Properties of a system of fundamental constituents of visible matter

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The systems in nature that allow for studying the bulk properties of a strongly interacting matter are: (a) the interior of atomic nucleus, (b) interior of nucleon, (c) interior of neutron star and (d) the de-confined state of quarks and gluons (fundamental constituents of any visible matter) called the quark–gluon plasma (QGP). The latter state of matter has been created in the heavy-ion (Au, Pb, U) collisions at the Relativistic Heavy-Ion Collider (RHIC) facility, Brookhaven National Laboratory[1–4] and the Large Hadron Collider (LHC) Facility, CERN[5–11]. It has been found that QGP behaves as (i) a nearly inviscid liquid and (ii) is highly opaque to energetic coloured (colour charge) probes. Here we report the development towards establishing these properties both theoretically and experimentally. The 14 years of progress in this research towards arriving at the inviscid liquid property is summarized[12] in Figure 1 and that towards the opaque property in Figure 2. Such has been the impact of this research that it has led to development in several new sub-fields of physics research: (a) relativistic viscous fluid dynamics and (b) application of gauge–gravity duality to strongly coupled quantum field theories.

Prior to the experiments at RHIC and LHC, the expectation for the high-temperature states of quarks and gluons to be created in nuclear collisions was that of a weakly coupled system (due to asymptotic freedom) that would behave like an ideal gas and expand isotropically. The first results on the azimuthal angle anisotropy measurements (denoted as anisotropy parameter v_n in Figure 1) of the produced particles in the collisions proved that this view was wrong. The measurements were found to be close to those obtained from an ideal hydrodynamics, indicating the formation of a strongly coupled system (a small value of shear viscosity to entropy density ratio, η/s). Later it was realized that Anti-de Sitter/Conformal Field Theory (AdS/CFT) calculations[13] could be used to calculate η/s for a strongly coupled system, in a regime where standard kinetic theory was known to break down. These calculations suggested a lower bound to $\eta/s = 1/4\pi$, providing a theoretical basis for the argument that excitations cannot be localized to a precision smaller than their thermal wavelength. However, this conjecture of a lower bound to η/s has been debated in the literature. For example, this bound could be violated for a system of nonrelativistic gas by increasing the number of species in the fluid while keeping the dynamics independent of the species type[14]. Detailed studies of several string theory-based models suggest that in a wide class of models such a bound is conceivable, but with models including fundamental matter leads to corrections which result in violation of this lower bound[15,16]. However all these do not take away the important question whether one can extend the AdS/CFT methods to do quantitative phenomenology relevant to physics at RHIC and LHC[17]. This led to the push in the theory community to develop a proper framework for relativistic viscous hydrodynamics. When the first results from relativistic viscous hydrodynamics calculations started to be compared with experimental data, it was realized that the extracted η/s values depend on the choice of initial condition in the calculations. Specifically, the importance of fluctuations in the initial geometric configurations of the nucleons in the colliding nuclei was discovered. The initial state of a nuclear collision was found not to be of smooth density, but varied from one collision to another. Further inspired from the multi-pole analysis procedures used for observing at anisotropies in the cosmic microwave background spectrum, it was realized that high-order components of azimuthal anisotropy could better constrain the values of η/s. The current estimates[18,19] of the shear viscosity to entropy density ratio for QGP at the

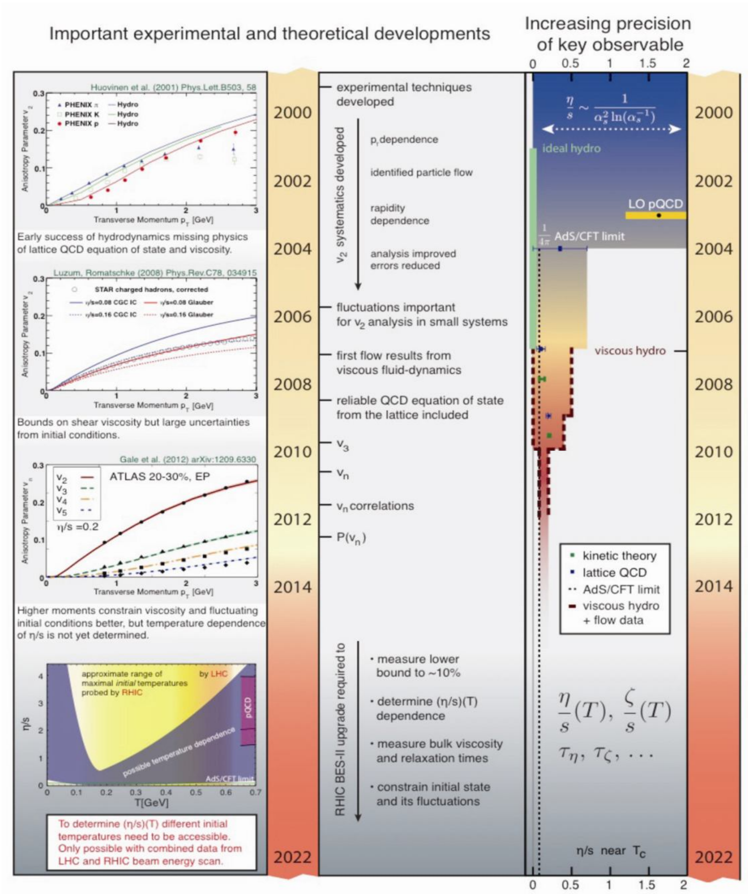

Figure 1. Availability of precision data and advances in theory on increasingly constraining the shear viscosity to entropy density ratio of the quark–gluon plasma near the transition temperature[12].

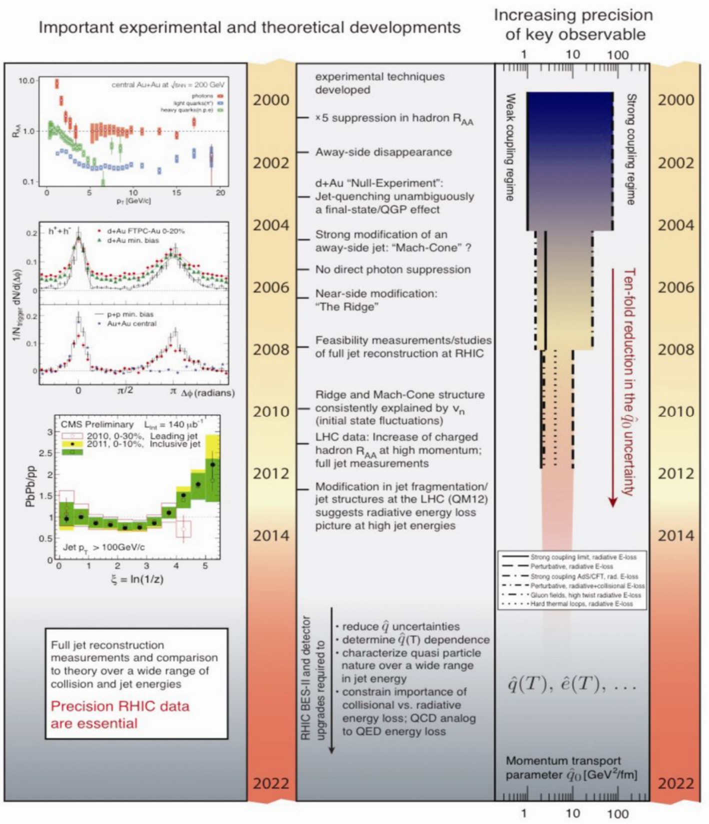

Figure 2. Availability of precision data and advances in theory leading to increasingly better constraints on a quantity which is a measure of opacity of the medium[12].

transition temperature (shown in Figure 1) are $(1 - 2)/4\pi$. Obtaining the temperature dependence of η/s is one of the near-term goals of this field of research.

The other important property of QGP is the determination of the stopping power ($-dE/dx$) for coloured parton (quarks and gluons which carry colour charge). This will provide us information analogous to the precise knowledge of such a quantity for ordinary matter towards electrically charged particles[20,21]. The measure of this stopping power in QGP is expressed in terms of a energy loss transport coefficient ($\hat{q}$, Figure 2), which reflects the square of the momentum transferred by the parton to the QGP per unit length. The first experimental measurements showed that the high momentum distribution of produced hadrons in high-energy nuclear collisions is significantly suppressed relative to nucleonic collisions (ratio R_{AA}, Figure 2). The phenomenon that could lead to such effect was first predicted by J. D. Bjorken and subsequently by others, to be due to energy loss of fast partons in a coloured medium (due to gluon bremsstrahlung and elastic collisions). This process was named as jet-quenching. Subsequent focus of the experimental measurements was towards characterizing the jet properties (through angular correlation measurements) and thereby extracting the stopping power of the medium. Remarkably large stopping power extracted led to the need for more precise measurements and attempts to fully reconstruct jets in high multiplicity environment as in nuclear collisions. Whereas on the theoretical side, innovative many-body perturbative QCD approaches for the propagation of quarks and gluons in QGP were devised. Currently, the value of energy loss transport coefficient has been estimated[22,23] to be 2–10 GeV^2/fm (Figure 2).

A rigorous phenomenological analysis of the precision data from relativistic heavy-ion collisions and theoretical advances over 14 years has led to quantitative estimates for some of the transport properties of a strongly interacting deconfined state of quarks and gluons. The shear viscosity to entropy density ratio is found to be $(1–2)/4\pi$ and that reflecting the stopping power is observed to be 2–10 GeV^2/fm. In addition to determining several other properties like conductivity, temperature dependence of η/s, etc. new questions have come up at the fundamental level in this field of research. (a) What is the mechanism of parton–plasma interactions and how does the plasma respond to energy being deposited in it? (b) Although we find the QCD plasma is strongly coupled but it remains to be studied at what scales? In addition, whether there is a true lower bound to η/s is still an open question. These will be hopefully addressed in the near future.

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