Open charm and dileptons from relativistic heavy-ion collisions

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We study the dynamics of open charm production and the dilepton radiation of the semi-leptonic decays of correlated $D\bar{D}$ pairs versus the quark-gluon plasma (QGP) radiation and hadronic sources in relativistic heavy-ion collisions. Our study is based on the Parton-Hadron-String Dynamics (PHSD) transport approach employing a non-perturbative QCD description of the strongly interacting quark-gluon plasma (sQGP) in terms of dynamical quasiparticles and the EoS based on lattice QCD. We compare the PHSD results for charm observables with the calculations from BAMPS (Boltzmann Approach to Multi-Parton Scatterings) which is based on perturbative QCD with massless partons and interaction cross sections calculated in leading order of the QCD coupling. We compare the p_T dependence of the ratio R_{AA} of D-mesons in $A + A$ over $p + p$ collisions scaled by the number of binary collisions N_{bin} as well as the elliptic flow v_2 of D-mesons calculated within the PHSD and BAMPS at LHC energies. In other study, based on the PHSD calculations we find that the dileptons from correlated D−meson semi-leptonic decays dominate the 'thermal' radiation from the QGP in central Pb+Pb collisions at the intermediate masses ($1.2 < M < 3$ GeV) for higher invariant energies However, for invariant energies $\sqrt{s_{NN}} < 40$ GeV the QGP radiation overshines the contribution from $D, \bar{D}$ decays such that one should observe a rather clear signal from the partonic dilepton radiation. This finding provides promising perspectives to measure the QGP radiation in the dilepton experiments at RHIC BES and the future FAIR/NICA facilities.

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Heavy-ion collisions provide a unique possibility to study the properties of strongly interacting matter under extreme conditions. The heavy quarks (D-mesons) and electromagnetic radiation (real photons and dileptons) are considered to be the most sensitive observables which provide access to the interior of HIC collisions from early to the final stages of the reaction. The charm quark ($c\bar{c}$) pairs are produced through initial hard nucleon-nucleon scattering in relativistic heavy-ion collisions. Since the production of heavy flavor requires a large energy-momentum, it can be described within perturbative QCD [1]. The produced heavy flavor then interacts with the hot dense matter (of partonic or hadronic nature) by exchanging energy and momentum. As a result, the ratio of the measured number of heavy flavors in heavy-ion collisions to the expected number in the absence of nuclear or partonic matter, which is the definition of R_{AA}, is suppressed at high transverse momentum, and the elliptic flow of heavy flavor is generated by the interactions in noncentral heavy-ion collisions [2].

The theoretical description of the charm energy loss is a challenging task since it requires the knowledge about the interactions of charm with the medium as well as the proper description of the medium time evolution and interactions of the internal degrees-of-freedom. In this respect microscopic transport approaches are powerful tools to model the charm dynamics. Our study of charm energy loss is based on two comprehensive transport approaches: PHSD (Parton-Hadron-String Dynamics) [3, 4] and BAMPS (Boltzmann Approach to Multi-Parton Scatterings) [5, 6]. The PHSD is a microscopic off-shell transport approach for the description of strongly interacting partonic and hadronic matter in and out-of equilibrium which is based on the solution of Kadanoff–Baym equations in first-order gradient expansion [8]. The realization of the QGP phase is based on the dynamical quasiparticle model (DQPM) [8, 9] which describes the strongly interacting, i.e. non-perturbative, partonic medium in terms of off-shell massive quasiparticles (quarks and gluons) with broad spectral functions; their properties, i.e. complex self-energies, are defined from the QGP thermodynamics in line with the lQCD EoS at finite temperature T and baryon chemical potential μ_B. The perturbative QCD cascade BAMPS is based on pQCD degrees-of-freedom, i.e. massless quarks and gluons which follow the leading-order pQCD interactions, including radiative processes in an improved Gunion-Bertsch approach [7] in line with a Boltzmann collision integral. The employment of the PHSD and BAMPS transport approaches allows to explore the charm interactions with a perturbative and non-perturbative QCD medium.

1. Charm production

The realization of charm dynamics in the PHSD is described in detail in Refs. [10]. In the QGP phase, the elastic and quasi-elastic interactions of charm quarks with off-shell quarks and gluons are calculated within the effective propagators and T-dependent couplings from the DQPM which allow to explain lQCD data on the temperature dependence of the drag coefficient D_S at μ_B=0 [9]. The PHSD includes the dynamical hadronization of charm quarks through coalescence and/or fragmentation (depending on transverse momentum). In the hadronic phase, D-mesons can interact with baryons and mesons with cross sections calculated in an effective hadronic model based on a lagrangian approach with heavy-quark spin symmetry (cf. Refs. in [10]).

In BAMPS, the interactions of charm quarks with the pQCD medium include elastic and radiative heavy flavor interactions calculated within the improved Gunion-Bertsch approximation
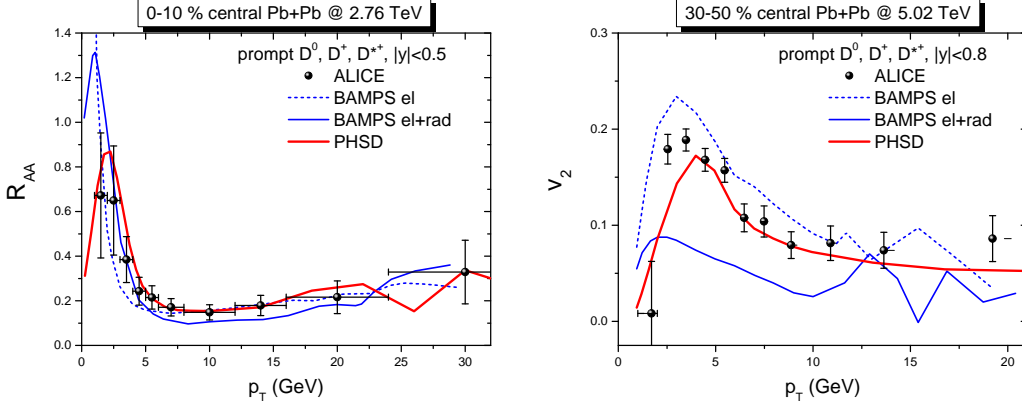
Figure 1: Left: The ratio R_{AA} of D^0, D^+, and D^{*+} mesons within $|y| < 0.5$ as a function of transverse momentum p_T in 0-10 % central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to the experimental data from the ALICE collaboration [13]. Right: The PHSD and BAMPS results for the elliptic flow v_2 of D^0 mesons within $|y| < 0.8$ in 30-50 % central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to the experimental data from the ALICE collaboration [14]. The solid red lines show the PHSD results, while the blue dashed lines display the BAMPS results including elastic scattering only and the blue solid lines – the BAMPS results with elastic and radiative processes.

[12]. The energy loss of the charm quarks has been extensively studed in Refs. [11].

In the left plot of Fig. 1 the comparison of PHSD and BAMPS results with ALICE data at 2.76 TeV [13] for the p_T dependence of the ratio R_{AA} of D-mesons in $A + A$ over $p + p$ collisions, scaled by the number of binary collisions N_{bin}, is shown while the right plot of Fig. 1 shows the elliptic flow v_2 of D-mesons for both approaches versus the ALICE measurement at 5.02 TeV [14]. The BAMPS results correspond to a scenario with running coupling $\alpha_S(Q^2)$ and scaling factor $K = 3.5$ for the elastic interactions which is needed for the description of the R_{AA} since the pQCD elastic scattering is too small to explain the experimental data on R_{AA} for $p_T < 30$ GeV and requires a large scaling factor of 3.5. Including radiative collisions, on the other hand, the pQCD description in compatible with the data, pointing out the potential importance of the radiative processes: as seen from the blue solid lines in Fig. 1 the pQCD radiative processes provide extra energy loss, however, their angular dependence - with a strong forward peak - leads to an underestimation of elliptic flow $v_2(p_T)$. Contrary, the non-perturbative QGP interactions with heavy partons and more isotropic angular distributions - as in the PHSD - allow to describe the $R_{AA}(p_T)$ and $v_2(p_T)$ simultaneously. We note that the gluon radiative processes in the DQPM (and correspondingly, in the PHSD) are strongly suppressed due to the large mass of thermal gluons contrary to the pQCD based models.

This example shows how sensitive the charm probes are to the properties of the underlying medium. We mention, that this issue has been studied extensively by the combined efforts of different worldwide groups working on charm dynamics [16–18].

## 2. Excitation function of dielectron production

The electromagnetic probes (dileptons and real photons) are considered to provide a powerful probe of the quark-gluon plasma as created in ultra-relativistic nuclear collisions. They interact

only electromagnetically and thus escape to the detector almost undistorted through the dense and strongly-interacting medium [4]. Although the dileptons from partonic scatterings in the QGP phase are of primary interest, there are variety of other dilepton channels, i.e. from hadronic decays and interactions in the hadronic phase as well as dileptons from semi-leptonic decays of correlated $D\bar{D}$ pairs.
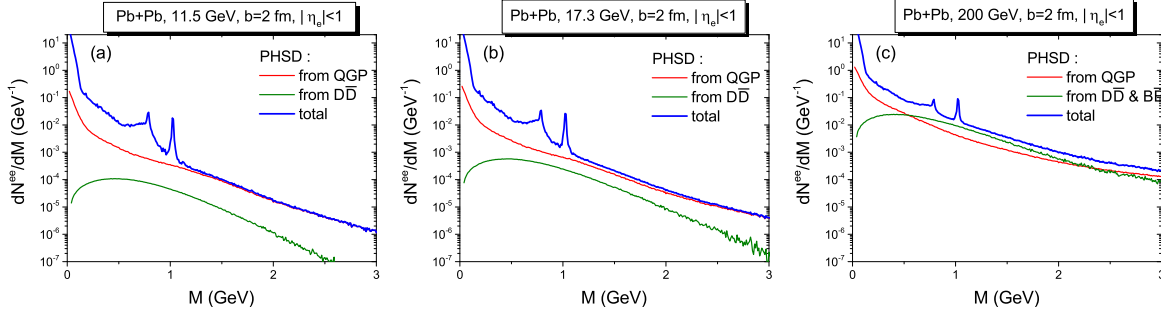
Figure 2: The invariant mass spectra of dileptons from partonic interactions (red lines) and from $D\bar{D}$ pairs (green lines) together with the total dielectron spectrum (blue lines) in central Pb+Pb collisions at $\sqrt{s_{NN}} =$ 11.5, 17.3, and 200 GeV from the PHSD at mid-pseudorapidity for the leptons.

In Ref. [15] we have compared the separate contributions from different dilepton channels in central Pb+Pb collisions at various energies from $\sqrt{s_{NN}} =$8 to 200 GeV within the PHSD. In Fig. 2 we show the contributions from the QGP (red lines), which is the sum of three partonic channels, i.e. $q + \bar{q} \rightarrow e^+ + e^-$, $q + \bar{q} \rightarrow g + e^+ + e^-$, and $q(\bar{q}) + g \rightarrow q(\bar{q}) + e^+ + e^-$, and from $D\bar{D}$ pairs (green lines) with the total dielectron spectrum (blue lines) at different collision energies for central Pb+Pb collisions. We find that the contribution from the hadronic channels increases only moderately with collision energy (in line with the hadron abundances), while the contribution from the QGP raises more steeply (in line with the enhanced space-time volume of the QGP phase). The contribution from correlated $D\bar{D}$ pairs is small at low-energy collisions, but becomes more and more important with increasing collision energy in competition with the production from the QGP channels.
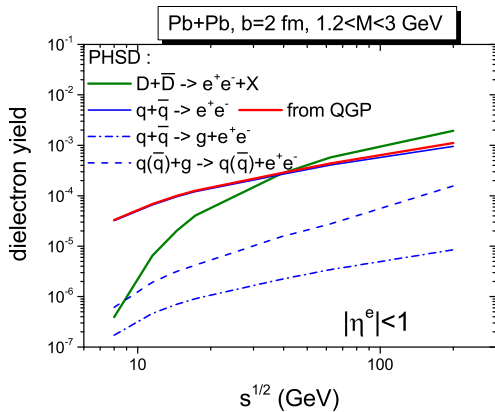
Figure 3: The contributions to intermediate-mass dielectrons (1.2 GeV $< M <$ 3 GeV) from $D\bar{D}$ pairs (green lines), different channels of partonic interactions, $q + \bar{q} \rightarrow e^+ + e^-$, $q + \bar{q} \rightarrow g + e^+ + e^-$, $q(\bar{q}) + g \rightarrow q(\bar{q}) + e^+ + e^-$ (see legend) as a function of $\sqrt{s_{NN}}$ for Pb+Pb collisions at $b = 2$ fm for midrapidity leptons. The red solid line displays the sum of the partonic contributions.

Fig. 3 compares the contribution from $D\bar{D}$ pairs (green lines) to the QGP contribution for intermediate mass dileptons (1.2 GeV $< M <$ 3 GeV) as a function of collision energy $\sqrt{s_{NN}}$ for Pb+Pb collisions at $b = 2$ fm. The figure clearly shows that the contribution from partonic

interactions, especially from $q + \bar{q} \rightarrow e^+ + e^-$, dominates the intermediate-mass range in low-energy collisions. However, the contribution from $D\bar{D}$ pairs rapidly increases with increasing collision energy, because the scattering cross section for charm production grows fast above the threshold energy. It overshines the contribution from partonic interactions around $\sqrt{s_{NN}} \approx 40$ GeV and dominates at higher energies.

Thus, our results in Figs. 2 and 3 clearly demonstrate that the window to study partonic matter by dielectrons at intermediate masses without substantial background from heavy flavor decays opens for collision energies $\sqrt{s_{NN}} < 40$ GeV. This finding provides promising perspectives for the dilepton experiments at RHIC BES and the future FAIR/NICA facilities.

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