Dileptons from the strongly-interacting Quark-Gluon Plasma within the Parton-Hadron-String-Dynamics (PHSD) approach

O. Linnyk, E. L. Bratkovskaya, W. Cassing

Abstract

Dilepton production in $In + In$ collisions at 158 A-GeV is studied within the microscopic Parton-Hadron-Strings Dynamics (PHSD) transport approach, which is based on a dynamical quasiparticle model (DQPM) matched to reproduce lattice QCD results in thermodynamic equilibrium. A comparison to the data of the NA60 Collaboration shows that the low mass dilepton spectra are well described by including a collisional broadening of vector mesons, while the spectra in the intermediate mass range are dominated by off-shell quark-antiquark annihilation in the nonperturbative QGP. In particular, the observed softening of the $m_T$ spectra at intermediate masses is reproduced.

1. Introduction

Dileptons are powerful probes that deliver multi-faced information: from the in-medium properties of hadrons to the nature of the deconfinement phase transition and to the properties of the deconfined state itself. Already in 1978, E. Shuryak proposed to use dileptons as probes of the QGP [1] because the temperature of the plasma should be given by the inverse slope of the expected exponential spectral shape of its dilepton radiation. On the other hand, dileptons are emitted over the entire space-time evolution of the heavy-ion collision, from the initial nucleon-nucleon collisions through the hot and dense phase and to the hadron decays after freeze-out. This is both a challenge and advantage of the probe.

Early concepts of the QGP were guided by the idea of a weakly interacting system of partons which might be described by perturbative QCD (pQCD). However, experimental observations at the Relativistic-Heavy-Ion Collider (RHIC) indicated that the new medium created in ultrarelativistic Au+Au collisions was interacting more strongly than hadronic matter and consequently this concept had to be given up. In the present work, the dynamical evolution of the system is described by the PHSD transport approach [2] incorporating the off-shell propagation of the partonic quasi-particles according to [3] as well as the transition to resonant hadronic states (or strings) in line with Lorentz-invariant off-shell transition rates (cf [2]) for the fusion of quark-antiquark pairs to mesonic states or three quarks (antiquarks) to baryonic states. Dilepton radiation by partonic off-shell quasi-particles is calculated in an effective field theory [4, 5]. By comparing our results to experimental data, we aim to deduce the in-medium vector meson properties as well as the properties of the nonperturbative QGP.
Figure 1: Diagrams contributing to the dilepton production from a QGP: (a) Drell-Yan mechanism, (b) gluon Compton scattering (GCS), (c) vertex correction, (d) gluon Bremsstrahlung (NLODY). Virtual photons (wavy lines) split into lepton pairs, spiral lines denote gluons, arrows denote quarks. In each diagram, the time runs from left to right.

**PHSD and dilepton emission in reactions with off-shell quarks**

A consistent dynamical approach — valid also for strongly interacting systems — can be formulated on the basis of the Kadanoff-Baym equations [6, 7] or off-shell transport equations in phase-space representation, respectively [3, 7]. In the Kadanoff-Baym theory the field quanta are described in terms of propagators with complex selfenergies. Whereas the real part of the selfenergies can be related to mean-field potentials, the imaginary parts provide information about the lifetime and/or reaction rates of time-like ‘particles’ [8]. Once the proper (complex) selfenergies of the degrees of freedom are known, the time evolution of the system is fully governed by off-shell transport equations (as described in Refs. [3, 7]).

The PHSD approach is a microscopic covariant transport model that incorporates effective partonic as well as hadronic degrees of freedom and involves a dynamical description of the hadronization process from partonic to hadronic matter [2]. Whereas the hadronic part is essentially equivalent to the conventional HSD approach [9] the partonic dynamics is based on the Dynamical QuasiParticle Model (DQPM) [10] which describes QCD properties in terms of single-particle Green’s functions (in the sense of a two-particle irreducible (2PI) approach) and leads to effective strongly interacting partonic quasiparticles with broad spectral functions as degrees of freedom. The off-shell parton dynamics also allows for a solution of the hadronization problem: the hadronization occurs by quark-antiquark fusion or 3 quark/3 antiquark recombination which is described by covariant transition rates. Since the dynamical quarks become very massive, the formed resonant ‘pre-hadronic’ color-dipole states (q̅q or qq̅) are of high invariant mass, too, and sequentially decay to the ground state meson and baryon octets increasing the total entropy. This solves the entropy problem in hadronization in a natural way [11].

The elementary processes involved in the dilepton radiation by the strongly interacting QGP are illustrated in Fig. 1. The diagrams look like those in pQCD, however, we use an effective theory, where important modifications to pQCD are incorporated: 1) the non-perturbative spectral functions and self-energies of the quarks, anti-quark and gluons are taken into account (i.e. the quark and gluon lines are dressed), 2) the running DPQM coupling $\alpha_S$ depends on the local energy density $\epsilon$ [10] related to a temperature $T$ by the IQCD equation of state. In particular, a non-zero width of quarks leads to higher-twist corrections to the standard pQCD approach [4, 5].

Note that the processes sub-leading in $\alpha_S$ are not small in this phenomenological model. To make quantitative comparison to data, we include the following $O(\alpha_S)$ partonic processes as sources of the dileptons in addition to the simple leading order Drell-Yan $q + \bar{q}$ annihilation mechanism: Gluon Compton scattering ($q + g \rightarrow \gamma^* + q$ and $\bar{q} + g \rightarrow \gamma^* + \bar{q}$) and quark + anti-quark annihilation with gluon Bremsstrahlung in the final state ($q + q \rightarrow g + \gamma^*$). By implementation of the off-shell cross sections into the PHSD transport we can calculate the dilepton radiation from
Comparison to NA60 data

Let us start with results on the in-medium properties of vector mesons and move to the dilepton radiation from the QGP later on. Various models predict that hadrons change in the (hot and dense) nuclear medium; in particular, a broadening of the spectral function or a mass shift of the vector mesons was expected to be considerable. Furthermore, QCD sum rules indicated that a mass shift may lead to a broadening and vice versa \[12\]; therefore both modifications should be studied simultaneously, too. Thus we explore three possible scenarios: (1) a broadening of the $\rho$ spectral function, (2) a mass shift, and (3) a broadening plus a mass shift. The HSD off-shell transport approach allows to investigate in a consistent way the different scenarios for the modification of vector mesons in a hot and dense medium. In the off-shell transport, meson spectral functions change dynamically during the propagation through the medium and evolve towards the on-shell spectral function in the vacuum.

As we find in Fig. 2 the NA60 data favor the scenario of the in-medium broadening of vector mesons. Note that in the data - presented in this plot - the $D$-meson contribution has not been subtracted. The NA60 collaboration has published acceptance corrected data with subtracted charm contribution recently. The comparison to the new data set leads to the same conclusions as here and will be presented in an extended publication \[15\]. Note that a comparison of HSD results for the free case and the three in-medium scenarios to the CERES data in \[16\] also has shown that the spectrum is described better, if a broadening of the $\rho$-meson spectral function in the medium is assumed (cf. Fig. 4 in \[16\]).
On the other hand, there is a discrepancy between the HSD (hadronic) results and the data in the intermediate of mass range above 1 GeV. This discrepancy is not accounted for by hadronic sources in HSD – in-medium or free – and might be seen as a signal of partonic matter, manifest already at the top SPS energy. The calculation of the QGP contribution in PHSD fully accounts for the observed excess (cf. the bands in Fig. 2).

The intriguing finding of the NA60 Collaboration is that the effective temperature of the dileptons in the intermediate mass range is lower than the effective temperature of the dileptons from the hadronic phase! This implies that the quark-antiquark annihilation (or partonic channels) occur dominantly before the collective radial flow has developed. This feature of the data is also reproduced in PHSD (cf. Fig. 3 rhs). A detailed look at the PHSD results confirms that the lower mass region is dominated by hadronic sources while the spectrum in the intermediate mass range is dominated by the off-shell partonic channels in the QGP [15].

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