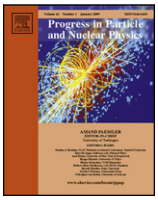
Progress in Particle and Nuclear Physics 76 (2014) 1–42

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp



Review

Gluon saturation and initial conditions for relativistic heavy ion collisions

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ARTICLE INFO

Keywords:
Heavy ion collisions
High-energy QCD
Gluon saturation
Quark–Gluon plasma

ABSTRACT

We present an overview of theoretical aspects of the phenomenon of gluon saturation in high energy scattering in Quantum Chromo Dynamics. Then we review the state-of-the-art of saturation-based phenomenological approaches to the study and characterization of the initial state of ultra-relativistic heavy ion collisions performed at RHIC and the LHC. Our review focuses mostly in the Color Glass Condensate effective theory, although we shall also discuss other approaches in parallel.

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http://dx.doi.org/10.1016/j.ppnp.2014.01.004
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1. Introduction

The main goal of the experimental programs on ultra-relativistic heavy-ion collisions (HIC) at Brookhaven's relativistic heavy-ion collider (RHIC) and at CERN's large hadron collider (LHC) is to study QCD matter under extreme conditions. As the RHIC experiments were announcing what is now considered the prime ingredient of RHIC's legacy – the discovery of a new state of matter of extremely high density and temperature called the Quark–Gluon Plasma (QGP) – a part of the community was studying the QCD description of the initial nuclei themselves, and what it implied for hadronic scattering in high-energy limit. At that time, the importance of a detailed understanding of the physics of the initial state was already recognized, but overall, perhaps under-appreciated. Rather, signals related to the expected thermal properties of the QGP were considered as the most promising observables for discovery.

As in any other hadronic collision process, a precise understanding of the partonic composition of the projectile nuclei at all the relevant scales is indeed crucial. A typical lead–lead collision at the LHC gives rise approximately 10 000 detected particles in the final state. Further $\sim$99% of such particles carry a relatively small transverse momentum compared to the center of mass collision energy, 2.76 TeV at the LHC, $p_t \lesssim$ 1–2 GeV. This simple observation, together with a ballpark analyses of the collision kinematics, leads immediately to the conclusion that most of the produced particles in a high-energy heavy ion collision are originated from partons (mostly gluons) that carry a small fraction x of the light-cone (equivalently, longitudinal) momentum of their parent nucleon. Typical values for RHIC and LHC energies at central rapidities are $x \sim 10^{-2}$ and $x \sim 10^{-4}$, although even smaller values are reached at more forward rapidities.[1]

Therefore, a detailed understanding of the – abundant – small-x gluons in the wave function of the colliding nuclei is mandatory for a proper characterization of the QCD medium produced in HIC. As the goal had become to turn the physics of the QGP into a quantitative science, it was realized that bulk observables in HIC were as much sensitive to features of the initial state as they are to properties of the quark–gluon plasma itself, making it impossible to precisely extract the medium transport coefficients, such as the viscosity over entropy density ratio, without a proper quantitative understanding of the physics of the initial state. This observation was confirmed by the first lead–lead results from the LHC.

Most recently, the results of proton–lead collisions at the LHC, which were thought of by many as a mere cold-matter control experiment, have instead put into question our interpretation of RHIC and LHC results on heavy-ion collisions: high-multiplicity proton–nucleus collisions seem to produce the same QGP signals as nucleus–nucleus do, without any sign of the systematic effects the smaller system size would imply. This has brought even more importance into the physics of the initial state as it is believed that the solution to this puzzle lays in the understanding of high-multiplicity proton–nucleus (and proton–proton) collisions.

As a matter of fact, one of the major challenges since the discovery of QCD has been to understand hadronic Fock-space wave functions in the high-energy limit. It was realized long ago that, due to the soft singularity of the splitting function of non-Abelian gauge bosons, hadronic wave functions would contain a large number of gluons with a small (light-cone) momentum fraction x [1]. This expectation was confirmed by e+p deep-inelastic scattering experiments at HERA (see below) and is accounted for by modern PDF parameterizations. At the same time it also became clear that such fast growth of the gluon densities in hadron towards small-x could not continue indefinitely or, otherwise, unitarity of the theory would be violated. Rather, it was proposed that at sufficiently small-x, a novel non-linear dynamics of the soft color fields would emerge, taming the non-abelian avalanche of soft gluons towards the small-x domain and restoring unitarity. This new phenomenon is commonly referred to as *saturation* of gluon distributions at low x and manifests itself in non-linear, density dependent terms in the QCD evolution equations.

The onset of gluon saturation effects is controlled by a dynamically generated transverse momentum scale, the saturation scale $Q_s(x)$. Although saturation effects are expected to be an intrinsic feature of any hadronic wave function at sufficiently high energies, the saturation momentum $Q_s(x)$ is boosted further in an ultra-relativistic heavy nuclei due to the superposition of the gluon fields of its constituent nucleons induced by Lorentz contraction in the longitudinal direction. In other words, the density of large-x "valence" charges per unit transverse area increases in proportion to the thickness $\sim A^{1/3}$ of a nucleus [2–4]. These represent the sources for the small-x soft gluon fields. Thus, non-linear color field dynamics should be operative in nuclear wave functions at higher transverse momentum scales than for nucleons.

While the need for non-linear corrections to QCD evolution equations in the high-energy regime is well established from a theoretical point of view, the relevant question for present analyses of HIC data is to what extent such corrections are present at available collision energies and, if so, what is the best theoretical framework for their description. Concerning the first of these two questions, one important lesson learned 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, for instance, from the measured charged particle multiplicities which exhibit a strong deviation from scaling with the number of independent nucleon–nucleon collisions: $\frac{dN^{AA}}{d\eta}(\eta = 0) \ll N_{coll}\frac{dN^{NN}}{d\eta}(\eta = 0)$. One is led to the conclusion that strong coherence effects among the constituent nucleons, or the relevant degrees of freedom at the sub-nucleon level, must be present during the collision process. In a QCD

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[1] This values arise from simple 2 → 1 kinematics neglecting fragmentation effects: $x \sim m_t e^{-y}/\sqrt{s}$, with $\sqrt{s}$ the nucleon–nucleon center of mass energy, m_t and y the transverse mass and rapidity of the produced particle.