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Quark-to-gluon composition of the quark-gluon plasma in relativistic heavy-ion collisions

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ABSTRACT

We study the evolution of the quark-gluon composition of the plasma created in ultra-Relativistic Heavy-Ion Collisions (uRHIC's) employing a partonic transport theory that includes both elastic and inelastic collisions plus a mean fields dynamics associated to the widely used quasi-particle model. The latter, able to describe lattice QCD thermodynamics, implies a "chemical" equilibrium ratio between quarks and gluons strongly increasing as $T \to T_c$, the phase transition temperature. Accordingly we see in realistic simulations of uRHIC's a rapid evolution from a gluon dominated initial state to a quark dominated plasma close to T_c. The quark-to-gluon ratio can be modified by about a factor of ~ 20 in the bulk of the system and appears to be large also in the high p_T region.
We discuss how this aspect, often overflown, can be important for a quantitative study of several key issues in the QGP physics: shear viscosity, jet quenching, quarkonia suppression. Furthermore a bulk plasma made by more than 80% of quarks plus antiquarks provides a theoretical basis for hadronization via quark coalescence.

The search for the Quark-Gluon Plasma (QGP) started its golden age thanks to the experiments at the Relativistic Heavy Ion Collider (RHIC) that have supplied convincing physical evidences that a new state of matter has been created [1,2]. Such a matter has a very small shear viscosity [3–5], a high opacity to high-p_T particles [6], a strong screening of the interaction able to significantly dissociate charmonia [7], and exhibits a modification of the hadronization respect to the vacuum toward a quark coalescence mechanism [8–10]. Furthermore some RHIC data hints to the creation of an "exotic" initial state of matter, the Color Glass Condensate (CGC), that could be the high-energy limiting state of the QCD interaction [6]. The new and upcoming experiments at the Large Hadron Collider (LHC) have confirmed the main gross properties observed at RHIC [11], but they will allow to explore a larger temperature range also with quite different heavy-quark abundancy and will provide more suitable conditions for creating CGC phase as initial state.

The several probes mentioned above rely on the comparison between experimental data and model predictions. A closer look into the several theoretical approaches to the different QGP probes reveals that in some cases the QGP is described as a Gluon Plasma. Indeed this initially should be the case because most of the particles come from low x momentum fraction where the nucleon parton distribution functions are gluon dominated. Hence, for example, is the case of the most popular jet quenching models assuming a bulk gluon matter. In other cases as in the viscous hydrodynamics a chemical quark-to-gluon equilibration is implicit in the employment of a lattice QCD (lQCD) equation of state $P(\epsilon)$. For the study of quarkonia instead usually one considers a plasma of gluons or an equilibrated QGP according to a massless quark-gluon description acting for dissociation. On the contrary the observation of quark-number scaling in the elliptic flow and the baryon over meson enhancement are explained by quark coalescence models based on a quark dominance in the plasma [8,10].

Certainly despite a lack of full integration of the different descriptions of the QGP, all of these have been useful simplifications that allowed to successfully identify the creation of the QGP plasma and its gross properties. Nonetheless once we have identified the main qualitative features of the matter created in uRHIC's a quantitative knowledge of properties like the η/s or the solution to open issues on the jet quenching mechanism (radiative vs. collisional), quarkonia dissociation-regeneration, hadronization mechanism and existence of a CGC matter, requires to consider the poorly explored issue of the "chemical" composition of the QGP.

The assumption of chemical equilibrium of the QGP, when considered, is usually discussed treating the QGP as a gas of massless

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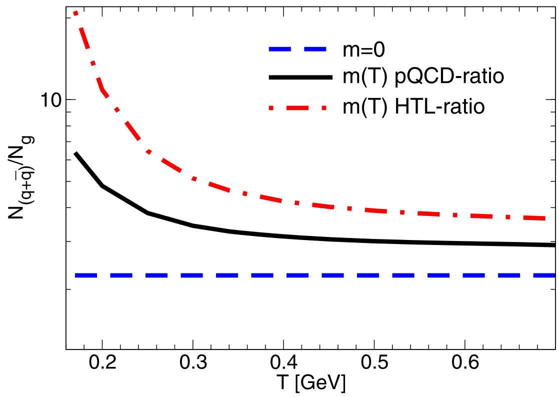

Fig. 1. Quark-to-gluon ratio at equilibrium as a function of the temperature as predicted by QPM [22]. Solid line is assuming an m_q/m_g ratio according to pQCD and dot-dashed line according to HTL; by dashed line it is indicated the massless case.

quarks and gluons; therefore the expected ratio is given simply by the ratio of the degrees of freedom $N_{q+\bar{q}}/N_g = d_{q+\bar{q}}/d_g = 2N_cN_f/(N_c^2-1) = 9/4$ for a system with 3 flavors. On the other hand, as well known from lQCD, the QGP appears to be significantly different from a mere massless gas, showing deviation of both the energy density and the pressure from the $\epsilon/T^4 = 3P/T^4 = cost.$, and in particular exhibiting a large trace anomaly $\langle\Theta^\mu_\mu\rangle = \epsilon - 3P$. It has been shown that such a behavior can be described in terms of a massive quasi-particle model in which both gluons and quarks acquire a thermal mass $m(T) \sim g(T)T$, as suggested also by the Hard Thermal Loop (HTL) approach [12–15] or dimensionally reduced screened perturbation theory (DRSPT) [17,18] or HTLpt [16]. This comes out also from extracting a gluon propagator from lattice results in the Landau gauge [19], or using the pinch technique [20] or a T-matrix approach from lQCD free-energy [21]. All such approaches suggest a finite $m_g \sim 0.5$–1 GeV, a value quite close to the one obtained by fitting a QPM to lQCD thermodynamics, as done in the present work.

A quasi-particle model (QPM) with a T-dependent Bag constant has been successfully applied to quantitatively describe lQCD results for equilibrium thermodynamics [22–24] including the recent ones performed with an unprecedented level of accuracy at the physical quark masses [25]. It is also interesting to note that QPM is able to correctly predict $\eta/s \leqslant 0.2$ close to T_c [22,26] with quasi-particle widths still significantly smaller than the mass itself [26]. We neglect in the present work the finite width which can be expected to marginally affect the quark-to-gluon ration respect to Eq. (1).

Moreover lQCD calculations on charge–charge correlations show that up, down and strange charges are transported as single charges and off-diagonal elements disappear above T_c indicating that quark and gluon quasi-particles are still good quantum numbers at least not too close to T_c.

We notice that if the QGP can be described in terms of finite mass excitations this has a strong impact on the quasi-particle chemical ratio $N_{q+\bar{q}}/N_g$. In fact at equilibrium one has

$$\frac{N_{q+\bar{q}}}{N_g} = \frac{d_{q+\bar{q}}}{d_g}\frac{m_q^2(T)K_2(m_q/T)}{m_g^2(T)K_2(m_g/T)}, \tag{1}$$

where K_2 is the Bessel function and $m_{q,g}(T)$ are the T-dependent quark and gluon masses that can be determined by a fit [22] to recent lQCD calculations [25]. In Fig. 1, we show by solid line the equilibrium ratio when the fit to lQCD $\epsilon(T)$ is done assuming $m_q^2/m_g^2 = 3/2 \cdot (N_c^2-1)/N_c(2N_c+N_f) = 4/9$ according to a pQCD scheme [23]. We plot also by dot-dashed line the expected ratio assuming the HTL ratio $m_q^2/m_g^2 = 1/9$ ratio. This of course leads to a larger quark abundancy due to larger difference between quark and gluon masses. Furthermore in Ref. [22] some of the authors have shown that in the last case one can better describe the diagonal quark susceptibilities, in the following we will consider the more commonly assumed pQCD case. This would also prevent from overestimating the magnitude of the effect discussed.

In this Letter we discuss the issue of the quark-to-gluon ratio of the matter created in uRHIC's at both RHIC and LHC energies. We employ a Boltzmann–Vlasov transport theory to simulate the partonic stage of the HIC in a realistic way. In the last years several codes have been developed based on transport theory at the cascade level [27–31], i.e. including only collisions between massless partons, with quite rare exceptions [32,33]. These approaches have been more recently developed to study the dynamics of the partonic stage of the HIC at fixed shear viscosity [31,33–35] with the advantages to explore possible effects of kinetic non-equilibrium having also a wider range of validity in p_T and in η/s.

We present here for the first time results within a transport approach that includes the mean field dynamics associated to the thermal self-energies generating the finite mass $m(T)$ in the QPM discussed above [22,23]. The approach is formally similar to the one developed in Ref. [33] for the NJL mean field dynamics, but here the quasi-particle mean field allows to account for the proper equation of state, $P(\epsilon)$, as evaluated from lQCD. In such a picture the relativistic Boltzmann–Vlasov equation can be written as follows:

$$\left[p^\mu\partial_\mu + m^*(x)\partial_\mu m^*(x)\partial_p^\mu\right]f(x,p) = \mathcal{C}[f](x,p) \tag{2}$$

where $\mathcal{C}(x,p)$ is the Boltzmann-like collision integral, main ingredient of the several cascade codes:

$$\mathcal{C} = \int_2\int_{1'}\int_{2'}(f_{1'}f_{2'} - f_1f_2)|\mathcal{M}_{1'2'\to12}|^2\delta^4(p_1+p_2-p'_1-p'_2) \tag{3}$$

where $\int_j = \int_j d^3p_j/(2\pi)^3 2E_j$, f_j are the particle distribution functions, while $\mathcal{M}_{f\to i}$ denotes the invariant transition matrix for elastic as well as inelastic processes. The elastic processes have been implemented and discussed in several previous works [27–29,31]. The inelastic processes between quarks and gluons ($gg \leftrightarrow q\bar{q}$) are instead the main focus of the present Letter. We have evaluated the matrix element in a pQCD LO order scheme. The tree diagrams contributing to the $gg \leftrightarrow q\bar{q}$ correspond to the u,t,s-channels: $\mathcal{M} = \mathcal{M}_s + \mathcal{M}_t + \mathcal{M}_u$. For the massless case the cross sections for such processes are the textbook pQCD cross section for jet production in high-energy proton–proton collisions. With massive quarks the calculations are the renowned Combridge cross sections [36] used to evaluate heavy-quark production. In our case we have considered a finite mass for both gluons and quarks together with a dressed gluon propagator. The details of the calculations are lengthy and will be published elsewhere [38], but they are quite similar to the one in [37] for finite current strange quark mass. We only mention that the cross section is dominated by the t- and u-channel and their interference while the s-channel alone is negligible. The squared matrix element of the t-channel is given by

$$\left|(t-m_q^2)\mathcal{M}_t\right|^2 = \frac{8}{3}\pi^2\alpha_s^2\left[(m_q^2-t)(m_q^2-u) - 2m_q^2(t+m_q^2) - 4m_q^2m_g^2 - m_g^4\right] \tag{4}$$

and of course by crossing symmetry the u-channel, can be obtained by $u \leftrightarrow t$ exchange.