LOW-MASS DILEPTONS IN HEAVY-ION COLLISIONS* **

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A review of low-mass dilepton production in heavy-ion collisions is presented, covering measurements performed over a very broad energy range from 1–2 AGeV at the BEVALAC or GSI, to 40–200 AGeV at the SPS and up to $\sqrt{s_{NN}} = 200$ GeV at RHIC.

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1. Introduction

Electromagnetic probes are an important and powerful tool to diagnose the hot and dense matter produced in relativistic heavy-ion collisions (RHI) [1]. They play a crucial role in the quest for the phase transition to the Quark–Gluon Plasma (QGP), the state of matter predicted by lattice QCD numerical calculations [2]. Due to their large mean-free-path, these probes do not suffer from final state interactions and once produced they can escape unaffected to the detector [3]. The interest is in the detection of dileptons and photons emitted early in the collision which can carry direct evidence of deconfinement or chiral symmetry restoration (CSR), the two fundamental properties of the QGP.

The physics potential of low-mass dileptons ($\mathrm{m}_{e^+e^-} \leq 1$ GeV$/c^2$) has been confirmed by the interesting results obtained so far. The discovery of an enhancement of low-mass e^+e^- pairs is one of the main highlights of the CERN SPS heavy-ion program. It provided evidence of the thermal radiation emitted by a high-density hadron gas via pion annihilation into dileptons ($\pi^+\pi^- \to \rho \to \gamma^* \to e^+e^-$) and it triggered a huge theoretical

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activity stimulated mainly by interpretations based on in-medium modifications of the intermediate ρ meson with a possible link to chiral symmetry restoration. (For theoretical reviews see [4–6]).

Low-mass dileptons have been studied at three different energy ranges: *(i)* 1–2 AGeV by the DLS experiment [7] at the BEVALAC followed more recently by the HADES experiment at the GSI [8, 9] ; *(ii)* 40–200 AGeV at the CERN SPS by the CERES [10–14], HELIOS-3 [15] and NA60 [16–20] experiments, and *(iii)* $\sqrt{s_{NN}} = 200$ GeV at RHIC by the PHENIX experiment [21]. An enhancement of low-mass dileptons has been observed at all energies and all systems studied although it is not clear that the enhancement reflects the same physics in all cases. There is redundancy at the two lower energies in the sense that at least two different experiments have performed similar measurements with reasonable agreement between them giving confidence on the robustness of the results. Given the difficulties of the measurements, this redundancy is an important element of the program. At RHIC energies, PHENIX is presently the only experiment capable of measuring low-mass dileptons.

In this paper I review the low-mass dilepton results focusing first on the SPS results from CERES and NA60, then on the RHIC results from PHENIX and finally on the low energy results from DLS and HADES.

2. Low-mass dileptons at the SPS

2.1. CERES results

The low-mass pair continuum has been systematically studied by the CERES experiment at CERN. In addition to the reference measurements in $p +$ Be and $p +$ Au at 450 GeV [22], CERES measured low-mass electron pairs in S + Au at 200 AGeV [10] and Pb + Au collisions at 158 AGeV [11–13] and at 40 AGeV [14]. Whereas in $p +$ Be and $p +$ Au collisions the e^+e^- mass spectrum is well described by the known hadron decays, in all nucleus–nucleus collisions studied an enhancement of electron pairs is observed in the mass region $m = 0.2$–0.6 GeV$/c^2$. Figure 1 shows the effect as observed in the last CERES data set in Pb + Au collisions at 158 AGeV compared to the cocktail of known hadronic sources. The yield is clearly enhanced with respect to the cocktail. The enhancement factor, defined as the ratio of the measured over the calculated yield in the mass range $m = 0.2$–1.1 GeV$/c^2$, amounts to $2.45 \pm 0.21(\mathrm{stat}) \pm 0.35(\mathrm{syst}) \pm 0.58(\mathrm{decays})$ (the last error represents the uncertainties in the ingredients of the cocktail calculation). CERES has also shown that the excess is mainly due to soft p_{T} pairs and that it increases faster than linearly with the event multiplicity [13].

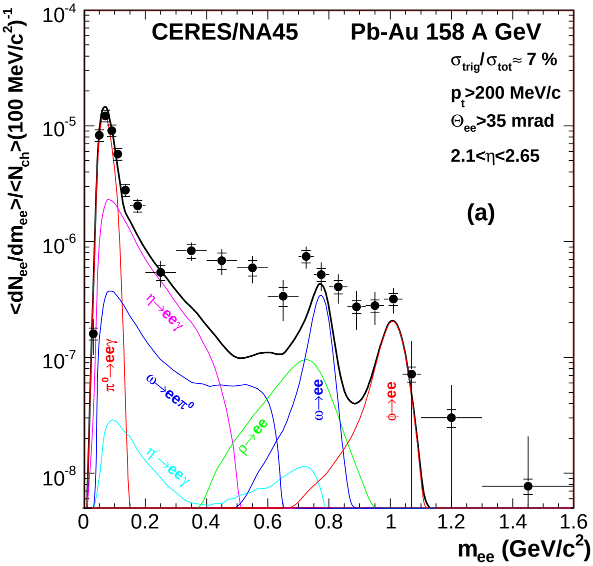

Fig. 1. The enhancement of low-mass e^+e^- pairs observed by CERES in Pb+Au collisions at 158 AGeV [11] compared to the cocktail of known hadronic sources (black line), showing also the individual contributions.

This low-mass dilepton enhancement triggered a wealth of theoretical activity due to its possible connection to CSR (for recent reviews see [4–6]). The prime candidate to explain the excess was the thermal radiation from the hadronic phase, dominated by the two-pion annihilation ($\pi^+\pi^- \to \rho \to e^+e^-$). This channel contributes a substantial yield of e^+e^- pairs below the ρ mass. However, all attempts using the vacuum ρ properties failed to quantitatively reproduce the data. To do so, it was necessary to introduce in-medium modifications of the intermediate ρ meson. Two main venues were used: *(i)* a decrease of the ρ-meson mass in the dense fireball [23] as a precursor of CSR, following the original Brown–Rho scaling [24]. In this scenario, the ρ-meson mass scales with the quark condensate $\langle\bar{q}q\rangle$ and the latter drops due to the high baryon density (rather than high temperature) of the medium and *(ii)* a broadening of the ρ-meson spectral function resulting from the scattering of the ρ meson mainly off the baryons in the dense hadronic medium [4,25,26]. Both approaches rely on the high baryon density at mid-rapidity which, at CERN energies, mainly originates from baryon stopping.

The success of these two different approaches, one relying on quark degrees of freedom, with a direct link to CSR, and the other one based on a many-body hadronic model, attracted much debate. The observation that at

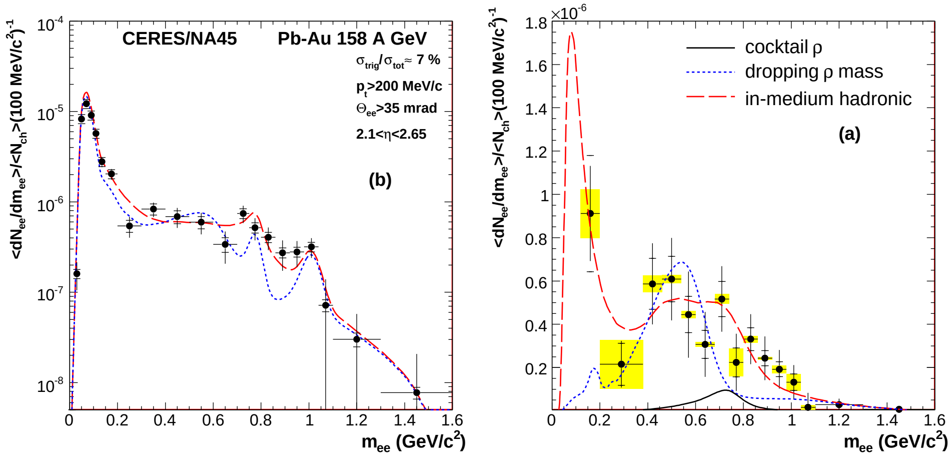

Fig. 2. CERES invariant mass spectrum of e^+e^- pairs in Pb+Au collisions at 158 AGeV (left panel) compared to calculations based on a dropping ρ mass model (dashed line) and on in-medium ρ spectral function (long-dashed line). The right panel shows the same data and the same calculations after subtracting the hadronic cocktail (excluding the ρ meson) [11].

temperatures close to the critical temperature T_C, the dilepton production rates calculated within the hadronic approach become very similar to the $q\bar{q}$ annihilation rate computed within perturbative QCD raised the interesting hypothesis of quark–hadron duality down to relatively low-masses [4,27] and provided a more direct connection of the widening of the ρ meson spectral function to CSR.

The two models give very similar results for masses m < 0.8 GeV/c^2 where the precision of the data is insufficient to discriminate between them. On the other hand, the data between the ω and the ϕ mesons favor the broadening scenario. This is better seen on the right panel, where the excess mass spectrum is plotted *à la* NA60, after subtracting from the data the hadronic cocktail excluding the ρ meson, and compared to the same model calculations.

2.2. NA60 results

NA60 measured dimuons from threshold up to ~ 5 GeV/c^2 in In + In collisions at 158 AGeV. One of the primary motivations of the experiment was to elucidate the origin of the dilepton excess discussed in the previous section.

The left panel of Fig. 3 exhibits the superb quality of the raw dimuon data in terms of resolution and statistics [16]. Whereas the spectrum in peripheral collisions is well reproduced by the cocktail of expected hadronic

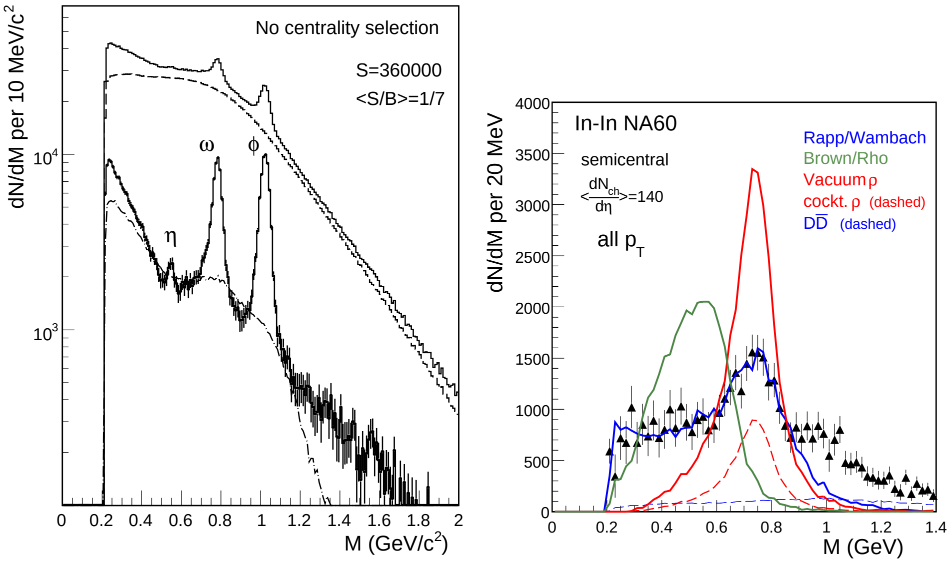

Fig. 3. NA60 data in 158 AGeV In + In collisions. Left panel: invariant mass spectra of unlike sign dimuons (upper histogram), combinatorial background (dashed line), fake signal (dashed-dotted line) and the resulting signal (lower histogram) [16]. Right panel: excess dimuons after subtracting the hadronic cocktail, excluding the ρ, compared to cocktail ρ (red dashed line), $\pi^+\pi^-$ annihilation with an unmodified ρ (red line), dropping ρ mass (dash-dotted line) and in-medium ρ broadening (blue line) [18].

sources — resonance decays of the η, ρ, ω, ϕ and Dalitz decays of the η, η', ω — this is not so any longer for more central collisions. The data show a clear excess of dimuons which increases with centrality and is more pronounced at low pair p_{T}. The results confirm, and are consistent with, the CERES results described previously. The NA60 data quality allows to go one step further. The excess mass spectrum, obtained after subtracting from the data the hadronic cocktail without the ρ is shown in the right panel of Fig. 3 (see Refs. [16–18] for details on the subtraction procedure). It exhibits a peak at the nominal position of the ρ meson mass, seating on top of a broad structure whose width and yield increase with centrality. The figure compares the excess with the two main models discussed above in the context of the CERES data: in-medium ρ broadening (blue line) according to the Rapp–Wambach model [4, 25, 26] and dropping ρ mass (green line) according to the Brown–Rho scaling [5, 24]. The data clearly rule out not only the $\pi^+\pi^-$ annihilation with a vacuum ρ which was already ruled out by the CERES data, but also the dropping ρ mass scenario. Predictions based on the many-body approach of Rapp and Wambach, reproduce very well the data for $m_{\mu^+\mu^-} \leq 0.9$ GeV$/c^2$. The deeper impact of these results is their possible relevance to the broader context of chiral symmetry restoration. If the system reaches, or is near to, chiral symmetry restoration then the dilepton results could be telling us that the approach to such a state proceeds through broadening, eventually leading to a melting of the resonances, rather than by dropping masses.

The excess dimuon mass spectrum, fully corrected for acceptance and reconstruction efficiency, with a p_{T} cut of 200 MeV$/c$ on the single muon tracks is shown in Fig. 4 covering the low and intermediate mass regions [19, 20]. The figure also shows recent calculations from three groups. The same calculations of Rapp and Wambach discussed above but including also contributions from multi-pion states, mainly 4π states, reproduce very well the data over the entire mass range [28, 29]. The calculations of Renk and Ruppert also reproduce quite well the NA60 data [30]. The low-mass excess is described there by the in-medium broadening of the ρ spectral function but at masses above 1 GeV$/c^2$ the thermal radiation from the QGP, and not the 4π annihilation, is found to dominate. Ref. [31] provides a very good description of the peripheral and semiperipheral mass excess with hadronic rates constrained by chiral symmetry arguments and experimental data.

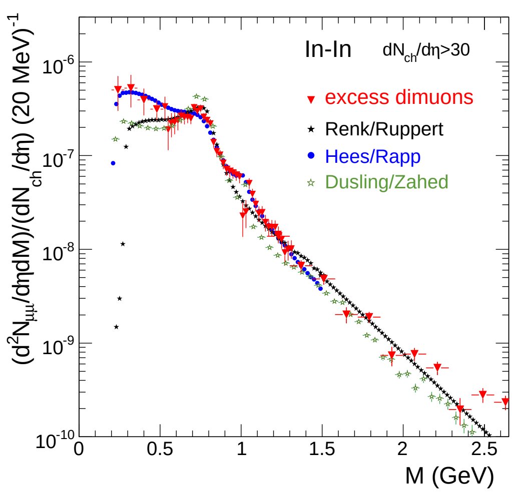

Fig. 4. Absolutely normalized excess dimuon mass spectrum corrected for acceptance and reconstruction efficiency, measured by NA60 in In + In collisions at 158 AGeV and compared to theoretical calculations of Renk/Ruppert [30], Hees/Rapp [28, 29] and Dusling/Zahed [31]. Both the data and the calculations are subject to a p_{T} cut of 200 MeV$/c$ on the single muon tracks [19, 20].

3. Low-mass dileptons at RHIC

RHIC allows the study of Au + Au collisions at energies up to $\sqrt{s_{NN}}$ = 200 GeV, more than one order of magnitude higher than the SPS top energy of $\sqrt{s_{NN}}$ = 17.6 GeV. The study of low-mass dileptons at RHIC was anticipated to be very interesting. The same model calculations that successfully reproduced the SPS results predicted that the enhancement of low-mass electron pairs persists at RHIC with at least comparable strength [32]. This is so because the *total* baryon density, the key factor responsible for in-medium modifications of the ρ meson at SPS energies, is almost as high at RHIC as at SPS [33].

The mid-rapidity spectrometers of the PHENIX detector have very good electron identification capabilities by combining a RICH detector with an electromagnetic calorimeter [34]. The experiment has also an excellent mass resolution of $\sim$ 1% at the ϕ mass, an essential requirement for precise spectroscopy studies of the light vector mesons. However, the experimental set-up is limited by a large combinatorial background. With a p_{T} cut of 200 MeV/c on single electron tracks, the signal to background ratio is of the order of S/B $\sim$ 1/200 at $m_{e^+e^-}$ = 400 MeV/c^2 in minimum bias Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

In spite of that, in a real tour de force, PHENIX mastered the mixed event technique for the evaluation of the combinatorial background to an unprecedented precision of 0.25%. Fig. 5 shows the first results of PHENIX on e^+e^- pairs measured in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV after subtracting the combinatorial background [21]. The expected yields from the light mesons, calculated using the EXODUS event generator, and from the correlated semi-leptonic decays of open charm, calculated using PYTHIA and constrained by the measured $c\bar{c}$ cross-section, are also indicated in the figure.

At very low masses, up to $\sim$ 100 MeV/c^2, the agreement is excellent; at high masses, above the ϕ meson, the continuum is fully accounted by the contribution from charm decays. In the low-mass continuum, from 150 to 750 MeV/c^2 there is a considerable excess of e^+e^- pairs, with an enhancement factor of 3.4±0.2(stat.)±1.3(syst.)±0.7(model) where the last error reflects the systematic uncertainty in the total calculated yield. The excess is concentrated at low pair p_{T} < 0.7 GeV/c [35]. For pair p_{T} > 1.5 GeV/c the Au + Au data is in reasonable agreement with the cocktail. To further characterize this enhancement PHENIX has studied its centrality dependence shown in Fig. 6 as a function of N_{part} for two mass windows. Whereas the low-mass yield ($0 < m_{e^+e^-} < 100$ MeV/c^2), dominated by π^0 Dalitz decays, is in very good agreement with the cocktail (bottom panel), the low-mass continuum ($150 < m_{e^+e^-} < 750$ MeV/c^2) shows a strong

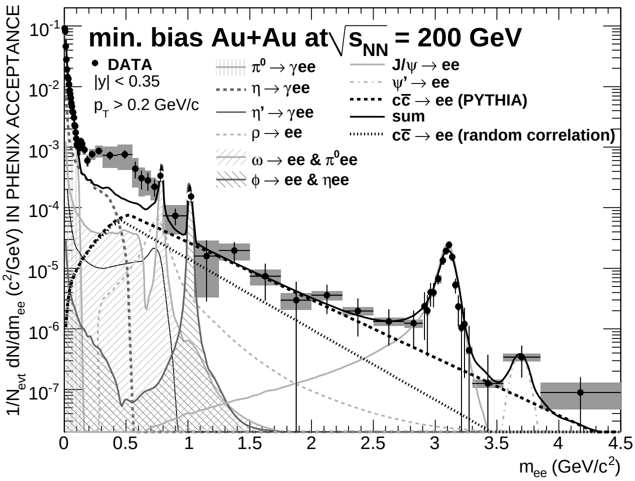

Fig. 5. Invariant mass e^+e^- spectrum measured by PHENIX in $\sqrt{s_{NN}} = 200$ GeV minimum bias Au+Au collisions at mid-rapidity. The data are compared to the expected yields from light mesons and semi-leptonic open charm decays. Statistical (bars) and systematic (boxes) errors are plotted separately. The cocktail uncertainty of 10–25% depending on mass is not shown [21].

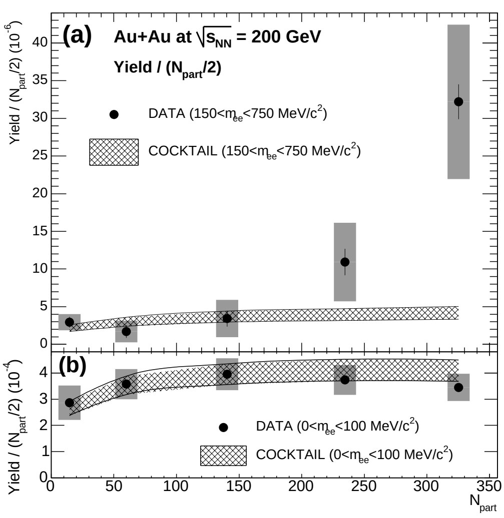

Fig. 6. Integrated yield per pair of participating nucleons as function of $N_{\rm part}$ compared to the calculated yield from the cocktail of light mesons and open charm decays, for two different mass windows, $0 < m_{e^+e^-} < 100$ MeV/c^2 (bottom panel) and $150 < m_{e^+e^-} < 750$ MeV/c^2 (top panel) from PHENIX [21].

centrality dependence (top panel). The enhancement appears concentrated in the two most central bins only, 0–10% ($\sim 2\sigma$ effect) where the enhancement reaches a factor of 7.7 and 10–20% ($\sim 1\sigma$ effect).

The PHENIX results are intriguing. They appear different from those observed at the SPS. The excess is more spread towards lower masses compared to the SPS where the excess is closer to the ρ meson. The centrality dependence is also different. Models that successfully reproduce the results of CERES and NA60, based on a broadening of the ρ meson spectral function fail to reproduce the PHENIX results [36–38]. Further experimental results will be provided by new data to be taken with the recently installed Hadron Blind Detector (HBD) [39–41]. This detector is expected to improve the S/B ratio by more than a factor of 20 bringing a new qualitative level in the PHENIX data.

4. Low-mass dileptons at low energies

The DLS Collaboration measured low-mass e^+e^- pairs in 1 AGeV C + C and Ca + Ca collisions at the BEVALAC [7]. The Ca results shown in Fig. 7 exhibit an enhancement of low-mass pairs in the mass range $m =$ 0.2–0.6 GeV/c^2, in comparison to transport model calculations based on the HSD (Hadron String Dynamics) approach that include all the expected sources and the pion annihilation ($\pi^+\pi^- \to \rho \to e^+e^-$) using the ρ meson spectral function modified in the medium [42]. The enhancement looks qualitatively similar to the one observed at the SPS. But contrary to the situation at SPS energies, all attempts to reproduce it failed [43–45]. This intriguing situation led to the denomination “DLS puzzle” that persists for almost a decade and motivated a new experiment, HADES, at the GSI.

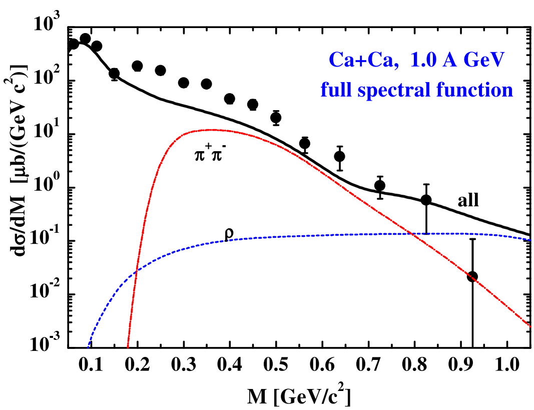

Fig. 7. DLS results in Ca + Ca collisions at 1 AGeV [7] compared to HSD calculations [42].

The first results from HADES [8, 9] are in very good agreement with the DLS results and show also an enhancement of low-mass dileptons in C + C collisions at 1 and 2 AGeV with respect to model calculations. The experimental results are therefore on a very robust ground. On the theoretical side, new transport calculations based on the HSD approach seem to get close to explaining the excess. Using an enhanced bremstrahlung contribution, in line with recent OBE (one boson exchange) calculations [46], Bratkovskaya and Cassing achieved very good agreement with the published DLS and HADES data on C + C collisions, as illustrated in the left panel of Fig. 8 [47].

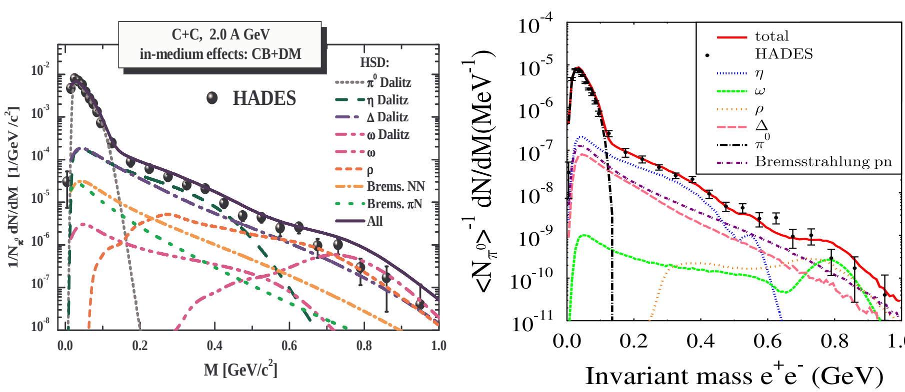

Fig. 8. Invariant mass e^+e^- pair spectrum measured by HADES in C+C collisions at 2 AGeV [8] compared to model calculations. Left panel: new HSD calculations with an enhanced bremstrahlung contribution and including collision broadening and dropping mass effects [47]. Right panel: IQMD simulations with a reduced $pn \to pn\omega$ cross-section using vacuum spectral shapes for the ρ and ω [48].

Recent IQMD calculations are also able to reproduce reasonably well the HADES C+C data at 2 AGeV by lowering the unknown cross-section $pn \to pn\omega$ (*cf.* right panel of Fig. 8) and/or invoking an in-medium mass decrease of the ω according to $m_\omega = m_\omega^0(1-0.13\rho/\rho_0)$ [48]. This emphasizes again how crucial it is to have a complete and precise knowledge of the elementary reactions for a reliable interpretation of the more complex nuclear collisions.

The measurement of elementary reactions is part of the HADES program. Preliminary results on $p+p$ and $d+p$ collisions at 1.25 AGeV show that the dielectron spectrum in C + C collisions at 1 AGeV, can be explained by a superposition of pp and pn collisions and that there is no compelling evidence to invoke any new source of dilepton or any in-medium modification of mesons. In this light system and at this low energy [49] the DLS puzzle seems to be reduced to an understanding of the elementary reactions.

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