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Low mass dileptons from Pb + Au collisions at 158 A·GeV

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Abstract. The medium modification of vector meson properties in hot/dense hadronic matter and its role in explaining the CERES/NA45 dilepton data at different centralities are discussed.

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Relativistic nuclear collisions are expected to produce extreme conditions of temperature and/or baryon density conducive for the liberation of bound color charges resulting in the formation of quark–gluon plasma (QGP). Spontaneously broken chiral symmetry is also expected to be restored. These phenomena constitute a massive restructuring of the QCD vacuum and is likely to affect the spectral properties of hadrons which are in fact excitations of the vacuum. Electromagnetic probes can be effectively used to study changes in hadronic properties in hot/dense medium because of their minimal final state interactions. The dilepton spectra in particular, exhibit a resonant structure which, in the low mass regime includes the ρ and the ω mesons. The spectral modifications of these vector mesons would be clearly revealed in the invariant mass spectra of the dileptons through the shift of the resonant peaks.

We have seen earlier [1] that the WA98 photon spectra from Pb + Pb collisions at the CERN SPS can be explained by either of the two scenarios of relativistic nuclear collision [1,2]: (a) $A+A \rightarrow$ QGP $\rightarrow$ mixed phase $\rightarrow$ hadronic phase or (b) $A+A \rightarrow$ hadronic matter; with downward shift of vector meson masses and initial temperature ~200 MeV. Our aim now is to check whether the same scenario can explain the dilepton data obtained in Pb + Au collisions at SPS by the CERES/NA45 Collaboration [3]. The possible sources in the low mass region are the dileptons coming from the decays of hadrons at freeze-out and from the in-medium propagation and decay of vector mesons. The data show a significant enhancement in the mass region 0.3 to 0.6 GeV which can be explained [4] by a substantial negative shift of the mass of vector mesons (the ρ meson in particular) in the thermal medium. A large broadening of the ρ meson spectral function due to the scattering of baryons can also explain this enhancement [5] though the photon yield is seen to be insensitive to such a broadening [6].

A substantial volume of literature has been devoted to the issue of temperature and/or density dependence of hadrons within various models [5,7–9]. The effects of the thermal shift of the hadronic spectral functions on both photon and dilepton emission have been considered in ref. [6] for an exhaustive set of models. An appreciable change in the space-time integrated yield of electromagnetic probes was observed for universal scaling [8] and quantum hadrodynamic (QHD) model [10] and we will consider only these in the present discussion.

Let us now briefly recapitulate the main equations relevant for evaluating dilepton emission from a thermal source. The emission rate of dileptons can be expressed in terms of the imaginary part of the retarded electromagnetic current correlation function as [11]

$$\frac{\mathrm{d}R}{\mathrm{d}^4p} = -\frac{\alpha}{12\pi^4 p^2} g^{\mu\nu}\,\mathrm{Im}W^R_{\mu\nu}(p)\left(1+\frac{2m_\mathrm{l}^2}{p^2}\right)\sqrt{1-\frac{4m_\mathrm{l}^2}{p^2}}\, f_{BE}(E,T), \tag{1}$$

where m_l is the lepton mass.

In the QGP, the dominant channel for dilepton productions is quark–antiquark annihilation. The rate for this process is obtained from the lowest order diagram contributing to the current correlator $W^{\mu\nu}$. In order to obtain the rate of dilepton emission from hadronic matter ($\rho/\omega \to l^+l^-$) from eq. (1) the electromagnetic current correlator is expressed in terms of the effective propagator of the vector particle in the thermal medium using vector meson dominance (VMD) so as to obtain

$$\mathrm{Im}W^R_{\mu\mu} = \frac{\pi e^2 m_V^4}{g_V^2}(2\rho^V_\mathrm{T} + \rho^V_\mathrm{L}),$$

with

$$\rho^V_{\mathrm{T(L)}} = \frac{1}{\pi}\left[\frac{\mathrm{Im}\,\Pi^V_{\mathrm{T(L)}}}{(p^2 - m_V^2 + \mathrm{Re}\,\Pi^V_{\mathrm{T(L)}})^2 + (\mathrm{Im}\,\Pi^V_{\mathrm{T(L)}})^2}\right], \tag{2}$$

where $\rho^V_{\mathrm{T(L)}}$ and $\Pi^V_{\mathrm{T(L)}}$ are respectively the transverse (longitudinal) parts of the retarded spectral function and self-energy of vector mesons arising out of interaction with excitations in the medium. The transverse and longitudinal components of the spectral function of ρ with interactions from the QHD model is shown in figure 1. The downward shift of the first peak of the spectral function with increasing density n_B and temperature T can be almost entirely attributed to the $\bar{N}N$ polarization of ρ in the modified Dirac sea. The narrowing down of the width with increasing T and n_B is due to the reduction of the phase space for the process, $\rho \to \pi\pi$ resulting from the decrease in ρ mass. The second peak in the spectral function is due to the $\bar{N}N$ threshold of the off-shell ρ which has negligible effects on the dilepton yield. For a discussion on the ρ spectral function in the scaling scenario, see ref. [6].

The observed dilepton spectrum originating from an expanding matter can be obtained by convoluting the static rates given above with the expansion dynamics. This is done using boost invariant relativistic hydrodynamics. For the QGP sector, we use the bag model equation of state with two-flavor degrees of freedom. The hadronic phase is taken to consist of π, ρ, ω, η and a_1 mesons and nucleons. The medium effects enter through the effective masses in the expressions for energy density and pressure. The entropy density is then parametrized as

$$s_H = \frac{\varepsilon_H + P_H}{T} \equiv 4a_{\mathrm{eff}}(T)T^3 = 4\frac{\pi^2}{90}g_{\mathrm{eff}}(m^*,T)T^3, \tag{3}$$

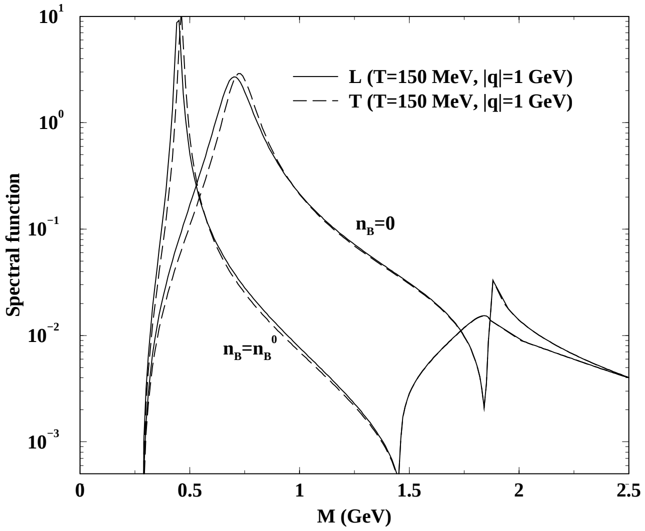

Figure 1. The spectral function of the ρ meson in quantum hadrodynamics (QHD).

where $g_{\rm eff}$ is the effective statistical degeneracy through which medium effects enter into the expansion dynamics of the system. The velocity of sound consequently becomes a function of T and differs substantially from its value corresponding to an ideal gas ($1/\sqrt{3}$). When the system is produced in the QGP phase, $g_{\rm eff}$ is replaced by $g_{\rm QGP}$ which for two quark flavors is 37. Note that the value of the initial temperature of a hot hadronic gas also depends on $g_{\rm eff}$. The freeze-out temperature $T_{\rm F}$ is taken as 120 MeV.

We now compare the results of our calculation with the dilepton spectra obtained by the CERES/NA45 Collaboration in figure 2. The upper panel (a) contains the results for $\langle {\rm d}N_{\rm ch}/{\rm d}\eta\rangle = 250$ where we have considered a hadronic gas scenario as well as a deconfined initial state with $T_{\rm i} = 180$ MeV which evolves into a hadronic gas via a mixed phase. The observed enhancement of the dilepton yield around $M \sim 0.3$–0.6 GeV can be reproduced with a QGP initial state once the variation of vector meson masses in the mixed and the hadronic phases are taken into account (solid line). The data is also reproduced by a hadronic initial state with $T_{\rm i} = 190$ MeV in the universal mass variation scenario (dashed line). The shift of the ρ-peak in the dilepton spectra towards lower invariant mass M is more for the universal scaling scenario compared to QHD model (long dashed line) indicating a stronger medium effect in the former case. The dilepton spectra for ${\rm d}N_{\rm ch}/{\rm d}\eta = 350$ is shown in the lower panel (b) of figure 2. Calculations with a hadronic initial state and universal scaling of hadronic masses with temperature (dashed line) describes the data reasonably well. The initial temperature in this case is $\sim$195 MeV. We have seen that with the temperature dependent mass from QHD model the low mass enhancement of the experimental yield cannot be reproduced (curve not shown). A good description of the data can also be obtained by taking $T_{\rm i} = 200$ MeV with QGP initial state for $T_{\rm c} = 190$ MeV (solid line). For comparison, we show the results due to a large broadening of the ρ spectral function in the medium (dash–dotted line). The broadening of ρ is modelled by assuming the temperature dependent width as: $\Gamma_\rho(T) = \Gamma_\rho(0)/(1 - T^2/T_{\rm c}^2)$. In all the cases background due to hadron decays (dotted line) are added to the thermal yields.

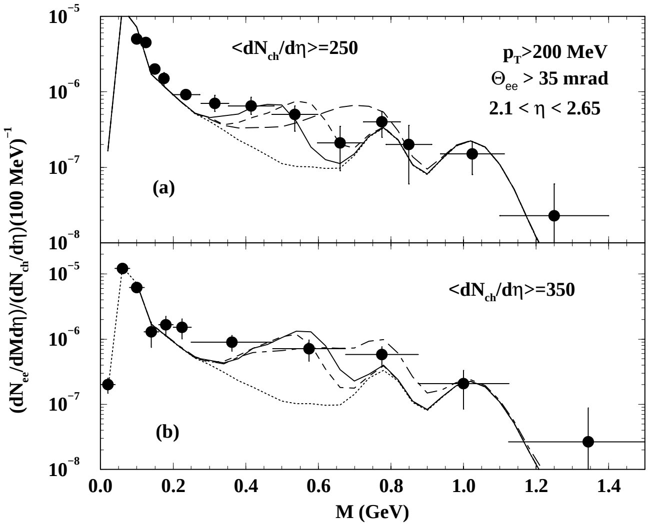

Figure 2. Dilepton spectra with different initial states and mass variation scenarios for (**a**) $\langle dN_{\rm ch}/d\eta\rangle = 250$ and (**b**) $\langle dN_{\rm ch}/d\eta\rangle = 350$.

In summary, we have evaluated the low mass dilepton yield in Pb + Au collisions at CERN SPS energies with different initial conditions for two values of the charge multiplicity. The effects of the variation of hadronic masses on the dilepton yield have been considered both in the cross section as well as in the equation of state. It is observed that the data can be described by both QGP and hadronic initial states with an initial temperature ∼200 MeV which is very much in agreement with our conclusion from the analysis of the WA98 photon data [1]. We have assumed $\tau_{\rm i} = 1$ fm/c at SPS energies, which may be considered as the lower limit of this quantity because the time taken by the nuclei to pass through each other in the CM system is ∼1 fm/c at SPS energies and the thermal system can be formed after this time has elapsed.

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