Electromagnetic emissivity of hot and dense matter

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Abstract. In this study we investigate dilepton production in heavy-ion collisions from √s_{NN} = 8 GeV to 5 TeV with a focus on the competition between the thermal QGP radiation and the semi-leptonic decays from correlated D−meson pairs. As a ‘tool’ we employ the parton-hadron-string dynamics (PHSD) transport approach incorporating for the first time a fully microscopic treatment of the charm dynamics and their semi-leptonic decays. We find that the dileptons from correlated D−meson decays dominate the ‘thermal’ radiation from the QGP in central Pb+Pb collisions at the intermediate masses (1.2 GeV < M < 3 GeV) for √s_{NN} > 40 GeV, while for √s_{NN} = 5 to 20 GeV the contribution from D, D̄ decays to the intermediate mass dilepton spectra is subleading such that one should observe a rather clear signal from the QGP radiation. We, furthermore, study the p_T-spectra and the R_AA(p_T) of single electrons at different energies.

1. Introduction

Relativistic heavy-ion collisions are well suited to generate hot and dense matter in the laboratory although within small space-time regimes. Whereas in low energy collisions one produces dense nuclear matter with moderate temperature T and large baryon chemical potential μ_B, ultra-relativistic collisions at Relativistic Heavy Ion Collider (RHIC) or Large Hadron Collider (LHC) energies produce extremely hot matter at small baryon chemical potential. In order to explore the phase diagram of strongly interacting matter as a function of T and μ_B both type of collisions are mandatory. According to lattice calculations of quantum chromodynamics (lQCD) [1, 2, 3, 4], the phase transition from hadronic to partonic degrees of freedom (at vanishing baryon chemical potential μ_B=0) is a crossover. This phase transition is expected to turn into a first order transition at a critical point (T_c, μ_c) in the phase diagram with increasing baryon chemical potential μ_B. Since this critical point cannot be determined theoretically in a reliable way the beam energy scan (BES) program at RHIC aims to find the critical point and the phase boundary by gradually decreasing the collision energy [5, 6]. Furthermore, new facilities such as FAIR (Facility for Antiproton and Ion Research) and NICA (Nuclotron-based Ion Collider fAcility) are under construction to explore in particular the intermediate energy range where one might study also the competition between chiral symmetry restoration and deconfinement as suggested in Refs. [7, 8].

Since the partonic phase in relativistic heavy-ion collisions appears only for a couple of fm/c, it is quite a challenge for experiment to investigate its properties. In particular the electromagnetic
emissivity of strongly interacting matter is a subject of longstanding interest [9, 10, 11, 12] and is explored also in relativistic nucleus-nucleus collisions, where the photons (and dileptons) measured experimentally provide a time-integrated picture of the collision dynamics. After decades of experimental and theoretical studies it has become clear that dileptons with invariant masses below about 1.2 GeV preferentially stem from hadronic decays providing some glance at the modification of hadron properties in the dense and hot hadronic medium (cf. [12, 13] and references therein) while the intermediate mass regime 1.3 GeV < M < 3 GeV should provide information about ‘thermal’ dileptons from the QGP \( (g+\bar{q} \rightarrow e^+e^-, g+\bar{q} \rightarrow g+\gamma^*, g+q(\bar{q}) \rightarrow q(\bar{q})+e^+e^-) \) as well as the amount of correlated open charm (semi-leptonic) decays from early production of \( c\bar{c} \) pairs [14, 15, 16, 17, 18, 19, 20]. Whereas at RHIC and LHC energies the background from \( DD \) pairs overshines the contribution from the QGP in the intermediate mass regime [13], one might expect to find some window in bombarding energy where the partonic sources dominate since the charm production drops rapidly with decreasing bombarding energy. In this contribution we intend to quantify this expectation and to identify optimal systems for future measurements at FAIR/NICA or at the RHIC Beam-Energy-Scan (BES) as well as at the Super Proton Synchrotron (SPS) by the NA61 collaboration.

We here employ the microscopic parton-hadron-string dynamics (PHSD) approach, which differs from the conventional Boltzmann-type models (with or without mean-fields [21, 22]) in the aspect [23] that the degrees-of-freedom for the QGP phase are off-shell massive strongly-interacting quasi-particles that generate their own mean-field potential. The masses of the dynamical quarks and gluons in the QGP are distributed according to spectral functions whose pole positions and widths, respectively, are defined by the real and imaginary parts of their self-energies [13]. The partonic propagators and self-energies, furthermore, are defined in the dynamical quasiparticle model (DQPM) in which the strong coupling and the self-energies are fitted to lattice QCD results [24]. We recall that the PHSD approach has successfully described numerous experimental data in relativistic heavy-ion collisions from the Alternating Gradient Synchrotron (AGS), SPS, RHIC to LHC energies [13, 23, 25, 26, 27, 28, 29, 30, 31, 32]. More recently, the charm production and propagation has been explicitly implemented in the PHSD and detailed studies on the charm dynamics and hadronization/fragmentation have been performed at top RHIC and LHC energies in comparison to the available data [33, 34, 35].

2. Charm pairs from p+p collisions

As pointed out in the Introduction the charm quark (\( c\bar{c} \)) pairs are produced through initial hard nucleon-nucleon scattering in relativistic heavy-ion collisions. We employ the PYTHIA event generator to produce the heavy-quark pairs and modify their transverse momentum and rapidity such that they are similar to those from the FONLL calculations at RHIC and LHC energies (cf. Ref. [35]). At SPS and lower energies we do not employ any modification of the PYTHIA results. Fig. 1 a) shows the charm production cross section for p+p collisions (as implemented in PHSD) as a function of the invariant energy \( \sqrt{s_{NN}} \) which is fitted to a wide range of experimental data. We can see a rather fast drop of the \( c\bar{c} \) cross section with decreasing energy especially close to threshold. Note, however, that the data show an uncertainty of about a factor of two which implies a corresponding uncertainty in the following PHSD calculations.

2.1. Multiplicities for \( c\bar{c} \) pairs in central Pb+Pb reactions

We recall that in heavy-ion reactions the number of \( c\bar{c} \) pairs produced is approximately given by the number of binary nucleon-nucleon collisions \( N_{bin}(b) \) (at given impact parameter \( b \)) times the probability to produce a \( c\bar{c} \) pair in an inelastic nucleon-nucleon collision at given \( \sqrt{s_{NN}} \) which is given by the ratio of the \( c\bar{c} \) cross section to the inelastic \( N+N \) cross section [36, 37]. The scaling of the \( c\bar{c} \) multiplicity with the number of binary \( N+N \) collisions is rather well reproduced in actual PHSD calculations where additionally the smearing of \( \sqrt{s_{NN}} \) by Fermi motion is taken.
Figure 1. a) The $c\bar{c}$ pair cross section in p+p reactions as a function of the invariant energy $\sqrt{s}$ as implemented in PHSD. The symbols denote experimental data from Refs. [38, 39, 40]. b) The number of primary $c\bar{c}$ pairs in Pb+Pb collisions at $b=2$ fm as a function of $\sqrt{s_{NN}}$. The shaded area in (b) shows the uncertainty in the number of $c\bar{c}$ pairs due to the uncertainty in the charm production cross section in p+p collisions.

into account as well as fluctuations in the number of binary nucleon-nucleon collisions $N_{bin}(b)$ on an event by event basis. The corresponding PHSD results for Pb+Pb collisions (at $b=2$ fm) are displayed in Fig. 1 b) as a function of $\sqrt{s_{NN}}$ and demonstrate that the average $c\bar{c}$ pair multiplicity in central collisions is far below unity at SPS and FAIR/NICA energies. In this case we may gate in the PHSD calculations on events with a single $c\bar{c}$ pair - selected by Monte-Carlo from the number of possible binary $N+N$ reactions - and follow the dynamics of the charm quarks throughout the time evolution in PHSD, i.e. partonic scattering, hadronization by coalescence or fragmentation, and final hadronic rescattering of charmed mesons and baryons (see below). At the end all observables have to be multiplied by the probability for the charm event as illustrated in Fig. 1 b). The shaded area in Fig. 1 b) shows the uncertainty in the number of $c\bar{c}$ pairs due to the uncertainty of the charm cross section in p+p collisions (cf. Fig. 1 a)). Note that for $\sqrt{s_{NN}}<20$ GeV no data are available and the number of $c\bar{c}$ pairs entirely stem from a parameterized function which takes into account the phase space of the final states.

The heavy quarks and antiquarks produced in early hard collisions - as described above - in case of heavy-ion collisions interact with the dressed lighter off-shell partons in the QGP. The cross sections for the heavy-quark scattering with massive off-shell partons have been calculated by considering explicitly the mass spectra of the final-state particles in Refs. [41, 42]. The elastic scattering of heavy quarks in the QGP is treated by including the non-perturbative effects of the strongly interacting quark-gluon plasma (sQGP) constituents, i.e. the temperature-dependent coupling $g(T/T_c)$ which rises close to $T_c$, the multiple scattering etc. [43]. The multiple strong interactions of quarks and gluons in the sQGP are encoded in their effective propagators with broad spectral functions (imaginary parts). As pointed out above, the effective propagators, which can be interpreted as resummed propagators in a hot and dense QCD environment, have been extracted from lattice data in the scope of the DQPM [24, 43].

The produced charm and bottom quarks from p+p collisions are hadronized by emitting soft gluons, which is denoted by ‘fragmentation’. As in Refs. [33, 34] we use the fragmentation function of Peterson [44]. In heavy-ion collisions the formation of $D$- and $B$-mesons also occurs via coalescence - preferentially at lower $p_T$ - and is described in detail in Refs. [33, 34]. In the hadronic medium the heavy mesons interact with the lighter mesons and baryons according to
cross sections that have been calculated in an effective lagrangian approach with heavy-quark spin symmetry [45, 46, 47]. Finally, after freeze-out of the $D$–mesons they produce single electrons through semi-leptonic decays [48] with the branching ratios given by the PYTHIA event generator.

3. Dilepton production channels

We recall that in the hadronic sector PHSD is equivalent to the Hadron-String-Dynamics (HSD) transport approach [49] that has been used for the description of $pA$ and $AA$ collisions from SIS to SPS energies and has lead to a fair reproduction of hadron abundances, rapidity distributions and transverse momentum spectra as well as dilepton spectra. In particular, HSD incorporates off-shell dynamics for vector mesons and a set of vector-meson spectral functions [50] that covers possible scenarios for their in-medium modification, i.e. in particular a collisional broadening of the vector resonances. Note that in the off-shell transport description, the hadron spectral functions change dynamically during the propagation through the medium and evolve towards the on-shell spectral function in the vacuum. The dilepton production by a (baryonic or mesonic) resonance $R$ decay can be schematically presented in the following way: e.g., in a first step a resonance $R$ might be produced in baryon-baryon ($BB$) or meson-baryon ($mB$) collisions. Then this resonance can couple to dileptons directly (e.g., Dalitz decay of the $\Delta$ resonance: $\Delta \to e^+e^-N$) or decays to a meson $m$ (+ baryon), which produces dileptons via direct decays ($\rho, \omega, \phi$) or Dalitz decays ($\pi^0, \eta, \omega$). The resonance $R$ might also decay into another resonance $R'$ which later produces dileptons via Dalitz decay. Note, that in the combined model the final particles – which couple to dileptons – can be produced also via non-resonant mechanisms, i.e. ‘background’ channels at low and intermediate energies or string decay at high energies. In addition to the hadronic channels above we account for the ‘$4\pi$’ channels, i.e. the dilepton production in the two-body reactions $\pi + \rho$, $\pi + \omega$, $\rho + \rho$, $\pi + a_1$ as described in detail in Ref. [51]. The latter provide the background from hadronic channels in the intermediate mass regime $1.2 \text{ GeV} < M < 3 \text{ GeV}$ [51], which is not shown explicitly in this study since the contribution of ‘$4\pi$’ channels is much smaller than the contribution from open charm decays and the QGP radiation.

We recall that the influence of in-medium effects on the vector mesons ($\rho, \omega, \phi$) has been extensively studied within the PHSD approach in the past (cf. Refs. [13, 50, 51]) and it has been shown that the collisional broadening scenario for the in-medium vector-meson spectral functions is consistent with experimental dilepton data from SPS to LHC energies in line with the findings by other groups [12]. Accordingly, in the present study we will adopt the collisional broadening scenario for the vector-meson spectral functions as the ‘default’ scenario.

In order to address the electromagnetic radiation of the partonic phase, off-shell cross sections of $q\bar{q} \to \gamma^*$, $q\bar{q} \to \gamma^*g$ and $gg \to \gamma^*q$ ($\bar{q}\bar{q} \to \gamma^*\bar{q}$) reactions - taking into account the effective propagators for quarks and gluons from the DQPM - have been calculated in Ref. [52]. Here $\gamma^*$ stands for the $e^+e^-$ or $\mu^+\mu^-$ pair. Dilepton production in the QGP - as created in early stages of heavy-ion collisions - is calculated by implementing these off-shell processes into the PHSD transport approach on the basis of the same partonic propagators as used for the time-evolution of the partonic system. For a review on electromagnetic production channels within PHSD we refer the reader to Ref. [13] and for the details of the dilepton cross sections from off-shell partonic channels to the Appendix of Ref. [53].

4. Results for heavy-ion reactions

Since the matter produced in heavy-ion collisions is extremely dense, the interactions with the bulk matter suppresses heavy flavors at high-$p_T$. On the other hand, the partonic or nuclear matter is accelerated outward (exploding), and a strong flow is generated via the interactions of the bulk particles and the repulsive scalar interaction for partons. Since the heavy flavor
strongly interacts with the expanding matter, it is also accelerated outwards. Such effects of the medium on the heavy-flavor dynamics are expressed in terms of the nuclear modification factor defined as

\[ R_{AA}(p_T) \equiv \frac{dN_{AA}/dp_T}{N_{binary} \times dN_{pp}/dp_T}, \]

where \( N_{AA} \) and \( N_{pp} \) are, respectively, the number of particles produced in heavy-ion collisions and that in p+p collisions, and \( N_{binary} \) is the number of binary nucleon-nucleon collisions in the heavy-ion collision for the centrality class considered. Note that if the heavy flavor does not interact with the medium in heavy-ion collisions, the numerator of Eq. (1) will be similar to the denominator. For the same reason, a \( R_{AA} \) smaller (larger) than one in a specific \( p_T \) region implies that the nuclear matter suppresses (enhances) the production of heavy flavors in that transverse momentum region.

4.1. Nuclear modification of dielectrons from heavy flavor

In this subsection we focus on the \( c\bar{c} \) dynamics and the dielectrons produced from heavy flavor pairs and their modification in relativistic heavy-ion collisions.

**Figure 2.** The transverse momentum spectra of \( D \) mesons (a) and the \( R_{AA}(p_T) \) of single electrons from semi-leptonic decay of \( D \) mesons (b) as a function of the transverse momentum \( p_T \) in central Pb+Pb collisions at \( \sqrt{s_{NN}} = 8, 11.5, 17.3, 39 \) and 200 GeV at midrapidity.

Fig. 2 (a) shows the transverse momentum spectra of \( D \) mesons in central Pb+Pb collisions at \( \sqrt{s_{NN}} = 8, 11.5, 17.3, 39, \) and 200 GeV for \( |y| < 1 \). Since the cross section for charm production increases with collision energy as shown in Fig. 1 (a), the transverse momentum spectrum of \( D \) meson enhances strongly with increasing collision energy and also becomes harder. Fig. 2 (b) displays the nuclear modification factor of single electrons from \( D \) meson semi-leptonic decays at mid-rapidity (\( |y| < 1 \)) for the same set of central Pb+Pb collisions. We mention that for the semi-leptonic decays of heavy flavors we use the subroutine ‘pydecay’ of the PYTHIA event generator [54]. Contrary to the \( R_{AA} \) at RHIC and LHC energies we find ratios well above unity at \( \sqrt{s_{NN}} = 8 \) and 11.5 GeV which implies an enhancement of the yield (at higher momenta) rather than the familiar suppression at RHIC and LHC. The enhanced \( R_{AA} \) at low energies (8 and 11.5 GeV) may be dominantly attributed to the Fermi motion of nucleons in the colliding nuclei, which does not exist in p+p collisions and slightly increases the collision energy in binary collisions.
nucleon-nucleon scattering. Since the collision energies are close to the threshold energy for charm production, where the production cross section increases rapidly as shown in Fig. 1 (a), a small enhancement of the collision energy gives a sizeable increase of the charm production and subsequently the decay products.

We note in passing that the invariant mass spectrum of dielectrons changes little for $\sqrt{s_{NN}} = 17.3$ GeV when including the charm interactions in the hot and dense medium, while it is considerably suppressed at large invariant mass at $\sqrt{s_{NN}} = 200$ GeV. For further details we refer the reader to Ref. [53].

4.2. Excitation function of dielectron production in Pb+Pb collisions from $\sqrt{s_{NN}} =$ 8 to 200 GeV

The dileptons produced in relativistic heavy-ion collisions can be classified into three parts: i) dileptons from heavy flavor pairs, ii) from partonic scatterings in the QGP phase, and iii) from hadronic interactions in the hadronic (HG) phase. In this subsection we compare the separate contributions in central Pb+Pb collisions at various energies from 8 to 200 GeV.

![Figure 3](image_url)

Figure 3. The invariant mass spectra of dileptons from the QGP (a), and $D\bar{D}$ pairs (b) in central Pb+Pb collisions at $\sqrt{s_{NN}} = 8, 11.5, 17.3, 39$ and 200 GeV from the PHSD.

Fig. 3 shows the dielectron mass spectra from partonic interactions in the QGP (a) and from the semi-leptonic decays of $D\bar{D}$ pairs (b) in central Pb+Pb collisions at $\sqrt{s_{NN}} = 8, 11.5, 17.3, 39$, and 200 GeV at mid-pseudorapidity $|\eta_e| < 1$ for the leptons. We mention that the contribution from the hadronic channels increases only moderately with collision energy (in line with the hadron abundances) [53], while the contribution from the QGP raises more steeply (in line with the enhanced space-time volume of the QGP phase) and that from $D\bar{D}$ pairs is most dramatically increasing (in line with the number of $c\bar{c}$ pairs, cf. Fig. 1b)). Accordingly, the contribution from heavy flavor is small at low-energy collisions, but becomes more and more important with increasing collision energy in competition with the production from the QGP channels.

In order to show the separate contributions explicitly, we compare in Fig. 4 the contributions from the QGP (red lines) and from $D\bar{D}$ pairs (green lines) with the total dielectron spectrum (blue lines) at different collision energies for central Pb+Pb collisions. In low-energy collisions the dielectrons from hadronic channels dominate in the low-mass region and those from partonic interactions dominate in the intermediate-mass range while the contribution from $D\bar{D}$ pairs is negligible. With increasing collision energy the contribution from $D\bar{D}$ pairs becomes more and more significant and comparable to that from partonic interactions at $\sqrt{s_{NN}} \approx 39$ GeV in the
The invariant mass spectra of dileptons from partonic interactions (red lines) and from $D\bar{D}$ pairs (green lines) together with the total dielectron spectrum (blue lines) in central Pb+Pb collisions at $\sqrt{s_{NN}} = 8, 11.5, 17.3, 39$ and 200 GeV from the PHSD at mid-pseudorapidity for the leptons.

Intermediate-mass range. Finally, it overshines the partonic contribution at $\sqrt{s_{NN}} = 200$ GeV (and above).

Fig. 5 compares the contributions from $D\bar{D}$ pairs (green lines) to three partonic channels, i.e. $q + \bar{q} \rightarrow e^+ + e^-$, $q + \bar{q} \rightarrow g + e^+ + e^-$, and $q(q) + g \rightarrow q(\bar{q}) + e^+ + e^-$, for intermediate mass dileptons ($1.2 \text{ GeV} < M < 3 \text{ GeV}$) as a function of collision energy $\sqrt{s_{NN}}$ for Pb+Pb collisions at $b=2$ fm. The figure clearly shows that the contribution from partonic interactions, especially from $q + \bar{q} \rightarrow e^+ + e^-$, dominates the intermediate-mass range in low-energy collisions. However,
the contribution from $D\bar{D}$ pairs rapidly increases with increasing collision energy, because the scattering cross section for charm production grows fast above the threshold energy as shown in Fig. 1 (a). It overshines the contribution from partonic interactions around $\sqrt{s_{NN}} \approx 40$ GeV and dominates at higher energies. Since the detectors of different collaborations have a different acceptance, we show in Fig. 5 (b) the results without any acceptance cuts, while Fig. 5 (a) shows the results for a mid-pseudorapidity cut on leptons of $|\eta| < 1$. However, the contributions from the partonic interactions and from $D\bar{D}$ pairs show a similar behavior in both cases.

One of most important issues in heavy-ion physics is to find and study the properties of partonic nuclear matter which is created in a small space-time volume in relativistic heavy-ion collisions. To this end one needs observables that are not blurred by hadronic interactions. Our results in Figs. 4 and 5 clearly demonstrate that the window to study partonic matter by dielectrons at intermediate masses without substantial background from heavy flavor decays opens for collision energies $\sqrt{s_{NN}} < 40$ GeV.

5. PHSD versus experimental data

In this section we compare the invariant mass spectra of dielectrons from the PHSD to the experimental data in Au+Au collisions from $\sqrt{s_{NN}} = 19.6$ to 200 GeV from the STAR collaboration and those in Pb+Pb collisions from the ALICE collaboration at $\sqrt{s_{NN}} = 2.76$ TeV. We note that the experimental data from the STAR collaboration and those from the ALICE collaboration have different centralities and different acceptance cuts. The STAR data are obtained for minimum-bias Au+Au collisions and electrons and positrons with transverse momenta $p_T \geq 0.2$ GeV and pseudo-rapidities $|\eta| < 1.0$. On other hand, the ALICE data are obtained for 0-10 % central Pb+Pb collisions and the electrons and positrons with transverse momenta $p_T \geq 0.4$ GeV and pseudo-rapidities $|\eta| < 0.8$. The sensitivity of the invariant mass spectra of dielectrons to the cross section for charm production and cuts in $p_T$ and pseudo-rapidity $\eta$ is discussed in more detail in the appendix of Ref. [53].

The first five panels of Fig. 6 show the invariant mass spectra of dielectrons from the Beam-Energy-Scan (BES) at $\sqrt{s_{NN}} = 19.6$, 27, 39, and 62.4 GeV and from the top RHIC energy. As discussed in the previous subsection, the contribution from hadrons is dominant in the low-
The invariant mass spectra of dielectrons from the PHSD in comparison to the STAR data in Au+Au collisions from $\sqrt{s_{NN}} = 19.6$ to 200 GeV [55, 56] and to the ALICE data in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [57]. The total yield is displayed in terms of the blue lines while the different contributions are specified in the legends. Note that the contribution from $J/\Psi$ and $\Psi'$ decays are not included in the PHSD calculations.

mass region and signals a broadening of the $\rho$ meson spectral function in dense nuclear matter (cf. Ref. [13]. On the other hand, the intermediate-mass range originates predominantly by dielectrons from partonic interactions and those from heavy flavor decays. Similar to the Pb+Pb
collisions in Fig. 4), the contribution from heavy flavor becomes more and more important with increasing collision energy. The contribution from heavy flavors and from partonic interactions cross around invariant masses $M \approx 1$ GeV in Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV. However, the crossing point shifts to 1.6 GeV at $\sqrt{s_{NN}} = 27$ GeV and to $\sim 2.0$ GeV at $\sqrt{s_{NN}} = 39$ and 62.4 GeV. At the top RHIC energy they cross at $\sim 2.4$ GeV.

The last panel of Fig. 6 is the invariant mass spectrum of dielectrons in central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. As in Au+Au collisions at the RHIC energies, the low-mass range is dominated by the dielectrons from hadronic channels and the intermediate-mass region by those from partonic interactions and heavy flavor decays. However, the crossing point of the contribution from partonic interactions and that from heavy flavor is lower than at the top RHIC energy, which is due to a couple of effects: i) the cross section for charm production no longer increases rapidly at the LHC energies as shown in Fig. 1 (a). It is also seen in Fig. 1 (b), which shows the number of produced charm pairs as a function of collision energy. As a result, the growth in the number of produced charm pairs is not faster than the growth of dielectrons from partonic interactions. Additionally the shadowing effect, which is the modification of the parton distribution function in nuclei [58], considerably suppresses charm production at the LHC energies [34]. ii) Another reason is the stronger suppression of the charm four-momentum by partonic scattering at the LHC energies. The strong interaction of heavy flavor with the medium reduces the invariant mass of dielectrons. Since the interaction is stronger at the LHC energies, we can expect a larger suppression of the dielectron spectrum at larger invariant masses. iii) Furthermore, at the LHC energies the contribution from semi-leptonic $BB$ decays becomes important. Comparing the lower two panels of Fig. 6, the contribution from $BB$ decays is found to be larger than that from $DD$ decays above $M \approx 2.2$ GeV in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, while the contribution from $BB$ decays is larger only above $M \approx 3$ GeV in Au+Au collisions $\sqrt{s_{NN}} = 200$ GeV. Since the contribution from $BB$ decays amounts to about 50% of the contribution from partonic interactions at the LHC energies, it will distort the information on partonic matter in the intermediate-mass range of the dielectron spectrum.

Besides the interesting points mentioned above, we close this subsection with the comment that the dilepton invariant mass spectra from the PHSD describe reasonably well the available experimental data for collision energies from 19.6 GeV to 2.76 TeV although the experimental data at $\sqrt{s_{NN}} = 2.76$ TeV are available only for invariant masses $M \leq 1$ GeV.

6. Summary
We have studied correlated electron ($e^+e^-$) production through the semi-leptonic decay of charm hadrons in relativistic heavy-ion collisions from $\sqrt{s_{NN}} = 8$ GeV to 2.76 TeV within the PHSD transport approach in extension of our work on $D-$meson production in relativistic heavy-ion collisions at RHIC and LHC energies [33, 34, 35] and low mass dilepton production from SIS to RHIC energies [13]. In the PHSD the charm partons - produced by the initial hard nucleon-nucleon scattering - interact with the massive quarks and gluons in the QGP by using the scattering cross sections calculated in the Dynamical Quasi-Particle Model (DQPM) which reproduces heavy-quark diffusion coefficients from lattice QCD calculations at temperatures above the deconfinement transition [43]. When approaching the critical energy density for the phase transition from above, the charm (anti)quarks are hadronized into $D-$mesons through the coalescence with light (anti)quarks. Those heavy quarks, which fail in coalescence until the local energy density is below 0.4 GeV/fm$^3$, hadronize by fragmentation as in $p+p$ collisions [34]. The hadronized $D-$mesons then interact with light hadrons in the hadronic phase with cross sections that have been calculated in an effective lagrangian approach with heavy-quark spin symmetry. Finally, after freeze-out of the $D-$mesons they produce single electrons through semi-leptonic decays with the branching ratios given by the PYTHIA event generator.

The dilepton production from hadronic and partonic channels in central Pb+Pb (or Au+Au)
collisions has been calculated including also the contribution from the semi-leptonic decays of heavy flavors in PHSD for the first time on a fully microscopic level. We recall that also the cross sections for dilepton production have been calculated by employing the same propagators and couplings as incorporated in the partonic dynamics in PHSD (cf. [53]). We find that even in central Pb+Pb collisions at $\sqrt{s_{NN}} = 8$ to 20 GeV the contribution from $D, \bar{D}$ mesons to the intermediate mass dilepton spectra is subleading and one should have a rather clear signal from the QGP radiation whereas at the top RHIC energy this contribution overshines the intermediate mass dileptons from the QGP. It is interesting to note that the dielectrons from $D, \bar{D}$ mesons do not increase any more relative to partonic interactions at the LHC energies for a couple of reasons: i) the cross section for charm production does not grow as fast as at low energies; ii) the shadowing effects, which suppress charm production at low transverse momentum, are stronger at LHC than at RHIC energies; iii) the charm quark pair loose more four-momentum in the partonic medium produced at the LHC, which suppresses the invariant mass of the dielectrons from the semi-leptonic decays. Furthermore, the contribution from $B, \bar{B}$ meson decays becomes more important and supersedes the contribution from $D, \bar{D}$ meson decays above $M = 2.2\sim2.3$ GeV at the LHC energies and amounts to about half the contribution from partonic interactions. All these effects strongly distort the information about partonic matter from intermediate-mass dielectrons at the LHC energies. The dilepton spectra at lower masses ($0.2$ GeV $\leq M \leq 0.7$ GeV) at SPS, FAIR/NICA and BES RHIC energies show some sensitivity to the medium modification of the $\rho$ meson where the data favor an in-medium broadening as pointed out in the earlier studies on dilepton production reviewed in Refs. [12, 13].

In general the PHSD calculations compare well with the available dilepton data from the BES program at RHIC as well as the LHC energy of $\sqrt{s_{NN}} = 2.76$ TeV where, unfortunately, only low mass dilepton data are available so far. As noted above, the large background from $D, \bar{D}$ as well as $B, \bar{B}$ correlated semi-leptonic decays - in the intermediate mass range - is by far subleading at lower SPS and FAIR/NICA energies which provides promising perspectives for the future dilepton measurements at these facilities and allows for a fresh look at the electromagnetic radiation from the QGP at finite baryon chemical potential.

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