Interpretation of Recent SPS Dilepton Data

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Abstract. We summarize our current theoretical understanding of in-medium properties of the electromagnetic current correlator in view of recent dimuon data from the NA60 experiment in In(158 AGeV)-In collisions at the CERN-SPS. We discuss the sensitivity of the results to space-time evolution models for the hot and dense partonic and hadronic medium created in relativistic heavy-ion collisions and the contributions from different sources to the dilepton-excess spectra.

1. Introduction

A main goal of relativistic heavy-ion collisions is to understand the phase structure of strongly interacting matter as inferred from Quantum Chromodynamics (QCD). Lattice-QCD calculations at high temperatures find a transition from hadronic matter to a deconfined and chirally restored quark-gluon plasma (QGP), where strong modifications of the spectral properties of hadrons are expected. In the low-mass region ($M \lesssim 1$ GeV), dileptons are valuable probes for medium modifications of the low-mass vector mesons, ρ, ω and ϕ. In particular the ρ meson, which has a small lifetime (~ 1.3 fm/c) already in the vacuum, mostly decays inside the hot and dense medium. Since dileptons do not suffer strong final-state interactions, they provide direct information about the in-medium spectral properties of the light vector mesons. In Pb(158 AGeV)-Au collisions at the Super-Proton-Synchrotron (SPS), an enhancement of dielectrons at low invariant masses [1] indeed indicates strong medium modifications of the electromagnetic (e.m.) current correlator. Recently, with the better mass resolution and statistics of the NA60 dimuon spectra in In(158 AGeV)-In collisions [2] a discrimination of models assuming different mechanisms underlying the dilepton excess has become possible: Models predicting a large in-medium broadening of the ρ-meson spectrum with little mass shifts are favored by the data over those implementing a dropping ρ mass [3, 4].

In addition to a careful description of the e.m. current correlator in thermal partonic and hadronic matter, a reliable theoretical interpretation of the measured dilepton spectra requires two more ingredients: (i) a model for the evolution of the hot and dense medium, typically including a QGP at the early collision stages, followed by a transition to a hadronic phase and subsequent expansion until thermal freeze-out; (ii) consideration

of non-thermal dilepton sources like primordial quark annihilation (Drell-Yan), decays of ρ mesons which have not thermally equilibrated with the medium ("Corona effect") and ρ decays after thermal freeze-out.

In the following we briefly summarize our model to describe emission of dileptons from a thermalized strongly interacting medium (Sec. 2) and refine our previous description [3] of non-thermal sources (Sec. 3).

2. Dilepton emission from a thermal source

Dilepton emission from a thermal source of strongly interacting particles is given by [5]

$$\frac{\mathrm{d}N}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{\alpha^2}{\pi^3}\frac{L(M^2)}{M^2}\,\mathrm{Im}\,\Pi_{\mathrm{em}}^{(\mathrm{ret})}(M,q)f_B(q_0), \tag{1}$$

where $\alpha \simeq 1/137$, f_B is the Bose distribution function and L a lepton-phase space factor. $\Pi_{\mathrm{em}}^{(\mathrm{ret})}$ denotes the retarded in-medium e.m. current-correlation function, which in the vacuum, and for $M < 1$ GeV, is saturated by the vector-meson spectral functions:

$$\mathrm{Im}\,\Pi_{\mathrm{em}}^{(\mathrm{ret})} = \sum_{V=\rho,\omega,\phi}\frac{m_V^4}{g_V^2}\,\mathrm{Im}\,D_V. \tag{2}$$

In a hot and dense hadronic medium, the current correlator is evaluated using many-body theory based on an effective hadronic Lagrangian. The model parameters (masses, coupling constants and form factors) are adjusted to empirical hadronic decay rates, scattering data like $\pi N \to VN$ and photo absorption on nucleons and nuclei. The vector-meson propagators are evaluated at finite temperature and density,

$$D_V(M,q) = (M^2 - m_V^2 - \Sigma_{VP} - \Sigma_{VM} - \Sigma_{VB})^{-1}, \tag{3}$$

where the three self-energy contributions are due to the interactions of the vector mesons with their pseudoscalar-meson cloud as well as mesons and baryons in the medium [6]. For the ρ meson, hadronic many-body models predict a strong broadening but small mass shifts with increasing temperature and density. For the ω meson, one also finds broadening ($\Gamma_\omega^{\mathrm{med}} \simeq 50$ MeV at nuclear-matter density, $\varrho_0 = 0.16/\mathrm{fm}^3$) [7]. The ϕ meson is expected to broaden in hot and dense matter mostly due to modifications of its kaon cloud. Data on nuclear photoproduction of ϕ mesons give absorption cross sections leading to an in-medium width of about 50 MeV at ϱ_0 [8]. In the intermediate-mass region ($M > 1$ GeV), the e.m. correlator is dominated by four-pion type states. We describe the pertinent dilepton emission in terms of the empirically known vacuum e.m. correlator augmented by model-independent effects of chiral mixing to leading order in T [9, 3]. In the QGP thermal dilepton radiation is due to $q\bar{q}$ annihilation for which we employ the hard-thermal loop improved perturbative QCD result [10].

## 3. Dilepton spectra from the medium created in heavy-ion collisions

We evaluate the dilepton spectrum from Eq. (1) by integration over the space-time history of the collision based on a cylindrical thermal fireball expansion [6, 3] with a
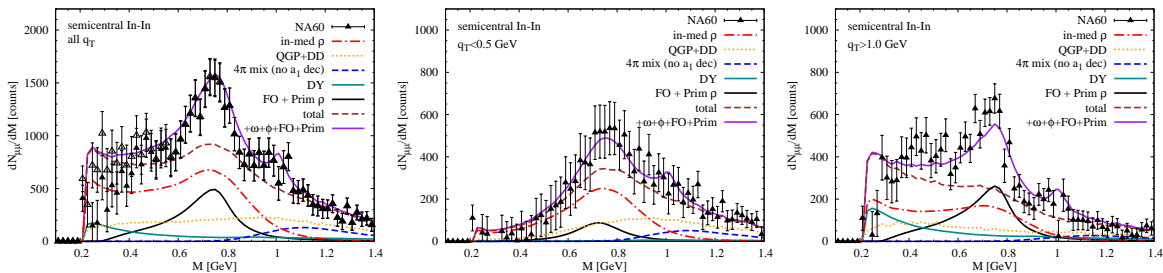
Figure 1. Excess dimuon spectra in semicentral In(158 AGeV)-In collisions in different q_T regions (from left to right: all q_T, $q_T < 0.5$ GeV, $q_T > 1$ GeV) compared to emission from QGP, in-medium ρ, ω and ϕ mesons, four-pion annihilation, correlated $D\bar{D}$ decays, primordial Drell-Yan annihilation and decays of ρ mesons after thermal freeze-out and non-equilibrated primordial ρ's.

linear transverse flow profile, $v_\perp(r,t)=v_s(t)r/R(t)$ where $v_s(t)=a_\perp t$ and $a_\perp=0.085c^2/$fm as an upper estimate of flow properties from hydrodynamic models [11] ($R(t)$: fireball radius). For central In(158 AGeV)-In collisions the isentropic expansion starts in the QGP phase at a temperature of $T_0=197$ MeV with an equation of state of massless gluons and $N_f=2.3$ light quarks. It evolves into a mixed phase coinciding with hadro-chemical freeze-out at $(T_c,\mu_B^c)=(175,232)$ MeV, followed by a hadronic evolution with fixed hadron abundances using meson-chemical potentials. The largest uncertainty in the dilepton yields is due to the fireball lifetime which we fix at ~ 7 fm/c implying thermal freezeout at $T\simeq 120$ MeV. The radial flow leads to moderate blue shifts of the e.m. radiation. For the NA60-detector acceptance we use an empirical acceptance matrix [12].

In addition to thermal emission, non-thermal sources of dileptons have to be considered: Primordial Drell-Yan annihilation is calculated as detailed in [13]. For primordially produced ρ's which leave the hot and dense medium without thermalizing we construct a schematic jet-quenching model. Starting from a power law for the initial q_T spectrum we calculate the escape probability with a "pre-hadron" absorption cross section of $\sigma_{ph}=0.4$ mb, and a hadronic one of $\sigma_{had}=5$ mb after a ρ-formation time of 1 fm/c. At low q_T we assume a scaling of the yield with the number of participants and at high q_T with the number of collisions, with a linear transition in the range 1 GeV$<q_T<3$ GeV. Our earlier treatment of ρ decays at thermal freeze-out in terms of thermal emission [6] has been replaced by a Cooper-Frye prescription assuming a "sudden freeze-out" of the entire fireball (entailing somewhat harder q_T spectra compared to thermal emission due to an extra $\gamma=q_0/M$ factor). In the low-mass region, the NA60 invariant-mass and q_T spectra are well described within this approach, cf. Figs. 1 and 2, respectively. For the ω and ϕ mesons there is at present little sensitivity to their in-medium spectral shapes. Both the q_T-binned mass spectra and the q_T spectra show the importance of contributions from non-equilibrated ρ mesons, i.e., those escaping the medium without (primordial ρ's) and those decaying after thermal freeze-out, which both exhibit harder q_T spectra than thermal radiation. The freeze-out contribution also has been found to be significant in [15]. In the intermediate-mass
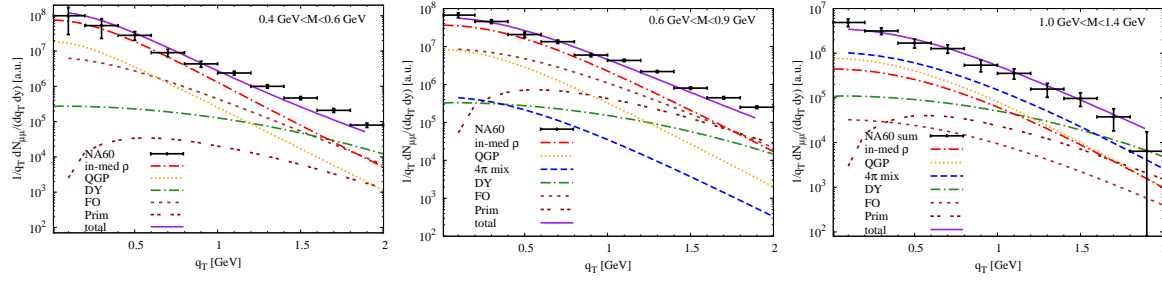
Figure 2. Acceptance corrected dimuon-q_T spectra in different mass regions (from left to right: $M = 0.4$–0.6 GeV, $M = 0.6$–0.9 GeV, $M = 1$–1.4 GeV) in semicentral In(158 AGeV)-In collisions [14] compared to emission from QGP, in-medium ρ, ω and ϕ mesons, four-pion annihilation, primordial Drell-Yan annihilation and decays of ρ mesons after thermal freeze-out and non-equilibrated primordial ρ's.

region the major sources of dileptons are four-pion annihilation as well as correlated $D\bar{D}$ decays and radiation from the QGP.

4. Conclusions and Outlook

Hadronic many-body models for in-medium vector mesons provide a fair description of dilepton emission at the SPS. High-q_T sources and centrality dependencies remain to be scrutinized. Comparisons to upcoming RHIC data are much looked forward to.

The next goal for theory must be to implement the description of the e.m. current correlator within chiral models in order to establish a direct connection to the QCD phase structure, i.e., to chiral-symmetry restoration. Here, a promising ansatz is to constrain chiral hadronic models by Weinberg sum rules [16, 17] which relate chiral order parameters of QCD to vector- and axial-vector current correlation functions.

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