Dynamics and hadronization at intermediate transverse momentum at RHIC

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Abstract. The ultra-relativistic heavy-ion program at RHIC has shown that at intermediate transverse momenta ($p_T' \approx 2-6$ GeV) standard (independent) parton fragmentation can neither describe the observed baryon-to-meson ratios nor the empirical scaling of the hadronic elliptic flow ($v_2$) according to the number of valence quarks. Both aspects find instead a natural explanation in a coalescence plus fragmentation approach to hadronization. After a brief review of the main results for light quarks, we focus on heavy quarks showing that a combined fragmentation and quark-coalescence framework is relevant also here. Moreover, within relativistic Langevin simulations we find evidence for the importance of heavy-light resonances in the Quark-Gluon Plasma (QGP) to explain the strong energy loss and collective flow of heavy-quark spectra as inferred from non-photonic electron observables. Such heavy-light resonances can pave the way to a unified understanding of the microscopic structure of the QGP and its subsequent hadronization by coalescence.

Keywords: Heavy Quarks, Quark-Gluon Plasma, Collective flow, Hadronization.

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INTRODUCTION

Experimental data from the Relativistic Heavy Ion Collider (RHIC) during the past few years have shown convincing evidence for a state of matter with energy densities, $\epsilon$, in substantial excess of the expected critical one, i.e., $\epsilon' \approx 15-20\epsilon_c$ with $\epsilon_c \approx 1$ GeV/fm$^3$. In the standard picture before 2003 the main concern in the study of produced hadrons at high transverse momentum ($p_T$) was the underlying modification of partonic spectra due to interactions in such a hot and dense medium, that would reflect in a similar pattern for all hadrons through independent fragmentation. Indeed, one of the most exciting observations at RHIC has been the suppression of high-$p_T$ particles in agreement with the non-abelian radiative energy-loss theory within perturbative QCD (pQCD) [1]. However, for light hadrons the observations of an anomalous baryon-to-meson production ratio at intermediate $p_T$ up to $\approx 6$ GeV and a scaling of the elliptic flow with the number of quark constituents, has enforced revisions of an independent fragmentation model for hadronization. Instead coalescence processes among massive quarks appear to be a convenient picture that can naturally and quantitatively account for the main features of light hadron production at intermediate $p_T$ [2, 3, 4, 5].

For heavy quarks (charm ($c$) and bottom ($b$)), the energy loss predicted by pQCD [6] turned out to be insufficient (at variance with the light quark case) to account for the observed large nuclear suppression (small $R_{AA}$) and collectivity (large $v_2$) in non-photonic single-electron spectra [7, 8, 9, 10, 11]. Here the challenge is mainly in the
understanding of the in-medium quark interactions, even if the acquired knowledge on
the hadronization mechanism from light quarks plays a significant role as well.

Lattice QCD (lQCD) results suggest that resonance structures survive in meson-
correlation functions at moderate temperatures \[ T_c \] above \[ T_c \]. Two of us have there-
fore suggested an effective model for heavy-light quark scattering via \( D \) and \( B \) res-
onances \[ 13 \]. To study the consequences of such interactions for the modification
of the heavy-quark (HQ) distributions, a Langevin simulation has been performed to
trace the evolution of HQ distributions through the fireball in heavy-ion Collisions
(HICs) \[ 14, 15 \]; hadronization has been modeled by a coalescence model similar to the
one applied to light quarks \[ 2, 3 \]. It has been found that the effect of resonant heavy-light
scattering is crucial \[ 15 \] and also provides a reasonable agreement with semileptonic \( e \)
spectra at RHIC data \[ 8, 11, 10 \].

We note that for heavy quarks (heavy-light) quark-antiquark resonances provide the
dominant medium effects on their distributions close to \( T_c \), which then naturally merges
into a coalescence-type description for hadronization processes \[ 16 \].

**MODIFICATION OF HADRONIZATION MECHANISM**

Hadronization at asymptotically large momentum can be described by a set of fragmen-
tation functions \( D_{a-H} (p=P) \) that parametrize, in a universal way, the probability that a
hadron \( H \) with momentum \( P \) is created from a parton \( a \) with momentum \( p \) in the vac-
um. Fragmentation functions have been measured in \( e^+ e^- \) collisions and work well for
hadron production at \( p_T > 2 \) GeV also in \( pp \) collisions at RHIC energies. Therefore it was
expected that in this \( p_T \) regime the QGP could be probed by focusing on modifications
of the spectra, \( E_dN=\int d\mathbf{p} \), at the parton level, but from \( Au+Au \) collisions it became clear
that this is not the case at least up to \( p_T \) '6 GeV. Two puzzling observations lead to this
conclusion: (a) baryons are much more abundant than predicted by fragmentation. A ra-
tio \( \bar{p}/p \) between 2 and 4 GeV/c has been measured, see Fig.1, much larger than the
value of 0.2 predicted by leading-twist pQCD. A similar trend is observed for \( p=\pi, \Lambda=K_0^0 \), i.e., \( p, \bar{p} \) and \( \Lambda \)'s do not seem to suffer jet quenching. The pertinent nuclear mod-
fication factors, \( R_{AA} \), are close to 1, unlike those of light mesons for which \( R_{AA} \sim 2 \) in central collisions; (b) the elliptic flow of all identified hadrons is found to scale ac-
cording to a quark-number scaling as reflected in a universal behavior of \( v_2_H (p_T=n)=n \)
where \( n \) is the number of constituent quarks in hadron \( H \). In particular, recent data for the
\( \phi \) (1020) also follow the scaling, suggesting the dominance of the quark content rather
than the mass effect, in agreement with the coalescence prescription \[ 17 \].

The main reason for the inadequacy of a pure fragmentation picture is the high
density of the matter created in HICs. In such an environment one may expect that
quarks could just coalesce into hadrons: three quarks into a baryon, a quark-antiquark
pair into a meson. In such a picture baryons with momentum \( p_T \) are mainly produced
from quarks with momenta ' \( p_T/3 \), while mesons with the same momentum mainly arise
from quarks with momenta ' \( p_T/2 \). This is contrary to the fragmentation process where
baryon production is suppressed with respect to mesons as more quarks are needed from
the vacuum. A coalescence model that is based on the simple overlap of the quark-
distribution function with a hadron-wave function has been developed to implement the
FIGURE 1. Left: $\pi$ and $p$ transverse-momentum spectra in $\sqrt{s_{NN}}=200$ AGeV Au+Au collisions. RHIC data \[18, 19\] are shown by circles ($\pi^0$) and squares ($\bar{p}$), lines are results from coalescence. Right: experiment vs. coalescence results for baryon-to-meson ratios for $p=\pi$ (lower part) and $\Lambda=K^0$ (upper part).

physical ideas sketched above \[2\]. In such a model the transverse-momentum spectrum of hadrons that consists of $n$ (anti-) quarks is given by the overlap between the hadron-wave function and $n$ quark phase-space distribution functions, $f_q(x_i;p_i)$:

$$\frac{dN_H}{d^2p_T} = g_H \prod_{i=1}^{n} \frac{d^3p_i}{(2\pi)^3E_i} p_i \; \sigma_q(x_i;p_i)f_H(x_1:\cdots:x_n;p_1:\cdots:p_n)\delta^2 \sum_{i=1}^{n} p_{T,i} \; ; \; (1)$$

$d\sigma$ denotes an element of a space-like hadronization hypersurface, $f_H$ is the Wigner distribution function of the hadron and $g_H$ the probability of forming a color-neutral object with the spin of the hadron from $n$ colored quarks. Therefore it is assumed that the probability of coalescence is simply given by the phase-space distance weighted by the wave function of the produced particle Eq. (1). In such an approach constituent-quark masses are included representative for non-perturbative effects. This is a further assumption that can be relaxed for heavy quarks owing to the smaller effect of the QCD vacuum on their masses. The distributions $f_q(x_i;p_i)$ are fixed as homogeneous Boltzmann distributions with an average radial flow $v_{1} = 0.35$ for $p_T < 2$ GeV, and quenched minijets for $p_T > 2$ GeV. The volume is fixed to reproduce the measured transverse energy at given centrality. In the left panel of Fig. 1 the $p$ and $\pi$ spectra obtained from the quark-coalescence model are shown together with the experimental data from PHENIX \[18, 19\].

The resulting $p=\pi$ ratio is shown in the right panel of Fig. 1 by lower lines \[20\], a similar effect is seen also for the $\Lambda=K_0^0$ ratio (upper lines) \[21\]. Similar conclusions are reached in other studies based on quark coalescence \[4, 5\].

HEAVY-QUARKS AT HIGH TEMPERATURES

Heavy quarks ($b,c$) are produced out of thermal equilibrium in the very early stage of the reaction; due to their large mass a perturbative evaluation of their in-medium interactions was expected to be reliable also at relatively small $p_T$. However, a small nuclear modification factor, $R_{AA} \sim 0.3$, has been deduced from semileptonic electron
spectra associated with decays of $D$- and $B$-mesons [8, 11], comparable to the pion one. Such a value is incompatible with pQCD jet-quenching mechanisms [6]. This statement is strengthened by the observed $v_2$ of up to 10% [7, 10], indicating substantial collective behavior of charm (c) quarks [3]. Moreover, a consistent description of $R_{AA}$ and $v_2$ cannot be achieved even if one artificially upscales the transport coefficients within pQCD energy-loss calculations [14]. This suggests that the physics underlying the heavy quark observables is not only a matter of a global evaluation of the interaction strength, but there is an opportunity for a more detailed understanding of the microscopic nature of the interaction (most likely of non-perturbative origin) and of the hadronization mechanism, as we briefly review in the following.

A hint on non-perturbative interactions of heavy quarks in the medium is provided by lQCD computations which exhibit resonance structures in meson correlation functions at moderate temperatures [12, 22]. Along this line two of us have suggested that $D$- and $B$-resonance exchange in the $\bar{q}Q$ channel may be the dominant scattering process that drives the HQ dynamics [13]. To evaluate the consequences of such a picture we have built a model based on an effective Lagrangian:

$$\mathcal{L} = \mathcal{Q} \Phi \frac{1}{2} \Phi \Gamma \bar{q} + \text{h.c.}$$

where $\Phi=D, B$. We have calculated elastic $Q + \bar{q} \rightarrow Q + \bar{q}$ scattering amplitudes via $\Phi$ exchange in the $s$- and $u$-channel. The existence of one $\Phi$ state (e.g., a pseudoscalar $J^P=0^-$), is assumed together with a minimal degeneracy following from chiral and HQ symmetries, represented by Dirac matrices $\Gamma=1, \gamma_5, \gamma^\mu, \gamma_5\gamma^\mu$ in Eq. (2).

The application to HICs is realized by treating HQ kinetics in the QGP as a relativistic Langevin process [15]:

$$\frac{\partial f}{\partial t} = \frac{\partial (\gamma p f)}{\partial p} + \frac{\partial^2 (D_p f)}{\partial p^2};$$

$\gamma$ and $D_p$ are drag and (momentum) diffusion coefficients which determine the approach to equilibrium and satisfy the Einstein relation, $T = D_p = \gamma M_Q$. The bulk medium is modeled by a spatially homogeneous elliptic thermal fireball which expands isentropically. Finally, hadronization is treated via coalescence at $T_c=180$ MeV, see Eq. (1), plus fragmentation processes evaluated as $f_{c,b} (p_T) \cdot \left[ P_{c,b} (D_A; p_{TA}) \right]$, where $P_{c,b} (D_A; p_{TA})$ is the probability for a heavy quark to coalesce.

For 200 AGeV Au+Au collisions results from the Langevin simulation including hadronization by coalescence+fragmentation (left) and fragmentation only (right) are shown in Fig. 2 together with experimental data [8, 9]. It is obvious that elastic scattering in a pQCD scheme is insufficient to account for the small $R_{AA}$, independent of the hadronization scheme applied. The red band shows the full calculation with $c \neq b$ quarks that scatter in the presence of hadron-like resonances with a width $\Gamma' \approx 0.4\text{--}0.75$ GeV (representing the interaction strength), supplemented by the pQCD elastic scattering in color non-singlet channels (dominated by gluons). We note that the contamination of single electrons from $B$ decays is significant already at $p_T \approx 2$ GeV (corresponding to a crossing of $c$ and $b$ spectra at around $p_T \approx 4-5$ GeV). Thus the inclusion of $B$ mesons (despite the inherent uncertainties in the $b/c$ ratio) is mandatory to draw reliable conclusions on the interaction processes underlying the experimental results.
When comparing the band in the left and right panel of Fig. 2 we can see a clear coalescence effect of hadronization in terms of an increase in the $R_{AA}$ at $p_T \sim 1$–$4$ GeV. This effect becomes more significant via a simultaneous enhancement of the elliptic flow $v_2$ \cite{3, 15}, see Fig. 3. This behavior is typical of a coalescence mechanism, reversing the usual correlation between $R_{AA}$ and $v_2$, and allows for a reasonable description of the experimental data on both $R_{AA}$ and $v_2$. Very recently, a Brueckner many-body scheme for in-medium T-matrices for HQ scattering off light quarks \cite{23} has been evaluated starting from lQCD potentials. The existence of $D$ and $B$-like resonances has been confirmed; furthermore, when embedding the pertinent drag and diffusion coefficients in the model described above, a comparable (or even better) agreement with the data is found \cite{23}.

**CONCLUSIONS**

The first stage of RHIC program has shown clear signs of modifications of the hadronization mechanism in the light-quark sector relative to $pp$ collisions. There are several evidences that hadronization proceeds through the coalescence of (massive) anti-/quarks which are close in phase space. The modification of hadronization for light quarks also
seems to play a role in the new challenge posed by heavy-quark probes. Here, the main issue is the dominant interaction mechanism (HQ diffusion) and its relation to the microscopic structure of the QGP. We have presented a scenario based on the existence of $B$- and $D$-like resonances in the QGP up to $T = 2T_c$. Reasonable agreement with experimental data is achieved owing to a positive interplay between the resonance scattering mechanism and the hadronization by coalescence. We note that such an approach provides an inherent consistency between the in-medium interactions of HQs and the subsequent hadronization by coalescence: a pole in the quark-antiquark propagator above $T_c$ can be viewed as a precursor of recombination.

Finally, it is important to keep in mind the interrelations of open and hidden charm, if regeneration makes up a good fraction of the charmonium yield as expected at RHIC and LHC. In this case, the study of $B$ and $D$ distributions can be related to that of $J=\psi$ and $\Upsilon$ due to the underlying common $c, b$ distributions; the consistency of such a picture should be checked in the near future.

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