Long wavelength perfect fluidity from short distance jet transport in quark-gluon plasmas

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Abstract

We build a new phenomenological framework that bridges the long wavelength bulk viscous transport properties of the strongly-coupled quark-gluon plasma (sQGP) and short distance hard jet transport properties in the QGP. The full nonperturbative chromo-electric (E) and chromo-magnetic (M) structure of the near “perfect fluid” like sQGP in the critical transition region are integrated into a semi-Quark-Gluon-Monopole Plasma (sQGMP) model lattice-compatibly and implemented into the new CUJET3.0 jet quenching framework. All observables computed from CUJET3.0 are found to be consistent with available data at RHIC and LHC simultaneously. A quantitative connection between the shear viscosity and jet transport parameter is rigorously established within this framework. We deduce the $T = \frac{160}{600}$ MeV dependence of the QGP’s $\eta/s$: its near vanishing value in the near $T_c$ regime is determined by the composition of E and M charges, it increases as $T$ rises, and its high $T$ limit is fixed by color screening scales.

Keywords: Relativistic Heavy Ion Collisions, Jet Quenching, Perfect Fluidity, Quark-Gluon Plasmas

1. Introduction

To probe the fundamental properties of hot quark matter and the mechanism of color confinement through ultrarelativistic nucleus-nucleus collisions, it is necessary to consider both the perturbative and nonperturbative aspects of QCD carefully in heavy-ion phenomenology. Present quantitative analyses of the strongly-coupled quark-gluon plasma (sQGP) created in A+A reactions at RHIC and LHC \cite{1} nevertheless divide in the two aspects: on the one hand, in the “soft” nonperturbative regime, the low transverse momentum ($p_T$) long wavelength “perfect fluidity” of the sQGP is described by relativistic hydrodynamical simulations; on the other hand, in the “hard” regime, high $p_T$ short distance jet transport properties in the QGP computed from perturbative QCD (pQCD) models are compatible with a wide range of data \cite{2}. A unified framework incorporating both aspects is however missing; it is therefore challenging to translate conveniently between heavy-ion and confinement physics.

Concentrated on pQCD, to build up such a framework, both the long and short distance transport properties of the QGP must be accounted for more systematically. In the “soft” sector, the “perfect fluid” like sQGP has a near vanishing shear viscosity to entropy density ratio $\eta/s = 1/4\pi$ bounded by quantum fluctuations \cite{3} \cite{4}. however from leading order (LO) pQCD estimate, the QGP in the weakly-coupled limit (wQGP) has an $\eta/s \approx 0.071(\alpha_s^2 \log(1/\alpha_s))^{-1}$ that approaches 1 \cite{5}. In the “hard” sector, it has been found
that most jet energy loss can describe the high $p_T$ light hadrons’ and open heavy flavors’ nuclear modification factor ($R_{AA}$) data, but the azimuthal elliptic anisotropy ($v_2$) is underestimated by 50% at RHIC and LHC near-universally [8].

The above necessitates (1) exploring the full nonperturbative chromo-electric (E) and chromo-magnetic (M) structure of QCD in the region near the critical transition temperature ($T_c$), (2) developing a microscopic, lattice-compatible description of the sQGP, and (3) implementing it into a systematic pQCD jet energy loss model and testing with high $p_T$ data. The new CUJET3.0 framework achieved all of them [9].

2. The CUJET3.0 framework

In CUJET3.0 [9], accounting for both chromo-electric (E) and chromo-magnetic (M) quasi-particles (QPs) as in the EM seesaw scenario proposed by Liao and Shuryak [10], the dynamical running coupling DGLV [11] energy loss kernel in CUJET2.0 [12] is generalized to:

\[ \frac{dN}{dx} \propto \int d^2q \left[ \rho \frac{\alpha}{2} \left( q_+^2 f_E^2 \right) \right] \rightarrow \int d^2q \left[ \rho_E (\alpha q_+^2 q_T^2 + f_E^2) f_M^2 \right] \quad . \quad (1) \]

Here $\alpha(\rho^2) \equiv \alpha(\rho_E^2) = \alpha / (1 + \frac{g}{\rho} \log(T_c^2 / T \rho_E^2))$ where the Polyakov loop $L(T) \equiv \langle \exp(i g^2 T_c^2 / T) \rangle$ is renormalized such that $L(T) \to \infty = 1$, $c_q$ and $c_T$ are Stefan-Boltzmann fraction coefficients. In the critical transition region, the semi-QGP degrees of freedom (DOFs) and emergent chromo-magnetic monopoles form a semi-Quark-Gluon-Monopole Plasma (sQMP) [9]. The parameter $f_E$ and $f_M$ is defined via $f_E \equiv \mu_{E} / \mu = \sqrt{T_c}$ and $f_M \equiv \mu_{M} / \mu = c_M \mu_{E}$, where $\mu_{E}$ and $\mu_{M}$ are the E and M screening mass respectively, and $\rho = \sqrt{4 \pi \alpha(\mu^2)} = \mu / (T \sqrt{T_c + N_f / 6})$.

The $L(T)$, $\mu_{E,M}(T)$, $\rho / T^3 \sim \rho / T^4 = \frac{1}{T^4} \log Z$, and equation of state (EOS) are all constrained by lattice QCD data, as shown in Fig. 1. A theoretical uncertainty in CUJET3.0 is originated from choosing the diagonal u-quark number susceptibility $\chi_3^T(T) = \frac{d^2(\rho_{u,T}^2)}{d(\mu_{u,T}^2)}$ over the Polyakov loop for the quark deconfinement rate, i.e. $\chi_3^T \rightarrow \chi_3^{QGP}(T) / \chi_3^{QGP}(\infty) + c_q L^2$, which will be analyzed lately. All other computational details in CUJET3.0 are the same as in CUJET2.0, including the 2+1D viscous hydrodynamical background profiles generated from VISHNU simulations [15].

![Fig. 1.](image-url) (Color online) (a) The parameterized fit to lattice QCD data [6] of the renormalized Polyakov loop $L$ and diagonal light quark susceptibility $\chi_3^T$ in the $\chi_3^T$ and $\chi_3^Q$ scheme within CUJET3.0. The inset shows the chromo-electric (E) and chromo-magnetic (M) quasi-particle fractions in corresponding schemes. (b) The temperature dependence of the $E$ and $M$ screening mass $\mu_{E,M}$ in CUJET2.0 (HTL QGP) and CUJET3.0 (sQGP) compare with lattice simulations [7]. (c) The HotQCD equation of state (EOS, pressure $p$, entropy density $s$) [8], the “bag” pressure (B), as well as the $E$ and $M$ quanta number density $\rho_{E,M}$ embedded in the CUJET3.0 framework.
3. Results and discussions

Jet quenching observables from three different schemes in the CUJET3.0 framework will be studied: (i) $\alpha_s=0.95$, $c_{\mu}=0.3$, $x^2_T$; (ii) $\alpha_s=0.95$, $c_{\mu}=0.4$, $x^2_T$; (iii) $\alpha_s=1.33$, $c_{\mu}=0.3$, $x^2_T$. The parameter set ($\alpha_s$, $c_{\mu}$) is constrained by the reference datum at LHC 20-30% Pb+Pb $\sqrt{s_{NN}} = 2.76$TeV $R^{pT}_{AA}(p_T = 12.5$GeV $) = 0.3$ and lattice date of $\mu_{E,M}(T)$ as shown in Fig. 3(b). Fig. 2 compares the CUJET3.0 results of leading light hadron (LH) and open heavy flavor (HF)'s $R_{AA}(p_T > 8$GeV) and $v_2(p_T > 8$GeV) at RHIC and LHC semiperipheral A+A collisions with corresponding data.

For high $p_T$ LHs, all three schemes can simultaneously describe the $R_{AA}$ and $v_2$ data at RHIC and LHC. The phenomenon that scheme (i) and (ii) generate a relatively larger $v_2$ than scheme (iii) implies that the azimuthal asymmetry is sensitive to how the relative value of $\mu_E$ and $\mu_M$ inverses near $T_c$ – the higher the inversion temperature, the longer the path length that jets interact with the monopole dominated medium at later time of the QGP evolution, the larger the high $p_T$ $v_2$.

For open heavy flavors, scheme (ii) and (iii)'s $R_{AA}$ overlap, both are larger than scheme (i)'s. Since the former two have the same color deconfinement scheme $x^2_T$ that is different from the latter's $x^2_T$, it is implicit that the HF's high $p_T$ $R_{AA}$ in CUJET3.0 is sensitive to the rate at which electric DOFs are liberated ($r_d = d\chi_T/dT$), i.e. the detailed composition of E and M DOFs near $T_c$. Meanwhile, Fig. 2(d) shows that the HFs' $v_2$'s are all different in scheme (i)(ii)(iii). It is therefore fair to conclude that the open charm and beauty's $R_{AA}(p_T)$ and $v_2(p_T)$ are excellent probes of the nonperturbative E and M structure of the sQGMP ($r_d, \mu_E, \mu_M$) near $T_c$ within CUJET3.0.

The jet transport parameter $\hat{q}(T, E) \equiv (q^2_T)/A$ in CUJET3.0 and CUJET2.0 can be extracted as in [9] and [12] [17] respectively. They are plotted in Fig. 3(a). Extrapolated $\hat{q}(T, E)$ down to thermal energy scales $E \sim 3T$, one can estimate the $\eta/s$ using kinetic theory, i.e. $\eta/s = \frac{1}{4\pi} \sum_{a} \rho_{a}(p) \omega_{a} l_{a} = \frac{mpT}{\pi^{2}} \sum_{a} \rho_{a}/\eta_{a}(T, E = 3T)$, where $\rho_{a}(T)$ is the quasi-parton number density of type $a = q, g, m$. The $\eta/s$ results from both CUJET3.0 and CUJET2.0 are shown in Fig. 3(b).
Fig. 3. (Color online) (a) The temperature dependence of the scaled jet transport parameter \( \hat{q}/T^3 \) for a quark jet (in the fundamental representation \( F \) of \( SU(N_c=3) \)) with initial energy \( E_0 = 10 \) GeV in various schemes within the CUJET3.0 framework, compared with the CUJET2.0 counterpart, as well as \( N = 4 \) Supersymmetric Yang-Mills (SYM) \( \hat{q}_{\text{SYM}} \) results from leading order (LO) AdS/CFT calculations \( \hat{q}_{\text{SYM}} = \frac{\pi^3}{15} \sqrt{T^3} \sqrt{T^3} / \sqrt{\pi^3} \). Note that \( 3T_{\text{SYM}}^3 = T^3 \) because of different number of degrees of freedom in \( N_c = 3 \) SYM and three-flavor QCD [17]. The gray band with dashed black edges corresponds to using \( 't \) Hooft coupling \( \lambda = 12r_{AA}(Q^2) \).

(b) The shear viscosity to entropy density ratio \( \eta/s \) estimated in the kinetic theory extrapolation \( \eta/s \sim T^3/\hat{q} \) from jet quenching parameters in panel (a). Note that \( T_c = 160 \) MeV. In CUJET3.0, a clear \( \hat{q}/T^3 \) maximum and \( \eta/s \) minimum appear at \( T \sim 1.3 - 1.4T_c \) where the scaled number density of emergent chromo-magnetic monopoles near \( T_c \) peaks. The \( \eta/s \) is determined by the deconfinement scheme \( \chi_{\text{L}}^2 \), i.e. EQP and MQP fractions near \( T_c \), and it approaches the KSS quantum bound \( \eta/s = 1/4\pi \). These indicate within the CUJET3.0 framework, the long wavelength “perfect fluidity” of the sQGP is generated from short distance jet transport properties controlled by \( \hat{q} \), and a quantitative \( \eta/s \sim T^3/\hat{q} \) connection is robustly established in a wide temperature range.

4. Summary

We conclude that taking full advantage of the new CUJET3.0 jet energy loss framework, data of high \( p_T \) light hadron (LH) and open heavy flavor (HF)’s \( R_{AA} \) and \( v_2 \) in heavy-ion collisions at RHIC and LHC can provide stringent constraints on the nonperturbative properties of the QCD matter near \( T_c \). After fixed model parameters with LH’s \( R_{AA} \) data, (1) LH’s \( v_2 \) regulates the E and M screening mass difference \( (\mu_E(T) - \mu_M(T)) \) near \( T_c \), (2) HF’s \( R_{AA} \) determines the rate at which color DOFs are deconfined \( (r_c(T)) \), (3) HF’s \( v_2 \) distinguishes \( r_c(T) \), \( \mu_E(T) \) and \( \mu_M(T) \).

In the CUJET3.0 framework, after included the semi-QGP suppression of chromo-electric charges and the emergence of chromo-magnetic monopoles in the nonperturbative near-critical QGP, the long wavelength “perfect fluidity” \( \eta/s \sim 1/4\pi \) is successfully generated from the short distance hard parton transport properties that are controlled by the jet quenching parameter \( \hat{q} \). Within this framework, a robust \( \eta/s \sim T^3/\hat{q} \) connection is established in all temperature ranges above \( T_c \). Overall, CUJET3.0 provides a quantitative bridge between heavy-ion phenomenology and fundamental confinement physics.

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