Probing in-medium vector meson decays by double-differential di-electron spectra in heavy-ion collisions at SIS energies

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Abstract

Within a transport code simulation for heavy-ion collisions at bombarding energies around 1 AGeV, we demonstrate that double-differential di-electron spectra with suitable kinematical cuts are useful to isolate (i) the $\rho$ meson peak even in case of strong broadening, and (ii) the in-medium $\omega$ decay contribution. The expected in-medium modifications of the vector meson spectral densities can thus be probed in this energy range via the di-electron channel.

\textit{Keywords}: heavy-ion collisions, di-electrons, in-medium modifications of vector mesons

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I. INTRODUCTION

One of the main goals of the experiments with the HADES detector [1] at the heavy-ion synchrotron SIS18 at GSI/Darmstadt is the search for a direct evidence of in-medium modifications of hadrons via the di-electron ($e^+e^-$) channel. This goal is supported by various theoretical indications concerning an important sensitivity of vector mesons to partial restoration of chiral symmetry in a dense and hot nuclear medium [2]. In particular, as shown within lattice QCD [3], the chiral quark condensate $\langle \bar{q}q \rangle$ as order parameter of the chiral symmetry breaking decreases with increasing baryon density and temperature. Since $\langle \bar{q}q \rangle$ is coupled to the vector meson spectral densities one can expect considerable in-medium effects of light vector mesons which manifest themselves, e.g., as resonance mass shifts and broadening of widths [4].

In spite of the efforts spent to predictions [5–13], there is no commonly accepted and reliably quantitative estimate of the change of the mentioned parameters or spectral functions in a nuclear medium. For instance, within the QCD sum rule analysis [5–7] the in-medium modification of the vector meson masses in zero-width approximation is dictated by the density and temperature dependence of the quark condensates. While the two-quark condensate $\langle \bar{q}q \rangle$ can be estimated by a model independent approach with reasonable accuracy, the so far poorly known four-quark condensates like $\langle (\bar{q}q)^2 \rangle$ lead to uncertainties for the
prediction of the vector meson mass shift [14]. From this point of view, direct measurements of the vector meson masses and widths, as being at reach with the high-resolution HADES detector system [1], can also shed light on fundamental problems such as the in-medium change of the four-quark condensate.

Since the most pronounced vector meson mass shift is expected for large baryon density in the nuclear medium, there is the hope to verify the effect in medium-energy heavy-ion collisions at SIS18 energies, where baryon densities up to 3n0 can be reached according to model calculations [15]. Unfortunately, in the case of heavy-ion collisions such measurements face a number of problems related to the expansion dynamics and the spatial inhomogeneity of the produced dense matter. Due to the collective expansion, the baryon density n depends on time so that obviously a time average of the mass shift is to be expected, i.e. the mass shift effect is distributed over an interval related to the temporal change of n. Also spatial variations of n will make the situation more complicated.

To extract the wanted information on the in-medium meson spectral function in heavy-ion collisions one has also to take into account that the di-electron spectrum \( dN/dM^2 \) as a function of the di-electron invariant mass \( M \) is actually a convolution of the considered spectral function and the probability to create the vector meson with given energy and momentum. The latter one usually drops down very fast with the energy making the resulting di-electron spectrum very steep. This can make the identification of the possible mass shift, superimposed to collision broadening and further in-medium broadening, in particular for the \( \rho \) meson, rather difficult. An additional problem arises for the \( \omega \) meson because of its comparatively long life time which, however, may change in a dense medium [11]. To measure an in-medium mass shift of the \( \omega \) resonance one should obviously separate lepton pairs produced by decays in the dense medium from such ones which originate from decays after the disintegration of the dense system.

The aim of the present note is to explore the extension of the usual analysis of the invariant mass spectrum \( dN/dM^2 \) to the more informative double-differential spectrum \( dN/dM^2 \, dM^2_\perp \), where \( M_\perp = \sqrt{M^2 + Q^2_\perp} \) is the transverse mass of the pair with transverse two-momentum \( Q_\perp \) perpendicular to the beam axis. As shown in [16] within a schematic fireball model, such an extension with suitable kinematical cuts allows to avoid the majority of the above mentioned difficulties in extracting information on the in-medium vector meson spectral function. Here we present results of our calculations of double-differential di-electron spectra in heavy-ion collisions at SIS18 energies obtained within a transport model of Boltzmann-Uehling-Uhlenbeck (BUU) type.

II. DI-ELECTRON PRODUCTION AND VECTOR MESON SPECTRAL FUNCTION

As elementary processes for the \( e^+e^- \) production we employ pion annihilation \( \pi^+\pi^- \rightarrow \rho \rightarrow e^+e^- \), direct vector meson decays \( V \rightarrow e^+e^- \) with \( V = \rho, \omega \), pion - nucleon and nucleon - nucleon bremsstrahlung, and Dalitz decays of mesons, \( \Delta \) and \( N^* \). Pions are produced solely in baryonic resonance decays, and these resonances are created either in baryon - baryon collisions via \( BB \rightarrow BB \) with \( B = N, \Delta, N^* \) or in meson - baryon collisions \( MB \rightarrow B \).
with \( M = \pi, \rho, \sigma \), while the “direct vector mesons” emerge in the elementary reactions \( BB \to VNN \) or \( \pi B \to VN \). Our treatment of these processes is described in some detail in [18]. To be specific, let us list our perturbative treatment of the \( \rho \) and \( \omega \) channels.

We use the parameterization [17] of the total cross section \( \sigma^{\text{vac}} \) for \( \pi^+\pi^- \to \rho \to e^+e^- \) in vacuum

\[
\sigma^{\text{vac}}(M) = \frac{4\pi}{3} \left( \frac{\alpha}{M} \right)^2 \sqrt{1 - \frac{4m^2_\pi}{M^2}} \frac{\tilde{m}_\rho^4}{(M^2 - \tilde{m}_\rho^2)^2 + (\tilde{m}_\rho \tilde{\Gamma}_\rho)^2} \tag{1}
\]

with \( \tilde{m}_\rho = 775 \text{ MeV}, \tilde{m}_\rho = 761 \text{ MeV}, \tilde{\Gamma}_\rho = 118 \text{ MeV} \) to generate the in-medium spectrum by

\[
\sigma(M) = \frac{m^2_\rho(n)}{m^2_\rho(0)} \frac{A(M; m_\rho(n), \Gamma_\rho(n))}{A(M; m_\rho(0), \Gamma_\rho(0))}, \tag{2}
\]

where the spectral function is

\[
A(M; m_\rho, \Gamma_\rho) = \frac{1}{\pi} \frac{m_\rho \Gamma_\rho}{(M^2 - m^2_\rho)^2 + (m_\rho \Gamma_\rho)^2}, \tag{3}
\]

with mass dependent width

\[
\Gamma_\rho(n) = \Gamma_\rho^{(0)}(n) \left( \frac{\sqrt{M^2 - 4m^2_\pi}}{\sqrt{m^2_\rho(n) - 4m^2_\pi}} \right)^3. \tag{4}
\]

Below we employ certain parameterizations of \( \Gamma_\rho^{(0)}(n) \) and \( m_\rho(n) \).

Similar to the case of \( \pi^+\pi^- \) annihilation, the distribution of in-medium decays of directly produced \( \rho \) mesons into \( e^+e^- \) follows in local density and pole mass approximation from\(^1\)

\[
\frac{d\sigma_{e^+e^-}}{dM} = \sigma_\rho(\sqrt{s}) 2M A(M; m_\rho(n), \Gamma_\rho(n)) Br(\rho \to e^+e^-) \tag{5}
\]

with the branching ratio of \( Br(\rho \to e^+e^-) = \Gamma(\rho \to e^+e^-)/\Gamma(\rho, \text{tot}) \), so that all in-medium effects are related to the modification of the vector-meson spectral function. We take the default value of \( Br \) as in vacuum, i.e., assume that the e.m. decay width and the total width change in the same manner. Such a choice of the branching ratio allows us to avoid an artificial change of the relative contributions of \( \rho \) and \( \omega \) mesons (see below for the case of the density dependent \( \omega \) mass shift). In Eq. (5), \( \sigma_\rho(\sqrt{s}) \) is a parameterization of the total cross section. For \( NN \to NN\rho \) we use \( \sigma_\rho = F_\rho S(\xi x^y)/(\xi + x)^2 \), where \( x = (\sqrt{s} - m_\rho(n))/\text{GeV} \) and \( S = 1, F_\rho = 1.5 \text{ mb}, \xi = 1.4, y = 1, z = 2 \). In case of \( N\Delta (\Delta\Delta) \) collisions the scaling factor \( S = 0.75 (0.5) \) is employed. The \( \pi N \to N\rho \) reaction is similarly parameterized, but \( F_\rho = 1.5 \)

\(^1\)This contribution is of sub-leading order (see below), therefore, an estimate of the maximum yield at pole position is sufficient here.
mb, \( \xi = 0.018, y = 2.2, z = 3.5 \). The scaling factors \( S \) here are 0.375 for \( \pi \Delta^{++} [\Delta^-] \), 0.125 for \( \pi^+ \Delta^0, \pi^- \Delta^+ \), and 0.25 for \( \pi^0 \Delta \).

The \( e^+ e^- \) decay spectrum of \( \omega \) mesons follows from

\[
\frac{d\sigma_{e^+e^-}}{dM} = \sigma_\omega \int_0^\infty dt \exp \{-\Gamma_\omega(n)\gamma t\} 2M A(M; m_\omega(n), \Gamma_\omega(n)) Br(\omega \to e^+e^-),
\]

where the path through matter with local density \( n(t, \vec{x}) \) is followed. \( \gamma \) is the Lorentz factor according to the velocity, and \( Br(\omega \to e^+e^-) \) denotes the vacuum branching ratio. The production cross section \( \sigma_\omega \) is given by the above parameterization with \( F_\omega = 0.36 \) mb, \( \xi = 1.25, y = 1.4, z = 2 \) for the reaction \( NN \to NN_\omega \) with the same scaling factors as for the \( \pi N \to N_\rho \) reaction and corresponding isospin channels. The reaction \( \pi N \to N_\omega \) follows from \( F_\omega = 1.38 \) mb, \( \xi = 0.0011, y = 1.6, z = 1.7 \), where the appropriate scaling factors \( S \) are 0.5 for \( \pi^0 N[N^*] \), 1 for \( \pi^+ n \) or \( \pi^- p \), and all others as above.

### III. NUMERICAL RESULTS

According to our experience [18], the di-electron spectra roughly scale when changing the mass numbers of the colliding nuclei. We choose, therefore, the scaled cross section \( d\sigma^{\text{scal}}/dM = \pi R^2 A^{-2} dN(b = 0)/dM \) with \( R = A^{1/3} \) 1.124 fm. Since we are going to demonstrate the advantage of certain observables for the case of strong medium effects, we focus on central collisions of gold nuclei at a beam energy of 1 AGeV.

First we use the parameterization \( \Gamma_\rho^0(n) = a \Gamma_\rho, m_\rho(n) = m_\rho - \Delta m_\rho \) with constant values of \( a \) and \( \Delta m_\rho \). This is schematic and aimed at verifying the previous finding [16] that a strong in-medium broadening of the vector meson widths smears out the \( \rho \) meson peak in the invariant mass spectrum, while the double-differential spectrum still allows to identify the \( \rho \) peak. This set should also illustrate the separate effects of mass shifts. While in [16] a fireball model with thermal and chemical equilibrium was used to calculate the di-electron spectra, here both these conditions are not longer required. Moreover, to contrast the present study with the one in [16] we switch off any rescattering of the \( \rho \) and \( \omega \) mesons once created thus not allowing thermalization and chemical equilibration of these species.

In Fig. 1 we exhibit the resulting double-differential cross section \( d\sigma^{\text{scal}}/dM dM_\perp \) for the parameters \( a = 3 \) and \( \Delta m_\rho = 0 \). Let us first consider the invariant mass spectrum arising by the full \( M_\perp \) integration (see lower panel in Fig. 1). We are interested in the invariant mass region \( M > 400 \) MeV, where obviously the pion annihilation channel \( \pi^+ \pi^- \to \rho \to e^+e^- \) dominates over Dalitz decay and bremsstrahlung contributions. The \( \omega \) peak sticks out, but the chosen broadening is so strong that any peak structure, attributable to the \( \rho \) meson by pion annihilation, disappears. Instead, a knee is reminiscent of the \( \rho \). This is the general expectation that a spectroscopy of the \( \rho \) meson becomes impossible due to broadening [6]. However, selecting an appropriate \( M_\perp \) window, say \( 850 \) MeV < \( M_\perp < 950 \) MeV, the \( \rho \) peak becomes clearly visible, even for the assumed extreme broadening (see upper panel in Fig. 1). Due to phase space weighting, the \( \rho \) peak position appears slightly shifted to smaller mass. At the high-\( M \) wing the direct \( \rho \) contribution and the pion annihilation yield compete. The \( M_\perp \) window around 900 MeV seems most suitable, as it represents a
compromise of suppressing unwanted background, not cutting off kinematically the \( \rho \) peak, and still allowing for sufficient statistics.

Next let us consider the effect of a mass shift, which is strongest for the \( \rho \) meson according to many predictions. Fig. 2 demonstrates for \( a = 3, \Delta m_\rho = 150 \) MeV that the above found features are persistent also in case of quite drastic mass shifts. The upper panel in Fig. 2 illustrates, indeed, that such a strong mass shift of the \( \rho \) meson is clearly visible even in case of the strong broadening in the spectrum \( d\sigma^{\text{scal}}/dM dM_\perp|_{M_\perp=850\ldots950\text{MeV}} \), while for the chosen parameters the invariant mass spectrum does not exhibit any \( \rho \) peak, due to the assumed strong broadening (see lower panel in Fig. 2).

Figs. 1 and 2 show that for identifying the \( \omega \) meson still the invariant mass spectrum is enough: For in-medium changes covered by the parameterization of set (i) there is no obvious advantage by a particular \( M_\perp \) selection. The important point here is that the \( \omega \) meson rides on the pion annihilation background.

Note that in Figs. 1 and 2 the distributions are according to the spectral function Eq. (3) and the phase space; in line with the model assumptions (no density dependence of \( \Delta m_V \) and \( \Gamma_V \), no rescattering), there is no need of an explicit propagation of the spectral function.

Let us now turn to temporal and spatial variations of the density which cause an additional distribution of the vector meson decay strength. Also here, the usefulness of the double-differential cross section with appropriate kinematical cuts still applies. We focus on an illustration of the \( \omega \) mass shift. Since the \( \omega \) in vacuum is a narrow resonance, often it is assumed to survive the dense stages during a heavy-ion collision and to decay after freeze-out with its vacuum parameters. Therefore, the \( \omega \) in-medium spectroscopy is considered as more useful in reactions of elementary projectiles with a nucleus under special kinematical conditions in which the \( \omega \) is roughly at rest and decays inside the static matter. We would like to analyze here the prospects of the \( \omega \) in-medium spectroscopy in heavy-ion collisions.

In focusing on the \( \omega \) meson, we leave for the moment being the \( \rho \) meson parameters unattached (i.e., take vacuum parameters) and choose \( m_\omega(n) = m_\omega - \delta m_\omega n/n_0, \Gamma_\omega(n) = \Gamma_\omega(n = 0) + \delta \Gamma_\omega n/n_0 \) with \( \delta m_\omega = 70 \) MeV and \( \delta \Gamma_\omega = 50 \) MeV entering the spectral function of the \( \omega \) which is of the form of Eq. (3). Given the still sufficiently narrow width of the in-medium \( \omega \) we propagate the peak according to local conditions and distribute it at each time instant with the spectral function Eq. (3) and sum up the decay products, cf. Eq. (6). These procedure is acceptable only for sufficiently narrow resonances (see discussion in [19]). Since the number of \( \omega \) mesons is normalized, an increase of the width means a reduction of the peak height. For the selected parameters, the \( \omega \) peak for the above in-medium parameters has a contribution from in-medium decays and vacuum decays. The first one shows clearly the down shift and the smearing due to the density dependence, see lower panel in Fig. 3. The vacuum peak sticks not longer so much above the pion annihilation yield. The in-medium and vacuum \( \omega \) contributions compete with the \( \rho \) contribution from \( \pi^+\pi^- \) annihilation. To increase the relative contribution of in-medium \( \omega \) decays, in [20] it has been proposed to select low-\( Q_\perp \) di-electrons which stem from very slow \( \omega \) mesons which decay in the medium, in contrast to fast \( \omega \) mesons which traverse quickly the medium and decay outside. This feature is also seen in our simulations for heavy-ion collisions in the upper panel in Fig. 3, where we selected di-electrons with \( Q_\perp < 100 \) MeV: the vacuum contribution becomes significantly less, while the in-medium \( \omega \) contribution is clearly seen as a shifted bump riding on the \( \pi^+\pi^- \) annihilation background. This is in contrast to the invariant
mass spectrum which is integrated over all $Q_\perp$ (see lower panel in Fig. 3) where the strong competition between the wanted $\omega$ meson signal and the $\pi^+\pi^-$ annihilation background makes a conclusion on an in-medium $\omega$ mass shift difficult. Therefore, the measurement of the double-differential di-electron spectrum at low values of $Q_\perp$ offers much better chances to verify a $\omega$ meson mass shift. Further cuts, e.g. setting an additional narrow rapidity window around mid-rapidity, suppress too strongly the yield but do not enhance efficiently enough the in-medium contribution.

With respect to the latest HADES $e^+e^-$ measurement in carbon - carbon collisions, we mention that in our simulations of central collisions C + C the $Q_\perp$ dependence is similar to the case of Au + Au. However, for C + C the "in-medium $\omega$ shoulder" appears below the $\pi^+\pi^-$ channel, since the in-medium $\omega$ contribution is attenuated due to the shorter life time and the smaller volume of compressed nuclear matter. The vacuum decay contribution dominates, even for small values of $Q_\perp$.

Finally, we would like to comment on the above choice of $Br = Br^{\text{vac}}$, which assumes that $\Gamma(\omega \to e^+e^-)$ and $\Gamma(\omega, \text{tot})$ scale in the same manner in medium. In contrast, often an in-medium change of $\Gamma(\omega, \text{tot})$ is assumed, and $\Gamma(\omega \to e^+e^-)$ is kept constant (cf. [15] for a discussion). In the latter case the in-medium contribution is noticeably suppressed, as evidenced in Fig. 4. Clearly, this issue, as the treatment of dynamical in-medium effects of $\rho$ and $\omega$ on a common footing, needs further investigations.

### IV. SUMMARY

Our results can be summarized as follows: (i) The spectrum $d\sigma/dM\,dM_\perp$ for $850\,\text{MeV} < M_\perp < 950\,\text{MeV}$ as a function of $M$ is dominated in the region $400\,\text{MeV} < M < 800\,\text{MeV}$ by the channel $\pi^+\pi^- \to \rho \to e^+e^-$ with a pronounced $\rho$ bump. This gives a good chance to measure the in-medium $\rho$ meson spectral function by a double-differential di-electron spectrum in heavy-ion collisions at SIS18 energies. (ii) By selecting di-electrons with small enough transverse momentum $Q_\perp < 100\,\text{MeV}$ one can isolate the in-medium $\omega$ decay contribution which signals the in-medium mass shift and a broadening of the $\omega$ meson. This $Q_\perp$ dependence may be useful for future $\omega$ spectroscopy. (iii) Bremsstrahlung and Dalitz decays are small in the region $M > 400\,\text{MeV}$, for the considered beam energies.

Our findings, which are not to be understood as quantitative predictions, also show that fairly independently of the specific form of the vector meson spectral function the double-differential di-electron spectrum with suitable cuts allows a better access to the in-medium effects and, therefore, can be an appropriate measurement strategy in HADES experiments.

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FIG. 1. Contributions to the di-electron spectrum $d\sigma^{\text{scal}}/dM$ for various bins of $M_\perp$ for central collisions Au(1 AGeV) + Au. A resonance broadening by a factor $a = 3$ is assumed as in [16] for both $\rho$ and $\omega$; no mass shift.
FIG. 2. As in Fig. 1 but with additional mass shift $\Delta m_\rho = 150$ MeV.
FIG. 3. Contributions to the di-electron spectrum $d\sigma^{\text{scal}}/dM$ for various bins of $Q_{\perp}$ for central collisions Au(1 AGeV) + Au. The parameters are $\delta\Gamma_\omega = 50$ MeV and $\delta m_\omega = 70$ MeV. For an orientation, also the $\rho$ contributions are shown, but with vacuum parameters.
FIG. 4. As in Fig. 3, but with an $\omega$ branching ratio as described in text.