Low mass dimuons within a hybrid approach

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Abstract. We analyse dilepton emission from hot and dense hadronic matter using a hybrid approach based on the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) transport model with an intermediate hydrodynamic stage for the description of heavy-ion collisions at relativistic energies. Focusing on the enhancement with respect to the contribution from long-lived hadron decays after freeze-out observed at the SPS in the low mass region of the dilepton spectra (often referred to as "the excess"), the relative importance of the emission from the equilibrium and the non-equilibrium stages is discussed.

1. Introduction

Electromagnetic probes, such as photons and lepton pairs, are penetrating probes of the hot and dense matter. Once created these particles pass the collision zone essentially without further interaction and can therefore mediate valuable information on the electromagnetic response of the strongly interacting medium. The analysis of such response is tightly connected to the investigation of the in-medium modification of the vector meson properties. Vector mesons can directly decay into a lepton-antilepton pair. One therefore aims to infer information on the modifications induced by the medium on specific properties of the vector meson, such as its mass and/or its width, from the invariant mass dilepton spectra.

Measurements of dileptons in heavy ion collisions have indeed revealed many exciting phenomena, triggering a copious theoretical activity. A first generation of ultra-relativistic heavy ion collision experiments performed in the nineties observed an enhancement of dilepton production in heavy systems at low invariant mass as compared to conventional hadronic cocktails and models [1, 2]. The enhancement could be later explained by the inclusion of a substantial medium modification of the ρ meson properties, see e.g. Refs. [3, 4, 5] for reviews or the review on photons and dileptons by S. Bathe in this volume. However, no discrimination between a "melting" of the ρ meson spectral function as expected within many-body hadronic models [6, 7, 8, 9, 10] and a dropping of the ρ meson mass according to the Brown-Rho scaling hypothesis [11] and the Hatsuda and Lee sum rule prediction [12] could be achieved. Recently, a substantial improvement in statistics and mass resolution in low-mass dilepton spectra has been achieved by the NA60 collaboration [13], who measured dimuon production in In-In collisions at 158 A GeV. The improved experimental accuracy enabled a subtraction of final-state hadron decay contributions (the so-called cocktail), except for ρ and charm decays. The dimuon spectra of the remaining "excess" over the cocktail strongly favour the broadening over the dropping

mass scenario. Typically, model calculations aimed at the interpretation of the data require a convolution of the dilepton emission rates over a realistic space-time model of the heavy-ion collision. Assuming local equilibrium, thermal fireball/hydrodynamics calculations have been performed over the last years and quite successfully applied to the interpretation of the NA60 data (see e.g. Fig.4 in Ref. [14]). Here, we present recent results on dimuon emission obtained using a hybrid approach for the description of the evolution dynamics. In such an approach, both thermal and non-thermal sources play a noticeable role and can be separately investigated. We will focus on the low invariant mass region of the dilepton spectra ($M < 1$ GeV), where the $\rho^* \to \mu\mu$ emission plays the dominant role. Extension of the model to the intermediate mass region ($1.0 < M < 1.5$ GeV) requires addition of further contributions and is currently under development.

2. Dilepton phenomenology within a hybrid model

The dynamics of the In+In collisions is simulated employing a hybrid approach based on the integration of an ideal hydrodynamic evolution into the UrQMD transport model [15]. This approach has been successfully applied to many bulk observables at SPS energies [15, 16, 17, 18, 19] and first applications to electromagnetic probes have been performed recently [20, 21]. Here, we describe it only briefly and refer the reader to the indicated references for details.

During the first stage of the evolution the particles are described as a purely hadronic cascade within UrQMD. The coupling to the hydrodynamical evolution proceeds when the two Lorentz-contracted nuclei have passed through each other. At this time, the spectators continue to propagate in the cascade and all other hadrons are mapped to the hydrodynamic grid. Subsequently, a $(3 + 1)$ ideal hydrodynamic evolution is performed using the SHASTA algorithm [22, 23]. The hydrodynamic evolution is gradually merged into the hadronic cascade. Transverse slices, of thickness 0.2 fm, are transformed to particles whenever in all cells of each individual slice the energy density drops below five times the ground state energy density. The employment of such a gradual transition allows us to obtain a rapidity independent transition temperature without artificial time dilatation effects. When merging, the hydrodynamic fields are transformed to particle degrees of freedom via the Cooper-Frye equation. The created particles proceed in their evolution in the hadronic cascade where final state interactions and decays of the particles occur within the UrQMD framework.

Concerning dilepton emission, during the locally equilibrated hydrodynamic stage the production of lepton pairs is described by radiation rates for a strongly interacting medium in thermal equilibrium. Invoking vector meson dominance the latter can be related, at low invariant masses, to the spectral properties of the vector mesons, with the ρ meson giving the dominant contribution. The thermal dilepton rate reads then [3]:

$$\frac{d^8 N_{ll}}{d^4 x d^4 q} = -\frac{\alpha^2 m_\rho^4}{\pi^3 g_\rho^2} \frac{L(M^2)}{M^2} f_B(q_0; T) \operatorname{Im} D_\rho(M, q; T, \mu_B),$$ (1)

where α denotes the fine structure constant, $M^2 = q_0^2 - q^2$ the dilepton invariant mass squared, f_B the Bose distribution function (for a moving fluid this must be substituted with the Jüttner function), and $L(M)$ a lepton phase space factor that quickly approaches one above the lepton pair threshold. The electromagnetic response of the strongly interacting medium is then contained in $\operatorname{Im} D_\rho(M, q; T, \mu_B)$, the imaginary part of the in-medium ρ meson propagator,

$$D_\rho(M, q; T, \mu_B) = \frac{1}{M^2 - m_\rho^2 - \Sigma_\rho(M, q; T, \mu_B)}.$$ (2)

In this application, the self-energy contributions taken into account are $\Sigma_\rho = \Sigma^0 + \Sigma^{\rho\pi} + \Sigma^{\rho N}$, where Σ^0 is the vacuum self-energy and $\Sigma^{\rho\pi}$ and $\Sigma^{\rho N}$ denote the contribution to the self-energy

due to the direct interactions of the ρ with, respectively, pions and nucleons of the surrounding heat bath. The self-energies have been calculated according to Ref. [24], where they were evaluated in terms of empirical scattering amplitudes from resonance dominance at low energies and Regge-type behaviour at high energy. Finally, in the evolution stage that precedes or follows the hydrodynamical phase dimuon emission from the ρ-meson is calculated employing the time integration method that has long been applied in the transport description of dilepton emission (see e.g. [25]).

In Fig. 1 hybrid model calculations are compared to recent acceptance-corrected NA60 data [14]. The calculations have been exemplary performed using a hadron gas equation of state (HG-EoS) for the hydrodynamical evolution. Since in such a scenario all the energy density is stored in hadronic degrees of freedom, for the sake of consistency dimuon emission according to Eq. (1) has been evaluated during the whole hydrodynamical phase, hottest cells included (in the central region some cells have initial temperatures up to $T \sim 240$ MeV). In general, however, if a phase transition from quark-gluon to hadronic matter occurs, the hadronic thermal rate would be only a fraction of the total thermal rate. Keeping in mind that the total life-time of the fireball affects the total dilepton yield too, we can quite generally say that the inclusion of a phase in which quarks and gluons are the relevant degrees of freedom would result in a reduction of the hadronic emission with respect to the calculation presented here, provided that the life-time of the fireball is comparable for the two equations of state. Calculations with such an EoS are on-going and suggest this reduction to amount to about 30%-40% across the entire dimuon invariant mass region considered here. Anyway, this baseline calculation performed with the HG-EoS still allows to point out qualitatively the main features of the present approach. More systematic studies and discussions will be presented elsewhere [26] in the next future.

We observe that the cascade emission dominates the invariant mass region around the vector meson peak for both low and intermediate transverse pair momenta p_T. At low p_T (left panel of Fig. 1), the very low invariant masses, $M < 0.5$ GeV, are filled by the thermal radiation with in-medium spectral function. The sum of both contributions, however, leads to an overestimation of the vector meson peak region at low transverse momenta of the dilepton pair. The reason for the discrepancy might partially lie in the specific spectral function used here and/or, presumably more severely, on the eventual presence of not yet negligible residual in-medium modification of the ρ meson spectral function during the cascade stage, that are here neglected. An additional source of uncertainty is the dependence of the total thermal yield on the specific criterium adopted to perform the switch from the hydrodynamic to the transport description. Further investigations are required to clarify these model dependences and quantify their effect on the total dilepton emission. With increasing p_T (right panel of Fig. 1), dilepton emission at very low invariant masses is reduced and the total spectra are almost completely determined by the cascade emission. This is not trivial. Indeed, thermal emission had already shown discrepancies for $p_T > 1$ GeV [27], pointing to the necessity to account for non-thermal contributions. In the present approach, the latters appear quite naturally.

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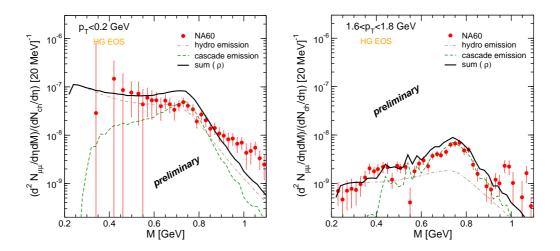
Figure 1. Left panel: Acceptance-corrected invariant mass spectra of the excess dimuons in In-In collisions at 158A GeV for transverse pair momenta $p_T < 0.2$ GeV, compared to hybrid model calculations based on thermal radiation from in-medium modified ρ meson spectral function and non-thermal cascade emission. Experimental data from Ref. [14]. Right panel: Same as in the left panel, but for the transverse momenta window $1.6 < p_T < 1.8$ GeV.

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