

Initial conditions in heavy ion collisions: from RHIC to the LHC

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I present a brief discussion of the different approaches to the study initial state effects in heavy ion collisions performed at RHIC and the LHC with emphasis in the Color Glass Condensate approach.

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1. Introduction

The studies of initial state effects in heavy ion collisions aim at providing a full dynamical description of the colliding system at early times, before the eventual thermalization of the system and the formation of a Quark Gluon Plasma (QGP). The importance of these studies is manifold: On the soft sector they determine the initial conditions (energy and entropy density, initial spatial anisotropy etc) for the subsequent hydrodynamical evolution of the system. On the hard probes sector, they provide a benchmark to quantify final state effects due to the presence of a QGP.

A main lesson learnt from experimental data collected in Au+Au and Pb+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. This 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: $\frac{dN^{AA}}{d\eta}(\eta = 0) \ll N_{coll} \frac{dN^{AA}}{d\eta}(\eta = 0)$. This observation leads to the conclusion that strong coherence effects among the constituent nucleons must be present during the collisions process. Indeed, any of the phenomenological models who successfully describe data include strong coherence effects, either at the level of the wave function and also at the level of primary particle production. To the first category correspond the nuclear shadowing (in a partonic language) or the percolation and string fusion (in non-perturbative approaches). In both cases, when different constituents, whichever the degrees of freedom chosen are, overlap in phase space according to some geometric criterium, recombination of such constituents happen, thus reducing the total number of scattering centers entering the collision process. Similar phase-space arguments motivate the implementation of energy-dependent cut-offs to regulate independent particle production from different sources, normally a working hypothesis in most Monte Carlo event generators for heavy ion collisions.

2. The Color Glass Condensate approach.

The CGC attempts at providing a complete, QCD-based, dynamical description of the coherence effects discussed above (for a review see, e.g., [12]). On one hand, the gluon *shadowing* is taken into account through non-linear renormalization group equations, the BK-JIMWLK equations, that describe the change in hadron structure towards small Bjorken- x (equivalently, higher collision energies). The non-linear terms in the BK-JIMWLK equations reflect the probability of gluon-gluon recombination processes in the high density regime. Those terms ensure unitarity of the theory and tame the growth of gluon densities towards small- x . They also imply the emergence of a dynamical transverse momentum scale, the saturation scale Q_s , such that gluon modes with transverse momentum $k_t \leq Q_s(x)$ are in the saturation regime [4]. Due to the complexity of the B-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

$$\frac{\partial \mathcal{N}(r, Y)}{\partial Y} = \int d^2 \mathbf{r}_1 K^{\text{run}}(\mathbf{r}, \mathbf{r}_1, \mathbf{r}_2) [\mathcal{N}(r_1, Y) + \mathcal{N}(r_2, Y) - \mathcal{N}(r, Y) - \mathcal{N}(r_1, Y) \mathcal{N}(r_2, Y)] \quad (2.1)$$

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. (2.1) [4]. Finally, Eq. (2.1) needs to be supplemented with initial conditions, which can be chosen to be of the McLerran-Venugopalan type [17]. This introduces two free parameters: The value x_0 where the evolution starts and the initial saturation scale Q_0 . Finally, the nuclear unintegrated gluon distribution entering the different production processes discussed below is related to the dipole amplitude in Eq. (2.1) through a Fourier transform:

$$\tilde{N}(x, k) = \int d^2\mathbf{r} e^{-i\mathbf{k}\cdot\mathbf{r}} [1 - \mathcal{N}(r, Y = \ln(x_0/x))], \quad (2.2)$$

3. Multiplicities

Two main features of the new LHC data [2, 1] can be highlighted: First, the energy dependence of mid-rapidity multiplicities in A+A collisions is well reproduced by a power law, $dN^{ch}/d\eta(\eta = 0) \sim s^{0.15}$. This observation seems to rule out the logarithmic trend observed for lower energies data and is in generic agreement with pQCD based approaches. Second, the centrality dependence of multiplicities is, up to an overall scale factor, very similar to the one observed at RHIC. This suggests a factorization of the energy and centrality dependence of the multiplicities, which, in turn, admits a natural explanation in the CGC formalism. There, mid-rapidity multiplicities rise proportional to the saturation scale of the colliding nuclei which, in a first approximation, is proportional to the local nuclear density or, equivalently, to the number of participants:

$$\frac{dN}{d\eta}(\eta = 0) \sim Q_s^2(x, b) \sim \sqrt{s}^\lambda N_{part}. \quad (3.1)$$

Fig. 1 (right) includes comparison of different Monte Carlo [9, 8] and saturation based calculations done in the framework of k_t -factorization ([13]): [14, 7, 3] to LHC data on Pb+Pb collisions. A best description of data is given by the MC-rcBK approach of [3] and in the MC HIJING approach [9], which includes a very strong impact parameter dependent shadowing. Aside of implementation details different CGC approaches differ mainly in their input for the ugd's: analytical models [14], models constrained from e+p and e+A data [7] or solutions from the running coupling BK equation. These choices lead to slightly varying effective values of the exponent $\lambda \sim 0.2 \div 0.3$ in (3.1) and partially explain the spread of *saturation* based predictions. Other distinguishing feature among saturation models is the treatment of impact parameter dependence. It varies from describing the nucleus by a single, average saturation scale, to mean field approaches with explicit b-dependence, to Monte Carlo methods. The latter are the best suited to account for the fluctuations in the initial geometry of the collision, a crucial ingredient for the subsequent analysis of multi-particle correlations, flow, etc. Presently there are two variants of CGC Monte Carlo methods, the MC-KLN [10] and MC-rcBK [3], schematically represented in Fig. (2). Their geometric set up is identical in both cases, differing in the dynamical input for the (x, k_t) -dependence of the ugd's, either the KLN model[14] or the rcBK approach. Particle production is then calculated according to k_t -factorization.

As shown in Fig. (2), MC-CGC approaches systematically yield a larger initial eccentricity than Glauber ones, both at RHIC and LHC energies. However, it is unclear to what extent such is a robust property of the CGC formalism (see for instance the CYM studies in [16]) or an artifact of

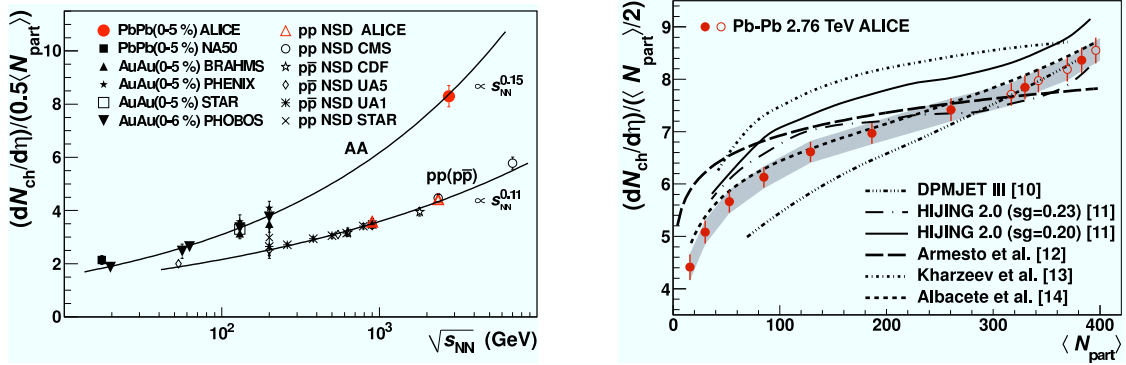


Figure 1: Energy (left) and centrality (right) dependence of mid-rapidity multiplicities in A+A and p+p collisions. Figures and LHC data by the ALICE collaboration [2, 1].

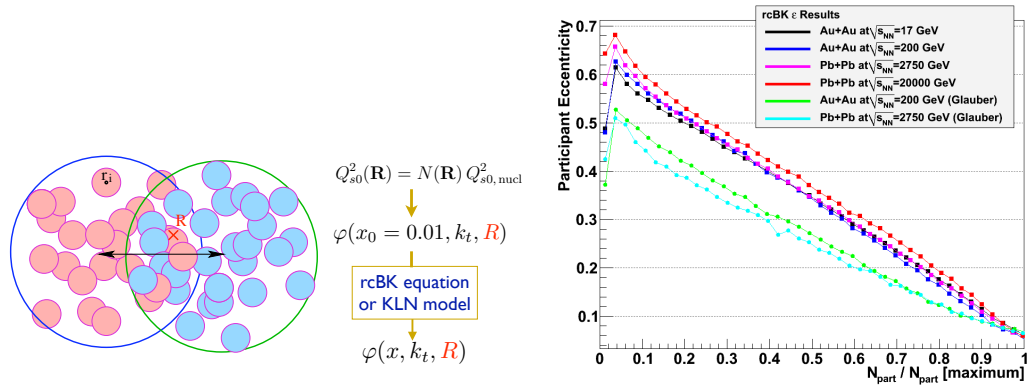


Figure 2: Left: Sketch of the CGC Monte Carlo implementation. Right: Participant eccentricity as a function of centrality for rcBK-CGC and Glauber initial conditions at different collision energies (courtesy of J. Nagle).

their current implementation in phenomenological works. Also, it should be kept in mind that initial spatial gradients are very sensitive to particle production in the dilute periphery of the collision area. There, the applicability of the CGC formalism, which relies in the presence of high gluon densities, is not guaranteed. Rather, non-perturbative effects may play an important role in that region. In that sense, aspects of the modeling in the MC tools used, such as the relevant sources of fluctuations or the model for the nucleon geometry themselves (e.g thick discs vs. gaussian) may be more relevant for the determination of initial eccentricities than the choice of underlying description for initial particle production, i.e CGC or Glauber.

4. High p_t : Forward particle production at RHIC

The observation of suppression phenomena in forward measurements in d+Au collisions at RHIC has been consistently explained in terms of CGC effects [6, 5]. Thus, the single inclusive spectra measured both in p+p and d+Au (Fig. (3)) left) are well described in the framework of the hybrid approach proposed in [11]. Also, the disappearance of forward azimuthal correlations

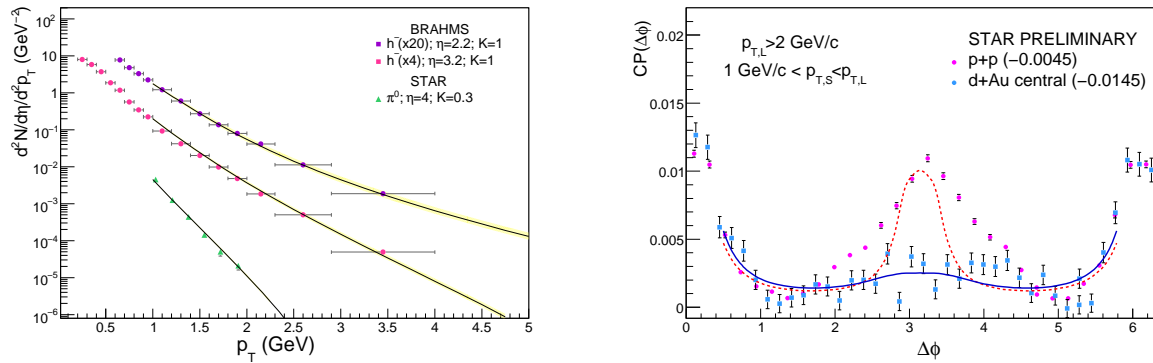


Figure 3: Suppression of forward single inclusive yields (left) and di-hadron azimuthal correlations (right) compared to CGC calculations [6, 5]. Data by BRAHMS and STAR collaborations, respectively .

(Fig. (3) right) can be interpreted as due to the presence of a dynamical, semi-hard scale in the nucleus wave function. The use of solutions of the running coupling BK equation to describe the x -evolution of the nuclear wave function turns out to be necessary in order to attain a good quantitative description of both observables. A caveat in both calculations is that high- x effects, such as energy loss effects or the effects [15] of multi-parton interactions, argued to be important in the forward region [19], are not taken into account. However, preliminary measurements by the STAR collaboration on neutron tagged events, thus reproducing *true* p+Au collisions, confirm the suppression of azimuthal correlations, thus eliminating the uncertainty on the role of multi-parton interactions and lending support to the CGC interpretation. These studies have been taken as a baseline to estimate the nuclear modification factors for single inclusive hadron production at the LHC, predicting a similar suppression in LHC p+Pb collisions at mid rapidity to the one observed in forward rapidities at RHIC. This is in contrast with predictions based on the use of collinear factorization and nuclear pdf's (see eg [18]). However, the predictions of [6] suffer of an uncertainty on the absolute normalization, due to the fact that the nuclear and proton saturation scales were fitted independently to data. The requirement that initial state, saturation effects should disappear at high enough p_t demands that they should be related through the thickness function. Such could be achieved by redoing the phenomenological analyses of [6, 5] in the MC-CGC set up.

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