

Dileptons in Heavy-Ion Collisions

Hendrik van Hees^a and Ralf Rapp^b

^a*Institut für Theoretische Physik, Justus-Liebig-Universität Giessen, D-35392 Giessen, Germany*

^b*Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas
77843-3366, U.S.A.*

Abstract

Due to their penetrating nature, dileptons are a valuable probe for the properties of the hot and/or dense medium created in relativistic heavy-ion collisions. Dilepton invariant-mass spectra provide direct access to the properties of the electromagnetic current-correlation function in strongly interacting matter. In this paper an overview is given of our current theoretical understanding of the dilepton phenomenology in comparison to recent data in heavy-ion collisions at the CERN SPS.

Key words: Relativistic Heavy-Ion Collisions; electromagnetic probes; chiral-symmetry restoration

PACS: 25.75.-q; 11.40.-q; 12.40.Vv

1. Introduction

Electromagnetic (EM) probes, i.e., photons and lepton pairs (dileptons), do not participate in the strong interaction and can therefore mediate valuable information on the EM current correlator in the interior of the hot and dense fireball created in ultrarelativistic heavy-ion collisions (URHICs) [1]; their spectra are nearly unaffected by final-state interactions.

In this paper our present theoretical understanding of recent data on invariant-mass (M) and transverse-momentum (q_t) spectra of dileptons in URHICs at the CERN SPS and BNL RHIC will be reviewed. The emission rate of dileptons with an invariant mass $M = (q_0^2 - q^2)^{1/2}$ and three-momentum, q , from a medium at temperature T is given by [2–4]

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha^2}{3\pi^3} \frac{L(M)}{M^2} \text{Im} \Pi_{\text{em}\mu}^\mu(M, q; T, \mu_B) f_B(q_0, T), \quad (1)$$

where $\alpha \simeq 1/137$ denotes the fine-structure constant, L the lepton-phase space factor, $\Pi_{\text{em}}^{\mu\nu}$ the retarded in-medium EM current correlator, and f_B the Bose-Einstein distribution. In the vacuum the hadronic EM correlator can be inferred from $e^+e^- \rightarrow \text{hadrons}$.

At low M it is well-described by the vector dominance model (VDM), including the light vector mesons, ρ , ω , and ϕ and at higher $M \gtrsim 1.5$ GeV by the perturbative QCD (pQCD) continuum.

The theoretical investigation of the dilepton signal in URHICs thus must aim at a concise model for the spectral properties of the light vector mesons, most importantly the ρ meson in the iso-vector-vector channel, which give the most important contribution to the EM current correlator, and of the Quark-Gluon Plasma (QGP). The remainder of this paper is organized as follows: In Sec. 2 theoretical models for the EM current correlator in partonic as well as hot and/or dense hadronic matter are summarized, followed by a comparison to recent dilepton data from the SPS in Sec. 3 and conclusions and outlook in Sec. 4.

2. In-medium properties of the EM current correlator

Approximate chiral symmetry (CS) in the light-quark sector of QCD is one of the most important ingredients for the building of effective hadronic models. In the vacuum and at low temperatures and/or densities CS is broken dynamically through the formation of a quark condensate, $\langle \bar{\psi}\psi \rangle \neq 0$, leading to the mass splitting of the mass spectra of chiral hadron multiplets. One of the most evident manifestations of CS breaking is seen in the measurement of the isovector-vector and -axialvector current correlators through $\tau \rightarrow \nu + n\pi$ -decay data (n : number of pions) [5,6]. Finite-temperature lattice-QCD (lQCD) calculations [7,8] find a melting of the quark condensate with increasing temperature and the restoration of CS above a critical temperature, $T_c \simeq 160$ -190 MeV. Another finding is that the CS restoration (CSR) and deconfinement transition temperatures, coincide [9]. From these findings one expects significant changes of the hadron spectra in a hot and dense medium close to CSR.

In the literature, two scenarios concerning the manifestation of CSR in the hadron spectrum have emerged: In one scenario it has been suggested that due to the melting of the quark condensate hadron masses should drop to 0 at the critical point [10]. The other mechanism is found in phenomenological hadronic many-body models, where hadron spectral functions show a significant broadening with small mass shifts [4,11–13]. It turns out, however, that both scenarios, i.e., either dropping masses or the broadening of in-medium hadron widths (“melting resonances”) are compatible with QCD-sum rule calculations [14–17]. Thus the dilepton signal in URHICs gives an important experimental insight into the nature of the CSR through the vector part of the EM current correlator. Since on the other hand a direct measurement of the axialvector correlation function in heavy-ion collisions is difficult, a direct assessment of CSR in HIC’s seems not to be possible. Thus, a promising theoretical evidence for CSR may be achievable by the application of finite-temperature Weinberg-sum rules [18,19] which relate moments of the difference of vector and axial-vector spectral functions to order parameters of CS like quark and four-quark condensates, which are in principle accessible in lQCD simulations.

A model-independent approach to the EM current correlator is the use of the chiral-reduction formalism based on a low-density (virial) expansion [20] to evaluate medium modifications with empirical vacuum-vector and axialvector-correlation functions as input. In this approach a mechanism for CSR is the mixing of the vector and axialvector correlators through pions in the medium, similar to the “chiral mixing” found on the basis

of current algebra and PCAC [21]. However, the applicability of such methods is limited to the low-density/temperature region of the medium. Thus the building of effective hadronic models and the application of quantum-field theory methods becomes necessary to assess the dilepton signal in URHICs realistically. The most important guideline for building effective hadronic models is CS, e.g., using (generalized) hidden local symmetry [22,23] to describe vector (and axial-vector) mesons as gauge bosons. Recently, it has been shown that within these models CS can be realized in the vector manifestation (VM), leading to a field-theoretical model for the dropping-mass scenario of CSR [24]. However, the same model also admits the usual Wigner-Weyl realization, where one finds degeneracy of the ρ and a_1 spectral functions with little mass shifts [25]. In general, this finding suggests that a decision in which way CS is realized in nature and how it is restored cannot be achieved from the fundamental principle of CS alone.

Another approach is the use of phenomenological Lagrangians which describe the vacuum properties of the vector mesons and evaluate medium modifications of their spectral functions within finite-temperature/density quantum field theory. To account for the strong couplings, hadronic many-body theory (HMBT) implements non-perturbative techniques like the dressing of, e.g., the pion propagator in the ρ -meson's pion cloud, as well as a resummation of direct interactions of the ρ with mesons and baryons of the medium (for a review see [1]). One finds small mass shifts of the vector mesons due to many repulsive and attractive interactions with cancellations in the real part of the vector-meson self-energy, but a substantial broadening of their spectral functions. An interesting result of the model in Ref. [13] is the apparent degeneracy of the pertinent hadronic dilepton-emission rates and that of hard-thermal-loop improved pQCD rates [26] at temperatures close to the critical region, $T_c \simeq 160$ -190 MeV, in a kind of “quark-hadron duality”, implying CSR through “resonance melting”. This finding is consistent with the smoothness of the isovector quark-number susceptibility in IQCD simulations [27].

Another possibility to assess in-medium properties of vector mesons is to employ empirical scattering amplitudes and dispersion-integral techniques within the $T\rho$ approximation for the in-medium selfenergies [28].

3. The dilepton signal in heavy-ion collisions

To confront the in-medium EM spectral functions from the above models to dilepton M and q_t spectra in URHICs a description of the entire evolution of the produced medium in its hadronic and partonic stages is necessary. The success of (ideal) hydrodynamics in the evaluation of the bulk of this matter implies local thermal equilibrium, i.e., the medium can be modeled by an energy-density and collective-flow field. In [29,30] a thermal fireball parameterization has been used. After a formation time the hot and dense matter is described as an ideal gas of quarks and gluons, evolving through a mixed phase to a hadron-resonance gas at a transition temperature of $T_c \simeq 160$ -190 MeV. As thermal-model evaluations of particle abundances in URHICs indicate, the chemical freeze-out temperature is about $T_{\text{ch}} \simeq 160$ -175 MeV [31,32], below which the particle ratios are fixed through the introduction of chemical potentials. The thermal freeze-out temperature, around which also elastic rescatterings cease, occurs at temperatures of $T_{\text{fo}} \simeq 90$ -130 MeV. The evolution of the medium is parameterized as a cylindrical ho-

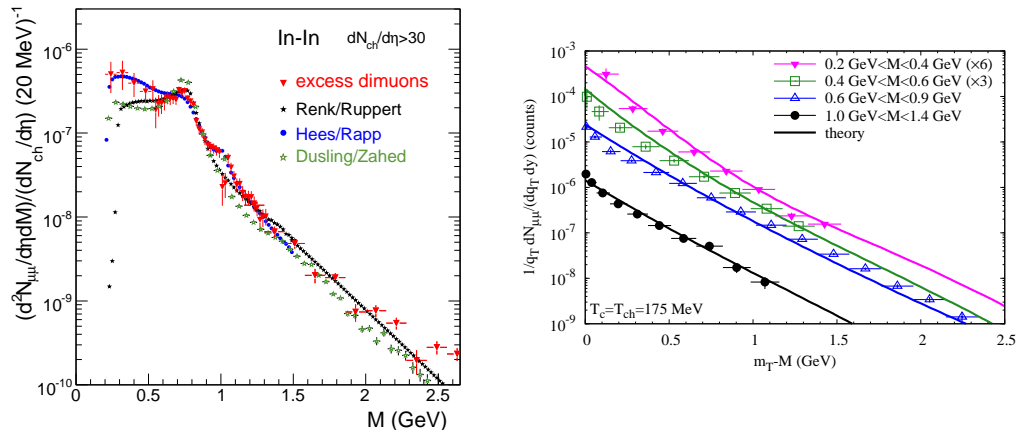


Fig. 1. (Color online) Left panel: Dimuon excess M spectrum in 158 AGeV In-In collisions [36] compared to model calculations in [30,37,38]. Right panel: q_t spectra [39] in various M bins compared to the model in [30] (using EoS-A and a radial acceleration $a_{\perp} = 0.085 c^2/\text{fm}$ in the fireball). Note that the measurements refer to centrality-inclusive data, while the calculation assumes semi-central collisions defined by $dN_{\text{ch}}/dy = 140$.

homogeneous fireball which is longitudinally and radially expanding. The temperature is given via the assumption of isentropic expansion and the equation of state of an ideal gas of massless gluons and $N_f = 2.3$ effective quark flavors with the total entropy fixed by the number of charged particles. After a mixed phase, which is described by a standard volume partition, the hadronic phase is modeled as a hadron-resonance gas.

Early on, measurements of dilepton M spectra in URHICs at the SPS have shown an indication of medium modifications via an increased yield in the low-mass region (LMR), $M < 1$ GeV, compared to expectations from pp collisions [33]. However, only the recent precision achieved in the dimuon measurement of the NA60 collaboration in 158 AGeV In-In collisions [34,35] has made it possible to subtract the “hadron-decay cocktail” contribution to obtain the excess spectrum and thus to significantly discriminate between models of the dropping-mass or the resonance-melting scenarios for CSR. The data clearly favor small mass shifts and a substantial broadening of the vector-meson spectral functions. In Fig. 1 we compare the absolutely normalized mass spectrum [36] to the following models (i) Ref. [30], using spectral functions from HMBT [13] supplemented with thermal radiation from multi-pion induced processes and non-thermal sources (Drell-Yan annihilation, decays of primordial ρ mesons not equilibrated with the medium and ρ decays after thermal freeze-out), (ii) Ref. [37], implementing spectral functions from the T_Q approach in [28], and (iii) Ref. [38], where the chiral-reduction formalism has been applied. For the medium evolution in (i) and (ii) fireball models are used, while in (iii) a hydrodynamical calculation is employed. The predicted broadening of the EM correlator, particularly in model (i) at low masses, is dominated by baryonic excitations of the vector mesons in the medium.

In the same figure, m_t spectra ($m_t^2 = M^2 + p_t^2$) in different mass bins have been compared to the model in [30]. The latter also contains studies of the sensitivity to uncertainties in (a) T_c as determined in present IQCD simulations, and (b) T_{ch} as extracted from thermal models for hadron production. Three equations of state with $T_c = T_{\text{ch}} =$

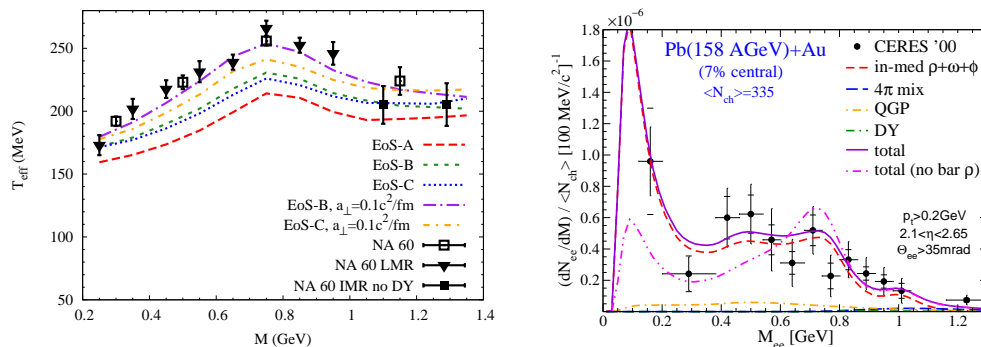


Fig. 2. (Color online) Left panel: effective slopes from m_t spectra for different equations of state and radial acceleration of the fireball [30], compared to NA60 data [34,35]. Right panel: Comparison of the same model [30] to recent CERES/NA45 dielectron spectra [40] in central 158 AGeV Pb-Au collisions.

175 MeV (EoS-A), $T_c = T_{ch} = 160$ MeV (EoS-B), and $T_c = 190$ MeV, $T_{ch} = 160$ MeV (EoS-C) have been used. In EoS-C a chemically equilibrated hadronic phase in the temperature region $160 \text{ MeV} \leq T \leq 190 \text{ MeV}$ has been assumed. The comparison to the M and m_t spectra is qualitatively comparable to that of EoS-A (up to small variations of the total dilepton yields which could be readjusted by small changes of the fireball lifetime). An interesting consequence of this insensitivity to T_c and T_{ch} is that the dimuon spectrum in the intermediate-mass region (IMR) $M \geq 1$ GeV can be equally well described with models where the dilepton yield is either dominated by radiation from a partonic (EoS-B) or a hadronic (EoS-C) source [30]. Since the emission in this M region is dominated from fireball stages with temperatures around the critical region, $T \simeq 160$ – 190 MeV, this insensitivity is due to the above described “parton-hadron duality” of the dilepton rates within this model. Thus, a definite conclusion whether the dileptons in the IMR are dominated by radiation from a partonic or hadronic medium can only be drawn if a more precise value of T_c is known.

As shown in the left panel of Fig. 2 the comparison of the effective slopes of the m_t spectra with the corresponding analysis of the NA60 data indicates that a larger radial flow of the medium is favored by the data. The right panel of Fig. 2 shows a comparison of the same model to the recent dielectron spectrum in central 158 AGeV Pb-Au collisions from the NA45/CERES collaboration [40]. The result of the same model *without* the interactions of the ρ meson with baryons in the medium corroborates their prevalence for the broadening of the ρ -spectral function, in a very pronounced way in the mass region below the two-pion threshold.

4. Conclusions and Outlook

The comparison of effective hadronic models for in-medium properties of the EM current-correlation function with high precision dilepton data in URHICs is a promising method to gain insights in the nature of CSR. Models based on hadronic many-body theory, predicting a strong broadening of the vector-meson spectral functions with little mass shifts, are favored by recent measurements compared to those implementing the dropping-mass conjecture. However, a more complete analysis of the generalized hidden-local symmetry model with the vector manifestation of CS, leading to dropping vector

and axialvector masses, including baryonic interactions is not available yet. The large enhancement of the dilepton yield in the LMR, recently observed by PHENIX in 200A GeV Au-Au collisions at RHIC [41], to date cannot be explained by any of the models which are successful at the SPS.

The extension of the present models to axialvector mesons, constrained by lQCD calculations of chiral order parameters in connection with Weinberg sum rules, might help to deduce more direct evidence for CSR from the dilepton signal in URHICs.

Acknowledgments. One of us (HvH) likes to thank the organizers for the invitation and generous support to attend an exciting conference. This work was supported in part by the U.S. National Science Foundation under grant no. PHY-0449489.

References

- [1] R. Rapp and J. Wambach, *Adv. Nucl. Phys.* 25 (2000) 1.
- [2] E. V. Shuryak, *Phys. Rept.* 61 (1980) 71.
- [3] L. D. McLerran and T. Toimela, *Phys. Rev. D* 31 (1985) 545.
- [4] C. Gale and J. I. Kapusta, *Nucl. Phys. B* 357 (1991) 65.
- [5] R. Barate et al. (ALEPH Collaboration), *Eur. Phys. J. C* 4 (1998) 409.
- [6] K. Ackerstaff et al. (OPAL Collaboration), *Eur. Phys. J. C* 7 (1999) 571.
- [7] Z. Fodor and S. D. Katz, *JHEP* 04 (2004) 050.
- [8] F. Karsch, *J. Phys. G* 34 (2007) S627.
- [9] F. Karsch and E. Laermann, *Phys. Rev. D* 50 (1994) 6954.
- [10] G. E. Brown and M. Rho, *Phys. Rev. Lett.* 66 (1991) 2720.
- [11] C. Gale and P. Lichard, *Phys. Rev. D* 49 (1994) 3338.
- [12] R. Rapp, G. Chanfray, and J. Wambach, *Nucl. Phys. A* 617 (1997) 472.
- [13] R. Rapp and J. Wambach, *Eur. Phys. J. A* 6 (1999) 415.
- [14] M. Asakawa and C. M. Ko, *Phys. Rev. C* 48 (1993) 526.
- [15] S. Leupold, W. Peters, and U. Mosel, *Nucl. Phys. A* 628 (1998) 311.
- [16] F. Klingl, N. Kaiser, and W. Weise, *Nucl. Phys. A* 624 (1997) 527.
- [17] J. Ruppert, T. Renk, and B. Müller, *Phys. Rev. C* 73 (2006) 034907.
- [18] S. Weinberg, *Phys. Rev. Lett.* 18 (1967) 507.
- [19] J. I. Kapusta and E. V. Shuryak, *Phys. Rev. D* 49 (1994) 4694.
- [20] J. V. Steele, H. Yamagishi, and I. Zahed, *Phys. Lett. B* 384 (1996) 255.
- [21] M. Dey, V. L. Eletsky, and B. L. Ioffe, *Phys. Lett. B* 252 (1990) 620.
- [22] M. Bando, T. Kugo, S. Uehara, K. Yamawaki, and T. Yanagida, *Phys. Rev. Lett.* 54 (1985) 1215.
- [23] M. Harada and K. Yamawaki, *Phys. Rept.* 381 (2003) 1.
- [24] M. Harada and C. Sasaki, *Phys. Rev. D* 73 (2006) 036001.
- [25] C. Sasaki, M. Harada, and W. Weise (2009), [arXiv: 0901.0842 \[hep-ph\]](https://arxiv.org/abs/0901.0842).
- [26] E. Braaten, R. D. Pisarski, and T.-C. Yuan, *Phys. Rev. Lett.* 64 (1990) 2242.
- [27] C. R. Allton et al., *Phys. Rev. D* 71 (2005) 054508.
- [28] V. L. Eletsky, M. Belkacem, P. J. Ellis, and J. I. Kapusta, *Phys. Rev. C* 64 (2001) 035202.
- [29] H. van Hees and R. Rapp, *Phys. Rev. Lett.* 97 (2006) 102301.
- [30] H. van Hees and R. Rapp, *Nucl. Phys. A* 806 (2008) 339.
- [31] A. Andronic, P. Braun-Munzinger, and J. Stachel, *Nucl. Phys. A* 772 (2006) 167.
- [32] F. Becattini, J. Manninen, and M. Gazdzicki, *Phys. Rev. C* 73 (2006) 044905.
- [33] G. Agakishiev et al. (CERES/NA45 Collaboration), *Phys. Rev. Lett.* 75 (1995) 1272.
- [34] S. Damjanovic et al. (NA60 Collaboration), *Nucl. Phys. A* 783 (2007) 327.
- [35] R. Arnaldi et al. (NA60 Collaboration), *Phys. Rev. Lett.* 100 (2008) 022302.
- [36] R. Arnaldi et al. (NA60 Collaboration) (2008), [arXiv: 0810.3204 \[nucl-ex\]](https://arxiv.org/abs/0810.3204).
- [37] J. Ruppert, C. Gale, T. Renk, P. Lichard, and J. I. Kapusta, *Phys. Rev. Lett.* 100 (2008) 162301.
- [38] K. Dusling and I. Zahed (2007), [arXiv:0712.1982\[nucl-th\]](https://arxiv.org/abs/0712.1982).
- [39] R. Arnaldi et al. (NA60 Collaboration) (2008), [arXiv: 0812.3053 \[nucl-ex\]](https://arxiv.org/abs/0812.3053).
- [40] D. Adamova et al., *Phys. Lett. B* 666 (2008) 425.
- [41] S. Afanasiev et al. (PHENIX Collaboration) (2007), [arXiv:0706.3034 \[nucl-ex\]](https://arxiv.org/abs/0706.3034).