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DILEPTON PRODUCTION IN HEAVY ION COLLISIONS*

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Dilepton spectroscopy in heavy ion collisions is one of the most promising tools to investigate hadron properties in hot and dense nuclear matter. Spectral functions of light vector mesons, in particular short lived ρ, are the key observables to study such effects. The connection of the mesons to virtual radiation from hot and dense nuclear matter is emphasized. Recent experimental results on dilepton production in relativistic heavy ion collisions obtained by various experiments at RHIC, SPS and low energy SIS/Bevelac facilities are presented and discussed.

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1. Introduction

V. Metag has presented motivation and status of search for in-medium mass modifications in elementary reactions [1]. In this experimental approach one probes spectral functions of light vector mesons $\rho(770)$, $\omega(782)$ and $\phi(1020)$ at normal nuclear matter density $\rho_0 = 0.17\ 1/\mathrm{fm}^3$ and no thermal excitation using photon or proton beams and nuclear targets.

In the heavy collisions we are able to compress ($\rho \sim 4-5\rho_0$) and to heat nuclear matter to temperatures even above the critical $T_\mathrm{c} \sim 170\,\mathrm{MeV}$, where transition from ordinary hadron gas to quark–gluon plasma is expected. Experiments using heavy ion collisions are the only possibility on earth to explore nuclear matter in conditions similar to those which appeared few microseconds after the Big Bang. In particular, one hopes to understand the mechanism of spontaneous chiral symmetry breakdown responsible for hadron mass generation which presumable took place during this stage of the universe evolution. Thus, the central questions addressed in these experiments are: Can we observe phase transition of hadronic matter? Can

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we experimentally verify that hadron masses change in nuclear medium? If yes, how this effect is related to chiral symmetry restoration.

The answer on the last question is the main motivation for the dilepton spectroscopy. Dileptons offer a unique possibility to directly access in-medium masses of hadrons because they do not experience strong final state interactions. However, using heavy ion collisions we do not create infinite, long-lived hot and dense nuclear matter. In contrary, created fireball changes its properties very rapidly, hence radiation of particles has to be integrated over the whole fireball evolution.

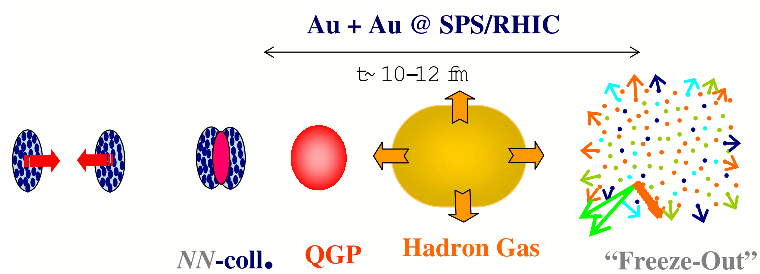


Fig. 1. Schematic view of phases in heavy ion collisions.

Fig. 1 shows schematic picture of the most important phases of ultra-relativistic heavy ion collision (URHIC) created at the CERN SPS ($6 < \sqrt{s} < 30$ GeV) or RHIC ($\sqrt{s} = 200$ GeV) energies. In the first stage (formation phase) dileptons are produced in hard, first chance nucleon–nucleon interactions. Energy density of up to 15 GeV/fm^3 can be reached in the formation phase at the top RHIC energies. Such density exceeds critical value of around 1 GeV/fm^3, predicted by the QCD lattice calculation [2]. In the next stage created partonic plasma expands and cools down, crossing again phase boundary, and turns into hot and dense hadronic phase (Hadron Gas) which freezes out 10–12 fm/c after initiation of the collision. This phase of the collision is the most interesting for our studies because it covers the time range from the birth of hadrons inside hot and dense phase to their freeze-out, where hadrons restore vacuum properties. It is the phase we can expect dramatic changes of the hadronic spectral functions.

The expected dielectron (e^+e^-) spectrum is shown in Fig. 2 [3]. Various phases of the collision are reflected in the pair invariant mass distribution: high mass region is dominated by radiation from the first stage of collision (< 0.1 fm) where quark–quark annihilation (Drell–Yann process) and heavy charmonium production take place. Intermediate mass region is governed by the open charm ($D, \bar{D}$) production whereas low mass region is populated by the radiation from the Hadronic Gas phase (< 10 fm). In the low mass region, two body decays of the light vector mesons ($\rho/\omega/\phi$) and Dalitz decays of π^0 and η dominate. The most important part takes place **before Chemical Freeze-out**, where particle composition of the fireball is settled. Therefore, the strategy of dilepton spectroscopy in heavy ion collisions is to extract the "in-medium" pair spectrum by subtracting from the total yield the contribution from free hadron decays at the freeze-out stage. This contribution, called **hadronic "cocktail"**, is known in a model independent way since production yields of the long-lived π^0,η,ω,ϕ mesons are known from other heavy ion experiments, where the mesons are identified by means of their hadronic decay channels. Alternatively, one can use the meson cross sections measured in nucleon–nucleon collisions appropriately scaled by the number of charged particles measured in the experiment (for more details see for example [4]).

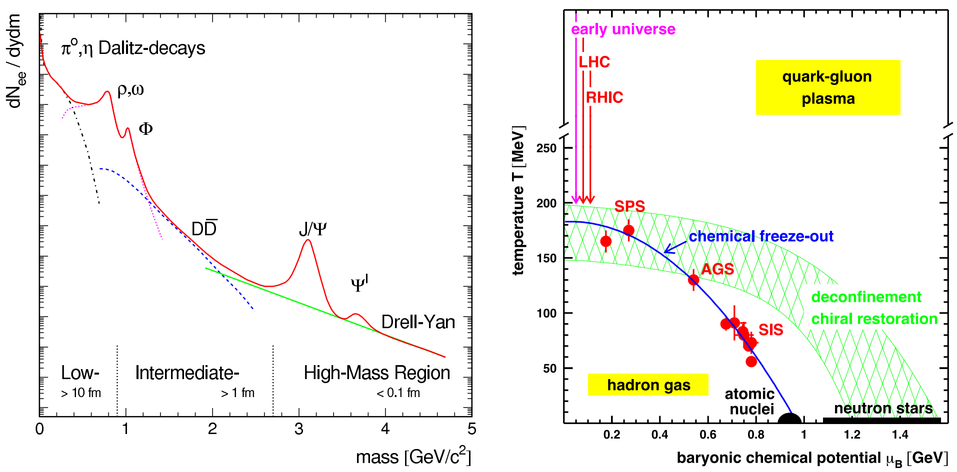


Fig. 2. Left: Expected sources of dielectron production as a function of invariant mass in URHIC [3]. Right: Nuclear matter phase diagram in the temperature and baryon chemical potential plane. Freeze-out points are extracted from particle ratios at SIS, AGS, SPS [5].

The evolution path of the colliding system in the nuclear matter phase diagram can be varied by changing the beam energy. This allows for investigation of the hadron spectral functions over the broad range of temperature and density. Fig. 2 (right) shows such diagram in a plane of the temperature T and the chemical potential μ_b (related to baryonic density) with indicated points of the chemical freeze-out determined by means of statistical model from particle ratios measured at various energies [5]. At the low beam energies, available at SIS/Bevalac, created nuclear matter can be characterized by moderate temperatures $T = (60–80)$ MeV and baryon densities of 2–3ρ_0. At energies of AGS, even higher densities can be reached but temperatures are still below expected for the phase transition (denoted by the shaded band). At SPS baryonic chemical potential decreases and reaches for the top RHIC energies $\mu_b \sim 30\,\mathrm{MeV}$ and freeze-out temperatures close to the $T_\mathrm{c} \sim 170\,\mathrm{MeV}$ [6]. Small μ_b indicate almost full restoration of baryon–antibaryon symmetry. For the dilepton production it means that composition of hadronic sources contributing to the invariant mass spectrum drastically change from the SIS to RHIC energies. At the lowest energy of SIS and AGS, excitation of baryon resonances (N^* and Δ) with subsequent decays into virtual photon dominates the invariant mass distribution. On the other hand, at the SPS and RHIC energies abundant meson production via string fragmentation plays a major role [7].

2. Radiation from the hot and dense hadronic matter

Dilepton radiation rate from a hot hadronic source in a thermal equilibrium is formally given by [8, 9]:

$$\frac{dR}{M_{ee}} = -\alpha^2 \frac{L(M_{ee}^2)}{3\pi^2 M_{ee}^2} \int dt V_\mathrm{FB}(t) \int \frac{d^3q}{q_0} f^\mathrm{B}(q_0, T)\,\mathrm{Im}\,\mathit{\Pi}_\mathrm{em}(M, q)\,, \qquad (1)$$

where α is the fine structure constant, M_{ee}, q, q_0 is the dilepton mass, momentum and energy, $L(M_{ee})$ is the phase factor and $f^\mathrm{B}(q_0, T)$ is the Boltzmann thermal distribution function depending on dielectron energy and bath temperature. The first integration takes into account fine life-time and volume of the fireball. The interesting physics, however, is encoded in the imaginary part of the time ordered electromagnetic quark–quark current correlator $\mathit{\Pi}_\mathrm{em}$ given as the thermal average:

$$\mathit{\Pi}_\mathrm{em} = -i \int d^4x\, \langle j_\mathrm{em}(x)\,|j_\mathrm{em}(0)\rangle_T\,, \qquad (2)$$

where $j_\mathrm{em} = e_q \bar{q}\gamma_\mu q$ is the mentioned quark electromagnetic current (γ_μ are the Dirac matrices). $\mathit{\Pi}_\mathrm{em}$ is experimentally well known in vacuum since it is related to the ratio R of the cross sections of the $e^+e^- \to$ hadrons to $e^+e^- \to \mu^+\mu^-$ [10]. At high $\sqrt{s} \geq 1.5\,\mathrm{GeV}$ R is well understood within perturbative QCD. It is expressed by means of quark (u, d, s) charges (e_q) and number of colors (N_c):

$$-12\pi\,\mathit{\Pi}_\mathrm{em}(M) = R = N_c \sum_{u,d,s} (e_q)^2 \left(1 + \frac{\alpha_s}{\pi} + \ldots\right)\,. \qquad (3)$$

At lower invariant masses one can see a strong contribution of the $\rho/\omega/\phi$ resonances. Fig. 3 (bottom) shows a recent compilation of data of $R/(12\pi^2)$ [3]. Upper part of Fig. 3 shows R for $I = 1$ (isovector), selected by the hadron production involving even number of pions, where ρ meson dominates. It is important to note that: *(i)* for $M < 1.5\,\mathrm{GeV}/c^2$ vector mesons carry the whole radiation yield — this phenomenon is called Vector Meson Dominance (VMD) *(ii)* there is a hadron–quark duality threshold around $1.5\,\mathrm{GeV}/c^2$. Dedicated calculations of the radiation from hadronic or quark–gluon gases show that both descriptions give similar radiation rate at $T \sim T_\mathrm{c}$ and is called hadron–quark duality [11].

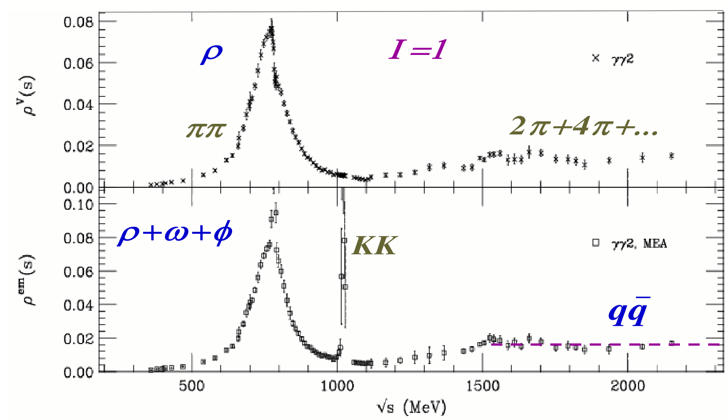


Fig. 3. Experimental cross sections ratio $R(s)/12\pi^2$ of $e^+e^- \rightarrow$ hadrons to $e^+e^- \rightarrow \mu^+\mu^-$. Upper part shows total distribution whereas lower extracted for $e^+e^- \rightarrow 2n\pi$ (isospin $I = 1$). Figure taken from [3].

As it was discussed by V. Metag, dropping of hadron masses according to the Brown–Rho scaling is a one possible scenario for in-medium modifications. Hadronic models based on many body interactions also predict significant broadening ("melting") of vector meson spectral function in nuclear matter (for recent review see [3]). These models predict even more dramatic changes of the vector meson spectral functions when heating of the medium is involved and there is no clear distinction between two scenarios. Therefore, experimental investigation of the evolution of the meson spectral functions on the phase diagram plane is considered as the most valuable information which should help to understand underlying physics. In this aspect low energy programme at SIS is specially important since it allows to study hadronic scenario in the environment governed by the baryonic degrees of freedom. This is of particular importance since in hadronic models coupling to baryons is responsible for large in-medium mass modifications.

For further discussion it is necessary to emphasize the dominant role of the ρ meson in heavy ion collisions (Eq. 1). Due to a finite fireball life time ($\tau_\mathrm{FB} \sim 10$–$12\,\mathrm{fm}/c$) and a short live time of the ρ meson ($\tau_\rho = 1/\Gamma_\rho = 1.3\,\mathrm{fm}$)

probability to decay inside the fireball $P \sim \tau_{\rm FB}/\tau_\rho * {\rm BR}_{e+e-}$ is almost an order of magnitude larger as compared to the ω or ϕ mesons. Furthermore, the main in-medium mechanism of the vector meson production in URHIC is pion annihilation ($\pi^+\pi^- \to e^+e^-$), time reversed process to the one shown in Fig. 3. The cross section for this process is proportional to the hadronic width $\Gamma_{\pi\pi}$ which is almost 3 orders of magnitude larger for the ρ as compared to the ω. Therefore, the ρ meson spectral function is the main observable for URHIC.

3. Overview of the experimental results

3.1. Results from URHIC

First dilepton data were obtained from proton–proton reactions at CERN SPS by the HELIOS (p+Be) (dimuons) [12] and later by the CERES (p+Be and p+Au) (dielectrons) [13] collaborations at beam energies of 450 GeV. Fig. 4 shows the respective invariant mass distributions measured by the CERES together with the cocktail of free hadron decays.

At low invariant masses $M < 0.6\,{\rm GeV}/c^2$ the e^+e^- yield is given by the Dalitz decays of mesons: $\pi^0(\eta) \to \gamma e^+e^-$ and, to a lesser extent, $\omega \to \pi^0 e^+e^-$. At higher masses two-body decays of the vector mesons dominate. Only very little contribution from the Drell–Yan process is expected in this mass range. The shaded region shows uncertainties related to the meson yields derived from other measurements.

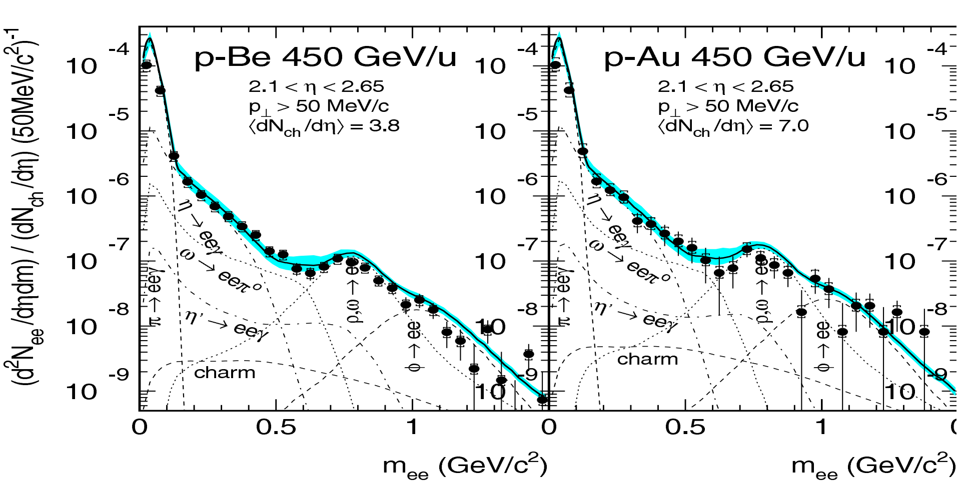
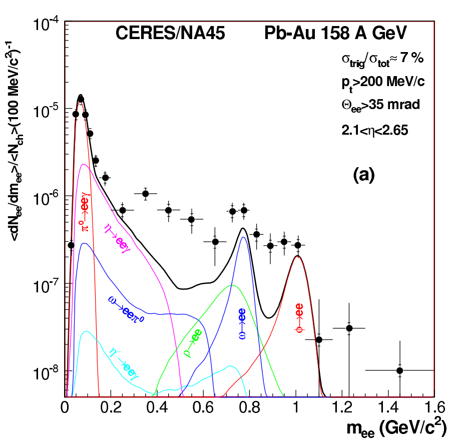


Fig. 4. Invariant e^+e^- mass distributions as measured by the CERES collaboration in p+Be (left) and p+Au (right) collisions [13]. Smooth lines show various hadron decay contributions (labeled explicitly) based on meson multiplicities measured in other experiments. Shaded bands denote systematic errors.

The situation changes drastically when going from the elementary to HI collisions. A spectacular excess of dielectron yield above the hadronic cocktail in the intermediate mass region $0.2 < M < 0.6$ GeV$/c^2$ is observed. Since the dielectron yields measured in $p + A$ and HI collisions were divided by the number of charged particles one can compare it directly to the same cocktail (after correction for slightly different $\sqrt{s}$). From this comparison it follows that the excess observed in HI is an evident in-medium effects. Fig. 5 (left) shows, as an example, recent CERES results obtained in Pb+Au collisions at 158 AGeV [14]. Similar observation has also been done in the earlier experiments investigating S+Au (CERES) [15] and S+W (HELIOS) [16] at 200 AGeV.

The main reason for the increased dielectron yield is already mentioned pion annihilation. However, the shape of the excess depends very much on the in-medium ρ shape. In order to access directly the in-medium ρ meson spectral function hadronic cocktail must be subtracted. Right part of Fig. 5 shows dielectron invariant mass distribution after subtraction of the cocktail consisting of the π^0, η and ω decays (note that ρ is not included). Resulting spectrum can be directly compared to various model calculations assuming in-medium ρ meson spectral functions folded with the fireball evolution as given by Eq. (1).



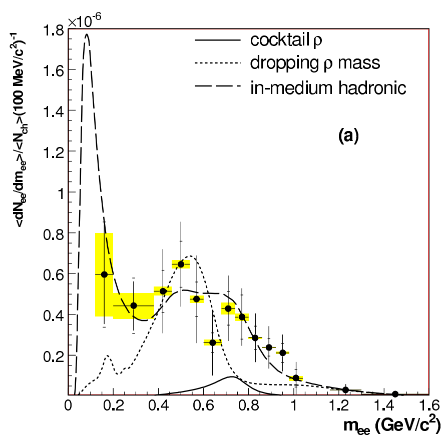


Fig. 5. Left: e^+e^- pair yield measured by CERES in Pb–Au collisions compared to the expectations from free hadronic decays (hadronic cocktail). Right: pair yield after subtraction of the cocktail. Statistical (ticks) and systematical (shaded boxes) errors are shown. Data are compared to hadronic (dashed line) and dropping mass (dotted line) scenario. Figure taken from [14].

Solid line (right panel) shows ρ contribution from the cocktail. It accounts only for a very small part of the excess. The dotted line displays predictions assuming that the in medium ρ mass scales with the density and temperature according to : $m^* = m(1 - C\rho^*/\rho_0)[1 - (T/T_{\mathrm{c}})^2]^{\alpha}$, with $C=0.15$ in accordance with the QCD sum rule estimations [17] and $\alpha=0.3$ inspired by studies of chiral condensate dependence on temperature [18]. The dashed line shows the result of calculations assuming hadronic spectral functions which take into account interactions of the ρ mesons with other mesons, baryons and particle-hole excitation of the type NN^{-1}, ΔN^{-1} and BB^{-1}. Closer inspection of all contributions reveals that the latter ones appear to be responsible for apparent shift of the ρ yield to the lower masses and, consequently, better description of the data. One should also emphasize that no scaling has been applied in the calculations [19]. In the context of quark–hadron duality discussed in second chapter, it is interesting to note that calculations assuming that e^+e^- production via $q\bar{q}$ annihilation at T_{c} is dominant describe the measured shape very well [14].

Similar conclusions can also be drown from the recent high precision NA60 measurement of dimuon production in In+In collisions at 158 AGeV [20]. Fig. 6 (left) presents dimuon invariant mass distribution (open circles) with no centrality selection. Prominent lines from two-body ω, ϕ and η dilepton decays are for the first time visible in heavy ion collisions. Solid line shows hadronic cocktail contribution derived from the peripheral data measured in the same experiment. Furthermore, the meson ratios of the cocktail are in a very good agreement with those derived from pp and p-Be data. Difference between the measured pair yield and the cocktail representing contribution from the freeze-out, is depicted by the full triangles (pair excess). The right panel of Fig. 6 shows a dimuon pair excess for semi-central In+In collisions compared to the model calculations assuming the same hadronic spectral functions (denoted as HBMT) of the ρ meson as for the CERES data [9]. Calculations are normalized in the absolute way and describe data very well. Similar calculations but with the dropping mass scenario demonstrate much worse agreement with the data and therefore support hadronic scenario (for details see [9, 20]).

The PHENIX experiment at RHIC has very recently published results on dielectron production in Au+Au collisions at $\sqrt{s} = 200\,A$GeV. For most central collisions a pair excess in the $0.15 < M < 0.75$ GeV/c^2 mass region of 7.7 ± 0.6(stat)±2.5(syst) over the hadronic cocktail has been reported [21]. It is almost 3-times larger as the one measured by the CERES [14] at $\sqrt{s} = 17.2$ GeV/c^2 Pb+Au collisions and indicate even larger strength at low masses. Furthermore, the excess increases faster with centrality then the number of participating nucleons, suggesting emission from scattering processes in dense medium. This exciting new results await theoretical interpretation.

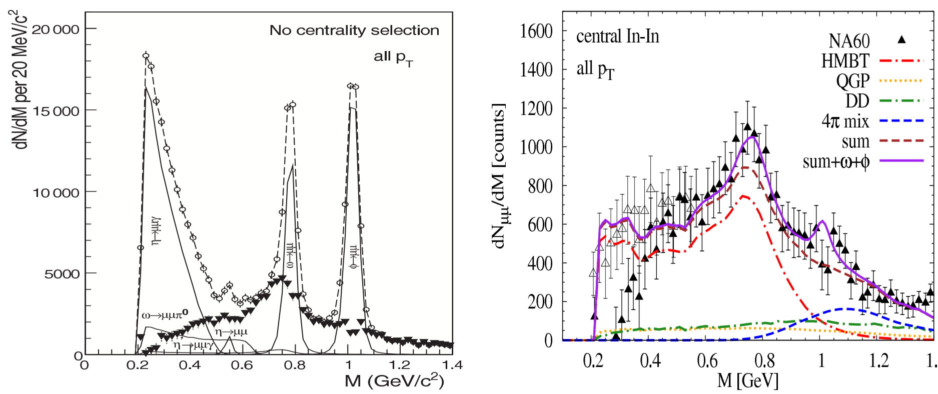


Fig. 6. Left: $\mu^+\mu^-$ pair excess above the hadronic cocktail (dashed lines) of various components (solid lines) measured by Na60 in In+In 158 AGeV collisions. Difference data are shown by thick triangles [20]. Right: Na60 pair excess compared to thermal dimuons using in-medium rates [9]. Solid line shows sum of various (labeled explicitely) components.

3.2. Results from SIS/Bevelac

Dielectron production at $1.5 < \sqrt{s} < 4$ beam energy range was investigated by the DLS collaboration at Bevelac in the middle of nineties [22, 23]. The dielectron yield measured in p–p and p–d collisions could be understood by superposition of hadron free decays. However, large data error bars and uncertainties in theory treatment of various elementary process like baryon Dalitz decays ($\Delta(N^*) \to Ne^+e^-$), NN nuclear bremmsstrahlung and vector meson production, in particular ρ, near the production threshold did not permit to derive unique conclusions. This can be clearly seen when various cocktail components predicted by different model calculations are compared in absolute way [24–26]. This somehow unsatisfactory situation calls for more precise data on elementary reactions and is one of motivations for a second generation experiment HADES at GSI. Furthermore, HI data from DLS on C+C and Ca+Ca collisions at 1 AGeV could not be properly described by none of the existing transport models even when various in-medium ρ meson spectral functions were assumed [7].

Fig. 7 presents as an example inclusive e^+e^- invariant mass distribution for Ca+Ca collisions at 1 AGeV [22]. The solid line shows hadronic cocktail obtained from the model calculations of Hadrons String Dynamics [7]. Large pair access above the cocktail, similar to this observed in URHIC, is clearly visible. This phenomenon still lacks explanation and is called a “DLS” puzzle.

First part of the HADES mission is to verify the DLS effect. To start tackling the problem, the light C+C system was investigated at two bombarding energies: 1 AGeV and 2 AGeV. Fig. 8 shows the e^+e^- invariant-mass

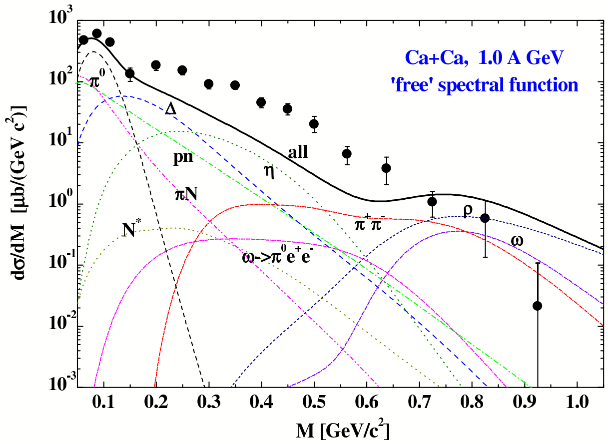


Fig. 7. e^+e^- pair yield measured in C+C at 1 AGeV by the DLS [22] compared to model calculations [7] (see text for more details).

distribution of the signal pairs normalized to the average number of charged pions $N\pi = 1/2(N\pi^+ + N\pi^-)$ measured in C+C collisions at 2 AGeV [27]. The results are compared to the hadronic cocktail, similarly as for the CERES and NA60, stemming from free π^0, η and ω meson decays (cocktail A). This cocktail accounts for all contributions emitted after the chemical freeze-out. Whereas the π^0 and η yields are directly constrained by data [28], the production rate of the ω meson is estimated assuming $m_{\rm T}$-scaling [7]. The cocktail undershoots the data for pair masses $M > 0.15\,{\rm GeV}/c^2$ (note a very good agreement in the π^0 region) and clearly calls for additional sources. Such contributions are indeed expected from the decay of short-lived baryonic resonances, mainly the $\Delta(1232)$ and the ρ meson, excited in the early phase of the collision. Including also those contributions (see [27] for details) cocktail B is shown (long-dashed line in Fig. 8). The calculation still falls short of reproducing the data.

To discuss in more detail the excess pair yield, Fig. 8 (bottom) shows the ratio F of data and cocktail A. In the intermediate mass range $M = 0.15$–0.55 GeV$/c^2$, the enhancement above the dominant η contribution is around 2 and increases for larger masses $0.5 < M < 0.7\,{\rm GeV}/c^2$ indicating shifting of the ρ strength towards the lower masses. Partially, this effect can be explained by reduced available phase for the ρ production and a strong coupling of the ρ to low lying baryonic resonances (*i.e.* $N^*(1520), \Delta(1700)$) as predicted by various transport models (different, labeled lines in Fig. 8). In analogous way the pair excess has been derived in the recently measured C+C collisions at 1 AGeV [29]. The excess is shown together with the DLS data point in Fig. 8 (right panel) as a function of beam energy. As one can see HADES and DLS are fully consistent with each other. It is also interesting to compare excitation function of the pair excess to those known for the η and π^0 inclusive productions in C+C collisions [28]. The observed energy scaling of the pair excess is remarkably similar to the known scaling of pion production but very different from the scaling expected for heavier η mesons. It suggests that the pair excess is indeed driven by pion dynamics, involving baryonic resonance excitation. In fact, this result is not surprising since at SIS energies $\sim 30\%$ of the fireball consists of excited nucleon states [30].

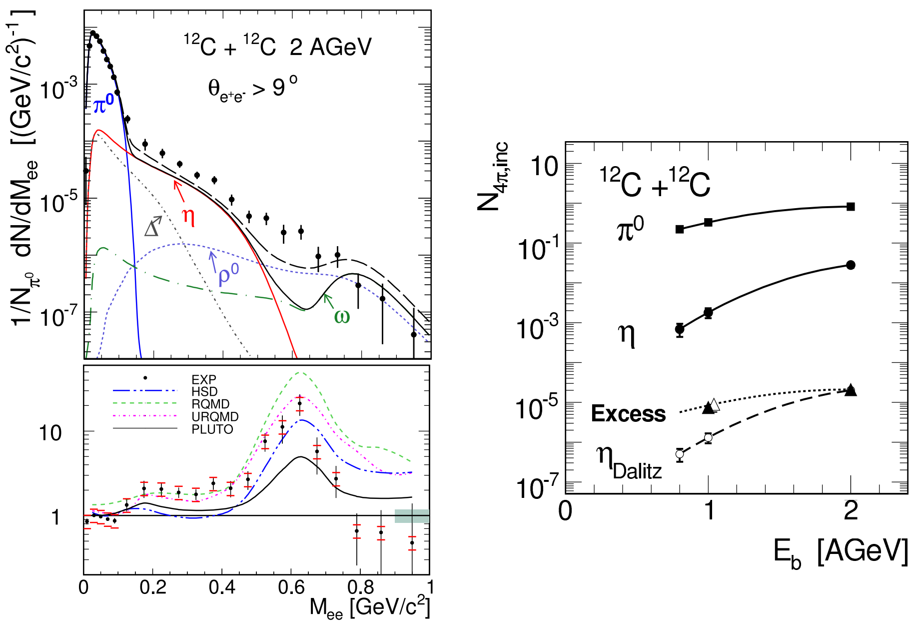


Fig. 8. Left: e^+e^- pair yield in C+C collisions measured by HADES. Solid line shows the hadronic cocktail (A), whereas the lower panel compares ratio of data to cocktail (A) to various model calculations (see text for details) [27]. Right: Excitation function of the pair excess (triangles) compared to the π and η inclusive multiplicity (solid lines) and expected η Dalitz rate (dashed line).

Recent microscopic calculations of One Boson Exchange model [31,32] indicate that Δ excitation plays also a dominant role in the NN bremsstrahlung process. It was also found that this process seems to play more important role in the dielectron cocktail as it was assumed before. It is expected that the bremsstrahlung contributes especially at lower beam energies below the η production threshold and has large isospin dependence. Whether this particular elementary process is responsible for the pair excess seen by the DLS and the HADES experiments is not completely clear. Preliminary model calculations performed with the HSD transport model indicate indeed that new OBE results are able to explain the pair access seen in the HI collisions [33]. However, the final conclusions have to wait until new precise data on e^+e^- production from $p+p$ and $p+d$ collisions, recently measured by HADES at 1.25 GeV, become available.

4. Summary and outlook

Dilepton production in heavy ion reactions over large beam energy range $1.5 \leq \sqrt{s} \leq 200\,\mathrm{GeV}/c^2$ have been measured. Clear pair excess above expected from hadron decays at the chemical freeze-out have been identified at SPS and RHIC energies. It has been connected to significant in-medium ρ mass modifications. At lower SIS/Bevalac beam energies it is not clear yet, to which extend observed pair excess is due to elementary processes, as decay of baryonic resonances or NN bremsstrahlung, and/or to in-medium vector meson modifications. Further measurements with the HADES detector at SIS should clarify this situation. It is expected that complete knowledge of the evolution of the vector meson spectral functions over the nuclear matter phase diagram should allow to understand underlying physics, of in-medium mass modifications.

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