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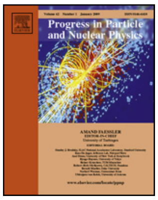

Review

Evaluating results from the Relativistic Heavy Ion Collider with perturbative QCD and hydrodynamics

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ABSTRACT

We review the basic concepts of perturbative quantum chromodynamics (QCD) and relativistic hydrodynamics, and their applications to hadron production in high energy nuclear collisions. We discuss results from the Relativistic Heavy Ion Collider (RHIC) in light of these theoretical approaches. Perturbative QCD and hydrodynamics together explain a large amount of experimental data gathered during the first decade of RHIC running, although some questions remain open. We focus primarily on practical aspects of the calculations, covering basic topics like perturbation theory, initial state nuclear effects, jet quenching models, ideal hydrodynamics, dissipative corrections, freeze-out and initial conditions. We conclude by comparing key results from RHIC to calculations.

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1. Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory started operations about a decade ago. The amount of data collected and the quality of the data have been outstanding. Besides a successful proton–proton and proton–nucleus program, RHIC has mostly provided data on nuclear collisions, from a few GeV center of mass energy up to 200 GeV per nucleon–nucleon pair. We have strong evidence that the central goal of the RHIC program, the discovery of quark gluon plasma (QGP), a deconfined state of nuclear matter, has been achieved. In order to draw this conclusion a wide variety of observables have been weighed against theoretical expectations and we will discuss a few of those in this article. Some key experimental discoveries at RHIC over the past decade were (i) the extremely strong jet quenching, many times that of ordinary nuclear matter [1,2]; (ii) the very large elliptic flow of the fireball that confirms collective behavior at energy densities larger than expected at the phase transition [3]; (iii) the surprising quark number scaling of elliptic flow that seems to indicate that the collective flow is carried by quarks [4,5] (see [6] for an attempt of an alternative explanation); and (iv) direct photon measurements that suggest large initial temperatures [7]. Even before the partonic nature of the fireball could be established there was mounting evidence that the hot matter at RHIC was not behaving like a weakly interacting gas, but rather like a strongly interacting liquid. This has led to the conjecture that quark gluon plasma is a nearly perfect liquid [8], at least close to the phase transition temperature. Conservative estimates for the initial energy density in the center of head-on collisions at top RHIC energy find a lower bound $\sim$3 GeV/fm^3, which is above the estimated critical energy density [3].

Perturbative quantum chromodynamics (pQCD) and relativistic hydrodynamics have been two important tools to understand and interpret RHIC data. It was found that the bulk of the produced particles at RHIC (for transverse momenta P_T smaller than $\approx$2 GeV/c) show signatures of collective behavior. The mean-free path of particles seems to be small enough for the dynamics to be described by relativistic fluid dynamics. This was a non-trivial finding since hydrodynamic descriptions for lower energy nuclear collisions routinely overestimated the amount of collectivity. While hydrodynamic modeling 10 years ago was still rough, based on $(2+1)$-dimensional ideal fluid dynamics with simple initial conditions and freeze-out, there has been an amazing amount of progress since then by going to full $(3+1)$-dimensional modeling, taking into account dissipative corrections, fine-tuning of initial conditions all the way to event-by-event calculations, and a deeper understanding of the hadronic phase with separate chemical and thermal freeze-outs, and through the advent of hybrid hydro + cascade models. We will highlight many of these improvements in this article. The progress has enabled hydrodynamic models — and the entire RHIC program — to enter a phase in which quantitative measurements are finally close. Prime candidates for such quantitative measurements are the equation of state of hot QCD, including the order of the phase transition between hadronic matter and QGP and the existence and location of a critical point, and the shear viscosities of these phases. The measurement of other bulk transport coefficients, like the bulk viscosity and relaxation times, are in principle possible but remain elusive for now. We will discuss the status and potential problems of such measurements.

Hydrodynamics describes the bulk of the particles in a collision (more than 98% of them). The tail of the particle P_T-spectra in nuclear collisions, which clearly contain particles that have not thermalized, should not simply be disregarded. In fact it was proposed a long time ago that they can serve as "hard probes" of the bulk matter created. In elementary $p+p$ or $p+\bar{p}$ collisions hadrons with transverse momenta of 5 GeV/c or more are created through a single hard scattering of two partons within the wave functions of the colliding hadrons, which then fragment in the vacuum away from the collision into collimated bunches of hadrons, called jets. This entire process can be calculated in perturbative QCD due to the large momentum transfer involved, while the unavoidable non-perturbative contributions can be treated in a controlled way through a formalism called collinear factorization. Perturbative QCD based on collinear factorization has been a great success story in elementary collisions [9]. Hard initial scatterings of partons from the initial nuclear wave functions should