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Discrepancy in low transverse momentum dileptons from 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 and 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, gets 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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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 BNL Relativistic Heavy-Ion Collider (RHIC) or the CERN 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 [1–3].

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 [4]. For example, dileptons with invariant mass less than 1.2 GeV dominantly stem from hadronic decays while those with invariant masses between 1.2 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 ρ meson broadening or a mass shift in nuclear matter [5,6]. 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 dominates over the partonic contribution at RHIC and LHC energies and is subleading only at collision energies per nucleon below about $\sqrt{s_{NN}} =$ 10 GeV [7].

Recently, dielectrons in Au+Au collisions at $\sqrt{s_{\rm NN}} =$ 200 GeV have been measured as a function of transverse momentum [8] for different centralities. Surprisingly 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 the case when the low p_T peak would be measured in ultraperipheral collisions [9] 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 regarding the coherent nature of the observed phenomenon. These surprising observations are puzzling and in this work we will investigate the question of whether hadronic and partonic in-medium effects might be the origin for the anomalous enhancement of dielectrons at low transverse momentum in peripheral collisions.

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We will employ the microscopic parton-hadron-string dynamics (PHSD) transport approach where quarks and gluons in the quark-gluon plasma are off-shell, massive, strongly interacting quasiparticles. The masses of quarks and gluons are assigned from their spectral functions at finite temperature whose pole positions and widths are, respectively, given by the real and imaginary parts of partonic self-energies [6]. The PHSD approach has successfully described experimental data in relativistic heavy-ion collisions for a wide range of collision energies from the GSI heavy-ion synchrotron (SIS) to the LHC for many hadronic as well as electromagnetic observables [6,10,11].

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 (ρ, ω, ϕ) or Dalitz decay (π^0, η, ω). 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 $\pi + \rho$, $\pi + \omega$, $\rho + \rho$, and $\pi + a_1$ [12], although the contributions are subleading. An important point is the modification of the vector-meson spectral functions (ρ, ω, ϕ), i.e., the collisional broadening of the vector-meson widths in nuclear matter is incorporated in PHSD (by default) [13], which leads to results consistent with the experimental data on dileptons from SIS to LHC energies [6,12,13].

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 γ^* 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) [6] have been employed for the calculation of the differential cross sections in Refs. [7,14]. 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 antilepton are produced in separate semileptonic 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 semileptonic 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. For example, 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

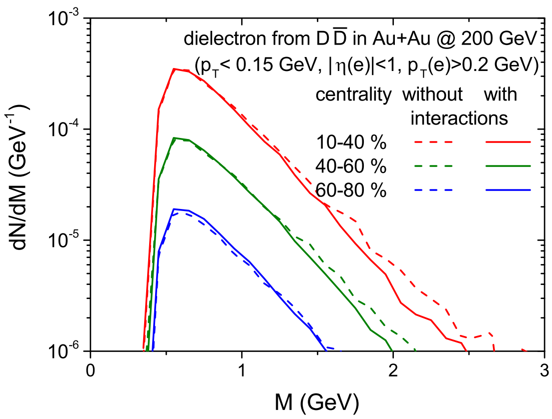

FIG. 1. Invariant mass spectra of dileptons from $D\bar{D}$ pairs with and without partonic and hadronic interactions in 10–40%, 40–60%, and 60–80% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

collisions affect the spectrum of dileptons as demonstrated in Ref. [7].

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. The figure shows that the interactions of heavy flavors soften the invariant mass spectra of dileptons especially in central collisions while the effect is hardly visible in very peripheral collisions. This change in slope is due to energy loss for high momentum heavy flavors by interactions which randomizes the correlation angle between charm and anticharm quarks [7]. The softening of the mass spectrum becomes weaker with decreasing centrality since there are less and less interactions of charm quarks.

Summarizing, there are three different medium modifications on dileptons in relativistic heavy-ion collisions, which cannot be described by hadronic cocktails: (1) the broadening of the vector-meson spectral functions in nuclear matter, (2) dilepton production from partonic interactions, and (3) the modification of the dilepton spectra from heavy-flavor pairs due to strong charm or beauty scatterings in particular in the partonic phase. We will now explore these effects on the momentum and mass spectra for dileptons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for different centrality classes.

Since dileptons have the invariant mass as an additional degree of freedom, compared to photons or other hadronic probes in heavy-ion collisions, it potentially provides more information on the matter produced in these collisions.

This is demonstrated in Fig. 2 where the invariant mass spectrum of dielectrons in minimum-bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is shown for the constraint that the transverse momentum of electron and that of position both are larger than 0.2 GeV/c and each rapidity is smaller than unity, i.e., $|y_e| \leqslant 1$. We note that dielectron bremsstrahlung from both partonic and hadronic collisions, as suggested long ago [16–21], is added to our previous study [7], although the contributions are subleading. For an estimate of the order of magnitude the differential bremsstrahlung cross section is

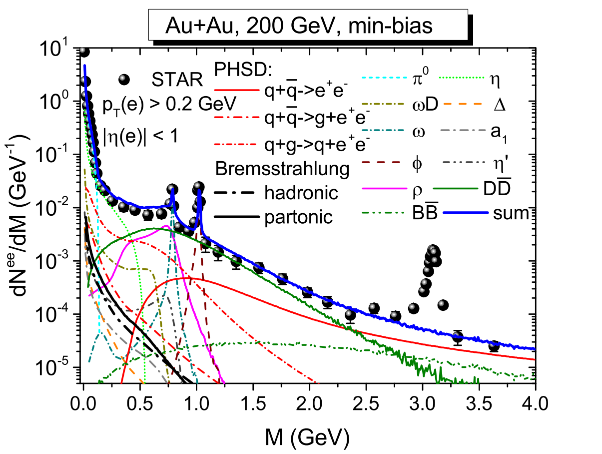

FIG. 2. Invariant mass spectrum of dileptons from the PHSD in minimum-bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in comparison to the experimental data from the STAR Collaboration [15]. The different channels are specified in the legend.

evaluated in the soft-photon approximation:

$$E\frac{d^2\sigma(e^+e^-)}{dMd^3p} = \frac{\alpha^2}{6\pi^3 M}\frac{|\epsilon\cdot J|^2}{e^2}\frac{\lambda^{1/2}(s_2, m_3, m_4)}{\lambda^{1/2}(s, m_3, m_4)}\sigma_{\rm el}, \quad (1)$$

where ϵ_μ is the polarization vector of the virtual photon and J_μ the electromagnetic current of the incoming and outgoing particles in the reaction $1 + 2 \rightarrow 3 + 4 + \gamma^*$. Furthermore, $\sigma_{\rm el}$ is the elastic scattering cross section and $\lambda^{1/2}(s_2, m_3, m_4)$ is the three-momentum of particle 3 or 4 in their center-of-mass frame at the invariant energy $s_2 = (p_3 + p_4)^2$ [6]. One can see from Fig. 2 that many hadronic sources contribute to the low-mass dilepton spectrum while the intermediate-mass range is dominated by the contribution from heavy-flavor pairs and that from partonic interactions. We note that the ρ meson considerably broadens and that the contribution from charmonia is not included in the PHSD calculations which explains the missing peak in the data from the STAR Collaboration [15] at about 3.1 GeV of invariant mass. Nevertheless, the description of the inclusive dilepton spectra within PHSD is very good for lower invariant masses.

In view of the completely different contributions for low-mass and intermediate-mass dileptons, it is helpful to separate them for studying transverse momentum spectra.

We show in Fig. 3 the transverse momentum spectra of low-mass ($0.4 < M < 0.79$ GeV) and intermediate mass ($1.2 < M < 2.6$ GeV) dileptons for the same acceptance cuts as in Fig. 2 for 10–40%, 40–60%, and 60–80% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The yields of low-mass dileptons within the acceptance cuts are 4.85×10^{-3}, 1.05×10^{-3}, and 2.1×10^{-4} for 10–40%, 40–60%, and 60–80% central collisions, respectively. For the intermediate-mass dileptons they are, respectively, 1.0×10^{-3}, 2.2×10^{-4}, and 4.5×10^{-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 yield on invariant mass is not so sensitive to the centrality in heavy-ion collisions, if the collision energy

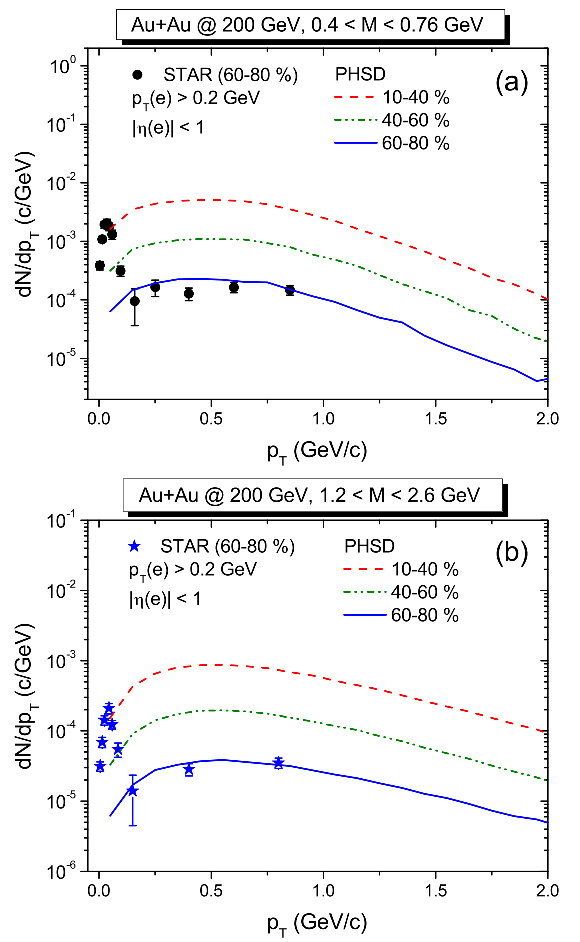

FIG. 3. Transverse momentum spectra of (a) low-mass and (b) intermediate-mass dileptons in 10–40%, 40–60%, and 60–80% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV compared to the experimental data (for 60–80% central collisions) [8].

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. 3 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.

To provide further information, we show in Fig. 4 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 $D\bar{D}$ pairs and ρ-meson decays. On the other hand, in the intermediate-mass dilepton sector the contribution from $D\bar{D}$ pairs and partonic interactions are dominant with some background from $B\bar{B}$ pairs.

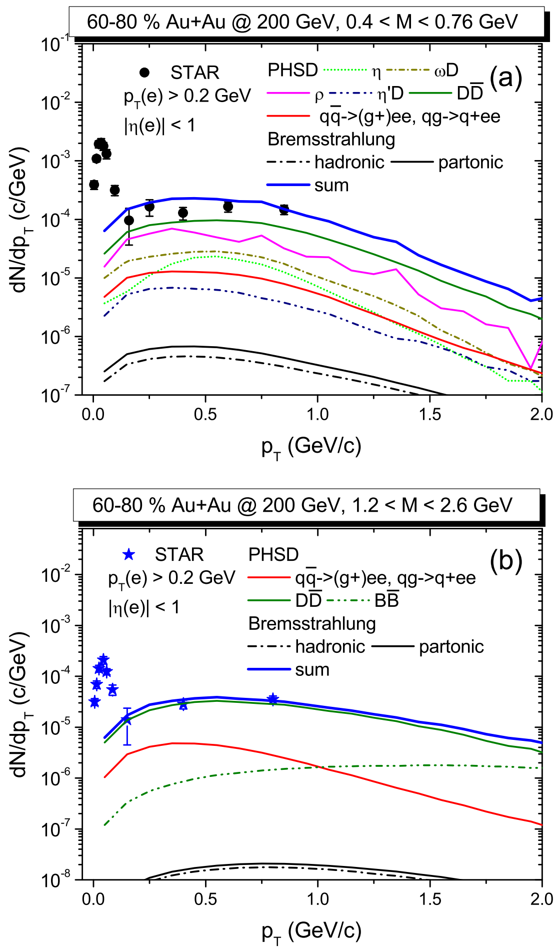

FIG. 4. Transverse momentum spectra of (a) low-mass and (b) intermediate-mass dileptons with the individual contributions shown additionally in 60–80% central Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV. The experimental data are taken from Ref. [8].

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. 1. Also the contributions from ρ-meson decays or partonic interactions are subdominant. Furthermore, the dilepton bremsstrahlung is peaked at low transverse momentum only for very small invariant mass, $M \to 0$, while in the two mass regions of interest the p_T spectra are broad and show no indication of a low p_T peak.

Figure 5, 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 compared 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 pronounced for 60–80% central collisions, which is consistent with Fig. 4, and implies

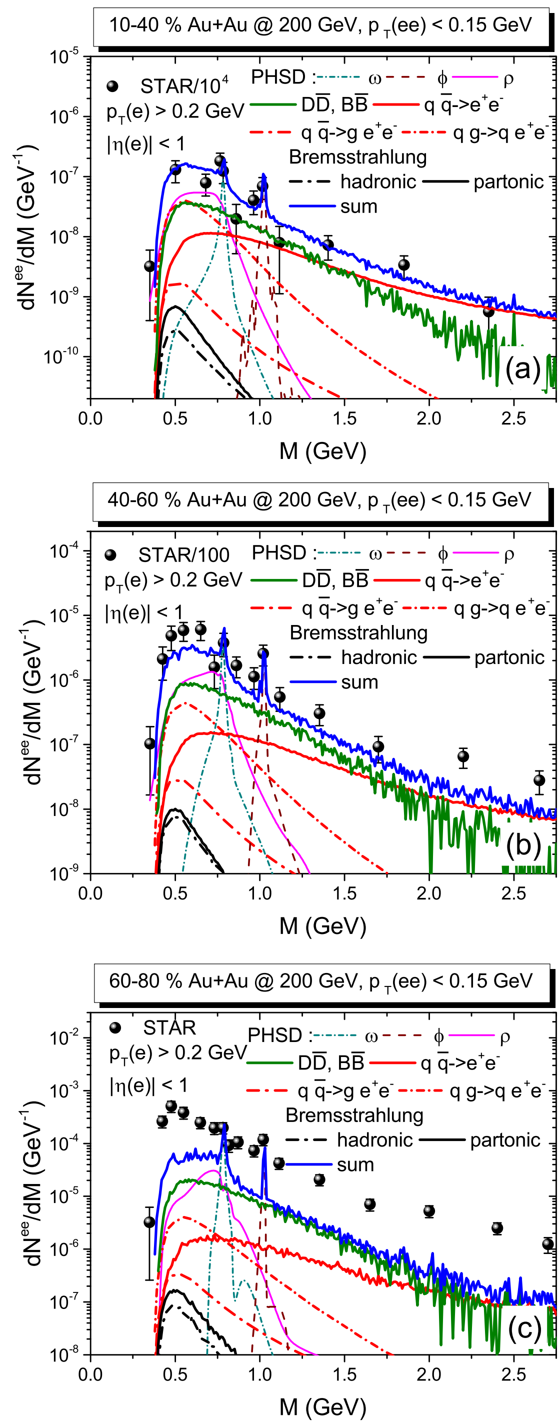

FIG. 5. Invariant mass spectra of dileptons with small transverse momentum ($p_T < 0.15$ GeV/c) in (a) 10–40%, (b) 40–60%, and (c) 60–80% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The experimental data are taken from Ref. [8].

that the anomalous enhancement of dileptons at low transverse momentum is only small or moderate in central collisions. If we assume that the dilepton spectrum is the same at low transverse momentum (in Fig. 3) 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.

In summary, 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 mesons broaden in nuclear matter, (ii) the correlation of heavy-flavor pairs is modified by partonic and hadronic interactions, and (iii) there are sizable 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, it underestimates the data below $p_T \approx 0.15$ GeV/c in very peripheral collisions. In extension of previous studies we have incorporated the production of dilepton pairs by hadronic and partonic bremsstrahlung processes, as suggested early in Refs. [16–21], employing the soft-photon approximation for an estimate. We find that these radiative corrections are by far subleading and, in the invariant mass regions of interest, do not peak at low p_T. 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 [6].

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