Duality and Chiral Restoration from Dilepton Production in Relativistic Heavy-Ion Collisions

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We discuss the recent status in the theoretical understanding of dilepton production in central heavy-ion reactions with the Pb-beam at the full CERN-SpS energy of 158 AGeV. In the low-mass region ($M \leq 1$ GeV) a strong broadening of the vector meson resonances in hot and dense matter (especially for the ρ meson) entails thermal dilepton rates very reminiscent to perturbative $q\bar{q}$ annihilation close to the expected phase boundary of the chiral symmetry restoring transition. A consistent description of the experimentally observed enhancement at both low and intermediate masses (1.5 GeV $\leq M \leq$ 3 GeV) in terms of thermal radiation from an expanding fireball can be obtained.

1 Introduction

The basic objective of the relativistic heavy-ion program is the investigation of the many-body properties of Quantum Chromodynamics associated with, *e.g.*, its phase diagram. Two of the main nonperturbative features characterizing the ground state (vacuum) of the theory – confinement and the spontaneous breaking of chiral symmetry – are expected to cease in possibly common phase transitions at finite temperature and/or density (see Ref. [1] for recent results from lattice simulations). Due to their negligible rescattering dileptons ($l^+l^- = e^+e^-, \mu^+\mu^-$) can in principle directly probe the highest excitation zones formed in the early stages of central nucleus-nucleus collisions. However, the measured spectra also contain radiation from later stages as well as the decay contributions from hadrons in the final state (the so-called 'cocktail'). Whereas the latter can be inferred from measured hadron spectra, the radiation from the fireball requires both the modeling of the space-time evolution of a heavy-ion reaction and the evaluation of dilepton production rates in strongly interacting matter.

In the low-mass region (LMR, $M \leq 1$ GeV), where hadronic properties are governed by the spontaneous breakdown of chiral symmetry, one hopes to witness its restoration through medium effects visible in the direct decays of the light vector mesons, $V \to l^+l^-$ ($V = \rho, \omega, \phi$). Definite conclusions, however, require the simultaneous treatment of their chiral partners: vector and axialvector mesons have to become degenerate at the transition. The central question then is, *how* this is realized, *e.g.*, do their masses merge to zero? Do their widths diverge? etc. (see Ref. [2] for a recent review).

The intermediate-mass region (IMR, 1.5 GeV $\leq M \leq$ 3 GeV) has long been proposed as a suitable window to observe thermal radiation from an equilibrated Quark-Gluon Plasma (QGP) [3]: at the larger masses the thermal signal is more sensitive to higher temperatures, whereas light-hadron decay contributions are concentrated at low masses and initial hard processes such as Drell-Yan annihilation, which dominate in the high-mass region ($M \geq 4$ GeV), might be sufficiently suppressed towards the IMR.

Here, we will try to give a unified description of both low- and intermediate-mass dilepton measurements at the CERN-SpS, in connection with possible indications of phase transition signatures. We first discuss various approaches to assess equilibrium dilepton production rates and their medium effects (Sect. 2), and then proceed to the application for evaluating dilepton observables coupled with a simplified space-time description of heavy-ion reactions (Sect. 3).

2 Electromagnetic Current Correlator and Medium Effects

The thermal dilepton production rate from a hot and dense medium can be decomposed as

$$\frac{dN_{l^+l^-}}{d^4x d^4q} = L_{\mu\nu}(q)\ W^{\mu\nu}(M,\vec{q};\mu_B,T)\ , \tag{1}$$

where $L_{\mu\nu}(q)$ is the standard lepton tensor, and the hadron tensor $W^{\mu\nu}$ contains all the non-trivial information on the hadronic medium of temperature T and baryon chemical potential μ_B. It is defined via the thermal expectation value of the electromagnetic (e.m.) current-current correlator,

$$\begin{aligned} W^{\mu\nu}(q) &= -i \int d^4x\ e^{-iq\cdot x}\ \langle\!\langle j^\mu_{\rm em}(x) j^\nu_{\rm em}(0)\rangle\!\rangle_T \\ &= \frac{-2}{\exp(q_0/T)-1}\ {\rm Im}\Pi^{\mu\nu}_{\rm em}(q)\ . \end{aligned} \tag{2}$$

Depending on the invariant masses probed, the e.m. correlator can be described by either using hadronic degrees of freedom (saturated by vector mesons within the well-established vector dominance model (VDM)) or the (perturbative) quark-antiquark vector correlator, *i.e.*,

$${\rm Im}\Pi^{\mu\nu}_{\rm em} = \begin{cases} \sum\limits_{V=\rho,\omega,\phi} ((m_V^{(0)})^2/g_V)^2\ {\rm Im}D_V^{\mu\nu}(M,\vec{q};\mu_B,T) & ,\ M \leq M_{dual} \\ (-g^{\mu\nu} + q^\mu q^\nu/M^2)\ (M^2/12\pi)\ N_c \sum\limits_{q=u,d,s} (e_q)^2 & ,\ M \geq M_{dual} \end{cases} \tag{3}$$

(ImD_V: vector meson spectral function). In vacuum the transition region is located at a 'duality threshold' of $M_{dual} \simeq 1.5$ GeV, as marked by the inverse process of e^+e^- annihilation into hadrons. Indeed, above M_{dual} the results from rather complete hadronic calculations closely coincide with the simple perturbative expression,

$$\frac{d^8 N_{l^+l^-}}{d^4x d^4q} = \frac{\alpha^2}{4\pi^4} f^B(q_0;T) \sum_{q=u,d,s} (e_q)^2 \ , \tag{4}$$

cf. Fig. 1. We note that in the IMR both temperature and density corrections, being of order $O(T/M)$ and $O(\mu_q/M)$, are negligible under the conditions probed at the SpS.

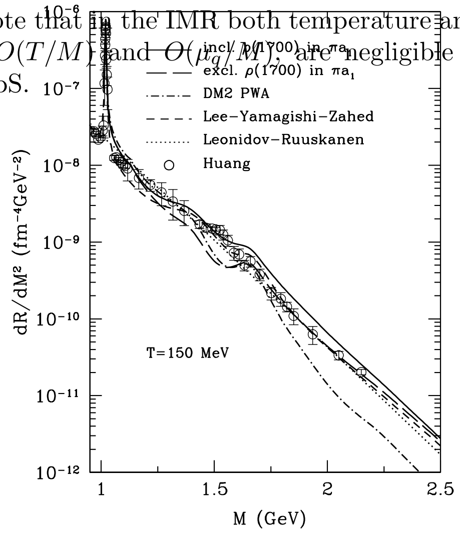

Figure 1: A compilation of 3-momentum integrated dilepton production rates in the IMR[4]. The open points are inferred[5] via empirical information from $\sigma(e^+e^- \to hadrons)$ including the mixing effect, Eq. (5), the dotted line corresponds to perturbative $q\bar{q}$ annihilation[6] and all other curves are variants of multi-hadronic calculations[4,7].

The situation is more involved in the LMR. Over the last years large efforts have been undertaken to assess medium effects in the vector correlator. Model independent results, based on current algebra together with a low-temperature (-density) expansion, have shown that (in the chiral limit) the leading effect is a mere mixing between the vector and axialvector degrees of freedom[8,9],

$$\begin{aligned} \Pi_V^{\mu\nu}(q) &= (1-\varepsilon)\ \Pi_V^{\circ\mu\nu}(q) + \varepsilon\ \Pi_A^{\circ\mu\nu}(q) \\ \Pi_A^{\mu\nu}(q) &= (1-\varepsilon)\ \Pi_A^{\circ\mu\nu}(q) + \varepsilon\ \Pi_V^{\circ\mu\nu}(q) \end{aligned} \tag{5}$$

with the mixing parameter $\varepsilon = T^2/6f_\pi^2$. Extrapolating to chiral restoration ($\varepsilon = 1/2$) one finds $T_c^\chi \simeq 160$ MeV (or $\rho_c^\chi \simeq 2.5\ \rho_0$[9]), which is not unreasonable. More surprisingly, the fully mixed vector correlator leads to a dilepton production rate which agrees well with perturbative QGP radiation down to the ϕ resonance[5], cf. open points and dotted line in Fig. 1 (note that the mixing does not affect the resonance structures in Π_V°). Thus one concludes that in the 1 GeV $< M <$ 1.5 GeV region chiral restoration is realized through a lowering of the in-medium duality threshold, being a 'weak' temperature effect.

The investigation of in-medium modifications of the low-lying vector resonances has been pursued in a variety of frameworks[2]. Within the mean-field approximation, and using arguments of scale invariance of the QCD Lagrangian at finite temperature/density, Brown and Rho predicted the ρ and ω meson masses to follow a universal 'scaling law'[10], *i.e.*, $m_{\rho,\omega}(\rho,T)$ drop (in line with other non-Goldstone hadrons) in accord with the vanishing the pion decay constant f_π, which is one of the order parameters of chiral restoration.

Other approaches aim at a proper description of the in-medium vector spectral functions based on phenomenologically well-established interactions with surrounding matter particles such as pions or nucleons in connection with standard many-body techniques. These calculations are based on chirally and gauge invariant couplings where the associated parameters are constrained by partial (hadronic and electromagnetic) decay widths of the excited resonances (*e.g.*, $a_1 \to \pi\rho, \pi\gamma$) or, if available, more comprehensive information as encoded, *e.g.*, in photoabsorption spectra on nucleons[11] and nuclei[12]. An example of such a calculation[13] is displayed in Fig. 2. As a result of multiple interactions in hot/dense matter the ρ spectral function (upper left panel) undergoes a strong broadening thereby losing its quasiparticle nature (as is also evident from the flattening of the real part, cf. lower left panel). At the highest temperatures/densities the corresponding dilepton production rates (right panel) exhibit a remarkable reminiscence to perturbative $q\bar{q}$ annihilation in the 0.5–1 GeV region (above, the lack of 4-pion states in the ρ propagator leads to the falloff of the full lines; cf. Fig. 1 for the more complete description in the IMR). This may be interpreted as a further penetration of the in-medium duality threshold down to rather low masses of 0.5 GeV, this time caused by strong rescattering effects resummed in the Dyson equation for the ρ propagator.

3 Dilepton Spectra in Pb(158 AGeV)-Induced Reactions

To compare with experiment, the dilepton rates discussed in the previous section have to be folded over a realistic space-time evolution[14] of a given heavy-ion reaction. We here employ a thermal fireball expansion based on a resonance gas equation of state. The latter is constructed in accord with recent analysis on the *chemical* freezeout at SpS energies[15], *i.e.*, the stage where particle abundances are frozen. Entropy as well as baryon-number conservation determine

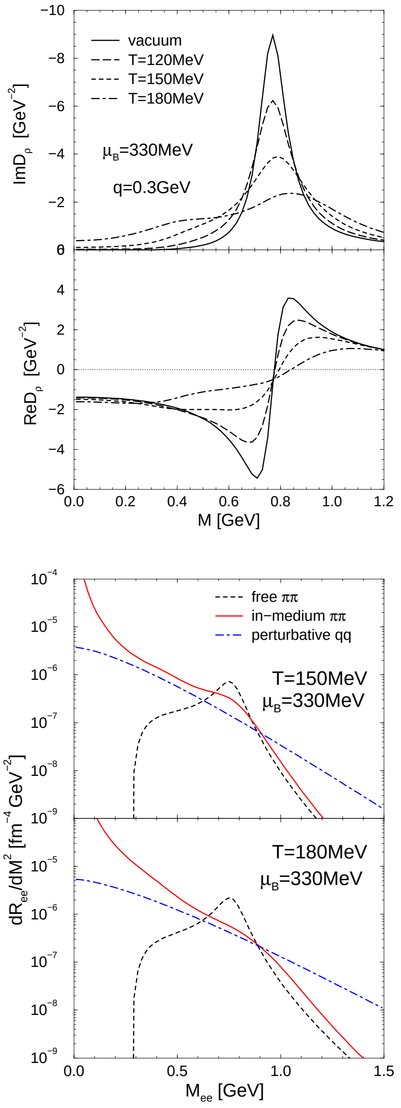

Figure 2: In-medium ρ propagator (left panel) and pertinent dilepton production rates (right panel, together with pQCD results) as emerging from a hadronic many-body calculation [13].

the thermodynamic trajectory towards *thermal* freezeout, where rescattering ceases. In addition, effective pion-number conservation induces the build-up of finite pion chemical potentials[16], reaching $\mu_\pi = 60 - 80$ MeV. The thermal radiation contribution from the fireball then takes the form

$$\frac{dN^{th}_{l^+l^-}}{dM} = \frac{\alpha^2}{\pi^3 M} \int\limits_0^{t_{fo}} dt\ V_{FC}(t) \int \frac{d^3q}{q_0}\ f^B(q_0;T,\mu_\pi)\ \mathrm{Im}\Pi_{\mathrm{em}}\ \mathrm{Acc}(M,q_t,y)\ , \quad (6)$$

where $\mathrm{Acc}(M,q_t,y)$ accounts for the specific detector acceptance and $V_{FC}(t)$ describes the (cylindrical) volume expansion. The thermal Bose factor f^B incorporates $\mu_\pi > 0$ in the hadronic phase, which in Boltzmann approximation amounts to an enhancement factor $(e^{\mu_\pi/T})^n$. In the LMR, where two-pion annihilation prevails, $n = 2$, whereas in the IMR $n = 4$ corresponding to the dominant πa_1 channel[4]. Results are shown in Fig. 3. In the LMR (left panels), the strong medium effects in the ρ spectral function (cf. Fig. 2) entail good agreement with the CERES data including the low-q_t nature of the excess. Within the same fireball model, but using the 'dual' rates from Fig. 1, the enhancement observed by NA50 in the IMR (1.5 GeV $\leq M \leq$ 3 GeV) can also be reproduced by thermal radiation[19,20] (right panels).

4 Conclusions

The excess of dileptons measured at low and intermediate masses in heavy-ion collisions at the full CERN-SpS energy can be consistently attributed to thermal radiation from an expanding fireball. Whereas the IMR contains a moderate fraction (∼25%) from the highest temperature phases indicative for a QGP, the LMR seems to require strong medium effects in the vector channel. Hadronic model calculations suggest that these might be interpreted as an in-medium lowering of the quark-hadron 'duality threshold' from its vacuum value of 1.5 GeV down to ∼0.5 GeV. In such a scenario chiral restoration is realized by a merging of the vector and axialvector correlator into their perturbative form. Advanced investigations of the axialvector channel, as well as the upcoming measurements at the CERN-SpS and RHIC, are essential for further progress.

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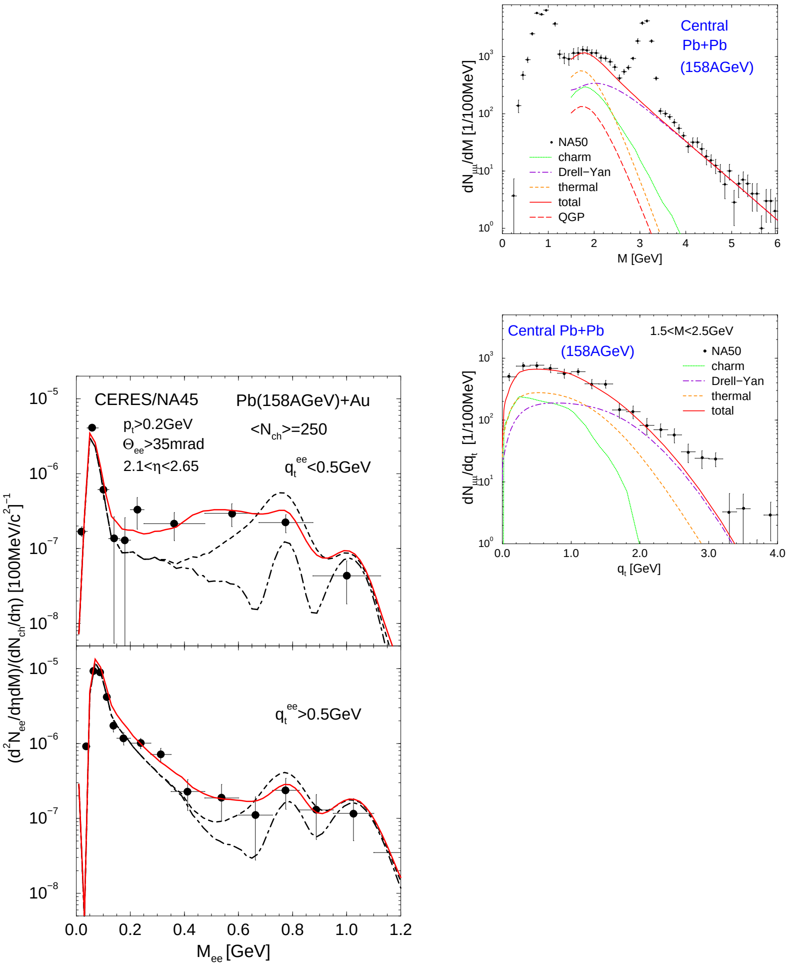

Figure 3: Dilepton Spectra at the CERN-SpS. Left panel: LMR, split into two q_t-bins, as measured by CERES/NA45 [17] in 30% central Pb+Au (dashed-dotted lines: hadronic cocktail, dashed line: cocktail + free $\pi\pi$ annihilation, solid lines: cocktail + in-medium $\pi\pi$ annihilation). Right panel: IMR as measured by NA50 [18] in central Pb+Pb (upper/lower panel: M-/q_t-spectra; the long-dashed line in the upper panel constitutes the contribution from the QGP phase assuming a critical temperature $T_c = 175$ MeV).

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