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The initial state and hard probes: a brief review

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Abstract

We provide a brief review of some of the recent developments in our understanding of the initial state in ultra-relativistic heavy-ion collisions.

Keywords: Color Glass Condensate, Glasma, Quark-Gluon Plasma

1. Introduction

In this talk, we will provide a brief, and therefore of necessity, incomplete review of recent developments in our understanding of the initial state in heavy-ion collisions. Acknowledging the scope of the conference, I will address a few examples where hard probes can provide insight into the nature of the initial state.

In studying the real time dynamics of strongly interacting gauge theories, there are two clean asymptotic limits where one can obtain clear answers to well posed questions. One is in the limit of large t'Hooft coupling $g^2 N_c$ and large N_c, where a duality may be established between correlation functions in strongly coupled supersymmetric Yang-Mills theories with $N = 4$ supercharges and weakly coupled gravity in a 10 dimensional $AdS\,5 \times S\,5$ spacetime [1]. The other clean limit is that of very weak coupling $g \to 0$ in QCD but $g^2 f \sim 1$ where f denotes the occupancy of gluon modes[1] [2, 3, 4, 5, 6]. Our focus here will be on the strongly correlated gluodynamics of the initial state and early time dynamics in weak coupling.

2. The CGC wavefunction

The strongly correlated dynamics of saturated gluons in hadron wavefunctions is described by the CGC effective theory [7]. The CGC initial state is a highly Lorentz contracted gluon shock wave that is "lumpy" in the transverse plane on a scale $1/Q_S$. This saturation scale is the color screening length measured by a quark-antiquark dipole probe. Q_S grows with energy (or decreasing Bjorken x) and with nuclear size; its rate of growth is described by the Balitsky-Kovchegov (BK) renormalization group (RG) equation [8, 9]. When $Q_S \gg \Lambda_{\rm QCD}$, the many-body parton dynamics inside nuclear wavefunctions can be described in weak coupling. Because the dynamics is captured by one emergent scale, the CGC framework has enormous predictive power in a regime of QCD where the equations describing color fields are strongly non-linear.

In high energy scattering, cross-sections are described in terms of dipole, quadrupole and in principle multipole products of lightlike Wilson line correlators. These appear in both Deeply Inelastic Scattering (DIS) and hadron-hadron scattering and their evolution with energy is described by the B-JIMWLK hierarchy of equations [8, 10, 11]; the BK equation is a closed form simplification of the equation for dipole correlators in the large N_c and large A limit. There has been significant progress in the last few years in extending the B-JIMWLK hierarchy to NLO; progress in this direction is reviewed in the plenary lecture by Beuf [12].

For practical applications, there are two widely adopted approaches to describe gluon saturation. One is within the framework of the IP-Sat model [13]. The key ingredient in this model is the previously noted dipole

[1] An equivalent gauge invariant measure is the field strength squared in units of a hard scale of interest.

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cross-section. Its behavior depends on $Q_S(x,b)$, which is now a function of x and impact parameter b. The latter dependence accounts for the fact that color screening may vary depending on whether the center or periphery of the proton is probed by the quark-antiquark dipole. In the IP-Sat model, $Q_S(x,b)$ is determined from fits to HERA inclusive and exclusive data [14]. A recent development in this regard is the neat observation by Mantysaari and Schenke [15] that a spherical impact parameter profile of glue in the proton does not describe HERA data on incoherent exclusive J/Ψ production. This measurement, which is sensitive to fluctuations of the dipole cross-section, is better fit by non-spherical profiles, such as for instance those that might be generated by bremsstrahlung of gluons from constituent quarks [16].

The other phenomenological approach is one where the dipole cross-section is determined within the framework of the BK equation. The state of the art here is the NLO BK equation; its numerical implementation is discussed in the talk by Lappi [17]. While this approach is better motivated from first principles, including impact parameter dependence in a reliable manner remains challenging and complicates phenomenological analyses.

3. Hadron-hadron collisions in the CGC framework

Collisions at high energies, being those of lumpy gluon shocks, are not classified by the atomic number of the projectile A or target B but instead by the respective saturation scales and the typical transverse momenta involved [18]. Dilute-dilute collisions, defined as $Q_{S,A}^2/k_{T,A}^2 << 1$ and $Q_{S,B}^2/k_{T,A}^2 << 1$ can correspond to high transverse momentum processes in nucleus-nucleus collisions or alternately, dynamics at moderate k_T in proton-proton collisions. In this regime, if $x << 1$, the CGC matches smoothly to pQCD computations of hard processes; its definition as an effective field theory depends on it! Dilute-dense collisions correspond to $Q_{S,A}^2/k_{T,A}^2 << 1$ and $Q_{S,B}^2/k_{T,B}^2 \sim 1$. In these kinematics, which corresponds for instance to final states in proton-nucleus (p+A) collisions or forward proton-proton (p+p) collisions, a hybrid pQCD/CGC description is feasible. Dynamics from the proton side is treated using collinear or k_T factorization while that from the nuclear side includes high twist effects represented by Wilson line correlators. These last can be computed, as noted, using the BK/B-JIMWLK RG equations. Finally, dense-dense power counting corresponds to $Q_{S,A}^2/k_{T,A}^2 \sim 1$, $Q_{S,B}^2/k_{T,B}^2 \sim 1$. In this case, which is relevant for the bulk properties of a heavy-ion (A+A) collision, there is no small parameter. However, the classical Yang-Mills equations describing the dynamics can be solved numerically in 2+1-D and 3+1-D, with the leading quantum fluctuations resummed into stochastic initial conditions [18, 19, 20].

3.1. Dilute-dense results for p+A collisions

A significant development is the treatment of the single inclusive hadron spectrum in p+A collisions beyond LO [21]. The first NLO computations gave NLO results that improved agreement with data at low p_T but gave unphysical results at p_T's greater than a few GeV [22, 23, 23]. This is because kinematical constraints become increasingly important in matching to collinear factorization at high p_T [24, 25]. As discussed in the talk by Yan Zhu [26], the problem may be resolved by proper treatment of rapidity factorization schemes.

Onium production in p+p and p+A collisions is successfully described in a CGC+NRQCD framework [27]. For forward p+p and p+A, the dilute-dense framework, employing the running coupling BK equation, gives a good description of RHIC and LHC data at low p_T [28, 29]. This framework smoothly matches to an NLO pQCD+NRQCD framework at higher p_T [30]. An interesting conclusion of this study is that color octet channels dominate the J/Ψ cross-section, with the color singlet contribution providing only a 10% contribution in p+p collisions and at most 15-20% of the cross-section in p+A collisions. Ducloe in his talk [31] showed that previous disagreement of data with CGC predictions [32] arose from an improper treatment of the p+A geometry [33, 34].

Both the Color Evaporation model (CEM) and NRQCD describe the p+A J/Ψ data within uncertainties; since octet mechanisms dominate both descriptions, this is perhaps not too surprising. As discussed in several talks, in particular the plenary lecture by Ferreiro [35], the $\frac{\Psi'}{J/\Psi}$ ratio can be described by rescattering; a very slight modification of the CEM model to account for initial state soft gluon comover exchanges describes the systematics of the data [36, 37].

Benic in his talk [38, 39] noted that a framework identical to the one for heavy quark pair production [40] gives the leading contribution to photon production in p+A collisions. Specifically, Low's theorem shows that the cross-section factorizes into the cross-section for quark-antiquark pair production times a kinematical factor corresponding to photon bremsstrahlung for soft photons. Another interesting result is that at high p_T this cross-section smoothly goes over into the collinearly factorized expression proportional to the nuclear glu-