Heavy Ion Physics in eRHIC

Jamal Jalilian-Marian

Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, WA, USA

Abstract. We review the physics of gluon saturation in heavy ions at small x and consider the applications of Color Glass Condensate formalism to Deep Inelastic Scattering (DIS) of leptons on nuclei and discuss the overlapping physics between high energy heavy ion collisions at RHIC and DIS in eRHIC.

Keywords: Deep Inelastic Scattering, structure functions, small x, Color Glass Condensate
PACS: 24.85.+p, 25.75.-q

DEEP INELASTIC SCATTERING

Fundamental constituents of hadron and nuclei can be studied in Deep Inelastic Scattering (DIS) lepton-hadron (nucleus) experiments where one the virtual photon radiated by the lepton probes the quark and gluon content of the target hadron or nucleus. The cross section for the lepton-hadron scattering can be written as a product of the leptonic tensor $L_{\mu\nu}$, which describes the electromagnetic part of the process, and the hadronic tensor $W^{\mu\nu}$ which contains all the information about the target hadron, written as

$$\frac{d\sigma}{dxdQ^2} \sim L_{\mu\nu} W^{\mu\nu} \tag{1}$$

where $Q^2 \equiv -q^2, x \equiv \frac{Q^2}{2q\cdot P}$ and k, q, P are the momenta of the incoming lepton, exchanged virtual photon and target hadron respectively. The leptonic tensor is well known and rather trivial. The hadronic tensor can be written in terms of two structure functions (for unpolarized processes and ignoring parity violating contributions) F_1 and F_2 as

$$\frac{d\sigma}{dxdQ^2} = \frac{2\pi\alpha_{em}^2}{Q^4}\left\{\left[1+(1-y)^2\right]F_2(x,Q^2) - y^2 F_L(x,Q^2)\right\} \tag{2}$$

where $y \equiv \frac{q\cdot P}{k\cdot P}$ and the longitudinal structure function F_L is defined as $F_L \equiv F_2 - 2xF_1$. The structure function F_2 is typically written in terms of quark and anti-quark distribution functions $q(x,Q^2), \bar{q}(x,Q^2)$ as

$$F_2(x,Q^2) = \sum_f e_f^2 \left[x q_f(x,Q^2) + x\bar{q}_f(x,Q^2)\right] \tag{3}$$

where the sum runs over all flavors. The quark and anti-quark distributions above then can then be used in a collinearly factorized cross section in order to, for example, calculate single inclusive particle production in hadron-hadron collisions via

$$E\frac{d\sigma^{h_1h_2\to hX}}{d^3p} \sim f_{h1}(x,Q^2) \otimes f_{h2}(x,Q^2) \otimes \frac{d\sigma}{dt} \otimes D_{f/h}(x,Q^2) \tag{4}$$

The usefulness of a relation like (4) lies in the fact that the non-perturbative ingredients of this relation, such as the parton distribution functions $f_{h1,h2}$ and $D_{f/h}$ are universal, i.e. process independent and can be measured in other processes, such as in DIS while the hard scattering cross section is process dependent, but can be calculated perturbatively.

It is important to note that the relation (4) is not exact and receives corrections which are suppressed by the hard scale in the problem, Q^2. This may be taken to mean that these corrections are small and can be neglected if one is at sufficiently high momentum. However, these corrections may be enhanced by effects which are energy or A (nucleon number) dependent which could make them quite large for sufficiently high energies and/or large nuclei. One such effect is the large longitudinal phase space which becomes available when the center of mass energy squared s is much larger than the hard scale Q^2 such that $\alpha_s \ln 1/x \sim \alpha_s \ln(s/Q^2)$ is large. This would lead to breakdown of (4) since it would necessitate re-summation of the $\alpha_s \ln 1/x$ terms which can not be readily included in (4). Furthermore, it is known that the parton distributions defined in (3) are modified in nuclei. This modification of nuclear parton distributions is quite non-trivial and would generically signify the inappropriateness of a relation like (4) for calculating particle production in high energy heavy ion collisions.

DIS at small x

At Small x and in the rest frame of the target, virtual photon-hadron (nucleus) interaction can be separated into two independent parts, first the virtual photon fluctuates into a quark anti-quark pair and in the second stage, this pair multiply interacts with the target hadron (nucleus). The virtual photon-target cross section can be written as

$$\sigma_{T,L}^{\gamma^\star p} = \int d^2b_t\, d^2r_t \int dz\, |\psi_{T,L}(z, r_t, Q^2)|^2\, \sigma_{q\bar{q}N}(x, r_t, b_t) \tag{5}$$

where $|\psi|^2$ is the probability of a virtual photon splitting into a quark anti-quark pair, with the quark carrying z and the anti-quark carrying $(1-z)$ fraction of the virtual photon energy. The quark anti-quark target cross section $\sigma_{q\bar{q}N}$ includes all the multiple scatterings of the pair on the target as well as the x evolution of the target wave function and is given by

$$\sigma(x, r_t, b_t) \equiv \frac{1}{N_c} \mathrm{Tr}_c \left\langle 1 - V(b_t + \frac{r_t}{2}) V^\dagger(b_t - \frac{r_t}{2}) \right\rangle_\rho \ . \tag{6}$$

and V is a matrix in the fundamental representation of $SU(N_c)$ which goes along the light cone and sums the non-Abelian phases of the quark propagating through the color field of the nucleus. The cross section σ satisfies the non-linear evolution equations known as the JIMWLK equation. In the large N_c limit, the JIMWLK equations simplify and can be written in a closed form, known as the BK equation which for the dipole cross section, takes the form

$$\frac{dN_F}{d\ln 1/x} \sim \alpha_s\, \kappa_{BFKL} \left\{ N_F - N_F^2 \right\} \tag{7}$$

where $N_F \sim \int d^2b_t\, \sigma(x, r_t, b_t)$. The Wilson line V (and its adjoint counterpart U) are the universal ingredients on which any cross section involving hadrons or nuclei in high energy depend. For example, in single and double particle production cross section in DIS and proton-nucleus collisions. The difference between a hadron and a nucleus target in this formalism is in the initial condition of the JIMWLK equations which the dipole cross section satisfies.

PROTON-NUCLEUS COLLISIONS

In high energy proton-nucleus collisions can be formulated as a collision of a dilute system of partons, quarks and gluons in a proton, with the classical field of a nucleus if the center of mass energy is high enough and if we are not too far in rapidity from the proton. In case of super high energies and rapidities not too close to the proton, one may have to treat the proton as a classical field as well. However, this is probably not the case for the current and proposed collider experiments such as RHIC and LHC and at not too low transverse momenta.

Single inclusive hadron production cross section in proton-nucleus collisions can be written as

$$\frac{d\sigma^{pA\to hX}}{dY\, d^2P_t\, d^2b} = \frac{1}{(2\pi)^2}\int_{x_F}^1 dx\, \frac{x}{x_F}\Bigg\{ f_{q/p}(x,Q^2)\, N_F[\frac{x}{x_F}P_t, b]\, D_{h/q}(\frac{x_F}{x}, Q^2) + f_{g/p}(x,Q^2)\, N_A[\frac{x}{x_F}P_t, b]\, D_{g/h}(\frac{x_F}{x}, Q^2)\Bigg\} \tag{8}$$

where Y and P_t are the rapidity and transverse momentum of the produced hadron and x_F is its Feynman-x while f and D are the proton parton distribution and parton-hadron fragmentation functions. Again, the cross section is written in terms of the (fundamental and adjoint) dipole cross sections. This makes it possible to use DIS on nuclear targets in order to extract or constrain the dipole cross section and use it in proton-nucleus collisions. This demonstrates how the Color Glass Condensate restores the universality of the ingredients of QCD cross sections in a dense environment, which is lost in a collinear factorization approach such as (4). Eq. (8) can be used to describe the recent RHIC data on charged particle production in the forward rapidity region where a good agreement with the charged hadron transverse momentum spectrum is found.

One can also investigate two particle production and the azimuthal correlation between the two produced particles in a proton-nucleus collision. In case of production of two hadrons, the cross section involves higher point functions of Wilson lines, such as three and four point functions. These expression are highly complicated and difficult to evaluate analytically even though one can investigate some interesting limits in transverse momentum and rapidity. Alternatively, one can use approximates solutions in different regions of interest and study the behavior of the correlations semi-quantitatively such as in where it has been shown that azimuthal correlations tend to get washed away due to x evolution, given there is a sufficiently large rapidity separation between the produced hadrons or jets.

Hadronization by its nature is non-perturbative and not well understood in QCD. One side-steps the question of the dynamics of hadronization by the use of fragmentation functions in perturbative QCD. However, there are theoretical uncertainties as well as experimental difficulties and limitation on the kinematics where these fragmentation functions can be measured. One can avoid these issues by investigating electromagnetic processes such as photon and dilepton production in proton nucleus collisions. Here, show the dilepton production cross section in proton nucleus collision using the Color Glass Condensate formalism. Again, the basic ingredients of the cross section are the Wilson lines which make it possible to use our knowledge from DIS. The cross section is given by

$$\frac{d\sigma^{qA\to ql^+l^-X}}{dz\,d^2b_t\,d^2k_t\,d\log M^2} = -\frac{2\alpha_{\rm em}^2}{3\pi}\int\frac{d^2l_t}{(2\pi)^4}\sigma(x,l_t,b_t,)$$
$$\left\{\left[\frac{1+(1-z)^2}{z}\right]\frac{z^2\,l_t^2}{[k_t^2+M^2(1-z)][(k_t-zl_t)^2+M^2(1-z)]}\right.$$
$$\left.-z(1-z)\,M^2\left[\frac{1}{[k_t^2+M^2(1-z)]}-\frac{1}{[(k_t-zl_t)^2+M^2(1-z)]}\right]^2\right\}$$

Nucleus-Nucleus Collisions

The knowledge gained from DIS and proton nucleus collisions will be invaluable for the pursuit of the so called Quark Gluon Plasma in high energy heavy ion collisions, such as those at RHIC and in the near future at LHC. A detailed knowledge of the nucleus wave function will be extremely useful in helping determine the initial conditions of a high energy heavy ion collisions, which is essential in determining the subsequent evolution of the produced hot and dense system. One can use the Color Glass Condensate formalism in order to determine the initial number of partons produced in the collisions and follow their further interactions after the collision until a possible thermalization or isotropization. One can determine the initial "temperature" and energy density of the produced system and use those as the input for kinetic theory or hydrodynamics type approaches. This avenue is of particular interest to heavy ion community and Deep Inelastic Scattering experiments at eRHIC will be able to explore kinematic regions which will be reached at LHC and where there is practically no information available on the structure of target nuclei.

In summary, there are strong indications from RHIC that the Color Glass Condensate has been observed in the forward rapidity region. The properties of the Color Glass Condensate can be precisely measured in eRHIC in a kinematic region desperately needed for the LHC experiment.

REFERENCES

1. For a review of Color Glass Condensate formalism and an extensive list of references, see J. Jalilian-Marian and Y. V. Kovchegov, arXiv:hep-ph/0505052.