Dileptons in a coarse-grained transport approach

Hendrik van Hees[1,2], Stephan Endres[1,2], Janus Weil[2] and Marcus Bleicher[1,2]

[1]Institut für Theoretische Physik, Universität Frankfurt, Max-von-Laue-Straße 1, 60438 Frankfurt, Germany

[2]Frankfurt Institute for Advanced Studies, Ruth-Moufang-Straße 1, 60438 Frankfurt, Germany

E-mail: `endres@th.physik.uni-frankfurt.de`

Abstract. We calculate dilepton spectra in heavy-ion collisions using a coarse-graining approach to the simulation of the created medium with the UrQMD transport model. This enables the use of dilepton-production rates evaluated in equilibrium quantum-field theory at finite temperatures and chemical potentials.

Due to their penetrating nature, the invariant-mass and transverse-momentum spectra of dileptons are considered unique probes for the in-medium properties of hadrons in strongly interacting hot and dense matter, created in heavy-ion collisions [1, 2]. The dilepton-production rates are proportional to the electromagnetic current-correlation function of the source [3] and thus provide insight into the corresponding excitations carrying the quantum numbers of the electromagnetic current. Particularly from the restoration of chiral symmetry one expects substantial modifications of the spectral shape of this current-correlation function. Particularly one hopes to gain insight into the microscopic realization of the chiral-symmetry restoration, e.g., whether it is due to dropping in-medium hadron masses as predicted by the Brown-Rho-scaling conjecture or models implementing the vector manifestation of chiral symmetry or substantial broadening of the pertinent light-vector-meson spectral shapes due to hadronic interactions within the medium ("melting-resonance scenario") as predicted by quantum-field-theoretical effective hadronic many-body theory (for a review see [1]).

Since the dileptons are produced and emitted undisturbed by final-state interactions during the entire evolution of the hot and dense medium, first a good understanding of all relevant microscopic sources of electromagnetic radiation in this medium is important.

For heavy-ion collisions at ultrarelativistic energies, in the early hot stage the relevant degrees of the medium are quarks and gluons forming a quark-gluon plasma (QGP) close to local thermal equilibrium, as is inferred from the successful description of the hadronic bulk observables like p_T spectra and angular anisotropies v_n by hydrodynamical models for the evolving medium. Here the main source of dileptons is the quark-antiquark annihilation $q+\overline{q} \rightarrow \ell^+ + \ell^-$ (with $\ell = \mathrm{e}, \mu$). In the later stages of the fireball evolution (or, in the case of heavy-ion collisions at lower energies, the entire evolution) the medium is described as a hot hadronic gas. In the low invariant-mass range, $2m_\ell \leq M \lesssim 1\mathrm{GeV}$ the dilepton sources are thus hadronic and phenomenologically well described within a vector-meson dominance (VMD) model [4], i.e., the assumption that the electromagnetic current of the hadrons is proportional to the light-vector meson field. This also implies that the electromagnetic transition form factors for the various Dalitz decays of hadron resonances contributing substantially to the dilepton yield in the low-mass tail are describable

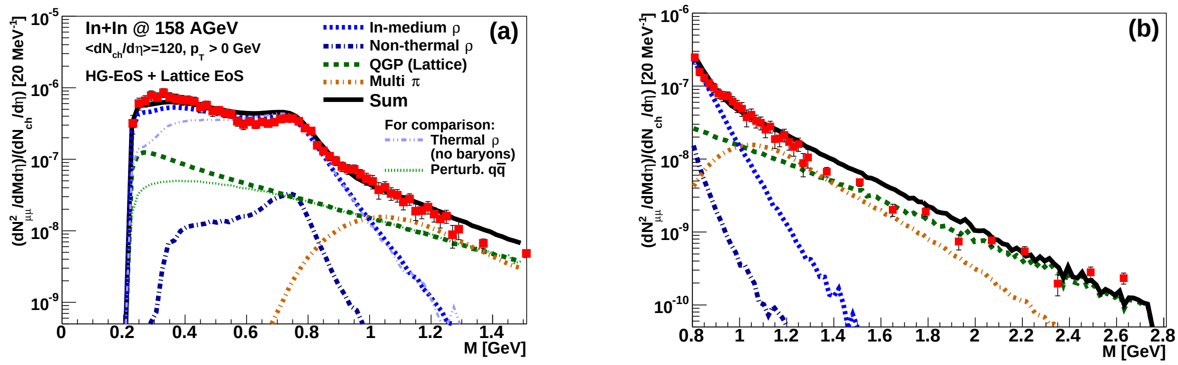

Figure 1. The dimuon spectra in $158A$ GeV In+In collisions at the CERN SPS in (a) the low-mass (LMR) and (b) the intermediate-mass region (IMR) in comparison to the data from the NA60 Collaboration [5, 6, 7]. In the LMR the dilepton yield is dominated by the decays of the in-medium ρ mesons (dotted blue line) and in the IMR by QGP and multi-pion hadronic processes. The comparison with a dilepton rate based on a thermal-ρ contribution, neglecting the effect of baryon couplings, shows the importance of the these contributions for the tremendous broadening of the ρ-spectral function as well as the yield in the very-low-mass range close to the two-muon threshold. Microscopically these contributions originate from Dalitz decays of various baryon resonances.

within the VMD model. In the intermediate-mass range also "multi-pion processes" become relevant.

All these microscopic processes have to be evaluated in a hot and dense medium, which is at present available in detailed many-body quantum-field theoretical calculations only for a medium in thermal equilibrium, with some chemical off-equilibrium taken into account in terms of effective baryon densities and pion- as well as kaon-chemical potentials [8, 9]. It has been quite well established that the observed excess of low-mass dilepton production in heavy-ion collisions as compared to the expectations from the "hadronic cocktail" (i.e., from a simple scaling of the findings in pp collisions by the number of nucleon collisions in the nuclear reaction) can be understood by effective hadronic models that predict a tremendous broadening of the light-vector mesons' spectral shape with small mass shifts [10, 11, 12, 13].

On the other hand, one also has to describe the evolution of the hot and dense medium in a reliable way. This is usually done either by employing macroscopic descriptions, reaching from quite simple thermal-fireball parametrizations ("blast-wave fits") [14] to detailed ideal or viscous hydrodynamics simulations [15, 16, 17, 18, 12, 19], or microscopic transport simulations [20, 21, 22, 23, 24, 25, 26, 27, 28, 29].

In the latter approach it is challenging to fully implement the medium modifications of the partonic and hadronic dilepton sources. In our approach this problem is solved by mapping the kinetic description of the fireball evolution via Monte-Carlo transport simulations to a state close to local thermal equilibrium. In this work, an ensemble of collision events simulated by the UrQMD model is used to calculate a coarse-grained energy-momentum tensor and net-baryon-number current on a space-time grid. Then, using the Eckart definition of the local rest frame, a temperature and baryo-chemical potential can be extracted via an equation of state (EoS), making use of a description of the energy-momentum tensor in terms of an anisotropic-fluid ansatz [30], where the pressure anisotropy, particularly relevant in the early stages of the fireball evolution, is taken into account. For the EoS we match a parametrization of lattice-QCD results [31] with a hadron-resonance gas EoS [32], which match very well in the region of the

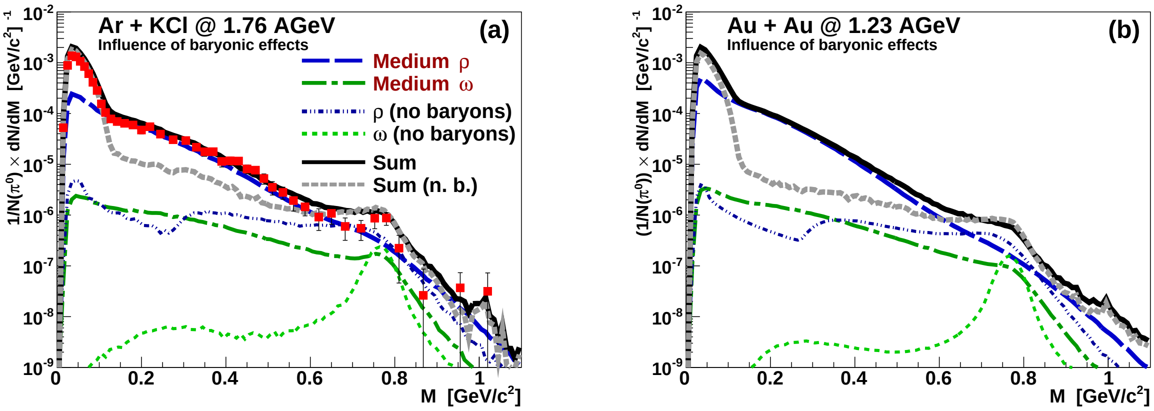

Figure 2. (Color online) (a) Dielectron invariant-mass spectrum for Ar+KCl collisions at $E_{\text{lab}} = 1.76A\,\text{GeV}$ and (b) for Au+Au at $E_{\text{lab}} = 1.23A\,\text{GeV}$. The results are normalized to the average total number of π^0 per event and shown within the HADES acceptance. The results for Ar+KCl are compared to the data from the HADES Collaboration [35]. The comparison of the dilepton spectra between using the full model and omitting the contributions of direct baryon couplings to the ρ and ω self-energies underlines the prevalence of the corresponding baryon-resonance Dalitz-decay processes processes for the in-medium modifications of these vector mesons, shifting substantial spectral strength to the low-invariant-mass region.

parton-hadron transition around the critical temperature of $T_c \simeq 170$ MeV.

In recent work [33, 34], we have combined this coarse-graining method for the bulk-medium evolution of the strongly interacting fluid via the UrQMD transport model with state-of-the art in-medium dilepton-production rates [8, 9] in order to evaluate the dilepton invariant-mass and p_T spectra in $158A$ GeV In+In collisions as measured by the NA60 Collaboration at the CERN SPS and in $1.76A$ GeV Ar+KCl and $1.23A$ GeV Au+Au collisions as measured by the HADES collaboration at the GSI SIS.

As exemplified by the comparison of the so calculated dimuon invariant-mass spectra in $158A$ GeV In+In Collisions with the NA60 data (Fig. 1) and corresponding dielectron invariant-mass spectra for $1.76A$ GeV Ar+KCl collisions with data from the HADES collaboration (Fig. 2, left panel), the model successfully describes the data. In the right panel of Fig. 2 we additionally provide our prediction for the $1.23A$ GeV Au+Au collisions as also measured by the HADES collaboration.

Both figures underline the importance of the interaction of the light vector mesons with baryons in the medium [in the present model [1] N(938), Δ(1232), N(1440), N(1520), Δ(1620), Δ(1700), N(1720), Δ(1900), N(2000)]. As expected, these processes are prevalent at the low GSI-SIS energy with high net-baryon densities but also relevant at CERN-SPS energies and even at higher RHIC energies. This is due to the fact that the strong interaction is CP invariant and thus not the net-baryon density, $N_B - N_{\overline{B}}$, but the total baryon-antibaryon density, $N_B + N_{\overline{B}}$, is relevant for the in-medium modifications of the light-vector mesons' spectral distributions.

In the near future we also plan to apply the model to dilepton production at RHIC energies as well as photon production in heavy-ion collisions.

Acknowledgments

We thank Ralf Rapp for providing the parameterization of the spectral function and many fruitful discussions. This work was supported by BMBF, HIC for FAIR and H-QM.

References

[1] Rapp R and Wambach J 2000 *Adv. Nucl. Phys.* **25** 1

[2] Rapp R, Wambach J and van Hees H 2009 *Landolt-Börnstein* **I/23** 4–1

[3] McLerran L D and Toimela T 1985 *Phys. Rev. D* **31** 545

[4] Sakurai J J 1960 *Ann. Phys. (NY)* **11** 1–48

[5] Arnaldi R *et al.* (NA60 Collaboration) 2009 *Eur. Phys. J. C* **59** 607–623

[6] Specht H J (NA60 Collaboration) 2010 *AIP Conf.Proc.* **1322** 1–10 URL `http://dx.doi.org/10.1063/1.3541982`

[7] Arnaldi R *et al.* (NA60 Collaboration) 2009 *Eur. Phys. J. C* **61** 711–720

[8] Rapp R and Wambach J 1999 *Eur. Phys. J. A* **6** 415–420

[9] Gale C and Rapp R 1999 *Phys. Rev. C* **60** 024903

[10] van Hees H and Rapp R 2006 *Phys. Rev. Lett.* **97** 102301

[11] van Hees H and Rapp R 2008 *Nucl. Phys. A* **806** 339

[12] Dusling K, Teaney D and Zahed I 2007 *Phys. Rev. C* **75** 024908

[13] Ruppert J, Gale C, Renk T, Lichard P and Kapusta J I 2008 *Phys. Rev. Lett.* **100** 162301

[14] Rapp R 2013 *Adv. High Energy Phys.* **2013** 148253

[15] Teaney D, Lauret J and Shuryak E 2001 (*Preprint* `arXiv: nucl-th/0110037`)

[16] Hirano T and Tsuda K 2002 *Phys. Rev. C* **66** 054905

[17] Kolb P F and Heinz U 2003 Published in R. C. Hwa, X.-N. Wang (Ed.), Quark Gluon Plasma 3, World Scientific

[18] Nonaka C and Bass S A 2007 *Phys. Rev. C* **75** 014902

[19] Vujanovic G, Young C, Schenke B, Rapp R, Jeon S *et al.* 2014 *Phys. Rev. C* **89** 034904

[20] Cassing W, Bratkovskaya E, Rapp R and Wambach J 1998 *Phys. Rev. C* **57** 916–921

[21] Schenke B and Greiner C 2006 *Phys. Rev. C* **73** 034909

[22] Schenke B and Greiner C 2007 *Phys. Rev. Lett.* **98** 022301

[23] Schenke B and Greiner C 2007 *Nucl. Phys. A* **785** 170–173

[24] Bratkovskaya E, Cassing W and Linnyk O 2009 *Phys. Lett. B* **670** 428–433

[25] Cassing W and Bratkovskaya E 2009 *Nucl. Phys. A* **831** 215–242

[26] Barz H, Kampfer B, Wolf G and Zetenyi M 2010 *Open Nucl. Part. Phys. J.* **3** 1–15

[27] Linnyk O, Bratkovskaya E, Ozvenchuk V, Cassing W and Ko C 2011 *Phys. Rev. C* **84** 054917

[28] Weil J, van Hees H and Mosel U 2012 *Eur. Phys. J. A* **48** 111

[29] Weil J, Mosel U and Metag V 2013 *Phys. Lett. B* **723** 120–125

[30] Florkowski W and Ryblewski R 2011 *Phys. Rev. C* **83** 034907

[31] He M, Fries R J and Rapp R 2012 *Phys. Rev. C* **85** 044911

[32] Zschiesche D, Schramm S, Schaffner-Bielich J, Stoecker H and Greiner W 2002 *Phys. Lett. B* **547** 7–14

[33] Endres S, van Hees H, Weil J and Bleicher M 2015 *Phys. Rev. C* **91** 054911

[34] Endres S, van Hees H, Weil J and Bleicher M 2015 *Phys. Rev. C* **92** 014911

[35] Agakishiev G *et al.* (HADES Collaboration) 2011 *Phys. Rev. C* **84** 014902