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Probing dense and hot matter with low-mass di-leptons and photons*

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Abstract. Results on low-mass di-leptons, covering the very broad energy range from the BEVALAC up to the SPS, are reviewed. The emphasis is on the open questions raised by the intriguing results obtained so far and the prospects for addressing them in the near future with the second generation of experiments, in particular HADES, NA60 and PHENIX.

1 Introduction

Electromagnetic probes are very valuable to diagnose the hot and dense matter produced in ultra-relativistic heavy-ion collisions. They play a crucial role in the quest for the QCD phase transition to the quark–gluon plasma, the state of matter predicted by lattice QCD numerical calculations [1] and characterized by deconfinement of quarks and gluons and restoration of chiral symmetry. 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 carrying information about the conditions and properties of the medium at the time of production [2]. The interest is in the detection of di-leptons and photons emitted early in the collision which can carry direct evidence of deconfinement or chiral symmetry restoration (CSR). The challenge is to identify them among the overwhelming yield of di-leptons and photons which are produced later in the collision, after freeze-out, from hadron decays. Precision $p+p$ and $p+A$ data are therefore an essential pre-requisite for a detailed mapping of these hadronic sources.

The physics potential of low-mass di-leptons ($m_{e^+e^-} \leq 1\,\mathrm{GeV}/c^2$) has been confirmed by the interesting and intriguing results obtained so far and by the large number of new experiments focusing on their study. The main experiments are presented in Fig. 1. One can distinguish two generations. The first generation consists of experiments already completed. They covered a rather broad energy range: the DLS at the BEVALAC studied di-electron production at 1 GeV per nucleon [3], the E325 experiment at the KEK-PS studied vector meson production in cold nuclear matter using $p+\mathrm{C}$ and $p+\mathrm{Cu}$ collisions at 12 GeV [4] and the CERES experiment at the CERN SPS studied nuclear collisions from 40 up to 200 GeV per nucleon [5–8].

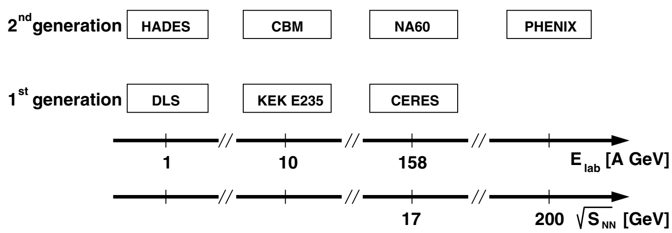

Fig. 1. Low-mass di-lepton experiments at a glance

For completeness one should also mention the HELIOS-3 [9] and the NA38/50 [10] experiments which also produced results on low-mass di-leptons. The second generation consists of four experiments. Three of them, HADES, CBM and NA60, repeat or extend under different or improved conditions the experiments of the first generation, DLS, E325 and CERES, respectively. The fourth experiment of the second generation, PHENIX, opens new ground by exploring electromagnetic probes at RHIC energies.

The discussion in this paper is limited to three topics. In Sect. 2, I review the most interesting results on low-mass di-leptons, and their possible link to chiral symmetry restoration, from the first generation of experiments emphasizing the open or controversial issues which are expected to be answered by the experiments of the second generation. In Sect. 3, I summarize the controversial results on the ϕ meson production at the CERN SPS and in Sect. 4 I examine the search for thermal radiation. A short summary is given in Sect. 5.

2 Low-mass di-leptons

2.1 Results from the CERN SPS

The low-mass pair continuum has been systematically studied by the CERES experiment at CERN in $p+\mathrm{Be}$

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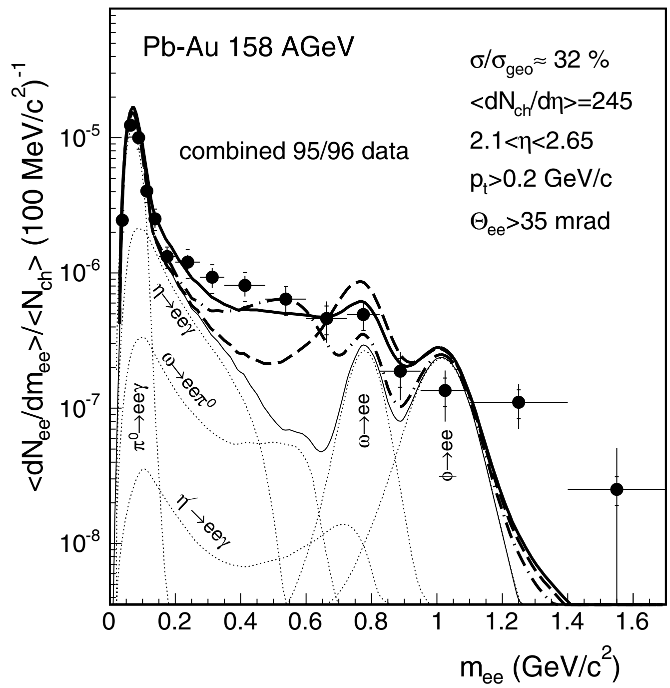

Fig. 2. CERES invariant mass spectrum of e^+e^- pairs compared to the expected cocktail of hadron decays (thin solid line). The figure includes also calculations assuming the vacuum ρ spectral shape (dashed), ρ dropping mass (dash-dotted) and in-medium ρ broadening (solid) [11]

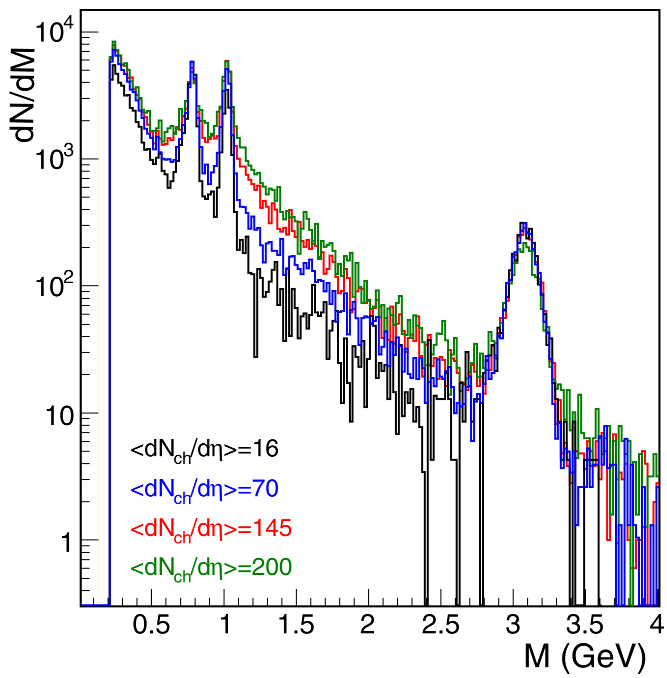

Fig. 3. Invariant mass spectra for four bins of centrality in In + In collisions at 158 AGeV, from NA60 [17]

(a good approximation to pp), $p+\text{Au}$ [5], $\text{S}+\text{Au}$ [6] and $\text{Pb}+\text{Au}$ collisions [7,8]. The results confirm the unique physics potential of this probe. The most prominent feature is the enhancement of electron pairs observed in the mass region $m = 0.2$–$0.6\,\text{GeV}/c^2$ in all heavy-ion collisions studied whereas in $p+\text{Be}$ and $p+\text{Au}$ collisions the spectrum is well described by the known hadron decays. A recent example of the enhancement observed by CERES in Pb+Au collisions at 158 AGeV from the combined analysis of the 95 and 96 runs is shown in Fig. 2 [11]. The results are presented in the form of pair production per event and per charged particle within the spectrometer acceptance and are compared to the cocktail of known hadronic sources (thin solid line). The yield is clearly enhanced with respect to this cocktail. CERES has also shown that this excess is mainly due to soft p_T pairs and that it increases faster than linearly with the event multiplicity [11].

This low-mass di-lepton enhancement is one of the highlights of the 15 year heavy-ion program at CERN. Its possible connection to CSR has triggered a wealth of theoretical activity (for recent comprehensive reviews see [12,13]). A simple superposition of pp collisions cannot explain the data and new physics has been invoked. The $\pi^+\pi^-$ annihilation channel, $\pi^+\pi^- \to \rho \to e^+e^-$, accounts for a fraction of the enhancement (dashed line) and provides first evidence for the thermal radiation emitted from a dense hadron gas. However, this process is insufficient for a quantitative description of the data. In order to do that, it is necessary to introduce in-medium modification of the intermediate ρ meson. Two main venues have been used.

(i) A decrease of the ρ meson mass in the dense fireball [14] as a precursor of CSR, following the original Brown–Rho scaling [15] (dash-dotted line). In this scenario, the ρ meson mass scales with the quark condensate $\langle \overline{q}q \rangle$ and the latter drops due to the high baryon density.

(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 [12] (solid line). Both approaches rely on the high baryon density at mid-rapidity which, at CERN energies, mainly originates from baryon stopping, and both achieve good agreement with the CERES data in the mass region $m = 0.2$–$0.6\,\text{GeV}/c^2$ (see Fig. 2). A similar or even stronger enhancement has been observed by CERES in Pb+Au collisions at 40 AGeV and this enhancement is also equally well reproduced by the two models [8]. The success of these two different approaches, one relying on quark degrees of freedom and the other one based on a pure hadronic model, has attracted much debate raising also the interesting possibility of quark–hadron duality at these relatively low-masses [16]. Precise data with high mass resolution and high statistics will be very valuable. In the mass region $m = 0.2$–$0.6\,\text{GeV}/c^2$, the two models are so similar that it will be very difficult to distinguish between them. However, at higher masses, in the region between the ω and the ϕ, the two models differ markedly as shown in Fig. 2 and the difference becomes even more pronounced with higher mass resolution. High statistics and high resolution data should therefore be able to discriminate between the two models. The CERES data obtained with the upgraded spectrometer (not yet available in a final form) seem marginal for

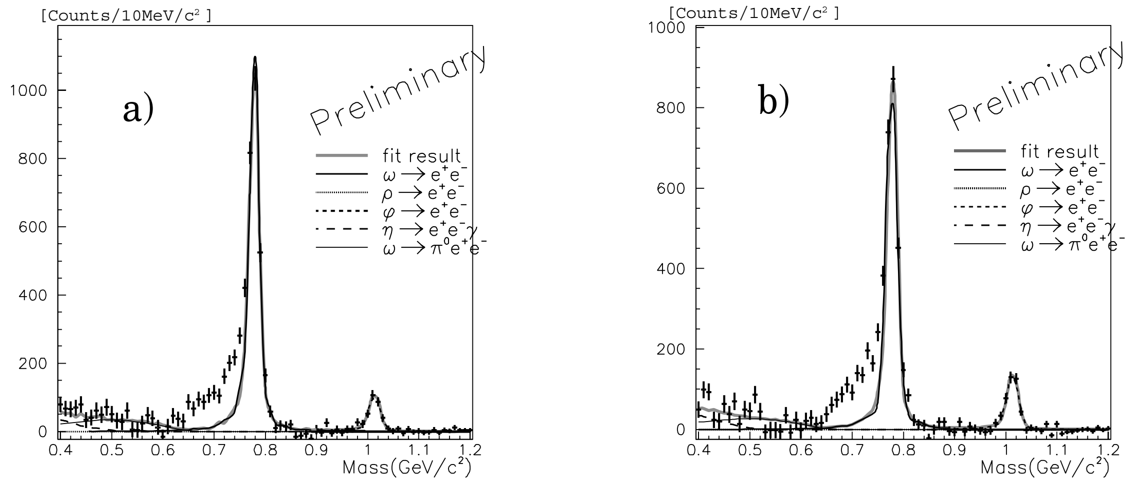

Fig. 4. Invariant mass spectra, after combinatorial background subtraction, measured in 12 GeV $p+$C **a** and $p+$Cu **b** collisions by the E325 experiment at KEK [4]

that. The NA60 experiment has the potential to achieve this goal.

NA60 has measured low-mass di-muon production in In + In collisions at 158 AGeV. Raw spectra at four centralities are shown in Fig. 3, arbitrarily normalized at the ω peak [17]. The experiment has limited p_{T} acceptance at low masses but it has an excellent mass resolution as illustrated in the figure. The ω and ϕ peaks are clearly resolved with a mass resolution of 23 MeV$/c^2$ at the ϕ. NA60 is also a high luminosity experiment. The spectra in Fig. 3 represent approximately 1/3 of the whole data sample. With such high quality data NA60 should be able to provide significant information on the low-mass di-lepton enhancement.

2.2 Results at low energies

Low-mass electron pairs have also been measured in $p+A$ collisions at 12 GeV at KEK by the E325 experiment [4]. The measurements were performed in the target rapidity region to enhance the decay probability of the virtual photon inside cold nuclear matter. An essential feature of this experiment is its excellent mass resolution, slightly better than 1% at the ϕ mass, which made it possible to observe a small but significant difference in the invariant mass spectrum below the ω meson, in $p+$C and $p+$Cu collisions; see Fig. 4 [4]. More recently, the same experiment reported the observation of similar differences below the ϕ meson [18]. Both effects are attributed to modifications of the meson spectral shape in nuclear matter at normal density as predicted e.g. by the models of Brown and Rho [15] or Hatsuda and Lee [19]. Further information in this energy regime, including nucleus–nucleus collisions, will have to await the new experiment CBM being designed at the future FAIR facility of GSI.

At even lower energies, the DLS results remain a puzzle. The DLS Collaboration has measured low-mass e^+e^- pairs in 1 AGeV Ca + Ca collisions at the BEVALAC [3]. The results are displayed in Fig. 5. In the left panel, the results are compared to a cocktail including hadron decays, proton–neutron (pn) and pion–nucleon (πN) bremsstrahlung and also the pion annihilation ($\pi^+\pi^- \to \rho \to e^+e^-$) using the vacuum or free ρ

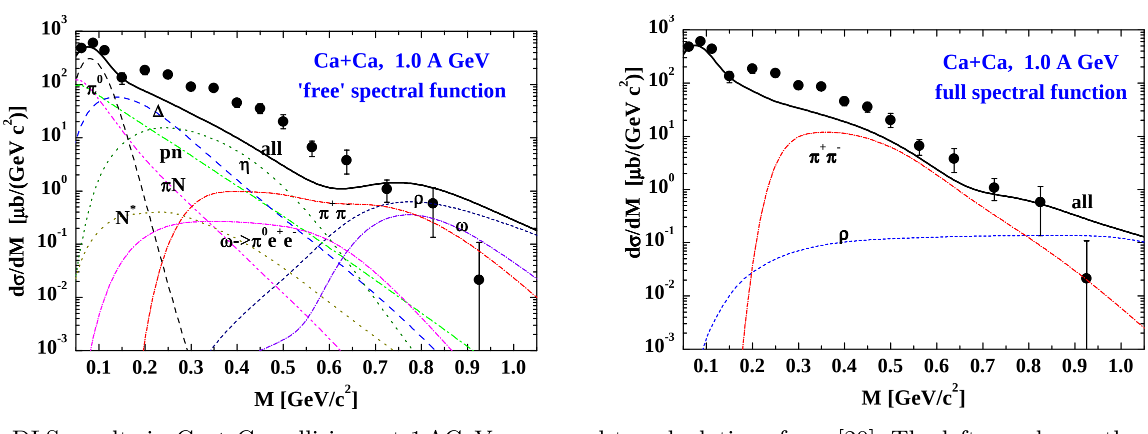

Fig. 5. DLS results in Ca + Ca collisions at 1 AGeV compared to calculations from [20]. The left panel uses the free ρ meson spectral function whereas the right panel shows the calculations with the full ρ spectral function

spectral function [20]. An enhancement of low-mass pairs is observed in the mass range $m = 0.2$–$0.6\,\mathrm{GeV}/c^2$, looking qualitatively similar to the CERES results. However, attempts to reproduce this enhancement have failed so far. The right panel in Fig. 5 compares the data with the same cocktail using this time the ρ meson spectral function modified in the medium. Part of the enhancement is explained but the calculations are still a factor of 2–3 below the data [20]. Over the last few years, the HADES experiment at the GSI has collected data on di-electron production in C + C collisions at 1 and 2 AGeV and first results should be available soon.

2.3 Prospects at RHIC

The study of low-mass electron pairs under the much better conditions offered at RHIC – higher initial temperature, larger energy density, possibly larger volume and longer lifetime of the system – promises to be very interesting. The total baryon density, which is the key factor responsible for in-medium modifications of the ρ meson at SPS energies both in the dropping mass and the collision broadening scenarios, is almost as high at RHIC as at SPS, contrary to previous expectations. At SPS, most of the baryons at mid-rapidity are participant nucleons. At RHIC there is a strong decrease in nuclear stopping but this is compensated by a copious production of baryon–antibaryon pairs such that the total baryon density is accidentally the same in both cases. Furthermore, the temperature factor which played a minor role at SPS energies is expected to be much more significant at RHIC energies. Updated calculations that incorporate results from global and hadronic observables at RHIC, predict indeed that the enhancement of low-mass electron pairs persists at the collider with at least comparable strength, as shown in Fig. 6 [21]. The figure compares the hadronic cocktail with the in-medium modified spectrum (labeled "thermal" in the figure). In addition to the ρ, the calculations also predict strong in-medium modifications of the ω and ϕ mesons. These are much less dramatic than in the case of the ρ meson but should nevertheless be readily observable with a mass resolution comparable or better than the natural width of the resonances. The figure shows that the low-mass region will also be sensitive to open charm production.

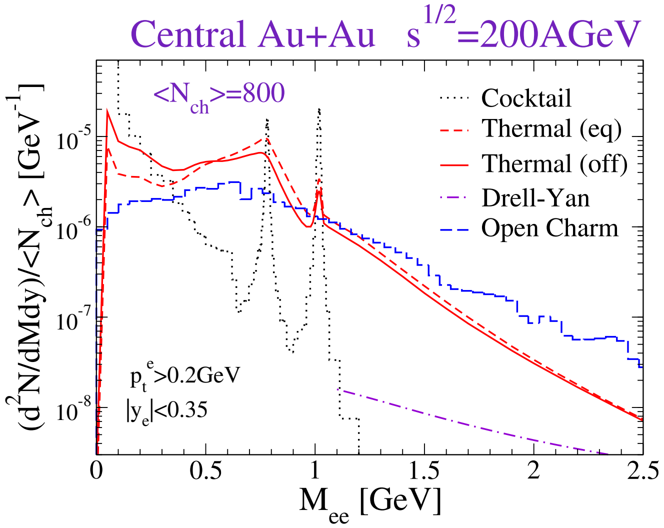

Fig. 6. Invariant mass spectrum of e^+e^- pairs emitted in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ calculated in the PHENIX acceptance comparing in-medium modified spectrum (thermal) to the cocktail of hadron decays, open charm decays and Drell–Yan annihilation [21]

PHENIX is the only experiment at RHIC that has the potential to measure low-mass electron pairs. The mid-rapidity spectrometers have good electron identification capabilities by combining a RICH detector with an electromagnetic calorimeter [22]. However, the strong magnetic field, starting at the collision vertex, causes a limited acceptance of tracks originating from π^0 Dalitz decays and γ conversions which leads to an overwhelming yield of combinatorial background pairs.

Figure 7 shows the electron–positron invariant mass spectrum from an analysis of the 2002 Au + Au data at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$, after subtraction of the combinatorial background determined with a mixed event technique [23]. The signal to background ratio is of the order of $S/B \sim 1/200$ (1/500) with a single electron p_{T} cut of 300 (200) MeV/c making the measurement of the low-mass pair continuum practically impossible.

PHENIX has developed the Hadron Blind Detector (HBD) as an upgrade to overcome this problem. The main task of the HBD is to recognize and reject electron tracks originating from π^0 Dalitz decays and γ conversions. The strategy is to exploit the fact that the opening angle of electron pairs from these sources is very small compared to pairs of heavier mass. The HBD is therefore located in a field-free region where the pair opening angle is preserved. An inner coil, recently installed in the central arms of PHENIX, counteracts the main field of the outer coils creating an almost field-free region close to the vertex and extending to ∼ 50–60 cm in the radial direction. Conceptual Monte Carlo simulations show that with an opening angle cut of ∼ 200 mrad, the combinatorial background arising from π^0 Dalitz decays and γ conversions is suppressed by approximately two orders of magnitude while preserving ∼ 50% of the signal [24].

The HBD is a windowless Cherenkov detector operated with pure CF_4, in a proximity focus configuration. The detector consists of a 50 cm long radiator directly coupled to a triple GEM detector [25] which has a CsI photocathode evaporated on the top face of the first GEM foil and a pad readout at the bottom of the GEM stack. In this scheme the Cherenkov light from particles passing through the radiator is directly collected on the photocathode forming a circular blob image rather than a ring as in a RICH detector. The validity of this novel HBD concept has been demonstrated in a comprehensive R&D program [26, 27] paving the way for the incorporation of such a detector in the PHENIX experiment.

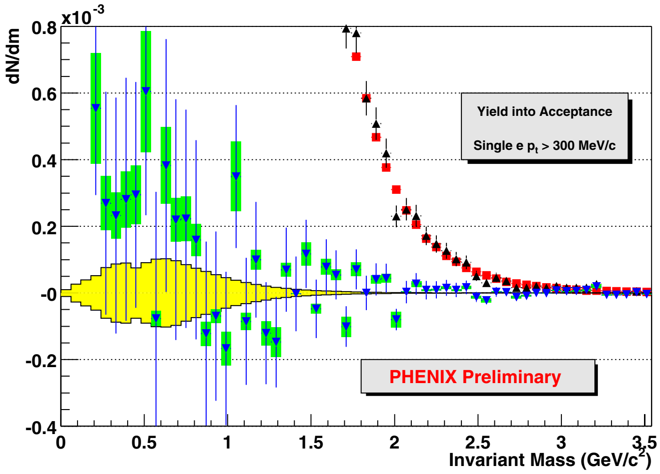

Fig. 7. Low-mass di-lepton mass spectrum from analysis of Au + Au data after subtraction of the combinatorial background from mixed events with an electron from one event and positron from a different event [23]

3 ϕ meson production

The ϕ meson is considered a sensitive probe for studying in-medium modifications of the vector mesons spectral shape (mass and/or width) as chiral symmetry restoration is approached [28]. With a lifetime of $\tau = 46\,\mathrm{fm}/c$ the ϕ mesons predominantly decay outside the medium after regaining the vacuum properties, with only a small fraction decaying inside the medium. Since the measurement integrates over the collision's history this may result in a small modification of the ϕ meson line shape manifesting itself a tail at lower masses. Nevertheless, PHENIX and NA60 with their excellent mass resolution might be able to observe such modifications. Furthermore, the simultaneous measurement of the ϕ decay into K^+K^- and di-leptons provides a very powerful tool in the search for such in-medium modifications. Since the ϕ meson mass is close to twice the kaon mass, even a small decrease of the ϕ meson mass may induce a large decrease in the $\phi \to K^+K^-$ yield. The interpretation might not be straightforward since the scattering and absorption of low-momentum kaons in the medium can also lead to a smaller yield of ϕ mesons reconstructed from the kaon channel than that reconstructed from the di-lepton channel.

There is only limited and even controversial information about the production of the vector mesons ω and ϕ at SPS energies. The ϕ meson production in central collisions at 158 AGeV has been studied via the muon decay channel by NA50 (Pb + Pb) [29] and via the kaon decay channel by NA49 (Pb + Pb) [30] and CERES (Pb + Au) [31]. The NA50 experiment observed a significant increase of the $\phi/(\rho + \omega)$ ratio with centrality which is attributed to an enhancement of the ϕ production [28]. The NA49 experiment found an increase of the ϕ/π ratio which is also attributed to an enhancement of ϕ production. However, the inverse slope parameters, T, as obtained from an exponential fit to the ϕ m_T distributions, are $T = 228 \pm 10\,\mathrm{MeV}$, $283 \pm 11\,\mathrm{MeV}$ and $305 \pm 15\,\mathrm{MeV}$ in the NA50, CERES and NA49 experiments, respectively, for central collisions. There is an even larger discrepancy in their measured ϕ yields. The NA50 yields are larger than those of NA49 by factors of 2 to 4 in the common m_T range covered by the two experiments. It is unclear whether these differences are of experimental origin or a manifestation of in-medium effects. Additional insight on this issue is provided by the first NA60 results from In + In collisions. The NA60 ϕ/ω ratio is in very good agreement with the NA50 results. However, the temperature parameter T shows a clear increase with centrality and appears closer to the NA49 results [17].

First results on ϕ meson production at RHIC are already available. Using the run-2 data, PHENIX attempted an analysis of ϕ meson production through the K^+K^- and e^+e^- decay channels [32]. The study of the ϕ meson production through the K^+K^- decay channel has recently been completed [33]. The results include the centrality dependence of particle density $\mathrm{d}N/\mathrm{d}y$, particle spectra and inverse slope parameter T. A line shape analysis revealed no significant change in the centroid and width values of the ϕ meson from the PDG values. The statistics accumulated in run-2 were insufficient for a similar quality study of meson production through the e^+e^- decay channel. This crucial comparison study is not yet available and is expected to be done with the higher statistics data accumulated in the fourth run of RHIC (2004).

4 Thermal photons

A central topic of interest in the field of relativistic heavy-ion collisions is the identification of thermal radiation emitted by the dense medium. Such radiation is a direct fingerprint of the matter formed, the quark–gluon plasma (QGP) or a high-density hadron gas (HG). The elementary processes involved are well known. The main channels for the production of thermal photons are $q\bar{q}$ annihilation and QCD Compton scattering $qg \to q\gamma$ in the QGP phase and pion annihilation ($\pi^+\pi^- \to \rho\gamma$ or $\eta\gamma$) and hadron–hadron scattering (like $\pi\rho \to \pi\gamma$) in the HG phase. The unambiguous identification of the thermal radiation from the QGP is considered as a very strong signal of deconfinement and its spectral shape should provide a direct measurement of the plasma temperature. The absolute yields, obtained by integrating the emission rate over the space-time evolution of the collision, have been calculated by several authors. The results point to rather well established features. At the same temperature, thermal photons from partonic and hadronic processes have a similar production rate. Their overall yield is relatively small compared to the inclusive photon yield. In a recent elaborate calculation the transverse momentum range $p_\mathrm{T} = 1$–$3\,\mathrm{GeV}/c$ appears as the most promising window where the QGP radiation could dominate over other contributions in central Au + Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ [34].

As mentioned in Sect. 2, the excess of low-mass electron pairs provides first evidence of thermal radiation from a high-density hadronic system at the SPS. However, there is no conclusive evidence for QGP thermal photons at the

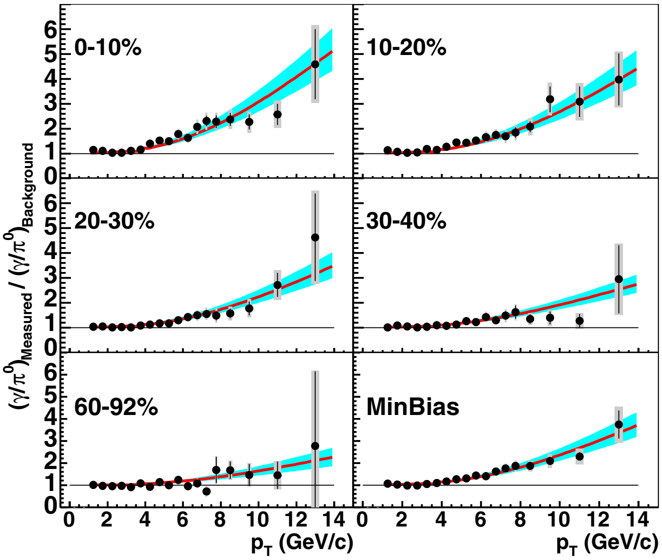

Fig. 8. PHENIX measurement of real photons per π^0 relative to the calculated background from hadron decays in central Au + Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$. The curves represent NLO pQCD calculations of direct photons in $p + p$ collisions scaled to Au + Au by the number of collisions N_{coll} for each centrality selection [38]

SPS. The initial measurements of WA80 [35] and CERES [36] with the 200 AGeV S beam yielded only upper limits of 15% of the total photon yield. In the two experiments the sensitivity was actually limited not by the statistics but rather by the systematic errors, too large to identify a thermal photon source which may only be of the order of a few percent of the inclusive photon yield. The WA98 experiment observed a small photon excess in central Pb + Pb collisions at 158 AGeV, whereas in peripheral collisions the yield is consistent with the expectations from hadron decays [37]. The excess is only a 1–2σ effect and occurs only at $p_\text{T} > 1.5\,\text{GeV}/c$. These results have attracted considerable theoretical interest. Although it is possible to explain the excess by the contribution from direct photons including k_T broadening (Cronin effect) it is not possible to rule out a small contribution from QGP thermal photons [34].

A first measurement of real photons in Au + Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ was performed by PHENIX using data from the second RHIC run, in the year 2002 [38]. After subtracting the hadron decays, there is clear evidence of an excess which can be explained by direct photons from initial hard scattering using NLO pQCD calculations for $p + p$ collisions scaled to Au + Au by the average number of collisions for each centrality bin (see Fig. 8). The errors however, are relatively large, leaving room for a comparable contribution of thermal photons. The high statistics accumulated in the fourth RHIC run shall provide the first real opportunity to search for the QGP thermal photons in PHENIX.

5 Summary

The low-mass di-lepton experiments, covering a very broad energy range from the BEVALAC to the SPS energies, have produced very exciting and stimulating results, most of them not fully understood and with a possible link to chiral symmetry restoration. A new generation of experiments with considerably improved performance will soon start to provide new results on the same energy range (HADES and NA60). The extension of these measurements to RHIC energies by the PHENIX experiment promises also to be very interesting. The quest for the thermal radiation from the QGP remains difficult. Results of the first real search for this elusive signal at RHIC using the high statistics Au + Au data from run-4 should be available soon.

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