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Turbulent thermalization process in high-energy heavy-ion collisions

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Abstract

We discuss the onset of the thermalization process in high-energy heavy-ion collisions from a weak-coupling perspective, using classical–statistical real-time lattice simulations as a first principles tool to study the pre-equilibrium dynamics. Most remarkably, we find that the thermalization process is governed by a universal attractor, where the space–time evolution of the plasma becomes independent of the initial conditions and exhibits the self-similar dynamics characteristic of wave turbulence [1]. We discuss the consequences of our weak-coupling results for the thermalization process in heavy-ion experiments and briefly comment on the use of weak-coupling techniques at larger values of the coupling.

Keywords: Pre-equilibrium dynamics; Thermalization process; Wave turbulence

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1. Introduction

The question of how exactly a thermalized Quark–Gluon Plasma (QGP) is formed in high-energy heavy-ion collisions is one of the major challenges in our current theoretical understanding of the experiments carried out at RHIC and the LHC. While practically all phenomenological models are based on the assumption that a close to thermal equilibrium state can be reached on

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a time scale of $\sim$1 fm/c, so far no clear theoretical understanding of this behavior has been established.

One of the major challenges in this regard is that the typical values of the coupling constant probed at present collider facilities ($\alpha_s \sim 0.3$) are not necessarily in a suitable range for weak or strong coupling methods. Nevertheless significant progress in the understanding of the thermalization process has come from the study of these two limiting cases, where first principles calculations of the out-of-equilibrium dynamics are feasible [2].

In this talk we discuss recent progress in the understanding of the thermalization process at weak coupling, which has been achieved by classical–statistical real-time lattice simulations [1]. Within their range of validity – at weak coupling ($\alpha_s \ll 1$) and high occupancy ($f(t,p) \gg 1$) [3] – these provide a first principles description of the non-equilibrium dynamics and allow for unprecedented insights into the thermalization process. We discuss the implications for the thermalization process at weak coupling in Section 2 and present an extrapolation towards more realistic values of the coupling. We also comment on the use of classical–statistical method at larger values of the coupling in Section 3 and present our conclusions in Section 4.

2. Thermalization process at weak coupling

2.1. Initial state

In the limit of weak-coupling and high collider energies the dynamics of the collision can be efficiently described in the color-glass condensate (CGC) framework [4,5]. Within this framework the initial state, formed immediately after the collision of heavy nuclei, is characterized by strong boost invariant color fields ($A^a_\mu \sim 1/g$) [6] usually referred to as the “Glasma”. Even though the coupling constant is weak, the characteristic field amplitudes are large $\sim 1/g$ and the system is strongly interacting.

2.2. Early time dynamics

The boost invariant (2 + 1D) Yang–Mills dynamics of the “Glasma” has been studied in great detail [7,8]. However, since the “Glasma” is a highly anisotropic state, it is unstable with respect to small vacuum fluctuations ($a^a_\mu \sim 1$) which break the longitudinal boost invariance. While this was realized a long time ago [9], and several studies have been performed since, the spectrum of vacuum fluctuations in the CGC framework was only obtained recently [10]. We performed 3 + 1D Yang–Mills simulations for these initial conditions to study the effect of instabilities at weak coupling ($\alpha_s \sim 10^{-6}$) where the classical–statistical framework is manifestly robust. Our preliminary results are summarized in Fig. 1 showing the single particle gluon distribution at different times of the evolution. While initially the spectrum is dominated by the boost invariant “Glasma” fields we find that plasma instabilities lead to a (quasi-)exponential growth of low momentum modes [11]. As a result, an over-occupied plasma – characterized by a non-perturbatively large occupancy of low momentum modes – is formed on a short time scale which is parametrically given by $Q\tau \sim \log^2(\alpha_s^{-1})$ (cf. [11]), where Q denotes the characteristic momentum scale. We find that at this stage of the evolution the system is still quite anisotropic and far from equilibrium. Nevertheless, this suggests that in weak coupling, the initial conditions of [16] may in principle be represented by the initial conditions proposed in our prior work for times $Q\tau \gtrsim \log^2(1/\alpha_S)$.