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Analysis of the Quark-Gluon Plasma by Heavy Quarks

J. Aichelin [1] **, V. Ozvenchuck, T. Gousset and PB. Gossiaux**

SUBATECH, Laboratoire de Physique Subatomique et des Technologies Associées,
Université de Nantes - IN2P3/CNRS - Ecole des Mines de Nantes
4 rue Alfred Kastler, F-44072 Nantes, Cedex 03, France

Abstract. We discuss the present status of the tomography of a quark gluon plasma (QGP) with help of heavy quarks. We address the question whether collisional or radiative energy loss dominates, how different expansion scenarios of the medium influence the observables and which state of the expansion is impressed in the R_{AA} and v_2 observables.

1. Introduction

Hadrons have a finite radius. Therefore, if the density becomes too high one expects naively that the hadrons start to overlap and the constituents of the hadrons, the quarks and gluons, can move freely from one hadron to another. Thus hadrons loose their identity and form a new stage of matter - a plasma of unbound gluons and quarks which is in local thermal equilibrium. Because the density increases with temperature we expect such a transition at some given temperature in analogy with the boiling temperature of water when the phase transition from the liquid state to vapor occurs.

The phase transition from the hadronic to the partonic phase is also predicted by the fundamental theory for strongly interaction systems, the Quantum Chromo Dynamics (QCD). This follows from so called lattice gauge calculations [1], which are presently the only known way to predict expectation values of observables in strongly interacting systems. These calculations are done assuming an infinite system in global thermal equilibrium.

If one wants to do systematic studies of the QGP and its properties there is only one possibility, to create a QPG in heavy ion reactions. There the situation differs substantially from the conditions used for the lattice QCD calculations, i.e. the infinite partonic matter in equilibrium: In heavy ion reactions such a state can be only created for a very short time (of the order of $10^{-23}s$) and has an extension of a couple of 10^{-15} m. Then the system, which expands with almost the speed of light, forms after about 10 fm/c hadrons which are finally observed in the detector. Thus, it is quite difficult to prove - from the theoretical as well as from the experimental side - that in a such small system in a very short time a partonic plasma has be formed.

The problem is therefore to reconstruct from the observed hadrons the existence and the properties of such a QGP. The vast majority of the observed hadrons are formed from light (u,d,s) quarks which, unfortunately, tell us little about the formation of a plasma. It turned

[1] invited speaker


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out that the multiplicity of light hadrons is very well described by statistical models [2]. This means that the system of light quarks or hadrons (made of light quarks) has reached a state of equilibrium (and the temperature is close to that predicted by lattice gauge calculations for the transition temperature). Therefore light hadrons do not contain information about the plasma properties at higher temperatures. One may argue that the spectra of light hadrons may give additional information. Unfortunately hadronic final state interactions are too strong and contain too many experimentally unknown cross sections in order to infer from the measured spectra the spectra at the moment when hadrons move out of equilibrium.

The light particle spectra are well described by so called event generators [3] which model the whole reaction on a computer. They assume that after a violent initial phase hadrons are formed which, if the energy density exceeds a given value, form a QGP. The expansion of the QGP is modelled either in viscous or in non viscous hydrodynamics. At a given energy density which is around $1GeV/fm^3$ [4] a sudden transition to the hadronic world takes place followed by a final state interactions among the hadrons. The problem is that the physics of the initial state is little known and leaves a lot of room for different assumptions. As a consequence, some model assume that the measured centrality dependence of the elliptic flow presents evidence for the need of viscous hydrodynamics [5] whereas other models describe the data equally well in an ideal hydrodynamical approach [6] assuming that not all particles take part in the hydrodynamical expansion.

Also the fast equilibration is not yet understood. Therefore other models [7] do not assume that a thermal equilibrium is established and describe the strongly interacting quark-gluon plasma by relativistic transport equations, derived from many-body Kadanoff-Baym equations, with a dynamical hadronization of partons to hadrons. This concept leads as well to a very satisfying description of a variety of data.

In a situation like this it is evident that one looks for possible observables which do not suffer from this memory erasing equilibrium phase. There are essentially two: High p_t hadrons which originate from jets as well as the p_t and v_2 distribution of heavy mesons which contain either a c or a b quark because neither jets nor heavy quarks come to an equilibrium with the plasma. Jets have the problem that the leading particle, i.e. that with the highest momentum, may change by interactions with the plasma. This makes the understanding of jets difficult.

Heavy quarks are produced in hard binary initial collisions between the incoming protons. Their production cross sections are known from pp collisions and can as well be calculated in pQCD calculations. Therefore the initial transverse momentum distribution of the heavy quarks is known. Comparing this distribution with that measured in heavy ion collisions allows defining $R_{AA} = (d\sigma_{AA}/dp_t^2)\ /\ (N_c\, d\sigma_{pp}/dp_t^2)$, where N_c is the number of the initial binary collisions between projectile and target. The deviation of R_{AA} from one measures the interaction of the heavy quark with the plasma because the hadron cross sections of heavy mesons are small. The heavy quark does not come to thermal equilibrium with the QGP therefore R_{AA} contains the information on the interaction of the heavy quark while it traverses the plasma. In addition, the distribution of heavy quarks at the moment of their creation is isotropic in azimuthal direction, therefore the elliptic flow $v_2 =< cos2(\phi - \phi_R) >$, where ϕ (ϕ_R) is the azimuthal angle of the emitted particle (reaction plane) is 0. The observed finite v_2 value of the observed heavy meson can only originate from interactions between light QGP constituents and the heavy quarks. The simultaneous description of R_{AA} and v_2 and their centrality dependence, presently the only observables for which data exist, give then the possibilities to understand the interactions inside the QGP.

Unfortunately the experimental results depend not only on the elementary interaction but also on the description of the expansion of the QGP [8]. Therefore the ultimate aim is to control the expansion by results on the light meson sector. This has not been achieved yet for the LHC and therefore it is difficult to asses the influence of the expansion on the observables. We use

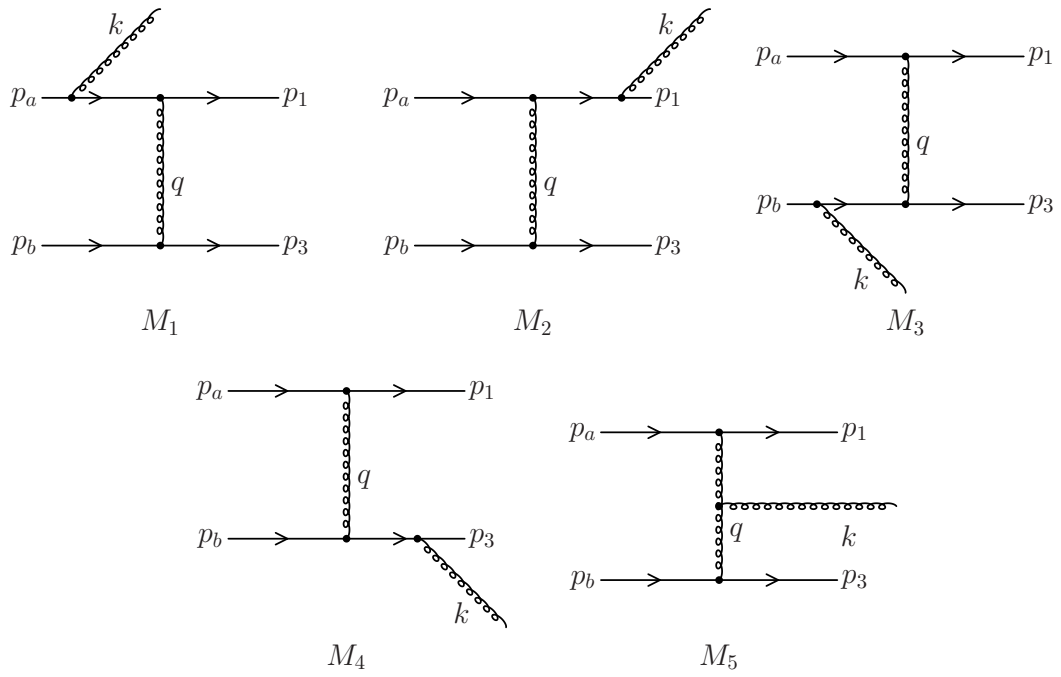

Figure 1. (Color online) The five matrix elements which contribute to the gluon bremsstrahlung.

here the approach from Kolb and Heinz which has reasonably well described the midrapidity light mesons at RHIC [9]. We adjust only the charged particle multiplicity to the value measured at LHC.

The R_{AA} of 0.2 values observed for large p_t heavy mesons are much smaller than originally expected. Early theoretical approaches based on perturbative QCD (pQCD) calculation gave much larger values and it has been doubted, whether pQCD is the right tool to describe this interaction. This early calculation, however, used ad hoc assumptions on the coupling constant α_s and the infrared regulator μ. With a standard choice μ and α_s an artificial K factor, an overall multiplication factor of the elastic cross section of around 10 [10, 11] had to be introduced to match the experimental data.

A while ago we advanced an approach for the collisional energy loss of heavy quarks in the QGP [12, 13, 14] in which a) μ has been fixed by the demand that more realistic calculations using the hard thermal loop approach give the same energy loss as our Born type pQCD calculation and b) the coupling constant is running and fixed by the sum rule advanced by Dokshitzer and later used by Peshier. Both these improvements increased the cross section especially for small momentum transfers and.

Later we included in addition the radiative energy loss [15, 16]. For this we have to consider the 5 Feynman diagrams displayed in fig.1. The commutation relation

$$T^b T^a = T^a T^b - i f_{abc} T^c \tag{1}$$

allows us regrouping the 5 matrix elements into 3 combinations, each of them being independently gauge invariant:

$$\begin{aligned} iM_{h.q.}^{QED} &= C_a i(M_1 + M_2) \\ iM_{l.q.}^{QED} &= C'_a i(M_3 + M_4) \end{aligned}$$

$$iM^{QCD} = C_c i(M_1 + M_3 + M_5). \quad (2)$$

h.q. (l.q.) mark the emission of the gluon from the heavy (light quark) line. C_a, C'_a and C_c are the color algebra matrix elements. The matrix elements labeled as QED are the bremsstrahlung diagrams already observed in Quantum Electrodynamics (QED), whereas that labeled QCD is the genuine diagram of Quantum Chromodynamics (QCD). The QCD diagram is the main objet of interest here because it dominates the energy loss of heavy quarks.

Collisional and radiative energy loss act quite differently as has been discussed in [17]. The cross section for collisional energy loss in our approach is rather large whereas that for radiational energy loss is small. However, in elastic collisions the energy transfer is small whereas in radiative collisions it is large. Fig. 2 shows the distribution of the number of elastic (left) and radiational collisions (right) of a heavy quark in a central heavy ion reaction of AuAu at $\sqrt{s} = 200MeV$. We see that there are on the average 40 times more elastic collisions than radiative collisions. This

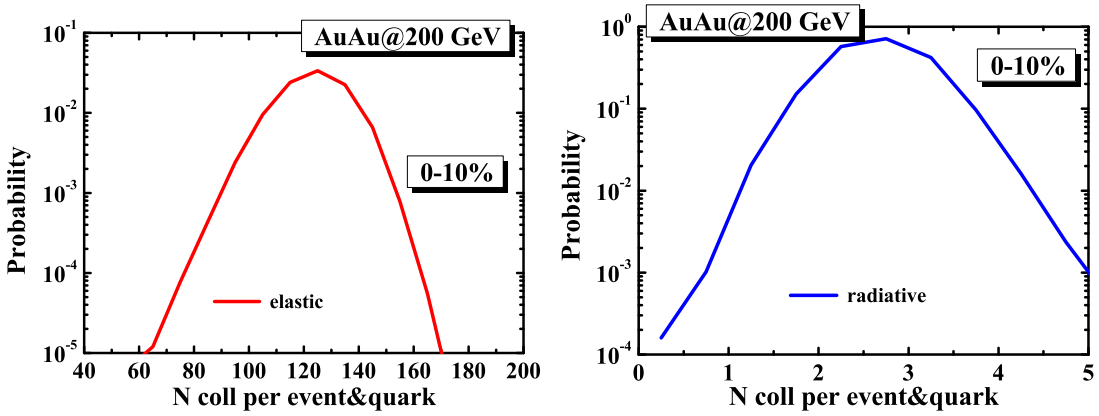

Figure 2. Distribution of the number of elastic collisions (left) and radiative collisions (right) a heavy quarks suffers in a central AuAu reaction at $\sqrt{s} = 200AGeV$.

quite different number of collisions triggered the hope that the form of the heavy meson spectra is different depending on the whether collisional and radiative energy loss dominates while the quark is traveling through the plasma. This hope has been in vain as is shown in Fig.3 which displays on the left hand side R_{AA}. If a nuclear reaction is nothing else than a superposition of pp collisions R_{AA} would be one. On the right side we display for the same reaction v_2, the second order Fourier coefficient of the azimuthal distribution, of heavy quarks with respect to the reaction plane. We display these quantities for two different scenarios. In scenario one we assume elastic collisions only and multiply the calculated cross section with an artificial factor K =1.5-1.8 to obtain the right energy loss. In scenario two we employ elastic and radiative collisions multiplied with K=0.8-1 to show how R_{AA} changes if one modifies slightly the cross sections. The expanding quark gluon plasma is modeled by the event generator EPOS II. We see first of all that R_{AA} differs strongly from one and therefore the heavy quarks interact strongly with the plasma (hadronic interactions of the D-mesons are neglected here). We observe furthermore that the form of R_{AA} is for both scenarios almost identical. Both calculations reproduce reasonably well the experimental results of the STAR collaboration [18]. We will come back to this later. Also the p_T dependence of v_2 is almost identical for the both scenarios and both scenarios give v_2 values close to the preliminary experimental results. On the basis of these two observables it is therefore impossible to discriminate experimentally between collisional and radiative energy loss of the heavy quarks.

The energy loss of heavy quarks in the expansing plasma depends on the one side on the elementary interaction of the heavy quarks with the plasma partons but on the other side as

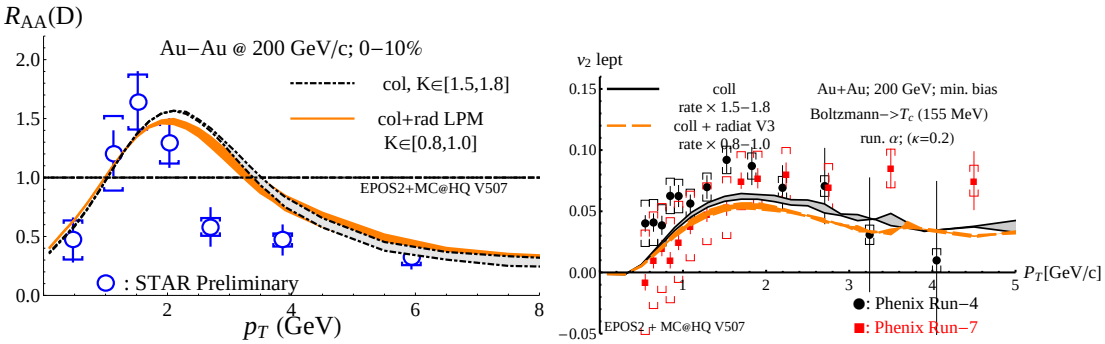

Figure 3. R_{AA} of D- mesons (left) and v_2 of non photonic electrons from the decay of heavy mesons (right) for central AuAu collisions at $\sqrt{s} = 200 AGeV$. For the different scenarios see text.

well on how the plasma expansion is described. Presently in most of the models the plasma expansion is described by (viscous) hydrodynamics. These hydrodynamical models describe a multitude of experimental observables of hadrons consisting of light quarks. They are, however, mostly sensitive to the end of the plasma expansions where the chemical composition of these hadrons follows the predictions for a statistically equilibrated system. As we will see later, the energy loss of heavy quarks is created very early in the expansion of the plasma and therefore heavy quarks are sensitive to the early phase of the hydrodynamical expansion.

In Fig. 4 we display R_{AA} and v_2 for two different models for the expansion of the QGP, keeping the elementary interaction between heavy quarks and plasma partons identical. In this case we use only collisional energy loss with a K factor of 1.5-2 and compare the result to central STAR data for R_{AA} and central Phenix data for v_2. The violet curve shows the results for EPOS2 calculations [3] whereas the red curve is the result for the Kolb-Heinz hydrodynamical approach [9]. Whereas the v_2 value is rather independent of the expansion scenario, the R_{AA} of

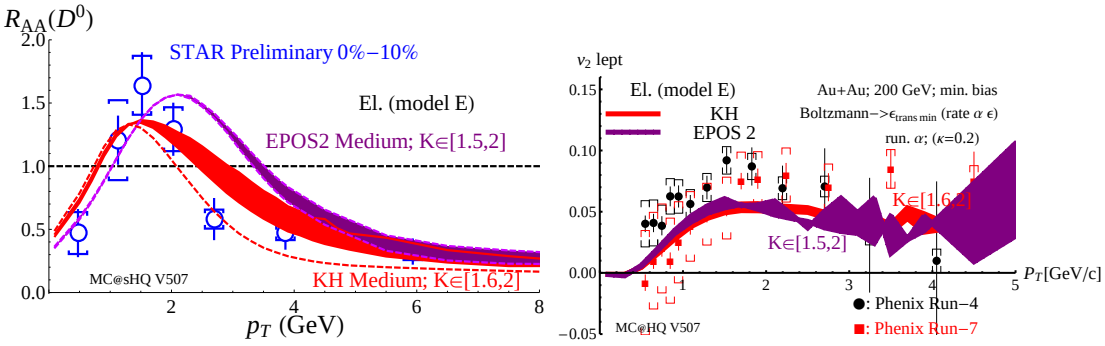

Figure 4. R_{AA} of D- mesons (left) and v_2 of non photonic electrons from the decay of heavy mesons (right) for central AuAu collisions at $\sqrt{s} = 200 AGeV$ for different plasma expansion scenarios. For the different scenarios see text.

the both approaches differ substantially for p_T around 2 GeV. This is a consequence of the early creation of a radial flow in the EPOS2 approach [3]. In the Kolb-Heinz approach this creation is much softer. This comparison makes evident that heavy meson spectra do not only test the elementary interaction between heavy quarks and the QGP partons but also the expansion of the QGP itself. Therefore for a comprehensive understanding of a heavy ion reaction light and heavy quark observables cannot be entangled and have to be studied simultaneously.

One may ask the question how R_{AA} and v_2 are formed during the expansion of the QGP. To study this in more detail we display in Fig. 5 the time evolution of these variables for central AuAu reactions at $\sqrt{s} = 200$ AGeV. We see that in our approach the R_{AA} is quite sensitive to the beginning of the expansion where the energy density is highest and therefore a lot of collisions take place. At 3 fm/c R_{AA} has almost obtained its asymptotic value. The elliptic flow, on the contrary, is more sensitive to the late phase of the expansion. Initially neither heavy nor light quarks have a v_2. The light quarks acquire it when hydrodynamics converts the initial special eccentricity of the interaction to an elliptic flow. This takes time. Only then the v_2 can be impressed on the heavy quarks by the collisional interaction with the light quarks. Therefore at 3 fm/c v_2 has not even half of the asymptotic value. If, as in our model, the partons of

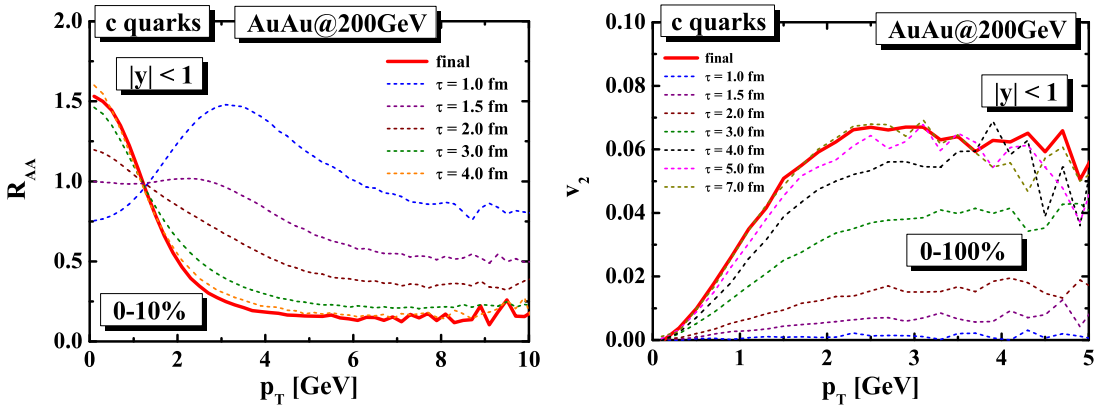

Figure 5. R_{AA} (left) and v_2 (right) of c quarks as a function from time. Final marks the time at which the c-quarks are converted into hadrons either by coalescence of by fragmentation.

the QGP are considered as massless when they interact with the heavy quarks, we can identify different time scales for the development of R_{AA} and v_2 of the heavy quarks. Whether this is also the case in models in which the plasma, with which the charm quarks interact, is described by nonequilibrium models like RSP [19, 20] or PHSD [21] remains to be seen. This observations opens in any case the opportunity to study the plasma expansion in detail, when the high precision data with new vertex detectors at the RHIC experiments will be published.

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