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Status and perspectives of electromagnetic probes: a bright future

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Abstract. After a number of years of sparse results from electromagnetic probes we have seen a revitalization of this field at this conference. Exciting first results obtained by NA60 at CERN, HADES at GSI, as well as PHENIX at RHIC, cover a broad range of initial conditions created in heavy-ion collisions. These experiments hold the promise to provide accurate new data, which will certainly furnish qualitatively new insights into matter at high temperature and density. In this paper I review the status of the field today and the perspectives for the future.

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1 Introduction

Already in the 70's electromagnetic radiation, real or virtual photons, was proposed as a penetrating probe to study quark matter [1]. The argument is the following: Electromagnetic radiation is emitted throughout the space-time evolution of the matter created during the collision. Since it interacts only electromagnetically it will leave the collision volume unperturbed by the strongly interacting medium. The observed spectra, after decomposition of the different contributions, can in principle give access to rich information, such as the temperature of the medium and the properties of resonances in the medium. However, the experiments are very challenging because of the large physical and unphysical backgrounds encountered.

To date only a few experiments have successfully measured electromagnetic radiation from ultra-relativistic nuclear collisions. Nonetheless, all successful attempts gave interesting results and discoveries with considerable theoretical impact. The most prominent result was the discovery of the low mass dilepton enhancement by the CERES collaboration at the CERN SPS in the early 90's [2], which has been linked to medium modified vector mesons related to chiral symmetry restoration in over 300 mostly theoretical publications. Data taken by other experiments, including experiments at much lower energies seem to corroborate this hypothesis. On the contrary, attempts to measure thermal photons have been less successful.

Since those initial experiments little progress has been made until recently. With the spectacular start of CERN's NA60 experiment, shown at this conference, a new era of high statistics and high resolution experiments has begun, given future running time at the SPS. Also the PHENIX experiment at RHIC promises interesting results at much higher energies, in the future.

In this paper I review the status of this field of research focusing on the experimental results and perspectives. I will start by reviewing the search for direct photons at the SPS and the most recent results from RHIC. I will briefly discuss the dilepton results from the SPS and point out in more detail the bright future this program may have. I will also discuss the status of the RHIC program concerning dileptons and conclude with a brief outlook.

2 Search for direct photons

Reygers reported in detail on direct photon production at this meeting [3]. Direct photons are usually classified in two groups, thermal photons and prompt photons. Thermal photons are thought to be black body radiation from the medium created during the collision and their observation would allow us to estimate the temperature of the medium. Prompt photons result from hard scattering processes early in the collision and, though interesting by themselves, constitute a physics background for the search for thermal photons. The difficulty of any direct photon measurement stems from the large neutral pion decay background which overshines the direct photon signal. Only if this background can be subtracted with sufficient accuracy will a measurement be possible. Indeed out of many attempts at the SPS only one experiment, WA98 [4], was able to reach the necessary precision and published direct photon spectra. All other SPS experiments, summarized in Table 1, resulted in upper limits [5–8]. The

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Table 1. Upper limits on direct photon production obtained by different experiments at the CERN SPS

Experiment	p_{T} (GeV/c)	System	Upper limit
HELIOS 2	0.1–1.5	p–W, O–W, S–W	13%
WA80	0.4–2.8	O–Au	15%
WA98	0.5–2.5	S–Au	12.5%
CERES	0.4–2.0	S–Au	14%

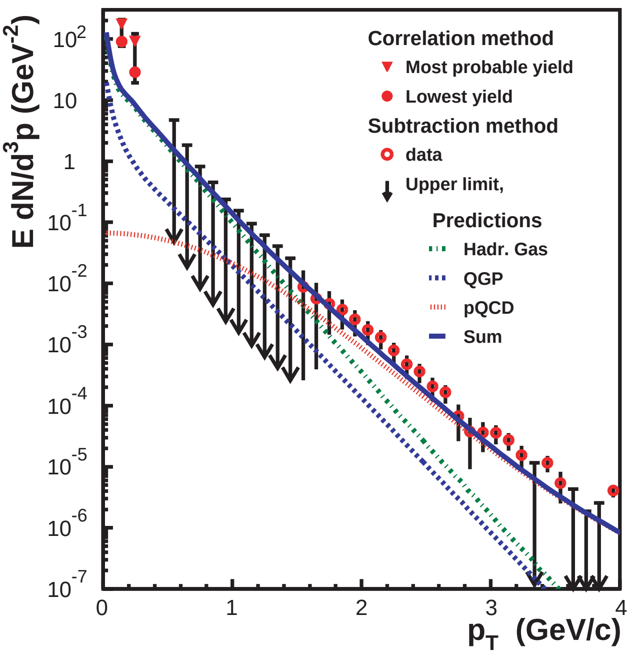

Fig. 1. Direct photon spectrum measured by WA98 in Pb–Pb collisions at the CERN SPS. Theoretical expectations for various direct photon sources are compared to the data

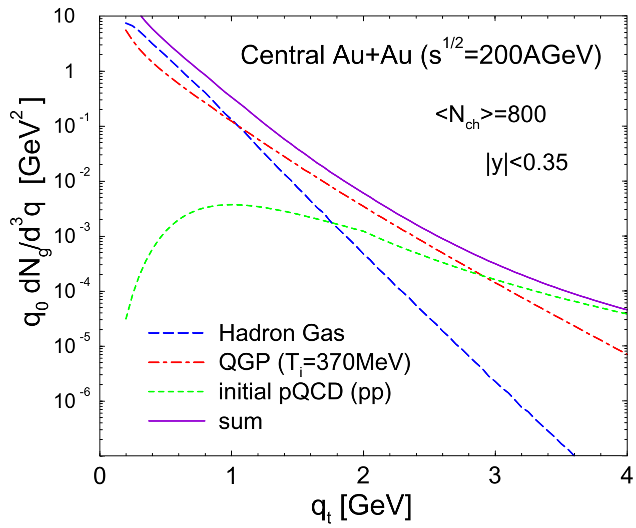

Fig. 2. Predicted direct photon spectrum in Au+Au collisions at RHIC [9]

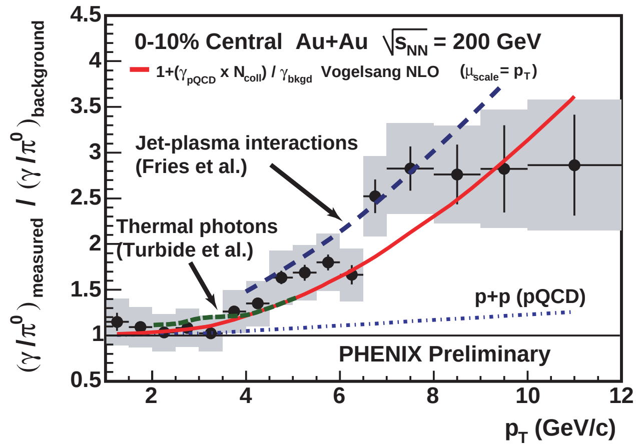

Fig. 3. Ratio of the measured inclusive photon spectrum to the photon spectrum from hadron decays in central Au + Au collisions at RHIC [10]. The expected thermal contribution (from Fig. 2) is indicated as a line for $p_{\mathrm{T}} < 4\,\mathrm{GeV}/c$

WA98 data are reproduced in Fig. 1. A clear prompt photon signal is observed above 1.8 GeV/c, consistent with perturbative QCD calculations. However, in the momentum range below, which should be sensitive to thermal radiation from the medium [9], the systematic uncertainties – though as small as 8–9% – are too large to obtain a signal and, again, only upper limits can be derived.

Figure 2 shows recent predictions of direct photon production at RHIC energies [9]. Assuming an initial temperature of approximately 370 MeV, the authors show that, in the range 1–3 GeV/c, direct radiation should be dominated by thermal radiation from the plasma phase. At lower momenta the radiation from the hadronic phase would dominate, while at larger p_{T} prompt radiation is the main contribution. Interestingly, at RHIC the measurement of prompt photons turns out to be simplified by the large suppression of π^0 production, about a factor of 5 in central Au–Au collisions. Reygers has shown initial PHENIX results at this meeting [10]; see Fig. 3. Though the systematic errors are as large as 30% a clear prompt component was identified above 5 GeV/c. I have converted the thermal yield shown in Fig. 2 into the ratio of total photons to photons from hadron decays, as shown in Fig. 3. Evidently the present level of experimental systematic errors is too large to extract a thermal yield. However, if the uncertainty can be reduced to less than 10%, which should be achievable, this component becomes accessible. I consider this to be one of the most important measurements to look forward to.

3 Dilepton measurements at CERN

In measurements of dileptons the neutral pion background can be avoided. For muon pair measurements it evidently does not exist and in dielectron measurements it only contributes to low invariant pair masses. The experimental challenge results from the overwhelming combinatorial

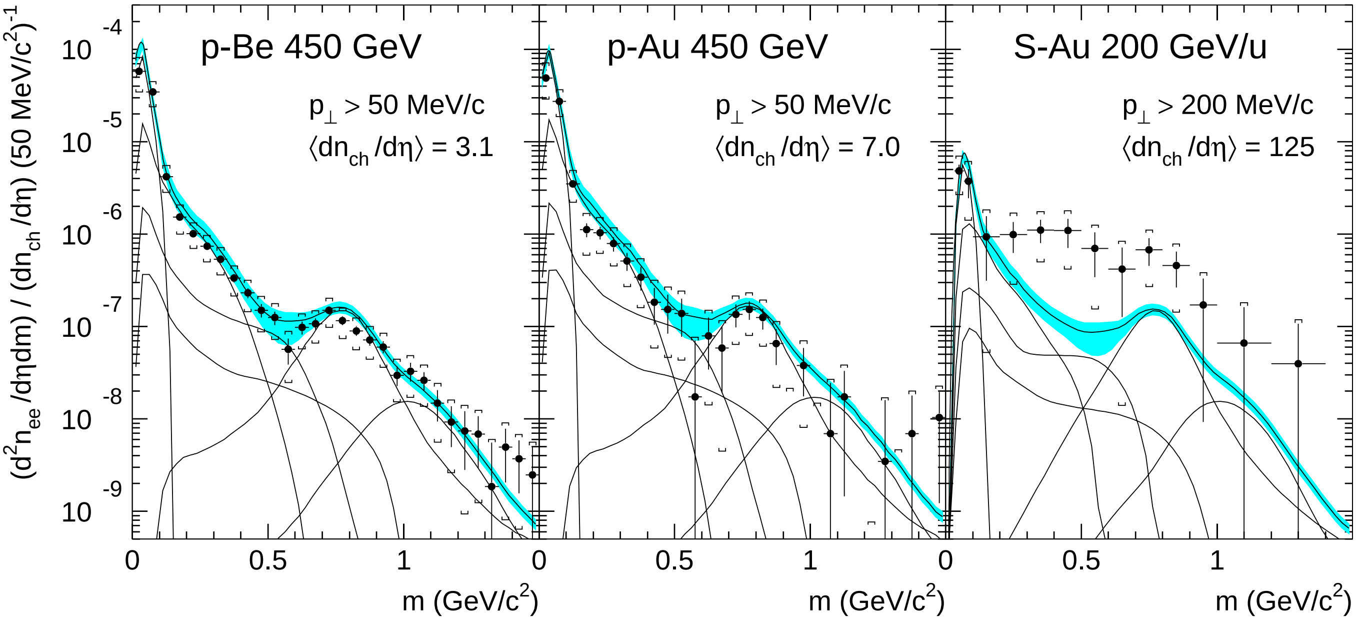

Fig. 4. Electron pair mass distributions from p–Be (left), p–Au (middle) and S–Au (right) collisions at the CERN SPS. The data are compared with the corresponding hadron decay cocktails

pair background due to random combinations of leptons. This issue is overcome by actively rejecting as much as possible of the background sources, i.e. photon conversions and π^0 Dalitz decays for electrons and pion and kaon decays for muons.

The CERES experiment at the SPS was specifically designed to measure electron pairs at midrapidity based on a sophisticated strategy to actively remove the pair background. Early measurements showed that the invariant mass spectra observed in p–nucleus collisions could fully be accounted for by the cocktail of hadron decay contributions [11]. In contrast, in S–Au collisions a significant enhancement was observed [2], as shown in Fig. 4. The discovery of the low (and intermediate) mass dilepton enhancement was later confirmed by HELIOS-3 [12] in S–W, NA38/NA50 in S-U [13,14], as well as by CERES in Pb–Au collisions [15].

Many theoretical calculations attributed this enhancement to pion annihilation in the dense hadronic medium altered by medium modifications to the ρ propagator. It is beyond the scope of this talk to give a full review of all this work and credit to all who have contributed; for comprehensive reviews see [16] or [17]. I will focus on the comparison made by CERES. Figure 5 (top) compares the CERES Pb–Au data, combined from two running campaigns in 1995 and 1996, to three different theoretical calculations. The dashed curve, which represents pion annihilation without medium modifications, clearly disagrees with the data. The dashed dotted and full lines assume dropping vector meson masses (Brown–Rho scaling [18]) and collision broadening of the spectral function of the vector mesons (Rapp–Wambach [19]), respectively. Both give a reasonable description of the data. The high baryon density is the driving key parameter in both models. A large enhancement was also found in the Pb–Au data at 40 AGeV beam energy [20] (see Fig. 5 (bottom)). This is consistent with the proposed medium modifications since the baryon density peaks at around this beam energy. Finally, it should be noted that most of the dilepton yield in either of these calculations is emitted during a long hadronic phase of the collision, after chemical freeze-out. The typical duration of the hadronic phase is assumed to be above 10 fm/c. While this assumption seemed well supported by the data at SPS energies, data taken at RHIC seem to indicate that the hadronic phase may be much shorter.

Another interesting observation made by CERES, now confirmed by first results from their running campaign in 2000, is the strong centrality dependence of the dilepton enhancement. Figure 6 reproduces a plot shown by Appelshäuser at this meeting. It shows the enhancement factor in three mass regions. A clear rise with centrality is observed, consistent with an almost quadratic dependence of the yield, which would be characteristic for medium radiation. It remains a challenge for theoretical calculations to reproduce these results.

NA50 has observed that the continuum enhancement persists beyond the ϕ meson mass all the way up to the J/ψ mass [14]. The results are shown in Fig. 7. This enhancement is consistent with a logical continuation of the calculation performed for lower masses [21] or a substantial enhancement (by a factor of ~ 3) of charm production. The experimental solution of this issue will have to come from new data taken by NA60.

NA60 is the latest dilepton experiment at CERN. It combines accurate vertex tracking with silicon detectors with the veteran muon spectrometer used by NA50. In several talks at this meeting, presented by Arnaldi, Shahoyan, Usai and Wöhri, the enormous potential of NA60 has been demonstrated [22–25]. The vertex tracker signif-

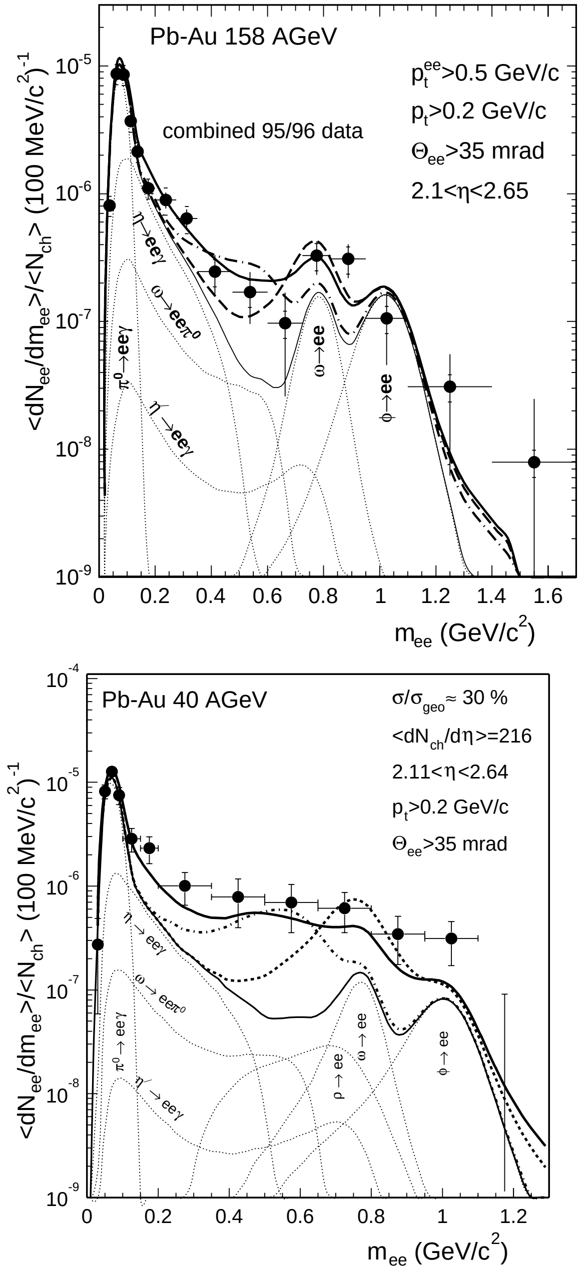

Fig. 5. Electron pair mass distribution from Pb–Au collisions at 158 AGeV (top) and 40 AGeV (bottom). The data are compared with the hadron decay cocktail as well as with three different theoretical calculations

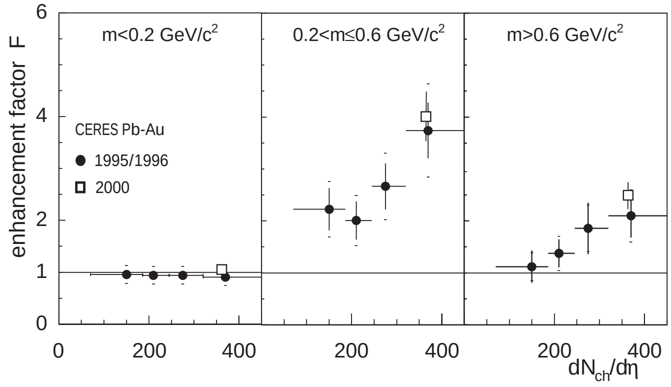

Fig. 6. Dielectron enhancement factor from Pb–Au collisions at 158 AGeV, in three mass ranges, as function of charged particle pseudorapidity density

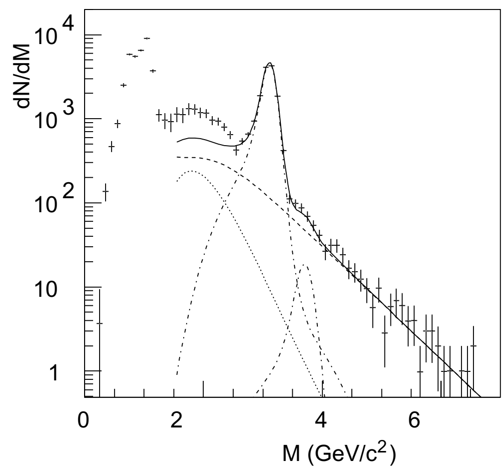

Fig. 7. Dimuon mass distribution from central Pb–Pb collisions at 158 AGeV. Expected contributions from Drell–Yan and correlated charm decays are shown as dashed and dotted lines, respectively

icantly improves the mass resolution, decay muon background rejection, and dimuon acceptance – specifically at low masses – and adds the capability to actively detect muons from charm decays.

Figure 8 shows the impressive improvement of the mass resolution obtained by matching tracks in the muon spectrometer with tracks in the silicon vertex telescope, as well as the significant reduction of the combinatorial background. Broad peaks indicating the ω and ϕ mesons turn into sharp peaks not only in p–A collisions but also in the In–In data (see Fig. 9). First preliminary data on the dimuon continuum have been shown by Usai [24]. Figure 10 reproduces one of the most striking plots. Four centrality selected mass distributions are compared on the same figure. Because the data have not been absolutely normalized yet, the data were normalized to the ω resonance, assuming it follows the charge particle multiplicity linearly. The ϕ enhancement, the J/ψ suppression and the continuum enhancement are evident. With the availability of data of this quality, I have no doubt that the next years will bring a significant revival of dilepton physics at CERN and that NA60 has the promise to answer many of the open questions.

So far NA60 has taken In–In data and substantial comparison data with p–A collisions but the program will remain incomplete without a future Pb–Pb running campaign. We will have to rely on the wisdom of the CERN management to continue the heavy-ion program at the SPS.

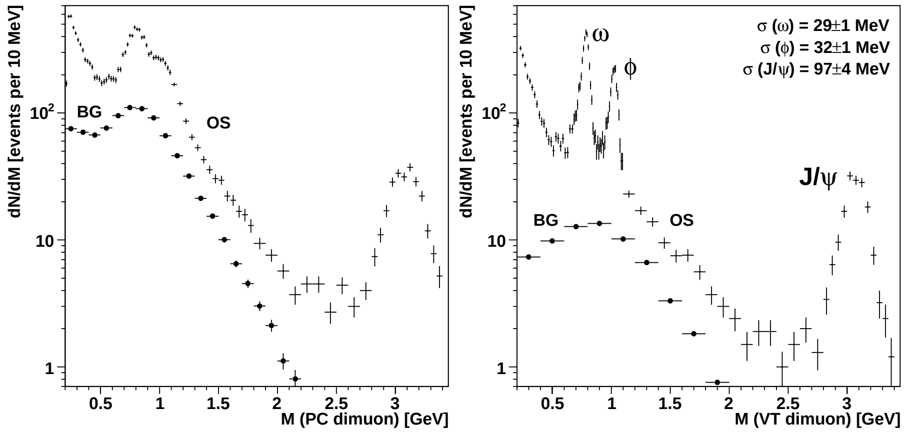

Fig. 8. Dimuon mass distributions from tracks measured in the NA60 muon spectrometer only (left panel) and after matching to tracks reconstructed in the vertex spectrometer (right panel). Opposite sign (OS) pairs are compared with the combinatorial background of random combinations (BG)

4 Dilepton experiments at other energies

Fixed target experiments at lower energies have also revealed interesting results. Tserruya has given a more complete overview in his talk. [26]. The DLS experiment at LBL's BEVALAC has published intriguing results [27] showing a dilepton yield enhanced even beyond expectations based on medium modified meson properties in C–C and Ca–Ca reactions at 1 AGeV beam energy. Final confirmation or falsification is expected from GSI's HADES experiment. HADES has just started data taking and the future will bring many more running campaigns to provide new precision data at low energies.

The KEK experiment E235 has found clear indications for medium modifications of the ρ meson mass in p–C and p–Cu collisions at 12 GeV beam energy [28]. These results are qualitatively consistent with dropping masses as expected by Brown–Rho scaling. After this conference, I became aware of similar results from the CBELSA/TAPS experiment [29], where a significant modification of the ω meson is observed in photoproduction of the ω meson on nuclei.

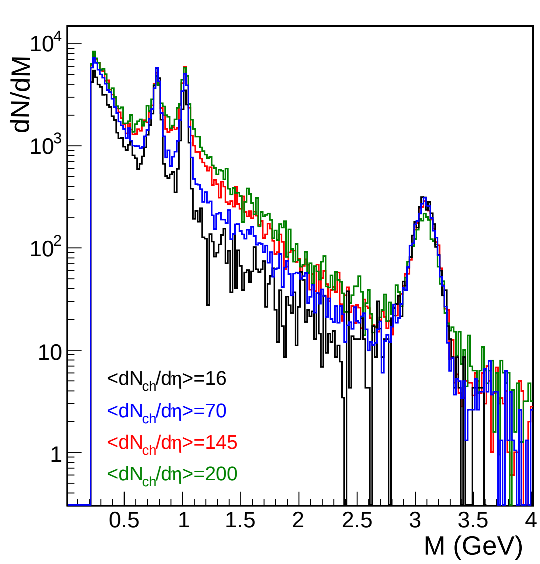

Fig. 10. Dimuon mass distributions measured by NA60 in In–In collisions for four different centrality selections. The spectra are arbitrarily normalized at the ω meson peak

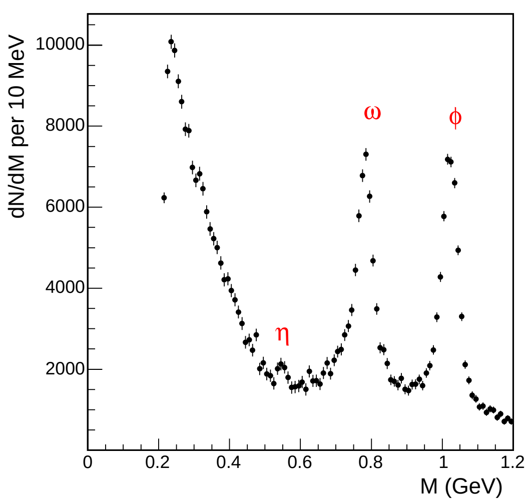

Fig. 9. Low mass dimuon spectrum measured by NA60 in In–In collisions at the CERN SPS

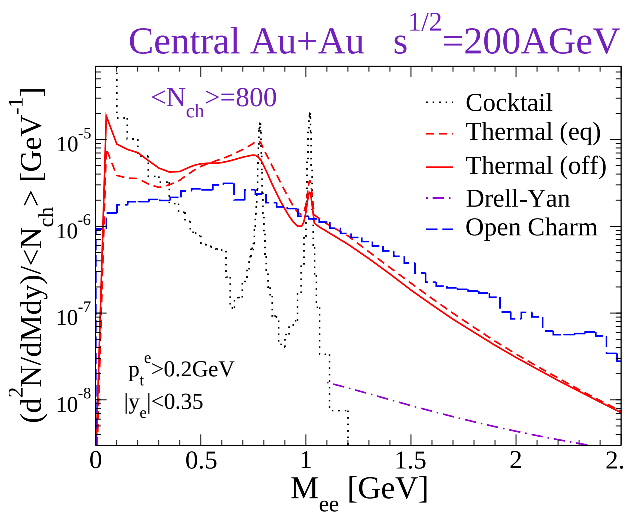

Fig. 11. Predictions for various contributions to the dielectron mass distribution in central Au–Au collisions at RHIC [31]

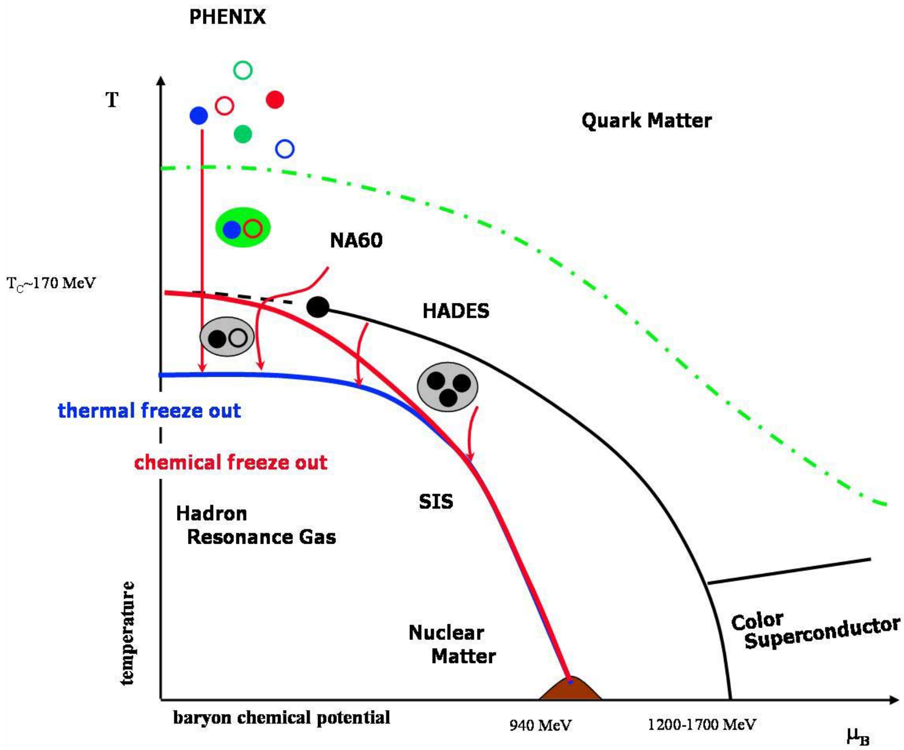

Fig. 12. Scheatic phase diagram of strongly interacting matter

As stated earlier, medium modifications are thought to be driven by the baryon density. Although at mid-rapidity the net baryon density, i.e. the baryon number density, is small at RHIC energies, the total baryon density, i.e. baryon plus anti-baryon, is as large as at the SPS. Consequently, it has also been proposed that medium modifications of vector mesons should be observable at RHIC energies [31]. Predictions for the dilepton continuum are shown in Fig. 11. Between twice the pion mass and the ϕ meson mass the continuum shows a substantial enhancement above the cocktail of meson decays. Due to the much larger charm production cross section at RHIC than at the SPS the continuum is dominated by associated charm anti-charm production above the ϕ mass – though charm energy loss in quark matter may alter this prediction.

The PHENIX experiment has been designed to measure electron pairs, focusing on the vector mesons decaying directly into e^+e^-. In its original layout it has excellent mass resolution but no background rejection capabilities which have proven so critical in the SPS experiments. With the present setup, continuum measurements will be difficult. First results may be obtained; however, precision measurements require adding the capability to reject the combinatorial background.

Ozawa presented the plans of the PHENIX collaboration to add a hadron blind detector (HBD) [30] in the next years. This innovative, windowless imaging Cherenkov detector is expected to tag 90% of all electron and positron tracks from photon conversions and Dalitz decays. Hence the combinatorial background will be reduced by about two orders of magnitude down to the level of irreducible background from uncorrelated charm meson decays. Combined with the planned precision charm detection in PHENIX, the HBD will open the way to accurate dilepton continuum measurements at RHIC.

5 Summary and outlook

I conclude this paper by showing a sketch of the QCD phase diagram, in Fig. 12, following the proposal of [32]. The new generation of dilepton experiments, HADES, NA60 and PHENIX, will continue to explore and provide key information about hot and dense matter created in heavy ion collisions. Many new results can be expected in the near future.

Experiments at different beam energies explore different region of the phase diagram. At 1–2 AGeV and above, matter is expected to be baryon rich and governed by hadronic degrees of freedom. HADES will continue the pioneering measurements of the DLS experiment in this domain, where dileptons are emitted before chemical freeze-out.

Experiments at CERN energies explore the transition region to quark matter. Dilepton production is thought to be dominated by properties of mesons in the hot hadronic phase between chemical freeze-out at the phase boundary and thermal freeze-out. CERES data have stimulated a tremendous theoretical development in understanding these in-medium meson properties. However, competing mechanisms of medium modifications cannot be distinguished by the data, mostly due to the lack of statistics and/or mass resolution. Both are overcome in the NA60 experiment. We have seen impressive first results from NA60 at this meeting which soon will be finalized and hopefully bring closure to many open issues. It is interesting to note that, in order to generate sufficient dilepton yields, long lifetimes of the hadronic phase are assumed in all calculations. Though consistent with hadron production data at CERN, new results from RHIC indicate that the lifetime may be much shorter than originally thought. If confirmed, many of the theoretical calculations will need to be reconsidered.

Last but not least, PHENIX will explore quark matter produced at RHIC. As pointed out earlier, the conditions in the hadronic phase are comparable to those obtained at the SPS. However, the partonic phase is not weakly coupled as assumed in most dilepton yield calculations, but strongly coupled. It has been suggested [32] that colored bound states exist beyond the phase transition and that the effective quark masses become approximately $1\,\mathrm{GeV}/c^2$. Decays of such bound states may leave their imprint in the dilepton spectra.

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