

Medium Modifications of Vector Mesons and NA60

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Abstract. We confront different models for medium modifications of the electromagnetic correlation function to recent dimuon spectra from the NA60 collaboration for central In-In collisions at the CERN-SPS. In the low-mass region ($M \lesssim 1.0$ GeV), we evaluate medium modifications of the spectral properties of ρ -, ω - and ϕ -mesons. In the intermediate-mass region ($M > 1.0$ GeV), we employ schematic models for the mixing of vector and axialvector current correlators, which provide a mechanism for chiral-symmetry restoration.

Keywords: ultra-relativistic heavy-ion collisions, dileptons, chiral symmetry

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1. Introduction

One of the main goals in the investigation of hot and dense matter produced in ultra-relativistic heavy-ion collisions (URHICs) is the understanding of the phase structure of Quantum Chromodynamics (QCD), the theory of the strong interaction. At low temperatures the relevant degrees of freedom are hadrons, and the approximate chiral symmetry of the light-quark sector is spontaneously broken. From asymptotic freedom of QCD one expects that at high temperatures and/or densities the partons are deconfined. Lattice-QCD simulations show a phase transition at a critical temperature of about $T_c \simeq 175$ MeV, above which chiral symmetry is restored and the partons are deconfined [1]. Since chiral-symmetry restoration implies that chiral multiplets in the hadron spectrum degenerate, significant in-medium modifications of hadron properties in the hadronic phase are expected.

Electromagnetic (e.m.) probes, i.e., leptons and photons, are particularly valuable for the investigation of the hot and dense medium since they are produced during all stages of the collision and leave the fireball nearly undisturbed by final-state interactions. An important finding in the CERN Super Proton Synchrotron (SPS) program in the 1990's is the large excess of low-mass dileptons ($M \lesssim 1$ GeV) in Pb-Au collisions compared to expectations from proton-proton collisions [2]. This result has been explained by medium modifications of the ρ meson [3], but no

decisive distinction between a broadening and a dropping mass could be made.

The objective of this talk is to evaluate different approaches to low-mass vector mesons in a hot and dense medium relative to recent dimuon spectra in In-In collisions by the NA60 collaboration at the SPS [4]. For the first time a discrimination of different theoretical mechanisms for chiral-symmetry restoration has become possible. We also investigate the mass-region beyond the ϕ ($1 \text{ GeV} < M < 1.5 \text{ GeV}$) within schematic models which implement a mixing of the vector and the axialvector current correlators, leading to their degeneracy at the critical point as a consequence of chiral-symmetry restoration.

2. Dilepton Rates and Spectra

The differential rate for the production of lepton pairs from a thermal source can be expressed in terms of the retarded e.m. current correlator, $\Pi_R^{\mu\nu}$ [5, 6, 7],

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

where $L(M)$ is the leptonic phase-space integral and f_B the Bose distribution.

Dilepton spectra in URHICs are obtained upon convoluting the above rate over the space-time evolution of the fireball,

$$\frac{dN_{ll}}{dM} = \int_0^{t_{fo}} dt V_{FB}(t) \int \frac{d^3q}{q_0} \frac{dN_{ll}}{d^4x d^4q} z_\pi^n \frac{M}{\Delta y} A(M, q_t, y), \quad (2)$$

where an average over the rapidity window, Δy , and the integration over the three-momentum of the pair have been carried out. A is the detector acceptance function which we have determined from NA60 simulations [8]. The pion-fugacity factor, $z_\pi^n = \exp(n\mu_\pi/T)$, accounts for chemical off-equilibrium in the hadronic phase, with $n=2, 3, 4$ for ρ , ω , and four-pion contributions to the dilepton rates, respectively. The thermal-fireball volume is assumed to expand cylindrically (and isotropically) [9], $V_{FB}(t) = (z_0 + v_z t) \pi (r_\perp + 0.5 a_\perp t^2)^2$. For central In(158 AGeV)-In we use a transverse acceleration $a_\perp = 0.08 \text{ c}^2/\text{fm}$, longitudinal speed $v_z = c$, and initial sizes $z_0 = 1.8 \text{ fm}/c$, $r_\perp = 5.15 \text{ fm}$. With a hadron-resonance gas equation of state and chemical freezeout at $(\mu_N^{\text{ch}}, T_{\text{ch}}) = (232, 175) \text{ MeV}$, a total fireball entropy of $S = 2630$ translates into $dN_{\text{ch}}/dy \simeq 195$. Assuming isentropic expansion we infer the temperature and baryon density from the entropy density, $s(t) = S/V(t)$. The initial QGP temperature is $T_0 = 197 \text{ MeV}$, at $T_{\text{ch}} \simeq T_c$ the system converts into hadronic matter, and the time evolution terminates with thermal freezeout at $t_{fo} = 7 \text{ fm}/c$ ($T_{fo} \simeq 120 \text{ MeV}$).

3. Hadronic Many-Body Approach and ‘‘Duality’’

In this Section the e.m. correlator, $\Pi_R^{\mu\nu}$, will be described by a combination of hadronic many-body theory (HMBT) for ρ , ω and ϕ at low mass, by lowest-order-in- T chiral mixing at intermediate mass, and by a hard-thermal loop improved

emission in the QGP [10]. The vector-meson propagators are directly related to the e.m. correlator employing the vector-dominance model,

$$\text{Im } \Pi_{R\mu}^\mu = \sum_{V=\rho,\omega,\phi} \frac{1}{g_V^2} \left(m_V^{(0)} \right)^4 \text{Im } D_{RV\mu}^\mu, \quad (3)$$

($g_V, m_V^{(0)}$: vector-meson coupling constants and their (bare) masses).

A particular appealing feature that emerges in this approach is the approximate degeneracy of the in-medium hadronic rate with the QGP one close to T_c , which has been interpreted as a reduction of the quark-hadron duality scale in the medium [11] and provides a "natural" scenario for chiral restoration.

3.1. ρ -Meson in Medium

The dominant contribution to Eq. (3) is the isovector part which at low mass is saturated by the ρ -meson. We here use the in-medium ρ spectral function as evaluated in hadronic many-body theory in Ref. [9]. Starting point is a realistic description of the (pion cloud of the) ρ in the vacuum, consistent with P -wave π - π scattering phase shifts and the pion e.m. form factor as encoded in the one-loop self-energy.

In hadronic matter, the pion cloud is dressed by Bose enhancement factors and pion-induced NN^{-1} and ΔN^{-1} excitations ("pisobars"). To approximately account for higher nucleon and thermally excited baryon resonances (B^*), an effective baryon density, $\rho_{\text{eff}} = \rho_N + \rho_{B^*}/2$, has been applied. In addition, direct ρ - BB^{-1} excitations ("rhosobars") on nucleons, Λ 's, etc., are included. In cold nuclear matter, the interaction vertices (coupling constants and form factors) have been constrained by a comprehensive fit to photo-absorption on the nucleon and nuclei [12] (including an extended vector dominance model [13]), as well as by $\pi N \rightarrow \rho N$ scattering.

Meson-gas contributions to the self-energy are calculated following Ref. [14] including a rather complete set of s -channel resonances up to 1.65 GeV with interaction vertices constrained by hadronic and radiative decay branchings.

As a result the in-medium ρ spectral function exhibits substantial broadening together with a small upward mass shift. This behavior is typical for hadronic many-body calculations since contributions to the imaginary part of the retarded self-energy are strictly of the same sign due to the retardation condition, while the real parts contain both attractive (negative) and repulsive (positive) interactions, which for a large set of excitations tend to compensate each other.

3.2. ω - and ϕ -Meson in Medium

The ω -meson is treated along similar lines as the ρ -meson [15]: the vacuum self-energy is constructed from a combination of $\rho\pi$ and 3π loops, whose couplings and form factors have been adjusted to the radiative width (assuming vector-meson dominance) and total hadronic decay width (with 50% from $\rho\pi$ and direct 3π pieces each). Medium modifications in the $\pi\rho$ loop are introduced by Bose-enhancement

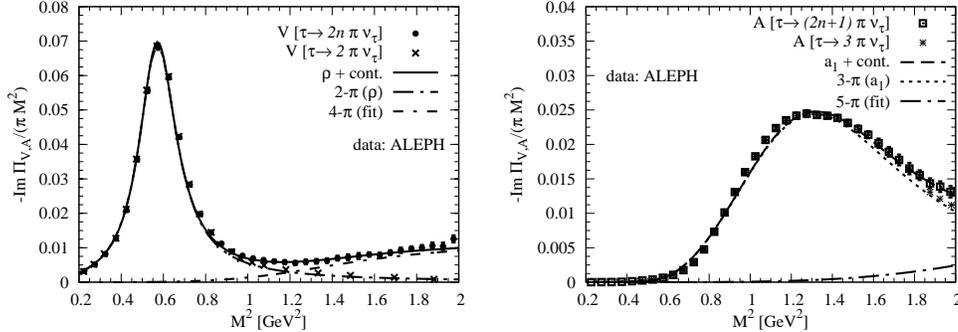


Fig. 1. Free isovector-vector (left panel) and -axialvector (right panel) current correlators from τ -decay data, compared to fits to three- and four-pion contributions (the two-pion part corresponds to the vacuum ρ -spectral function).

factors and the in-medium ρ spectral function as described above. Meson-gas modifications include the inelastic channel $\omega\pi \rightarrow \pi\pi$ [16] and scattering off thermal pions via the $b_1(1235)$ which is the empirically dominant $\omega\pi$ resonance. The effects of direct resonances on baryons have been assigned to $N(1520)N^{-1}$ and $N(1650)N^{-1}$ excitations. The total in-medium width of the ω in hadronic matter representative for URHICs amounts to $\Gamma_{\omega}^{\text{med}} \simeq 100$ MeV.

Recent developments render the situation for the ϕ -meson more involved. Its collisional broadening in a meson gas has been predicted as large as $\Delta\Gamma_{\phi}^{\text{coll}} \simeq 20$ -50 MeV at $T=150$ -180 MeV [17]. In cold nuclear matter, at saturation density $\rho_0=0.16 \text{ fm}^{-3}$, dressing the kaon-cloud was found to induce $\Delta\Gamma_{\phi}^{KK} \simeq 25$ MeV [18]. This result appears to underestimate the absorption inferred from recent nuclear photoproduction data by about a factor of 2 [19]. We therefore assume an in-medium broadening which, when averaged over the fireball evolution, amounts to $\Gamma_{\phi}^{\text{med}} \simeq 80$ MeV. Furthermore, the ϕ abundance is corrected for a two-kaon fugacity factor, z_K^2 , and a strangeness-suppression factor, γ_s^2 with $\gamma_s \simeq 0.75$ [20].

3.3. Four-Pion Contributions

At masses above 1 GeV, four-pion (and higher) states dominate the free e.m. correlator, cf. left panel of Fig. 1. We implement medium effects in this regime by employing model-independent predictions by chiral symmetry. To lowest order in T these amount to a pion-induced mixing of vector (V) and axialvector (A) correlators [21]:

$$\Pi_{V,A} = (1 - \epsilon) \Pi_{V,A}^{(\text{vac})} + \epsilon \Pi_{A,V}^{(\text{vac})}, \quad (4)$$

where ϵ is the mixing parameter ($\epsilon = T^2/6f_{\pi}^2$ in the chiral limit, $f_{\pi} = 93$ MeV) arising from pion tadpole diagrams. The admixture of the a_1 resonance (right panel of Fig. 1) entails an enhancement of the dilepton rate for $M \simeq 1$ -1.4 GeV. We evaluate

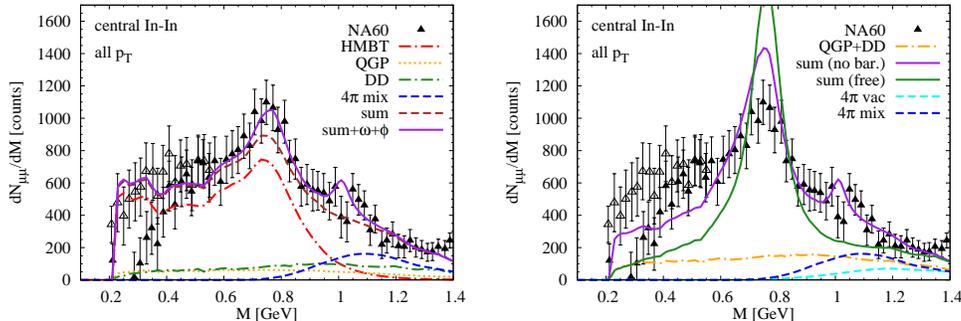


Fig. 2. NA60 data [4] compared to thermal $\mu^+\mu^-$ spectra from an expanding fireball using in-medium dilepton rates. Left panel: hadronic many-body theory for vector mesons and chiral mixing for 4- π contributions; right panel: removing the effects of baryons (“no bar.”) or neglecting medium effects altogether (“free”).

the tadpole integral including both finite pion-mass and chemical potential [22],

$$I_\pi(T, \mu_\pi) = \int \frac{d^3k}{(2\pi)^3} \frac{f^\pi[\omega_\pi(k), \mu_\pi]}{\omega_\pi(k)} \quad (5)$$

($\omega_\pi(k) = \sqrt{k^2 + m_\pi^2}$). An upper estimate of the mixing is then obtained by assuming V - A degeneracy at T_c by setting

$$\epsilon = \frac{1}{2} \frac{I_\pi(T, \mu_\pi)}{I_\pi(T_c, \mu_\pi = 0)}. \quad (6)$$

The vacuum V and A spectral functions are fitted to τ -decay data from the ALEPH collaboration [23] (Fig. 1). Note that the two-pion contributions are omitted here as they are included in the (in-medium) ρ -meson (which also incorporates the mixing).

3.4. Comparison to NA60 Data

In Fig. 2 (left panel) the combined thermal $\mu^+\mu^-$ yield (ρ , ω , ϕ , 4 π with mixing and QGP, convoluted over the fireball) is compared to NA60 data in central In-In. The spectra are well described with absolute normalization. Compared to earlier predictions [24, 4], the fireball acceleration has been increased which reduces the lifetime from 10 to 7 fm/ c and generates harder q_t spectra. We emphasize that the relative strength of the various thermal sources is fixed, which renders the overall agreement very encouraging. In the right panel of Fig. 2 we illustrate the importance of baryonic (medium) effects on the ρ , as well as the enhancement due to chiral V - A mixing. A reduction of the uncertainties in the η -cocktail subtraction (illustrated by the two data sets close to threshold) can further test these predictions.

4. Alternative Approaches for Medium Modifications

To further scrutinize the sensitivity of the NA60 data we here study the consequences of different approaches to implement medium effects on the e.m. correlator.

4.1. Chiral Reduction Formalism

A model-independent treatment of the in-medium e.m. correlator is obtained by coupling a low-temperature and -density expansion with chiral reduction techniques [25], similar in spirit to Sec. 3.3 but in a more sophisticated way using vacuum scattering amplitudes off pions and nucleons. The amplitudes are constructed from τ -decay data (Fig. 1) and photoabsorption on the nucleon. Appropriate fugacity factors, z_π^n , are included according to the fireball as used above (for simplicity, we neglect ω and ϕ contributions, but include QGP radiation as before).

The left panel of Fig. 3 compares pertinent thermal spectra to NA60 data. The mass region above 1 GeV is well described, while in the low-mass region the e.m. spectral function produces a too narrow peak structure around the ρ -mass. This is due to the density expansion in the chiral reduction formalism which does not generate a broadening of the ρ spectral function.

4.2. A Dropping ρ -Mass Scenario

In the 1990's, a dropping ρ -mass has successfully been implemented to describe the low-mass dilepton enhancement observed by CERES/NA45 [2]. We here check the consequences of this assumption for NA60 using an in-medium mass parameterization [3] of type $m_\rho^* = m_\rho(1 - C\rho_B/\rho_0)[1 - (T/T_c)^2]^\alpha$, where the density dependence with $C = 0.15$ resembles QCD sum rule estimates [26], while $\alpha=0.3$ is motivated by the temperature evolution of the chiral condensate [27]. The pertinent ρ spectral function (which has also been supplemented by a small thermal broadening) is then evolved through the same fireball as above, maintaining the absolute normalization of the spectra. The ρ contribution is furthermore supplemented with QGP and four-pion components (including chiral mixing).

The right panel of Fig. 3 shows that the observed enhancement below the free ρ mass is accounted for, but the yield in the peak region is underpredicted. Whether the introduction of a cocktail component (free ρ) can provide a consistent resolution of this discrepancy is questionable at present. Modifications of (or neglecting altogether) the T -dependence of the dropping-mass parameterization does not affect this conclusion.

Recent studies of axial-/vector-mesons within a renormalization-group framework for the phase diagram of a generalized hidden-local-symmetry model at finite T support the notion of dropping masses, but also imply a violation of the VDM [28]. Whether this approach can be reconciled with the NA60 data is currently not known. An explicit calculation of pertinent spectral functions at finite temperature *and* baryon-density is needed before further conclusions can be drawn.

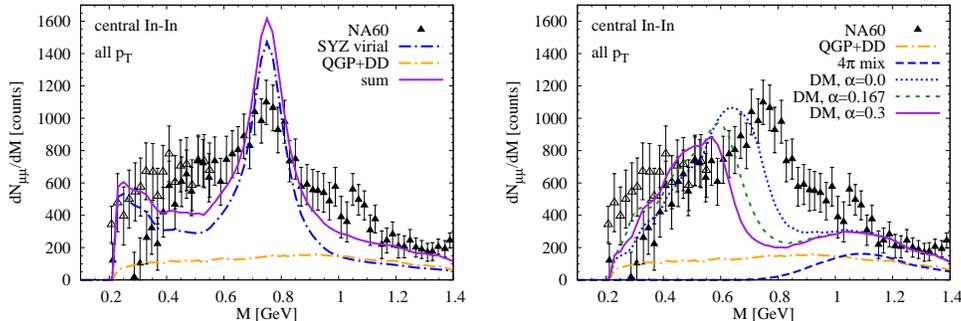


Fig. 3. NA60 data [4] compared to $\mu^+\mu^-$ spectra from a thermal fireball using in-medium dilepton rates from the chiral-reduction formalism [25] (left panel) and from a dropping ρ -meson mass scenario (right panel). The absolute normalization of the spectra, as following from the fireball, is the same as in Fig. 2.

5. Conclusions and Outlook

Recent NA60 dimuon data have opened the possibility to study in-medium modifications of vector mesons with unprecedented sensitivity. We have confirmed that predictions from hadronic many-body approaches, whose main feature is a strong broadening of the ρ spectral function, quantitatively describe the spectra in central In(158 AGeV)-In. While the absolute normalization is subject to current uncertainties of the underlying fireball lifetime (which do not affect the spectral shape significantly), the relative strength of the different thermal sources is fixed. In the mass region above 1 GeV, four-pion contributions to the e.m. correlator prevail and account for the observed enhancement, especially if effects of chiral V - A mixing are incorporated. The NA60 dimuons thus support a “melting” ρ -meson and the notion of a “quark-hadron duality” of the e.m. spectral function around T_c . We have also indicated that future analyses may be able to extract information on in-medium ω and ϕ spectral functions, which has not been possible to date.

We have investigated alternative approaches to describe the NA60 data. A naive dropping-mass scenario, as used to explain CERES data in the 1990’s, is disfavored, unless a large component of free ρ decays can be argued for (q_t -spectra will provide valuable insights). The chiral-reduction formalism is roughly in line with the spectra, but quantitatively lacks ρ broadening and/or low-mass enhancement.

To theoretically corroborate our findings, future studies within chirally symmetric models are mandatory, including the effects of baryons which we confirmed as important agents of medium effects. Model-independent constraints, e.g. from chiral [29] or QCD sum rules [30], will enable further progress as well.

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