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Shear viscosity η to electric conductivity σ_{el} ratio for the quark–gluon plasma

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ABSTRACT

The transport coefficients of strongly interacting matter are currently subject of intense theoretical and phenomenological studies due to their relevance for the characterization of the quark–gluon plasma produced in ultra-relativistic heavy-ion collisions (uRHIC). We discuss the connection between the shear viscosity to entropy density ratio, η/s, and the electric conductivity, σ_{el}. Once the relaxation time is tuned to have a minimum value of $\eta/s = 1/4\pi$ near the critical temperature T_c, one simultaneously predicts σ_{el}/T very close to recent lQCD data. More generally, we discuss why the ratio of $(\eta/s)/(\sigma_{el}/T)$ supplies a measure of the quark to gluon scattering rates whose knowledge would allow to significantly advance in the understanding of the QGP phase. We also predict that $(\eta/s)/(\sigma_{el}/T)$, independently on the running coupling $\alpha_s(T)$, should increase up to about ~ 20 for $T \to T_c$, while it goes down to a nearly flat behavior around $\simeq 4$ for $T \geq 4T_c$. Therefore we in general predict a stronger T dependence of σ_{el}/T with respect to η/s that in a quasi-particle approach is constrained by lQCD thermodynamics. A conformal theory, instead, predicts a similar T dependence of η/s and σ_{el}/T.

Relativistic Heavy Ion Collider (RHIC) at BNL and Large Hadron Collider (LHC) at CERN have produced a very hot and dense system of strongly interacting particles as in the Early Universe with temperatures largely above $T_c \simeq 160$ MeV [1–3], the transition temperature from nuclear matter to the Quark–Gluon Plasma (QGP) [4–6]. The phenomenological studies by viscous hydrodynamics [7–10] and parton transport [11–16] of the collective behavior have shown that the QGP has a very small value of η/s, quite close to the conjectured lower-bound limit for a strongly interacting system in the limit of infinite coupling $\eta/s = 1/4\pi$ [17]. This suggests that hot QCD matter could be a nearly perfect fluid with the smallest η/s ever observed, even less dissipative than the ultra cold matter created by magnetic traps [18,19]. As for atomic and molecular systems a minimum in η/s is expected slightly above T_c [20,21].

Another key transport coefficient, yet much less studied, is σ_{el}. This transport coefficient represents the linear response of the system to an applied external electric field. Several processes occurring in uRHIC as well as in the Early Universe are regulated by the electric conductivity. Indeed HICs are expected to generate very high electric and magnetic fields ($eE \simeq eB \simeq m_\pi^2$, with m_π the pion mass) in the very early stage of the collisions [22,23]. A large value of σ_{el} would determine a relaxation time for the electromagnetic field of the order of ~ 1–2 fm/c [24,25], which would be of fundamental importance for the strength of the Chiral-Magnetic Effect [26], a signature of the CP violation of the strong interaction. Also in mass asymmetric collisions, like Cu + Au, the electric field directed from Au to Cu induces a current resulting in charge asymmetric collective flow directly related to σ_{el} [23]. Furthermore the emission rate of soft photons should be directly proportional to σ_{el} [27–29]. Despite its relevance there is yet only a poor theoretical and phenomenological knowledge of σ_{el} and its temperature dependence. First preliminary studies in lQCD have extracted only few estimates with large uncertainties [30,33] and only recently more safe extrapolation has been developed [31,32,35].

In this Letter, we point out the main elements determining σ_{el} for a QGP plasma and in particular its connection with η. In fact, while one may expect that the QGP is quite a good conductor due to the deconfinement of color charges, on the other hand, the very small η/s indicates large scattering rates which can largely damp the conductivity, especially if the plasma is dominated by gluons that do not carry any electric charge.

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The electric conductivity can be formally derived from the Green–Kubo formula and it is related to the relaxation of the current–current correlator for a system in thermal equilibrium. It can be written as $\sigma_{el} = V/(3T)\langle \vec{J}(t=0)\cdot\vec{J}(t=0)\rangle \cdot \tau$, where τ is the relaxation time of the correlator whose initial value can be related to the thermal average $\frac{\rho e^2}{3T}\langle p^2/E^2\rangle$ [36], with ρ and E the density and energy of the charge carriers. Generalizing to the case of QGP one can write:

$$\sigma_{el} = \frac{e^2}{3T}\left\langle \frac{\vec{p}^{\,2}}{E^2}\right\rangle \sum_{j=q,\bar{q}} f_j^2\,\tau_j\rho_j = \frac{e_\star^2}{3T}\left\langle \frac{\vec{p}^{\,2}}{E^2}\right\rangle \tau_q\rho_q \tag{1}$$

where $e_\star^2 = e^2\sum_{j=u,d,s}^{\bar{u},\bar{d},\bar{s}} f_j^2 = 4e^2/3$ with f_j the fractional quark charge. Eq. (1) in the non-relativistic limit reduces formally to the Drude formula $\frac{\tau e^2\rho}{m}$, even if we notice that τ in Eq. (1) has not to be equal to $1/(\sigma\rho)$ as in the Drude model. The relaxation time of a particle of species j in terms of cross-sections and particle densities can be written in the relaxation time approximation (RTA) as $\tau_j^{-1} = \sum_{i=q,\bar{q},g}\langle \rho_i v_{rel}^{ij}\sigma_{tr}^{ij}\rangle$ where $j=q,\bar{q}$ while the sum runs over all particle species with ρ_i the density of species i, v_{rel}^{ij} is the relative velocity and σ_{tr}^{ij} is the transport scattering cross-section. In Ref. [37] it has been shown that RTA is able to describe with quite good approximation σ_{el} in agreement with numerically simulation of the Dynamical QP model (DQPM) known as PHSD, see also more generally for a numerical approach Refs. [41,42].

As done within the Hard-Thermal-Loop (HTL) approach, we will consider the total transport cross section regulated by a screening Debye mass $m_D = g(T)T$, with $g(T)$ being the strong coupling:

$$\sigma_{tr}^{ij}(s) = \int \frac{d\sigma}{dt}\sin^2\Theta\, dt = \beta^{ij}\frac{\pi\alpha_s^2}{m_D^2}\frac{s}{s+m_D^2}h(a) \tag{2}$$

where $\alpha_s = g^2/4\pi$, the differential cross section $\frac{d\sigma}{dt} = \frac{d\sigma}{dq^2} \simeq \alpha_s^2/(q^2+m_D^2)^2$ where $q^2 = \frac{s}{2}(1-\cos\theta)$. The function $h(a) = 4a(1+a)[(2a+1)\ln(1+1/a)-2]$, with $a = m_D^2/s$ accounts for the anisotropy of the scatterings: for $m_D \to \infty$, $h(a)\to 2/3$ and one recovers the isotropic limit. The coefficient β^{ij} depends on the pair of interacting particles: $\beta^{qq} = 16/9$, $\beta^{qq'} = 8/9$, $\beta^{qg} = 2$, $\beta^{gg} = 9$. These factors are directly related to the quark and gluon Casimir factor, for example $\beta^{qq}/\beta^{gg} = (C_F/C_A)^2 = (4/9)^2$.

The shear viscosity η is known from the Green–Kubo relation to be given by $\eta = V/T\,\langle\Pi_{xy}^2(t=0)\rangle\cdot\tau$, where the initial value of the correlator of the transverse components of the energy–momentum tensor can be written as $\frac{\rho}{15T}\langle p^4/E^2\rangle$ [38–40]. Hence for a system with different species can be written as [43,44]:

$$\eta = \frac{1}{15T}\left\langle\frac{p^4}{E^2}\right\rangle\left(\tau_q\rho_q^{tot} + \tau_g\rho_g\right) \tag{3}$$

where the relaxation time τ_g has a similar expression as above with $j=g$ while ρ^{tot} is the sum of all quarks and anti-quarks flavor density. The thermodynamical averages entering Eqs. (1) and (3), will be fixed employing a quasi-particle (QP) model tuned to reproduce the lattice QCD thermodynamics [45], similarly to [46–49]. The quark and gluon masses are given by $m_g^2 = 3/4\,g^2T^2$ and $m_q^2 = 1/3\,g^2T^2$ in terms of a running coupling $g(T)$ that is determined by a fit to the lattice energy density, which allows to well describe also the pressure P and entropy density s above $T_c = 160$ MeV. In Ref. [45] we have obtained:

$$g_{QP}^2(T) = 48\pi^2/(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2 \tag{4}$$

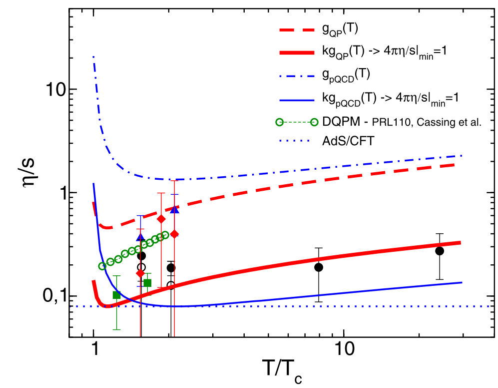

Fig. 1. Shear viscosity to entropy density ratio η/s: dashed line represents QP model results, dot-dashed line is pQCD, stars is DQPM [50]. Red thick solid line and blue thin solid line are obtained rescaling $g(T)$. Blue dotted line is AdS/CFT result from [17]. Symbols are lattice date: full squares [58], diamonds and triangles [59], open and full circles [53].

with $\lambda = 2.6$, $T_s/T_c = 0.57$. We warn that the previous equation is a good parametrization only for $T > 1.1\,T_c$. We notice that a self-consistent dynamical model (DQPM), that includes also the pertinent spectral function, has been developed in [14] and leads to nearly the same behavior of the strong coupling $g(T)$. We will consider the DQPM explicitly, showing that the considerations elaborated in this Letter are quite general and can be only marginally affected by particle width.

We notice that the only approximation made in deriving Eq. (3) is to consider $\langle p^4/E^2\rangle$ equal for quarks and gluons. We have verified that $\langle p^4/E^2\rangle_g \simeq \langle p^4/E^2\rangle_q$ within a 5% in the QP model but also more generally even when m_q and m_g are largely different but $m_{q,g} \lesssim 3T$, which means that Eq. (3) is valid also for light and strange current quark masses and massless gluons. The $\langle p^4/E^2\rangle$ in a massless approximation is simply $4\epsilon\, T/\rho$, we have checked that the validity of this expression is kept using the QP model (i.e. massive excitation) with a discrepancy of about 2%. Hence the first term in Eq. (3) is determined by the lQCD thermodynamics and does not rely on the detailed $m_{q,g}(T)$ in the QP model. We note that even if the QP model is able to correctly describe the thermodynamics it is not obvious that it correctly describes dynamical quantities like the relaxation times with the same coupling $g(T)$ employed to fit the thermodynamics. However our key point will be to find a quantity independent of $g(T)$, see Eq. (5).

For its general interest and asymptotic validity for $T\to\infty$, we also consider the behavior of the pQCD running coupling constant for the evaluation of transport relaxation time: $g_{pQCD}(T) = \frac{8\pi^2}{9}\ln^{-1}\left(\frac{2\pi T}{\Lambda_{QCD}}\right)$. On one hand, close to T_c, such a case misses the dynamics of the phase transition, on the other hand it allows to see explicitly what is the impact of a different running coupling. The η/s calculated is shown in Fig. 1: red dashed line is the result for the QP model using $g_{QP}(T)$ for relaxation times and transport coefficient, blue dot-dashed line labeled as g_{pQCD}, means that we used the pQCD running coupling for evaluating the relaxation time, green stars are the DQPM [50] and by symbols several lQCD results. We warn that the different lQCD data are obtained with different methods and actions. The main difference between our QP model and DQPM comes from the fact that the latter assumes isotropic scatterings which decrease the relaxation time by about 30–40%. Anyway, the η/s predicted is toward higher value with respect to the conjectured minimum value of $\eta/s \sim 1/4\pi$, supported also by several phenomenological estimates [7–11]. However within the QP model it has been discussed in the literature also another approach for τ where the relaxation times are $\tau_{q,g} = C_{q,g}\,g^4 T\ln(a/g^2)$ [51] with $C_{q,g}$ and a fixed to repro-

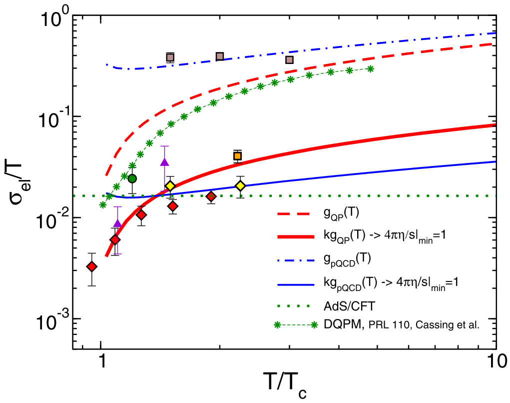

Fig. 2. Electric conductivity σ_{el}/T as a function of T/T_c: red dashed line represents QP model results, blue dot-dashed line is pQCD, red thick solid line and blue thin solid line are respectively QP and pQCD considering the rescaled $g(T)$ in order to reproduce the minimum of η/s. Green line are AdS/CFT results from [54]. Green stars represent DQPM [37]. Symbols are Lattice data: grey squares [30], violet triangles [31], green circle [32], yellow diamond [33], orange square [34] and red diamonds [35]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

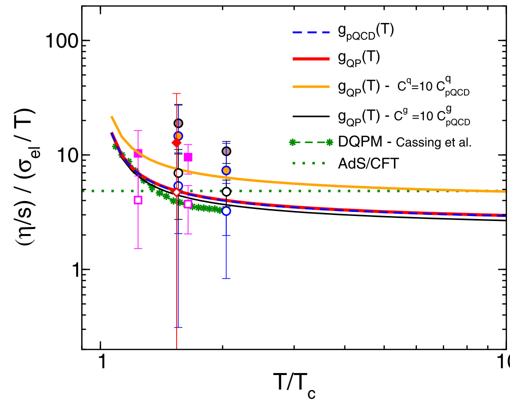

Fig. 3. Shear viscosity η/s to σ/T ratio as a function of T/T_c: red solid line is the QP model, blue dashed line pQCD, green stars DQPM [50]. Orange line is obtained using $C^q = 10\,C^q_{pQCD}$, black thin line $C^g = 10\,C^g_{pQCD}$. Green dotted line represents AdS/CFT results [17,54]. Symbols are obtained using available lattice data (see text for details).

duce both the pQCD estimate asymptotically [52] and a minimum for $\eta/s(T) = 1/4\pi$ [45,48]. In the T region of interest, the result is quite similar to upscaling the coupling $g(T)$ by a k-factor in such a way to have the minimum of $\eta/s(T) = 1/4\pi$. Therefore we do not employ the above parametrization but compute the transport coefficients using the definition of τ of Eq. (6), where enters the cross section in Eq. (2) with the coupling upscaled. The corresponding curves are shown in Fig. 1 by red thick solid line for the $g_{QP}(T)$ coupling (rescaled by $k = 1.59$) and by blue thin solid line for the $g_{pQCD}(T)$ (rescaled by $k = 2.08$). One obtains $\tau_g \simeq \tau_q/2 \sim 0.2$ fm/c and also $\eta/s(T)$ roughly linearly rising with T in agreement with quenched lQCD estimates, full circles [53].

A main point we want to stress is that, once the relaxation time is set to an $\eta/s(T) = 0.08$, the σ_{el}/T predicted, with the same τ_q as for η/s, is in quite good agreement with most of the lQCD data, shown by symbols in Fig. 2 (see caption for details). Therefore a low σ_{el}/T is obtained at variance with the early lQCD estimate, Ref. [30], as a consequence of the small $\tau_{q,g}$ entailed by $\eta/s \simeq 0.08$. In Fig. 2, we show also the predictions of DQPM (green stars) [37,50].

In Fig. 2, we also plot by green dotted line the $\mathcal{N} = 4$ Super Yang Mills electric conductivity [54] that predicts a constant behavior for $\sigma_{el}/T = e^2 N_c^2/(16\pi)$. We note that in our framework one instead expects that, even if the η/s is independent of the temperature, the σ_{el} should still have a strong T-dependence. This can be seen noticing that one can write approximately, $\eta/s \simeq T^{-2}\tau\rho$, being $\langle p^4/E^2\rangle \simeq \epsilon T/\rho$, and $\sigma_{el}/T \simeq T/m(T)\eta/s$, being $\langle p^2/E^2\rangle \simeq T/m(T)$, which means an extra T dependence for σ_{el} leading to a steep decrease of σ_{el}/T close to T_c. $m(T)$ increases as $T \to T_c$ because it is fitted to reproduce the decrease of energy density ϵ in lQCD. We notice that for a conformal theory $T^\mu_\mu = \epsilon - 3P = 0$, as for massless particles, one has $\sigma_{el}/T \sim \eta/s$ like found in AdS/CFT. It seems that the large interaction measure is the origin of such extra T dependence of σ_{el}/T with respect to η/s. This indication is corroborated also by the recent result in AdS/QCD [61] that presents a similar strong T dependence for $T > T_c$ at variance with AdS/CFT.

The σ_{el} appears to be self-consistent with a minimal η/s, but the specific T dependence of both are largely dependent on the modeling of $\tau_{q,g}$, we point out that the ratio $(\eta/s)/(\sigma_{el}/T)$ can be written, from Eq. (1) and Eq. (3), as:

$$\frac{\eta/s}{\sigma_{el}/T} = \frac{6}{5}\frac{T\langle p^2/E^2\rangle^{-1}}{s\,e_\star^2}\left\langle\frac{p^4}{E^2}\right\rangle\left(1 + \frac{\tau_g}{\tau_q}\frac{\rho_g}{\rho_q^{tot}}\right) \tag{5}$$

in terms of generic relaxation times. Eq. (5) is quite general and does not rely on specific features or validity of the quasi-particle model. A main feature of such a ratio is its independence on the k-factor introduced above, and, more importantly, even on the $g(T)$ coupling as we can see writing explicitly the transport relaxation time for quarks and gluons:

$$\tau_q^{-1} = \langle\sigma(s)_{tr} v_{rel}\rangle(\rho_q \sum_{i=u,d,s}^{\bar{u},\bar{d},\bar{s}} \beta^{qi} + \rho_g\beta^{qg})$$
$$\tau_g^{-1} = \langle\sigma(s)_{tr} v_{rel}\rangle\left(\rho_q^{tot}\beta^{qg} + \rho_g\beta^{gg}\right) \tag{6}$$

where the β^{ij} were defined above. Hence the ratio of transport relaxation times appearing in Eq. (5) can be written as:

$$\frac{\tau_g}{\tau_q} = \frac{C^q + \frac{\rho_g}{\rho_q}}{6 + \frac{\rho_g}{\rho_q}C^g} \tag{7}$$

where the coefficients $C^q = (\beta^{qq} + \beta^{q\bar{q}} + 2\beta^{q\bar{q}'} + 2\beta^{qq'})/\beta^{qg}$ and $C^g = \beta^{gg}/\beta^{qg}$ are the relative magnitude between quark–(anti-)quark and gg with respect to $q(\bar{q})g$ scatterings. Using the standard pQCD factors for β_{ij}, $C^q|_{pQCD} = \frac{28}{9} \simeq 3.1$ and $C^g|_{pQCD} = \frac{9}{2}$.

In Fig. 3 we show $(\eta/s)/(\sigma_{el}/T)$ as a function of T/T_c: the red thick solid line is the prediction for the ratio using $g_{QP}(T)$, but it is clear from the Eq. (5) that the ratio is completely independent of the running coupling itself; the result for $g_{pQCD}(T)$ is shown by blue dashed line. The ratio is instead sensitive just to the relative strength of the quark (anti-quark) scatterings with respect to the gluonic ones, hence we suggest that a measurement in lQCD can shed light on the relative scattering rates of quarks and gluons, providing an insight into their relative role. It is not known if such ratios, linked to the Casimir factors of $SU(3)_c$, are kept also in the non-perturbative regime, which may be not so unlikely [55]. We remark that we have computed the ratio in a very large temperature range 1–10 T_c: at large temperatures ($T > 5$–$10\,T_c$) deviation from the obtained value, $(\eta/s)/(\sigma_{el}/T) \simeq 3$, would be quite surprising, on the other hand for $T < 1.2$–$1.5\,T_c$ one may cast doubts on the validity of the Casimir coefficients. In the following we evaluate also the impact of modified Casimir Coefficients.

As $T \to T_c$ a steep increase is predicted that is essentially regulated by $\langle p^2/E^2 \rangle$. It is interesting to notice that in the massless limit (conformal theory) the factor before the parenthesis in Eq. (5) becomes a temperature independent constant and hence also the ratio. This is in quite close agreement with the AdS/CFT prediction shown by dotted line in Fig. 3.

We also briefly want to mention that one possible scenario could be that when the QGP approaches the phase transition, the confinement dynamics becomes dominant and the $q\bar{q}$ scattering, precursors of mesonic states, and di-quark qq states, precursor of baryonic states, are strongly enhanced by a resonant scattering with respect to other channels, as found in a T-matrix approach in the heavy quark sector [56]. For this reason, we explore the sensitivity of the ratio $(\eta/s)/(\sigma_{el}/T)$ on the magnitude of C^q and C^g. The orange solid line shows the behavior for an enhancement of the quark scatterings, $C^q = 10\,C^q_{pQCD}$. We can see in Fig. 3 that this would lead to an enhancement of the ratio by about a 40%. We also see that instead the ratio is not very sensitive to a possible enhancement of only the gg scattering with respect to the $q\bar{q}, qq, qg$; in fact even for $C^g = 10C^g_{pQCD}$ one obtains the thin black solid line. This is due to the fact that already in the pQCD case $\tau_g/\tau_q \sim 0.3$–0.4. Furthermore already in the massless limit $\rho_g/\rho_q^{tot} \simeq d_g/d_{q+\bar{q}} = 4/9$ even not dwelling on the details of the QP model where the larger gluon mass further decreases this ratio. Therefore the second term in parenthesis in Eq. (5) is of the order of 10^{-1} and further decrease of its value would not be visible because the ratio is anyway dominated by the first term equal to one. We reported in Fig. 3 also the ratio from the DQPM model, as deduced from [50] and we can see that, even if it is not evaluated through Eq. (5), it is in very good agreement with our general prediction. We notice that the value of the coupling and hence of the screening mass determines the absolute value and the T-dependence of the transport coefficients. However, their specific behavior cancels out in the $(\eta/s)/(\sigma_{el}/T)$ which remains sensitive only to ratio of the relaxation times. In this respect we have also considered the screening mass extracted from Lattice QCD in Ref. [60] finding that the T-dependence of the ratio is identical to the red solid line in Fig. 3.

In Fig. 3 we also display by symbols the ratio evaluated from the available lQCD data, considering for $4\pi\,\eta/s \lesssim 4$ while for σ_{el}/T we choose red diamonds [35] as a lower limit (filled symbols) and the others in Fig. 2 as an upper limit (open symbols), excluding only the grey squares [57]. To compute $(\eta/s)/(\sigma_{el}/T)$ we do an interpolation between the data point of σ_{el}. We warn to consider these estimates only as first rough indications, in fact the lattice data collected are obtained with different actions among them and have quite different T_c with respect to the most realistic one, $T_c \sim 160$ MeV [4,5], that we employed to tune the QP model [45].

In this Letter we point out the direct relation between the shear viscosity η and the electric conductivity σ_{el}. In particular, we have discussed why most recent lQCD data [31,32,35] predicting an electric conductivity $\sigma_{el} \simeq 10^{-2}T$ (for $T < 2\,T_c$), appear to be consistent with a fluid at the minimal conjectured viscosity $4\pi\,\eta/s \simeq 1$, while the data of Ref. [30] appear to be hardly reconcilable with it. Also a steep rise of σ_{el}/T, in agreement with lQCD data, appears quite naturally in the quasi-particle approach as inverse of the self-energy determining the effective masses needed to correctly reproduce the lQCD thermodynamics. This result is at variance with the AdS/CFT [54], but our analysis suggests that it is due to the conformal thermodynamics that does not reflect the QCD one. It is quite interesting that an AdS/QCD approach [61], able to correctly describe the interaction measure of lQCD, also modifies the AdS/CFT result predicting a strong T dependence of σ_{el}/T for $T < 2$–$3\,T_c$. We note that the extra T dependence predicted for σ_{el}/T with respect to η/s is determined by the $\langle p^2/E^2 \rangle$ constrained to reproduce the lQCD thermodynamics. If instead one imposes conformality with $m = 0$, this leads to $\langle p^2/E^2 \rangle = 1$ and the T dependence of η/s becomes quite similar to the one of σ_{el}/T apart from differences that can arise between quark and gluon relaxation times.

We identify the dimensionless ratio $(\eta/s)/(\sigma_{el}/T)$ as not affected by the uncertainties in the running coupling $g(T)$. Moreover, due to the fact that gluons do not carry an electric charge, the ratio is regulated by the relative strength and chemical composition of the QGP through the term $(1 + \tau_g\rho_g/\tau_q\rho_q^{tot})$. Our analysis provides the baseline of such a ratio that in this decade will most likely be more safely evaluated thanks to the developments of lQCD techniques. This will provide a first and pivotal insight into the understanding of the relative role of quarks and gluons in the QGP. Deviations from our predictions for $(\eta/s)/(\sigma_{el}/T)$ especially at high temperature $T \gtrsim 2$–$3\,T_c$, where a quasi-particle picture can be derived from QCD within the HTL scheme [62], would be quite compelling.

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