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2013 J. Phys.: Conf. Ser. 446 012018

(http://iopscience.iop.org/1742-6596/446/1/012018)

“Chemical“ composition of the Quark Gluon Plasma

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Abstract. In this article we discuss the issue of the quark to gluon ratio in the Quark Gluon Plasma (QGP). Our model to describe the QGP evolution is based on transport theory including the mean field dynamics described by a quasi-particle model.The last is able to take into account for the lattice QCD thermodynamics and implies a ”chemical” equilibrium ratio between quarks and gluons strongly increasing as T approaches to the temperature of the phase transition T_c. We present first the tests performed in a fixed box to check that our code is able to reproduce the equilibrium ratio and then the results obtained for the simulations of ultra-Relativistic Heavy Ion Collisions (uRHIC’s) at RHIC and LHC energies. We observe a rapid evolution from a gluon dominated initial state to a quark dominated plasma and we see that near T_c almost 80% of the particles composing the plasma are quarks. This has potentially a strong impact on several quantitative aspects of QGP probes and furnishes a justification to the coalescence hadronization model.

1. Introduction

The main purpose of this article is to study how the QGP created in uRHIC’s at both RHIC and LHC energies approaches to chemical equilibrium, i.e the equilibrium value between quark and gluon abundancy. In fact the matter created just after the collision should be prevalently composed by gluons because most of the particles come from low x momentum fraction, where the nucleon parton distribution functions are gluon dominated and is sometimes called Glasma. During the evolution of the fireball the inelastic collisions should lead the system towards chemical equilibrium with a consequent enhancement of the number of quarks. A detailed analysis of the chemical equilibration of the plasma have not been performed yet and the several theoretical approaches describing the different QGP probes reveals that the different models assumes different chemical composition for the Quark Gluon Plasma. In some cases, as for examples in the most popular jet quenching models, the QGP is treated as a Gluon Plasma. In Hydrodynamics instead the assumption of a chemical equilibrated QGP is implicit in the employment of a lattice QCD equation of state $P(\epsilon)$. On the other hand the coalescence model [1, 2, 3] assumes a quark dominance in the region of phase transition.

The results obtained in our work clearly indicate that the inelastic collisions cause a quick change of the chemical composition of the plasma. More precisely during the evolution there is a substantial enhancement of the percentage of quarks and such enhancement is substantially larger if one considers that both quarks and gluons acquire a thermal mass.

2. Our model to describe the QGP

Usually the studies of the chemical composition of the QGP have been made considering the plasma as a massless gas. In this case the equilibrium value for $N_{q+\overline{q}}/N_g$ is simply given by the ratio of the degrees of freedom $N_{q+\overline{q}}/N_g = d_{q+\overline{q}}/d_g = 2N_c\,N_f/(N_c^2-1) = 9/4$ for a system with 3 flavors. On the other hand the data coming from lattice QCD for energy density, pressure

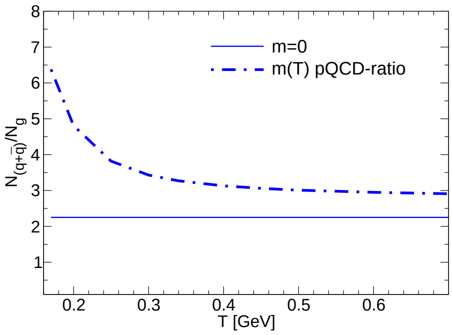

Figure 1. By dot-dashed line it is indicated the quark to gluon ratio at equilibrium as a function of the temperature, as predicted by QPM [4]; by thin solid line it is indicated instead the massless case.

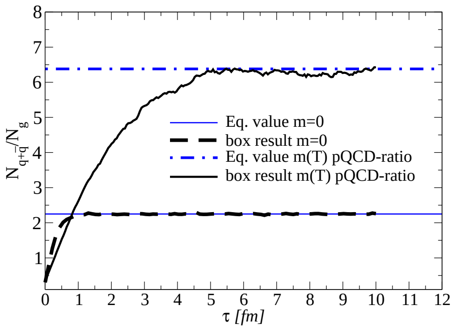

Figure 2. Time evolution of ratio $N_{q+\overline{q}}/N_g$ in box calculation. The solid line indicates the massive case while the dashed line indicates the massless case. The equilibria value are indicated as in Fig. 1.

and trace anomaly of the QGP are not compatible with those expected for a massless gas and strong deviations from the ideal gas behaviour have been observed. It has been shown [4] that the lattice data can be described by a Quasi-Particle Model (QPM) in which both quarks and gluons acquire thermal masses. We notice that such thermal masses has a strong impact on the ratio between quarks and gluons, as shown in Fig.1, and they introduce a temperature dependence on the ratio.

Our approach to describe the partonic stage of the matter created in ultra-relativistic heavy ion collisions is based on transport theory including the mean field dynamic described by a quasi-particle model. In such a picture the relativistic Boltzmann-Vlasov equation can be written as follows:

$$[p^\mu \partial_\mu + m^*(x)\partial_\mu m^*(x)\partial_p^\mu] f(x,p) = \mathcal{C}[f](x,p) \tag{1}$$

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

$$\mathcal{C} = \iiint\limits_{2 1' 2'} (f_{1'} f_{2'} - f_1 f_2) |\mathcal{M}_{1'2'\to 12}|^2 \delta^4(p_1 + p_2 - p_1' - p_2') \tag{2}$$

where $\int_j = \int_j d^3p_j/(2\pi)^3\, 2E_j$, f_j are the particle distribution functions, while $\mathcal{M}_{f\to i}$ are the invariant transition matrix for elastic as well as inelastic processes; see article [5, 6] for more details. In order to include the QPM in the transport theory it is necessary to couple the equation (1) with the gap-like equation

$$\frac{\partial B}{\partial m_i} = -\int \frac{d^3\vec{p}}{(2\pi)^3} \frac{m_i(x)}{E_i(x)} f_i(x,p) \tag{3}$$

with $i = q, \overline{q}, g$. The previous equation assures the thermodynamical self consistency of the QPM and allows us to evaluate locally the masses appearing in Eq. (1), also in non-equilibrium conditions, guaranteeing the conservation of the energy momentum tensor of the fluid. The numerical solution of the Boltzmann equation is the same described in [7, 8, 9]. In order to check if our code is able to reproduce correctly the chemical equilibrium we have carried out simulations in which a particle ensemble, far from to the chemical equilibrium, is enclosed in a fixed box and evolves dynamically. In Fig.2 the results of such kind of simulations are shown for the massless case and for the massive case. We observe in both cases that the system reaches the expected equilibrium ratio.

3. Results for the simulations of heavy-ion collisions

We have carried out simulations for both RHIC (Au+Au at $\sqrt{s} = 200$ AGeV) and LHC energies $Pb + Pb$ at $\sqrt{s} = 5.5$ATeV. The initial conditions in the coordinate space are given by the standard Glauber model conditions. For the momenta space we use a Boltzmann-Juttner distribution function up to a transverse momentum equal to $p_T = 2$, while for larger momenta mini-jet distributions are implemented, as calculated by pQCD at NLO order [2]. Regarding the initial ratio between the number of quarks and the number of gluons we start from a situation in which 75 % of particles are gluons and 25 % are quarks. However our results are not significantly influenced by the initial quark to gluon ratio. We have considered in our simulations a running coupling $\alpha_s(Q^2)$ according to first order expansion and the energy scale given by $Q^2 = (\pi T)^2$. In Fig.3 the time evolution of the ratio $R_{qg} = N_{q+\bar{q}}/N_g$ for both the massless case (dashed lines) and the massive quasi-particle case (solid lines) is shown for both RHIC and LHC energies. We observe that in the massless case the system reaches very quickly the chemical equilibrium given by $R_{qg} \sim 2$. If the quasi-particle massive case is considered we can again see that one can

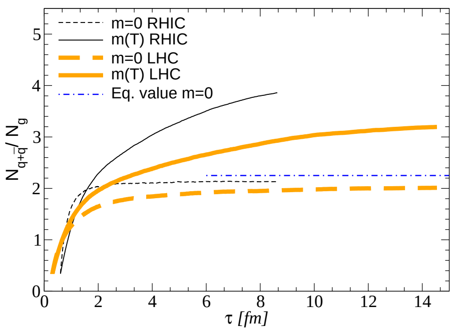

Figure 3. Quark plus anti-quark to gluon ratio as a function of τ at RHIC (black thin lines) and at LHC (light thick lines). Dashed lines are for the massless case and the solid for the massive case.

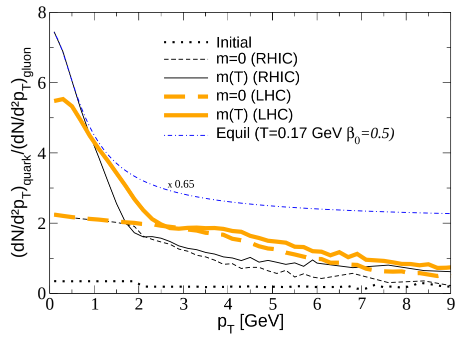

Figure 4. Quark to gluon ratio as a function of transverse momentum at the freez-out temperature. Labels as in Fig.3. The thin dot-dashed line represents the equilibrium ratio; see text for details.

reach also quickly a value of $R_{qg} \sim 2$, then there is a slower rise with a continue increase up to $R_{qg} \sim 4$ at RHIC . We have seen that in the massive case the equilibrium value, especially at low T, is higher compared to the massless case (see Fig.1), however as the temperature decreases the system becomes more dilute and it is not capable to reach the full chemical equilibration. Despite that in the region of phase transition ($T \sim T_c$) the fireball is composed by about 80% of quark plus anti-quarks. At LHC the trends are very similar but a longer part of the lifetime is spent in a T-region where the equilibrium R_{qg} is nearly constant and this implies a moderately smaller final ratio. Particularly interesting it is to analyze the momentum dependence of the quark to gluon ratio shown in Fig.4. We observe a strong decrease of the ratio with p_T that is due to the decreasing of the collision rate with the transverse momentum. We see a large difference between the massless and the massive case and such difference is much wider in the low p_T region. In particular in the massive case we note a quite strong dependence below $p_T = 2$ GeV that has not to be interpreted as a fast detachment from the chemical equilibrium. In fact the momentun dependence of the equilibrium ratio can be evaluated analytically [5, 6] at equilibrium and it is shown by the dot dashed line in Fig. 4. We observe that the results obtained in our simulations follow very closely the equilibrium behavior at least up to $p_T \sim 1.5$ GeV, nonetheless a significant gluon to quark conversion happens also at $p_T \geq 5$ GeV. In Fig.5, as example, we show how the ratios, $(p+\overline{p})/2\pi^0$, $(p+\overline{p})/(K+\overline{K})$, can be modified when the gluon conversion mechanism is included. We find that the effect of the inelastic collisions $q+\overline{q} \leftrightarrow g+g$ is to

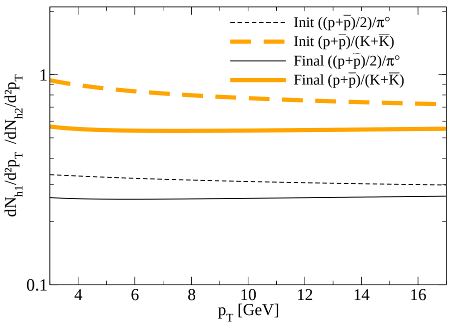

Figure 5. Ratio of hadrons obtained with the AKK fragmentation functions [10]. The dashed lines are the ratio according to the initial partons distributions, the solid lines are at the freeze-out considering the effect of the inelastic collisions.

reduce both the ratios. This disagrees with the results obtained in [11, 12, 13] in which it is shown that the inelastic collisions cause a decreasing of the proton/pion ratio able to explain the experimental observations. However this difference is due to the different choice of the initial parton spectra and in particular to the different initial q/g ratio.

4. Conclusions

Our studies show that the initially gluon dominated plasma created in uRHIC's evolves into a plasma dominated by quark plus anti-quarks close to the cross-over temperature T_c. This result supplies a theoretical justification of the *massive-quark* coalescence hadronization models able to explain the experimental observations of the quark-number scaling in the elliptic flow and the baryon over meson enhancement.
Moreover our results can have a wide impact on the main physical issues of the QGP physics as a quantitative estimate of the viscosity, the study of the identified high-p_T particles and the related jet quenching mechanism as well as on the physics of the quarkonia suppression.

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