The dilepton probe in heavy-ion collisions

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Abstract. Dileptons provide direct observables of the electromagnetic current-current correlator in the hot and/or dense medium formed in heavy-ion collisions. In this article an overview is given about the status of the theoretical understanding of the dilepton phenomenology in heavy-ion collisions from studies of the in-medium properties of hadrons and partons within many-body theory and about connections to fundamental questions concerning the chiral phase transition.

1. Introduction

In heavy-ion collisions electromagnetic probes, i.e., photons and lepton pairs ("virtual photons") provide one of the most valuable possibilities to study the interior of the hot and dense medium created in the interaction over its whole history since their spectra are nearly unaffected by final-state interactions [1].

This paper will be restricted to invariant-mass (M) and transverse-momentum (q_T) spectra of dileptons whose rate is given by [2, 3, 4]

$$\frac{\mathrm{d}N_{ll}}{\mathrm{d}^4 x \mathrm{d}^4 q} = -\frac{\alpha^2}{3\pi^3} \frac{L(M)}{M^2} \operatorname{Im} \Pi^\mu_{\mathrm{em}\mu}(M, q; T, \mu_B) f_B(q_0, T), \tag{1}$$

where $\alpha \simeq 1/137$ denotes the fine-structure constant, $M = q_0^2 - q^2$ the invariant mass of the lepton pair of energy, q_0, and three-momentum, q, T the temperature, μ_B the baryon chemical potential, f_B the Bose distribution, and $L(M)$ the lepton-phase space factor. As is known from $e^+ e^- \to$ hadrons, in the vacuum the retarded hadronic electromagnetic (em.) current correlator, Π_{em}, at low invariant masses, $M \lesssim M_{\mathrm{dual}}$ is well described by the vector-meson dominance (VMD) model for the light vector mesons ρ, ω, and ϕ and by the perturbative QCD (pQCD) continuum at higher masses ($M \gtrsim M_{\mathrm{dual}}$), where $M_{\mathrm{dual}} \simeq 1.5\,\mathrm{GeV}$ denotes a "duality scale". The hadronic "resonance part" is dominated by the isovector channel (ρ meson).

For a theoretical description of dilepton production in relativistic heavy-ion collisions (HICs) thus the first goal must be an understanding of the in-medium spectral properties of the light vector mesons in the hadronic and the QGP in the partonic phase of the fireball evolution. This review of recent progress in this field is organized as follows: In Sect. 2 first the constraints on the em. current correlator in

strongly interacting matter from QCD as the underlying fundamental theory of strong interactions will be discussed, followed by a brief summary on effective hadronic models. In Sect. 3 these models are confronted with data from ultrarelativistic HICs. Sect. 4 contains brief conclusions and an outlook.

2. The electromagnetic current correlator in strongly interacting matter

Ab-initio constraints. In the vacuum and at low temperatures and densities the light-quark sector of QCD is governed by (approximate) *chiral symmetry* which is spontaneously broken by the formation of a quarks condensate, $\langle \bar{\psi}\psi \rangle \neq 0$, in the QCD vacuum which manifests itself in the mass splitting of chiral partners in the hadron spectrum, as can be seen, e.g., in the experimental determination of the isovector-vector and -axialvector current correlator through $\tau \rightarrow \nu + n\pi$ decays [5, 6]. From (lattice) QCD at finite temperature one expects a decrease of the quark condensate at high temperatures and/or densities and restoration of chiral symmetry. Thus the mass spectra of hadrons are expected to soften and to degenerate with their pertinent chiral partners above a critical temperature, T_c. One indication of the interrelation of chiral symmetry and confinement is that in lattice-QCD (lQCD) calculations the critical temperature, $T_c \simeq 160\text{-}190\,\mathrm{MeV}$, for the chiral and the deconfinement (cross-over) transitions coincide [7].

From hadronic modeling two microscopic mechanisms for chiral symmetry restoration (CSR) have emerged: On the one hand it has been conjectured that the hadron masses drop to zero at the critical point due to the melting of the quark condensate) [8]. On the other hand within phenomenological hadronic many-body models the hadron spectra show a significant broadening with little mass shifts ("melting-resonance scenario") [4, 9, 10, 11]. A direct relation between in-medium spectral properties of hadrons, in our context particularly vector mesons, to QCD is provided by QCD sum rules which relate moments of the (in-medium) spectral functions for various currents in different isospin channels in the space-like region to the pertinent quark and four-quark condensates. Detailed studies [12, 13, 14, 15] show that (in cold nuclear matter) both the "dropping-mass" and the "melting-resonance" scenarios for CSR are compatible with QCD sum rules. One objective for the investigation of dileptons in high-energy heavy-ion collisions is thus to gain insight in the in-medium spectral properties of the light vector mesons through the em. current correlator to constrain the mechanism leading to the softening of the spectral functions. Due to the experimental problems to assess the spectral properties of the axial-vector channel, an indirect theoretical approach may be to connect chiral hadronic models, describing successfully the measured dilepton observables, with CSR via finite-temperature Weinberg-sum rules [16, 17] which relate moments of the *difference of vector- and axial-vector-current correlators* to quark and four-quark condensates, i.e., order parameters of chiral symmetry, providing constraints on these models from lQCD.

Hadronic many-body theory. A (model-independent) approach to assess

medium modifications of vector (and axial-vector) mesons is based on the chiral reduction formalism, providing a low-density expansion of the in-medium vector- and axial-vector current correlators in terms of the corresponding vacuum quantities which are taken from experimental data such as $\tau \to n\pi\nu$. The most intriguing feature of these kind of models is the "in-medium mixing" of the vector- with the axial-vector current correlator due to pions in the medium [18] which may provide a mechanism for the onset of CSR. However, the applicability of the low-density approximation is restricted to very low temperatures and densities.

Another ansatz is to use chiral models in various realizations of chiral symmetry. One possibility is to describe vector- (and axial-vector) mesons as gauge bosons within the *(generalized) hidden-local symmetry models* [19, 20]. Here a particular realization of chiral symmetry, the *vector manifestation*, becomes possible, where the chiral partner of the longitudinal ρ meson is the pion, thus providing a definite chiral model for the "dropping-mass scenario". A detailed renormalization-group analysis shows that such a model together with Wilson-matching of the effective model to QCD (leading to an "intrinsic" temperature/density dependence of the effective-model parameters), inevitably leads to a vanishing ρ mass at the critical point and a violation of VMD [21].

In the hadronic many-body theory (HMBT) approach, starting from a phenomenological Lagrangian to describe the vacuum properties of the vector mesons, the in-medium modifications of their spectral properties are evaluated within finite-temperature/density quantum-field theory, involving non-perturbative techniques such as the dressing of, e.g., the pion propagator to account for the modification of the ρ-meson's pion cloud and implementation of interactions of the ρ-meson with mesons and baryons in the medium (for a review, see [1]). It is characteristic for such models that the various excitations result in a *substantial broadening of the vector mesons and small mass shifts*, i.e., a realization of the "melting-resonance scenario" of CSR. An intriguing property in connection with the model proposed in [11] is that the resulting dilepton-emission rates, cf. Eq. (1), match that of the hard-thermal-loop improved pQCD rate, when both are extrapolated to the expected chiral-phase transition temperature $T_c \simeq$ 160-190 MeV, i.e., a kind of "quark-hadron duality" [11]. This behavior is consistent with the smoothness of quark-number susceptibilities in the corresponding isovector channel across the phase transition in recent lQCD calculations [22].

Another approach to assess in-medium properties of vector mesons is the use of empirical scattering amplitudes and dispersion-integral techniques to assess the in-medium ρ-meson propagator via the $T\varrho$ approximation [23].

3. Dilepton phenomenology in heavy-ion collisions

In this Section we compare theoretical models of the in-medium em. current correlator to experimental results from ultrarelativistic heavy-ion collisions. For such a comparison, not only detailed models for the in-medium behavior of the correlation function itself in both partonic (QGP) and hadronic states of the medium are required, but also a
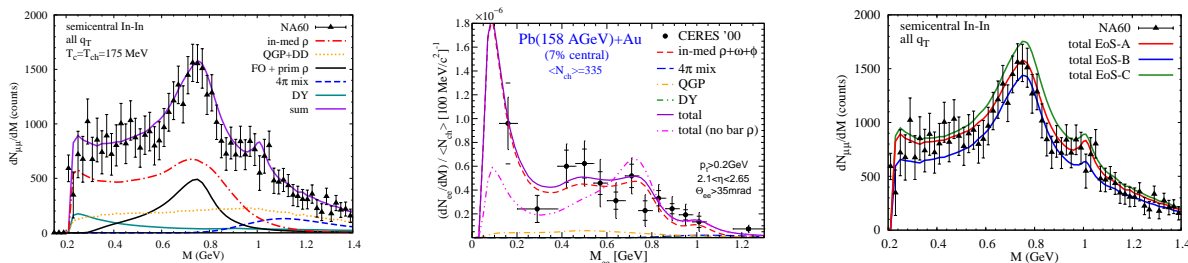
Figure 1. Left panel: dimuon excess spectrum [25] with an equation of state with $T_c = T_{ch} = 175\,\mathrm{MeV}$ in semicentral $158\,A\mathrm{GeV}$ In-In collisions compared to data by the NA60 collaboration [31]; middle panel: dielectron excess spectrum from the same model for central $158\,A\mathrm{GeV}$ Pb-Au collisions compared to data by the CERES/NA45 [32] collaboration. The dash-dotted line shows the result with a ρ-meson spectral function including only medium modifications in a meson gas, underlining the importance of baryon effects; right panel: the dilepton excess spectrum based on the implementation of different equations of state in the fireball evolution (EoS-A: $T_c = T_{ch} = 175\,\mathrm{MeV}$, EoS-B: $T_c = T_{ch} = 160\,\mathrm{MeV}$, EoS-C: $T_c = 160\,\mathrm{MeV}$, $T_{ch} = 160\,\mathrm{MeV}$).

description of its entire "thermal evolution" over which the rate (1) has to be integrated to compare to the experimental observables.

The bulk of hot and dense matter created in ultrarelativistic heavy-ion collisions at the CERN SPS and RHIC can be successfully described by ideal hydrodynamics [24], which implies local thermal equilibrium. Thus the medium is characterized by a temperature- and collective-flow field. In [25, 26] a simple thermal model has been used, which after a "plasma-formation time" describes the medium by an ideal-gas equation of state of quarks and gluons which according to recent lQCD calculations [27, 28] undergoes a phase transition at $T_c \simeq 160\text{-}190\,\mathrm{GeV}$ to a hadron-resonance gas. Thermal models [29, 30] for the yields of various hadron species indicate that at a temperature close to the phase transition of $T_{ch} \simeq 160\text{-}175\,\mathrm{MeV}$, inelastic reactions within the medium cease, and the corresponding particle ratios are fixed (*chemical freeze-out*), before the particles decouple and freely stream to the detector. This *thermal freeze-out* occurs at temperatures around $T_{fo} \simeq 90\text{-}130\,\mathrm{GeV}$ (depending on the system size). This evolution of the medium is implemented through a cylindrical homogeneous fireball model, including radial flow and longitudinal expansion [25]. The temperature is inferred from the equation of state (massless gluons and $N_f = 2.3$ effective quark flavors in the QGP and a hadron-resonance gas model in the hadronic phase) and the assumption of an isentropic expansion in accordance with ideal-fluid dynamics. Between the pure QGP and hadronic phases a standard volume partition for a mixed phase is employed. The hadronic phase is characterized by the build-up of hadron-chemical potentials to keep the particle-number ratios fixed at the observed values. The largest uncertainty is the total fireball lifetime which has been adjusted to the total experimental yield.

Invariant-mass spectra. While earlier dilepton measurements at the SPS have shown an enhancement of the dilepton yield at invariant masses in the low-mass region (LMR), $2m_l \leq M \leq 1\,\mathrm{GeV}$, a definite conclusion concerning the nature of the expected
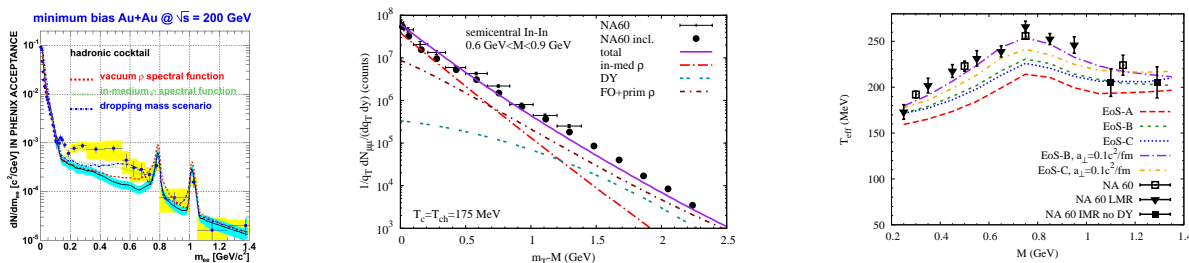
Figure 2. Left panel: Comparison of dielectron-M spectra based on a hadronic-many-body calculation [33] with recent data from 200 AGeV-Au+Au collisions at RHIC from the PHENIX collaboration [34]; middle panel: m_T-dimuon spectrum in the mass range $0.6\,\text{GeV} \leq M \leq 0.9\,\text{GeV}$ compared with the NA60 data in 158AGeV In-In collisions [35, 36]; right panel: effective slopes from q_T spectra compared to NA60 data for different equations of state and transverse acceleration of the fireball.

CSR could not be reached since models for in-medium modifications of the ρ meson based on either the "dropping-mass" or the "melting-resonance" scenario could describe the data within the experimental mass resolution and errors. Only recently with the precision reached in the measurement of dimuon-invariant-mass (M) spectra by the NA60 collaboration [31] in 158 GeV In-In collisions, it could be shown that models predicting a broadening of the vector mesons with small mass shifts (cf. left panel of Fig. 1) seem to be favored compared to those implementing the "dropping-mass scenario". As can be seen in the middle panel of Fig. 1 the same model is also consistent with a recent analysis of 158 AGeV Pb-Au data on the dielectron-M spectrum by the CERES/NA45 [32] collaboration. As shown by the comparison with the model only implementing mesonic medium effects, baryonic processes are the prevalent effect leading to the massive broadening of the ρ meson necessary to explain the observed dilepton enhancement in the LMR (including the related enhancement below the two-pion threshold).

While in the LMR the observed access yield over the standard hadronic cocktail is mostly due to the emission from the medium-modified light vector mesons, in the intermediate-mass region (IMR), $1\,\text{GeV} \leq M \leq 1.5\,\text{GeV}$, it is either dominated by hadronic "multi-pion processes" (estimated using chiral-mixing formulas) or $q\bar{q}$-annihilation in the QGP phase (given by hard-thermal loop resummed $\bar{q}q$ annihilation) [26, 25], depending on the equation of state (T_c) as will be described below. As shown in the right panel of Fig. 1, despite small deviations in the overall yield (which can be adjusted by slight variations of the fireball lifetime), the spectra are robust against details of the equation of state within the boundaries of T_c from lQCD calculations and T_{ch} from thermal-model analyses. The insensitivity of the dilepton spectra with respect to the equation of state reflects the "quark-hadron duality" of the dilepton rates in the relevant temperature range close to T_c (see Sect. 2). Using the spectral functions from the above described chiral-reduction approach [37] within a hydrodynamic description of the fireball evolution [38, 39] leads to similar results for the mass region below and above

the ρ region but less broadening in the resonance region which is to be expected from the low-density (virial) expansion treatment of the medium effects. The spectral-functions, based on empirical ρ-scattering data [23] have been implemented within another fireball-evolution model (using a cross-over QGP-hadron phase transition) [40], showing results for the M spectra comparable to those in [26, 25] but with less enhancement in the mass region below the ρ (particularly below the two-pion threshold), which may be traced back to the use of the $T\varrho$ approximation to the medium modifications. In the IMR the model in [40] shows a large fraction of dilepton emission from the partonic phase. We close our brief review on invariant-mass spectra with the remark, that the enhancement of the dilepton yield in the LMR, observed by the PHENIX collaboration in $200A$ GeV Au-Au collisions at RHIC [34], cannot be described with the present models [33, 41].

Transverse-momentum spectra. The dimuon transverse-momentum (q_T) spectra and pertinent effective-slope fits by the NA60 collaboration [35, 36] provide information which is sensitive to the temperature and collective flow of the medium due to the *blue shift* of the dileptons radiated from a moving thermal source. While the model in [26] describes the q_T spectra for $q_T \lesssim 1$ GeV reasonably well (which is consistent with the agreement in the inclusive M spectra) they were underpredicted at $q_T \gtrsim 1$ GeV although the fireball parameterization of the temperature and flow agrees well with results from a hydrodynamic calculation [39]. Thus sources for dileptons at high q_T have been investigated, including an improved description of dileptons from ρ decays after thermal freeze-out which benefit from the maximal blue shift due to the fully developed transverse flow [42, 25]. In this connection it is important to note that the q_T spectrum for emission from a thermal source cf. (1) is softer by a Lorentz factor $M/E = 1/\gamma$ compared to that from a freely streaming ρ meson due to the dilation of its lifetime. In former calculations the standard description for dileptons from freeze-out ρ decays has been to prolong the fire-ball lifetime for this contribution by $1/\Gamma_\rho \sim 1$ fm/c [11, 26]. In addition decays of hard "primordial" ρ mesons, produced in the initial hard NN collisions which are subject to jet quenching through the medium but leaving the fireball without equilibrating, have been taken into account. Another source of hard dileptons is Drell-Yan annihilation in primordial NN collisions which has been extrapolated to small invariant masses by imposing constraints from the real-photon point. Finally, t-channel-meson (e.g., ω) exchange contributions to the yield of thermal dileptons have been studied. Although the latter show the hardest q_T spectra among all thermal sources, their absolute magnitude is insufficient to resolve the discrepancies in comparison to the data at high q_T, which however has improved through the above described more detailed implementation of the hard (non-thermal) dilepton sources (cf. Fig. 1 middle panel). The model of [40] shows larger slopes (also compared to the hydrodynamic fireball simulation [39]).

Finally a study of different parameters for the equation of state has been conducted. The "standard scenario" in [11, 26] uses $T_c = T_{\rm ch} = 175$ GeV (EoS-A). To investigate the sensitivity of the dilepton spectra with respect to uncertainties in the equation of state, T_c has been varied within the boundaries of 160-190 GeV given by different lQCD

calculations [27, 28] (EoS-B: $T_c = 160\,\text{MeV}$, EoS-C: $T_c = 190\,\text{MeV}$), using a chemical freeze-out temperature of $T_{\text{ch}} = 160\,\text{GeV}$ to cover the range of thermal-model fits to hadron-number ratios in heavy-ion collisions. For EoS-C a chemically equilibrated hadronic phase between $T_c = 190\,\text{MeV}$ and $T_{\text{ch}} = 160\,\text{MeV}$ has been assumed. The agreement of the model with the measured M spectra is robust. Variations in the absolute yield can be adjusted by slight changes in the fireball lifetime. It is important to note that in the IMR the partition of the dilepton yield in hadronic and partonic contributions depends sensitively on the equation of state: A scenario like EoS-B with a low critical temperature results in a long QGP+mixed phase, leading to a parton-dominated regime in the IMR, while EoS-C with a high critical temperature describes a hadron-dominated source since the QGP and mixed phase become shorter. Thus, contrary to suggestions in the literature [36, 43], a definite conclusion whether the dilepton yield in the IMR is originating from partonic or hadronic sources can not be drawn at present. In the right panel of Fig. 2 effective slopes extracted from the q_T spectra by a fit to $\mathrm{d}N_{ll}/(m_T\mathrm{d}m_T) = C\exp(-m_T/T_{\text{eff}})$ are shown. The slopes from the calculations with EoS-B and EoS-C benefit from the larger freeze-out temperature of $T_{\text{fo}} = 136\,\text{MeV}$ compared to $T_{\text{fo}} = 120\,\text{MeV}$ for EoS-A. To reach the measured effective slopes however, an enhancement of the transverse acceleration of the fireball (from $a_\perp = 0.085c^2/\text{fm}$ to $a_\perp = 0.1c^2/\text{fm}$), leading to larger blue shifts in the spectra, is necessary. The slopes in the IMR are not so sensitive to the radial flow since the emission in this region is dominated by radiation from (either partonic or hadronic, depending on T_c) sources at earlier times where the flow is smaller.

4. Conclusions and outlook

In conclusion, the confrontation of phenomenological models for the em. current correlator of strongly interacting matter with precise data on dilepton emission in high-energy heavy-ion collisions provides a unique opportunity for a better understanding of the nature of chiral symmetry restoration. Models based on the application of many-body theory to phenomenological hadronic models to assess the medium modifications of the em. current correlator, predicting a strong broadening of the light-vector-meson spectrum with small mass shifts, are favored by the data compared to models implementing a dropping-mass scenario (as, e.g., implied by the intrinsic temperature dependencies of the model parameters of the generalized hidden-local symmetry model due to "Wilsonian matching" with QCD close to T_c [44] although a final confrontation of this particular realization of chiral symmetry with dilepton data in HICs has to be completed by an implementation of baryonic interactions). However, the origin of the large dilepton enhancement in the LMR observed by the PHENIX collaboration in 200 AGeV Au-Au collisions at RHIC remains unexplained so far.

Future investigations will have to find even closer connections between em. observables in heavy-ion collisions and the chiral phase transition. One possibility is the extension of the hadronic-model calculations with a detailed study of the in-medium

properties of both the vector and the axial-vector correlator within a chiral framework, constrained by lQCD calculations of chiral order parameters via Weinberg-sum rules.

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