A puzzle from low transverse momentum dileptons in relativistic heavy-ion collisions

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The dilepton transverse momentum spectra and invariant mass spectra for low $p_T < 0.15$ GeV/c in Au+Au collisions of different centralities at $\sqrt{s_{NN}} = 200$ GeV are studied within the parton-hadron-string dynamics (PHSD) transport approach. The PHSD describes the whole evolution of the system on a microscopic basis, incorporates hadronic and partonic degrees-of-freedom, the dynamical hadronization of partons and hadronic rescattering. For dilepton production in p+p, p+A and A+A reactions the PHSD incorporates the leading hadronic and partonic channels (also for heavy flavors) and includes in-medium effects such as a broadening of the vector meson spectral functions in hadronic matter and a modification of initial heavy-flavor correlations by interactions with the partonic and hadronic medium. The transport calculations reproduce well the momentum integrated invariant mass spectra from the STAR Collaboration for minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, while the description of the STAR data - when gating on low $p_T < 0.15$ GeV/c - is getting worse when going from central to peripheral collisions. An analysis of the transverse momentum spectra shows that the data for peripheral (60-80%) collisions are well reproduced for $p_T > 0.2$ GeV/c while the strong peak at low $p_T < 0.15$ GeV/c, that shows up in the experimental data for the mass bins ($0.4 < M < 0.7$ GeV and $1.2 < M < 2.6$ GeV), is fully missed by the PHSD and cannot be explained by the standard in-medium effects. This provides a new puzzle for microscopic descriptions of low $p_T$ dilepton data from the STAR Collaboration.

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I. INTRODUCTION

Relativistic heavy-ion collisions are well suited to produce hot and dense matter in the laboratory. Whereas low-energy collisions create nuclear matter at high baryon chemical potential and moderate temperature, high-energy collisions at the Relativistic Heavy-Ion Collider (RHIC) or the Large Hadron Collider (LHC) produce a dominantly partonic matter at high temperature and almost vanishing baryon chemical potential. The latter is controlled by lattice quantum chromodynamics (lQCD) which shows that the phase transition between the quark-gluon plasma (QGP) and the hadronic system is a crossover at low baryon chemical potential [1,2].

Since the partonic matter in relativistic heavy ion collisions survives only for a couple of fm/c within a finite volume, it is quite challenging to investigate its properties. In this context hard probes (heavy flavor or jets) and penetrating probes (photons or dileptons) are of particular interest. Dileptons have the advantage of an additional degree of freedom compared to photons, i.e. their invariant mass, which allows to roughly separate hadronic and partonic contributions by appropriate mass cuts [3]. For example, dileptons with invariant mass less than 1.2 GeV dominantly stem from hadronic decays while those with invariant masses between 1.2 GeV and 3 GeV stem from partonic interactions and correlated semileptonic decays of heavy flavor hadrons. In the first case it is possible to study the modification of hadron properties such as a $\rho$ meson broadening or a mass shift in nuclear matter [4,5]. On the other hand the dileptons with intermediate masses provide information on the properties of partonic matter once the background from semileptonic heavy flavor decays is subtracted. This background overshines the partonic contribution at RHIC and LHC energies and is subleading only at collision energies per nucleon below about $\sqrt{s_{NN}} = 10$ GeV [6].

Recently, dielectrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV have been measured as a function of transverse momentum [7] for different centralities. It turned out as a surprise that the yield of dielectrons is largely enhanced at low transverse momentum - compared to expected hadronic decays - in particular in peripheral collisions of 60-80% centrality. In case the low $p_T$ peak would be measured in ultra-peripheral collisions [7] - for impact parameters larger than roughly twice the radius of the nuclei - one could attribute it to a coherent source from the strong electromagnetic fields generated by the charged spectators [8]. However, an interesting point is that the low $p_T$ enhancement is observed in peripheral collisions with dominant hadronic reaction channels, which are expected to be under control by independent $p+p$ measurements. This raises severe doubts on a coherent nature of the observed phenomenon. These surprising observations come up as a puzzle and in this work we will investigate the question if hadronic and partonic in-medium effects might be the origin for the anomalous enhancement of dielectrons at low transverse momentum in peripheral collisions.

We will employ the microscopic parton-hadron-string...
II. DILEPTON PRODUCTION IN RELATIVISTIC HEAVY-ION COLLISIONS

The production channels for dileptons in relativistic heavy-ion collisions may be separated into three different classes: i) hadronic production channels, ii) partonic production channels and iii) the contribution from the semileptonic decay of heavy-flavor pairs. The production of dileptons in the hadronic phase includes the following steps: First a resonance $R$ is produced either in a nucleon-nucleon (NN) or meson-nucleon (mN) collisions. The produced resonance $R$ may produce dileptons directly through Dalitz decay, for example, $\Delta \rightarrow e^+e^−N$, or the resonance $R$ decays to a meson which produces dielectrons through direct decay ($\rho, \omega, \phi$) or Dalitz decay ($\pi^0, \eta, \omega$). Additionally the resonance $R$ may decay to another resonance $R'$ which then produces dileptons through Dalitz decay. In the PHSD we take into account also dilepton production by two-body scattering such as $\pi + \rho, \pi + \omega, \rho + \rho, \rho + a_1$ \cite{22}, although the contributions are subleading. An important point is the modification of the vector-meson spectral functions ($\rho, \omega, \phi$), i.e. the collisional broadening of the vector-meson widths in nuclear matter is incorporated in PHSD (by default) \cite{23}, which leads to results consistent with the experimental data on dileptons from SIS to LHC energies \cite{22, 23, 24}.

In partonic matter dileptons are produced through the channels $q\bar{q} \rightarrow \gamma^*, q\bar{q} \rightarrow \gamma^* g$ and $qg \rightarrow \gamma^* q (\bar{q}g \rightarrow \gamma^* \bar{q})$ where the virtual photon $\gamma^*$ decays into $e^+e^-$ or $\mu^+\mu^−$ pair. We note that $q(\bar{q})$ and $g$ in the above processes stand for off-shell partons and the effective propagators for quarks and gluons from the Dynamical QuasiParticle Model (DQPM) \cite{25} have been employed for the calculation of the differential cross sections in Refs. \cite{26, 27, 28}. We recall that the dileptons from the QGP are produced in the early stage of heavy-ion collisions and have a relatively large invariant mass and high effective temperature.

The production of dileptons from heavy-flavor pairs is different from the other channels since the lepton and anti-lepton are produced in separate semi-leptonic decays. However, since heavy flavor is always produced by pairs, it contributes to dilepton production with the probability that both heavy flavor and anti-heavy flavor have semi-leptonic decays. Furthermore, the heavy flavor pairs - produced very early in heavy-ion collisions - suffer from strong interactions with the partonic or hadronic medium and thus the kinematics of the pair change in time. E.g., the heavy flavor quarks are suppressed at high transverse momentum due to the energy loss in partonic matter, while slow heavy flavor quarks are shifted to larger momenta due to collective flow. These modifications of heavy flavor pairs in heavy-ion collisions affect the spectrum of dileptons as demonstrated in Ref. \cite{29}.

To show these effects quantitatively we compare in Fig. 1 the invariant mass spectra of dileptons with transverse momenta less than 0.15 GeV/c from heavy-flavor pairs with and without partonic and hadronic interactions in 10-40, 40-60, and 60-80 % central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

![FIG. 1: Invariant mass spectra of dileptons from $D\bar{D}$ pairs with and without partonic and hadronic interactions in 10-40, 40-60, and 60-80 % central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.](image)

The softening of the mass spectrum becomes weaker with decreasing centrality since there are less and less interactions of charm quarks. The softening of the mass spectrum becomes weaker with decreasing centrality since there are less and less interactions of charm quarks.
200 GeV for different centrality classes.

### III. \( M\) - AND \( p_T\) - SPECTRA OF DILEPTONS

Since dileptons have the invariant mass as an additional degree of freedom, compared to photons or other hadronic probes in heavy-ion collisions, it provides more information on the matter produced in these collisions. Whereas low-mass dileptons are mainly produced from hadronic sources the intermediate-mass dileptons dominantly stem from partonic interactions and heavy-flavor pairs. Since the cross section for heavy flavor production increases rapidly - starting from the threshold energy - the dileptons from partonic interactions are dominant in the intermediate mass range only for collision energies up to a few tens of GeV bombarding energy, whereas at higher energies the dileptons from heavy-flavor pairs overshine the partonic sources [2].

This is demonstrated in Fig. 2 where the invariant mass spectrum of dielectrons in minimum-bias \( Au+Au \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) is shown for the acceptance cuts as in Fig. 3 for 10-40, 40-60, and 60-80 % central \( Au+Au \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) in comparison to the experimental data (for 60-80 % central collisions) [3].

We show in Fig. 3 the transverse momentum spectra of low-mass (0.4 < \( M < 0.79 \text{ GeV} \)) and intermediate mass (1.2 < \( M < 2.6 \text{ GeV} \)) dileptons for the same acceptance cuts as in Fig. 2 for 10-40, 40-60, and 60-80 % central \( Au+Au \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). The yields of low-mass dileptons within the acceptance cuts are \( 4.85 \times 10^{-3}, 1.05 \times 10^{-3} \), and \( 2.1 \times 10^{-3} \) for 10-40, 40-60, and 60-80 % central collisions, respectively. For the intermediate-mass dileptons they are, respectively, \( 1.0 \times 10^{-3}, 2.2 \times 10^{-4} \), and \( 4.5 \times 10^{-5} \). Comparing the low-mass and intermediate-mass dileptons, the ratio of the dilepton yields in 10-40 % central collisions to that in 40-60 % or 60-80 % central collisions is very similar. This demonstrates that the dependence of the dilepton

\[ \sqrt{1.4} \]
yield on invariant mass is not so sensitive to the centrality in heavy-ion collisions, if the collision energy is the same. The shape of the transverse momentum spectra of dileptons is neither sensitive to the centrality as shown in Fig. 3. However, with increasing transverse momentum the spectrum of low-mass dielectron decreases faster than that of intermediate-mass dileptons as expected.

Furthermore, in Fig. 4 we compare the results from the PHSD with the experimental data for 60-80 % central collisions. It is seen that the PHSD reproduces very well the experimental spectra both for low-mass dileptons and for intermediate-mass dileptons down to $p_T \approx 0.15$ GeV/c. The experimental data show an anomalous enhancement of dileptons below $p_T \approx 0.15$ GeV/c for the very peripheral collisions, which is not described by the PHSD at all.

FIG. 4: Transverse momentum spectra of (a) low-mass and (b) intermediate-mass dileptons with the individual contributions shown additionally in 60-80 % central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The experimental data are taken from Ref. [8].

In order to provide further information, we show in Fig. 5 all contributions to the transverse momentum spectra of low-mass and intermediate-mass dileptons in 60-80 % central collisions. As in Fig. 2 the low-mass dilepton sector has contributions from various hadronic and partonic channels and the most dominant contributions are from $DD$ pairs and $\rho$-meson decays. On the other hand, in the

![Image](image_url)

FIG. 5: Invariant mass spectra of dileptons with small transverse momentum ($p_T < 0.15$ GeV/c) in (a) 10-40, (b) 40-60, and (c) 60-80 % central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The experimental data are taken from Ref. [8].
intermediate-mass dilepton sector the contribution from $DD$ pairs and partonic interactions are dominant with some background from $BB$ pairs. As mentioned in the previous section, there are three kinds of nuclear modifications on dileptons in heavy-ion collisions, but none of them can explain the enhancement of dileptons at low transverse momentum. We recall that the dileptons from heavy flavor pairs are not visibly modified in very peripheral collisions due to the low amount of rescattering as shown in Fig. [I]. Also note that the contributions from $\rho$-meson decays or partonic interactions are subdominant.

Fig. [I] furthermore shows the invariant mass spectra of dileptons with small transverse momentum ($p_T < 0.15$ GeV/c) in 10-40, 40-60, and 60-80 % central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in comparison to the experimental data from Ref. [8]. The PHSD can reproduce the experimental data in 10-40 % central collisions very well, but begins to deviate slightly from the data in 40-60 % central collisions; the deviation becomes huge for 60-80 % central collisions, which is consistent with Fig. [I] and implies that the anomalous enhancement of dileptons at low transverse momentum is not seen - or only very small - in central collisions. If we assume that the dilepton spectrum is the same at low transverse momentum (in Fig. [I]) regardless of centrality, then the anomalous source is quite strong in 60-80 % central collisions, less strong in 40-60 % central collisions, and hardly seen in 10-40 % central collisions. Furthermore, since the $p_T$ range is very small we conclude that the transverse mass distribution from the anomalous source is almost the same as from hadronic and partonic contributions in central collisions.

The other point is that differences between the experimental data and the PHSD results in 40-60 and 60-80 % central collisions do practically not depend on the invariant mass of the dileptons but are rather constant in magnitude. For example, the yield of low-mass dielectrons $(0.4 < M < 0.79$ GeV) and that of intermediate-mass dielectrons $(1.2 < M < 2.6$ GeV) from the experimental data in 60-80 % central collisions are alike but about ten times larger than those from the PHSD. These findings are hard to reconcile.

IV. SUMMARY

In this study we have addressed the low $p_T$ enhancement of dileptons from peripheral heavy-ion collisions where the experimental data show a large anomalous source regardless of the dilepton invariant mass. We have employed the PHSD transport approach to describe the transverse momentum spectra of dileptons in relativistic heavy-ion collisions which incorporates three in-medium effects in heavy-ion collisions: i) The spectral functions of vector meson broaden in nuclear matter, ii) the correlation of heavy-flavor pairs is modified by partonic and hadronic interactions, and iii) there are sizeable contributions from partonic interactions which do not exist in hadronic cocktails. Taking all matter effects into account, the PHSD reproduces the experimental data for dileptons down to $p_T \approx 0.15$ GeV/c at all centralities, however, underestimates the data below $p_T \approx 0.15$ GeV/c in very peripheral collisions. Accordingly, the large enhancement of dileptons at low transverse momentum in peripheral heavy-ion collisions is still an open question and the solution of the puzzle is beyond standard microscopic models that have shown to be compatible with dilepton data from heavy-ion collisions in the range from SIS to LHC energies.

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[1] C. Bernard et al. [MILC Collaboration], Phys. Rev. D 71, 034504 (2005).
[2] Y. Aoki, G. Endrodi, Z. Fodor, S. D. Katz, and K. K. Szabo, Nature 443, 675 (2006).
[3] A. Bazavov, T. Bhattacharya, M. Cheng, C. DeTar, H. T. Ding, S. Gottlieb, R. Gupta, P. Hegde, U. M. Heller, F. Karsch et al., Phys. Rev. D 85, 054503 (2012).
[4] R. Rapp and J. Wambach, Adv. Nucl. Phys. 25, 1 (2000).
[5] R. Rapp, Adv. High Energy Phys. 2013, 148253 (2013)
[6] O. Linnyk, E. Bratkovskaya, and W. Cassing, Prog. Part. Nucl. Phys. 87, 50 (2016).
[7] T. Song, W. Cassing, P. Moreau, and E. Bratkovskaya, Phys. Rev. C 97, 064907 (2018).
[8] C. Yang, EPJ Web of Conferences 171, 18016 (2018).
[9] J. Adams et al. [STAR Collaboration], Phys. Rev. C 70, 031902 (2004).
[10] V. P. Konchakovski et al., J. Phys. G 42, 055106 (2015); Phys. Rev. C 85, 011902 (2012), Phys. Rev. C 85, 044922 (2012), Phys. Rev. C 90, 014903 (2014).
[11] E. Seifert and W. Cassing, Phys. Rev. C 97, 024913 (2018); Phys. Rev. C 97, 044907 (2018).
[12] O. Linnyk, E. L. Bratkovskaya, V. Ozvenchuk, W. Cassing, and C. M. Ko, Phys. Rev. C 84, 054917 (2011).
[13] E. L. Bratkovskaya and W. Cassing, Nucl. Phys. A 807, 214 (2008).
[14] O. Linnyk, J. Phys. G 38, 025105 (2011).
[15] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. C 92, 024912 (2015).