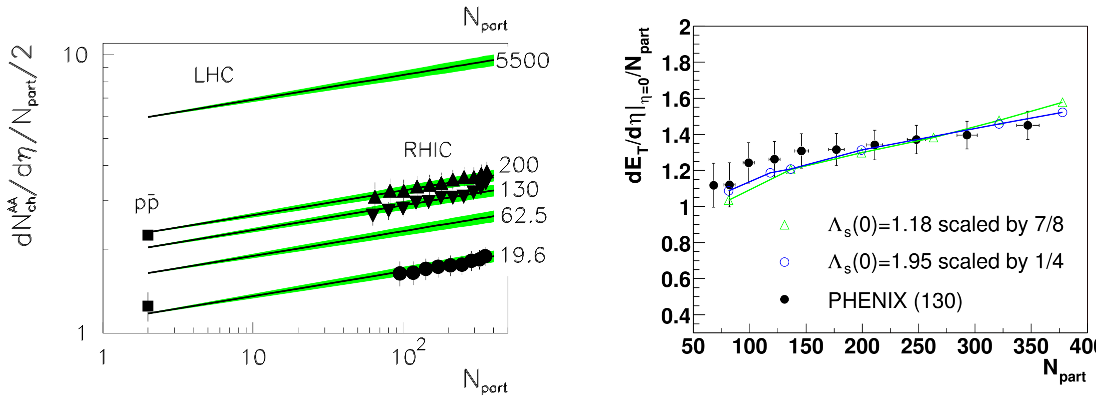

Fig. 2: Right plot: Centrality dependence of charged particle multiplicities in Au-Au collisions at $\sqrt{s}$ = 19.2, 130 and 200 GeV calculated in [27]. Data from [28]. Left plot: Transverse energy of produced gluons in Au-Au collisions at $\sqrt{s}$ = 130 GeV from the classical calculation in [29]. Data from [30].

An alternative approach to describe the multiplicities in Au-Au RHIC collisions was suggested in [31]: The gluon fields immediately after the collision can be calculated via the classical Yang-Mills equations of motion in the presence of a source term, given by the fast *valence* degrees of freedom of the colliding nuclei, $[D_\mu, F^{\mu,\nu}] = J^\nu$. Such approach has been intensively pursued in numerical calculations, see e.g. [29, 32]. The results of these calculations are also consistent with the bulk features of RHIC multiplicities discussed previously, as shown in in the right panel of Fig 2, where centrality dependence of the transverse energy of produced gluons in Au-Au collisions is compared to experimental data.

3 Nuclear modification factor in d-Au collisions

d-Au collisions are free of the highly distorting final state effects induced by the QGP, which permits a better exploration of saturation effects in more exclusive observables, such as particle spectra. The nuclear effects or, equivalently, the departure from superposition of incoherent nucleon-nucleon scatterings, are normally discussed in terms of the nuclear modification factor, defined as

$$R_{AB} = \frac{\frac{dN^{AB}}{d^2b\, dp_t\, dy}}{N_{coll}\frac{dN^{pp}}{d^2b\, dp_t\, dy}}\,, \tag{5}$$

where N_{coll} is the number of binary collisions. R_{dAu} corresponding to charged particle spectra in d-Au collisions (and in central over peripheral Au-Au collisions) at mid-rapidity exceeds unity in an intermediate transverse momentum range of a few GeV, as seen in the left panel of Fig. 3. Such enhancement is commonly referred to as Cronin peak and admits a clear interpretation in the semi-classical MacLerran Venugopalan model: the produced parton acquires an average transverse momentum of the order of the saturation scale due to the multiple rescatterings in the gluon field of the nucleus, which explains enhancement in the region $p_t \sim Q_s$. At larger rapidities towards the deuteron fragmentation function the Cronin enhancement turns gradually into a uniform suppression in all the kinematic range accessible experimentally: $R_{pA} < 1$. As argued in [9, 10], such suppression is rooted in the shadowing built up by the non-linear small-x evolution of the nuclear gluon densities. Thus, the suppression is originated in the slower growth of nuclear densities with respect to those of the deuteron due to the relative enhancement of the non-linear effects in denser systems. Presently, the agreement between theory and data is of semi qualitative nature. Managing a more precise quantitative description of the suppression rate and of the particle species dependence of R_{pA}, which is different for e.g. pions and protons, remain nowadays as challenging issues.

An important step in that direction was made in [35], where an excellent description of data for charged particle production in d-Au collisions at different values of rapidity was achieved, see Fig 3. The new ingredients in that calculation are a *collinear* treatment of the dilute projectile, i.e. described by means of standard parton distribution functions and DGLAP evolution, plus an improved parametrization of the rapidity and transverse momentum dependence of the nuclear udg's, adjusted to reproduce HERA DIS data and some analytically known properties of the solutions of BK-JIMWLK equations. The recent developments in the determination of NLO corrections to the BK-JIMWLK equations also contribute largely to reduce the theoretical uncertainties associated to the determination of the nuclear udg's.

Contrary to d-Au collisions, the p_t spectra in Au-Au collisions at midrapity is uniformly suppressed, i.e. $R_{Au-Au} < 1$. The empiric observation that R_{pA} and R_{AA} follow opposite patterns with varying collision energy and centrality is crucial to interpret the suppression of the latter as a final state effect due to *jet quenching* induced by the presence of a QGP.

4 Others

Another experimental result which suggests the presence of saturation effects is the phenomenon of *limiting fragmentation*, the empirical observation that the rapidity distributions of produced particles at various collision energies tend to some universal curve in the fragmentation region. In the CGC framework, this property follows naturally from the unitarization of scattering amplitudes in the dense target, and the approximate Bjorken scaling in the fragmenting nucleus. The limiting curve then appears to be a reflection of the *valence*, large-x d.o.f of the projectile nucleus [37]. Additionally, the calculations of valence quark production in d-Au collisions of [38]

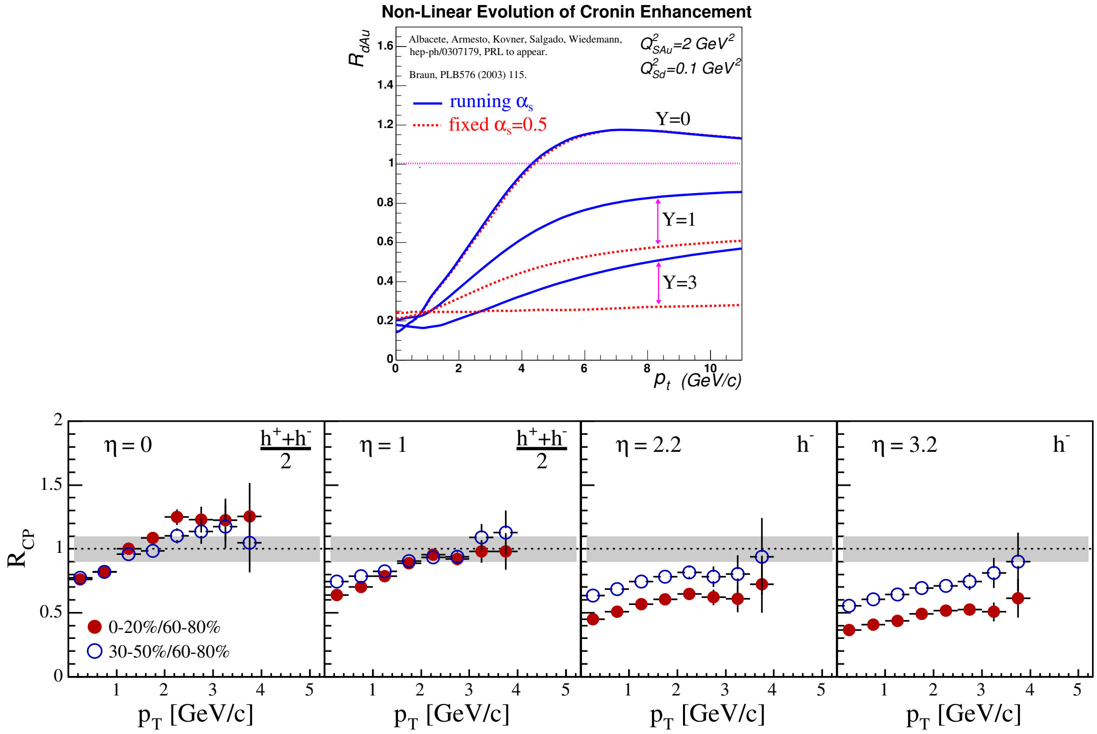

Fig. 3: Nuclear modificaton factor in d-Au collisions. Upper plot: theoretical results obtained with fixed (from [20]) and running coupling (udg's taken from [33]) evolution. Lower plot: Central over peripheral nuclear modification factor at pseudorapidity $\eta = 0$, 1, 2.2 and 3.2. Data from [34].

provide a qualitative explanation for the phenomenon of *baryon stopping*. The determination of heavy flavour production of [39] for d-Au collisions is in agreement with available experimental data. Other production processes have already been calculated in the framework of CGC (see [40] for an extensive review): Electromagnetic probes (lepton and photon production), long range in rapidity di-hadron correlations originated from di-gluon and gluon-valence quark production etc. However, the experimental test of the predictions stemming from these calculations is not yet possible due to the lack of the pertinent experimental data.

The definitive confirmation of the tentative conclusions drawn after the RHIC era awaits until the start of operation of the CERN LHC, which will operate at unprecedentedly large collision energies (5.5 TeV in Pb-Pb collisions and 7 TeV in p-Pb collisions). At such energies saturation effects are expected to manifest at their best and the applicability of a purely high energy formalism as the CGC is much better justified.

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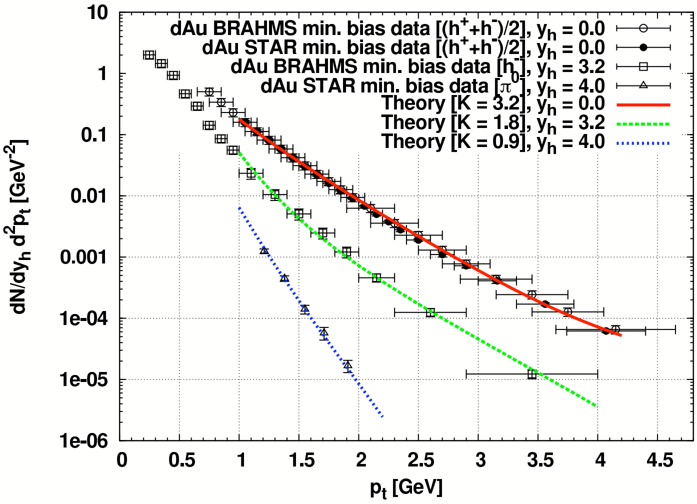

Fig. 4: Charged particle spectra in minimum bias d-Au collisions at rapidities 0, 3.2 and 4, from [35]. Data from [36].

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