Dilepton signature of a 1st-order phase transition

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At high temperatures and vanishing baryon chemical potential, μ_B=0, QCD matter undergoes a smooth cross-over transition from a hadronic phase with spontaneously broken chiral symmetry to a chirally restored plasma of quarks and gluons. It is conjectured that the hadron-quark transition develops a second order endpoint with a first-order transition line attached toward higher μ_B and smaller temperatures (which may occur, e.g., in the interior of neutron stars). In heavy-ion collisions a large region of the phase diagram can be probed by lowering the collision energies from the ultra-relativistic regime at RHIC and the LHC down to a few GeV per nucleon pair in the center of mass. However, clear evidence for a 1st-order transition remains elusive to date, but sustained efforts to explore the QCD phase diagram continue.

In the present work [1] we investigate dilepton radiation from the hot and dense fireballs created in Au-Au collisions at projectile energies of 1-2 AGeV for potential signatures of a 1st-order transition. Toward this end, we employ hydrodynamic simulations with a different equation of state (EoS), with and without a phase transition. The latter is constrained by susceptibilities computed in lattice-QCD at μ_B=0, as well as by neutron star properties [2], while the former is implemented via modifications of the mean fields in the quark phase. The resulting time evolutions of temperature and baryon density are shown in Fig. 1, indicating higher values for both quantities in the 1st-order case due the softer EoS compared to the crossover scenario. In addition, a significantly longer fireball lifetime is observed for the 1st-order EoS. These features are not unexpected but are notoriously difficult to discern using hadronic final-state observables.

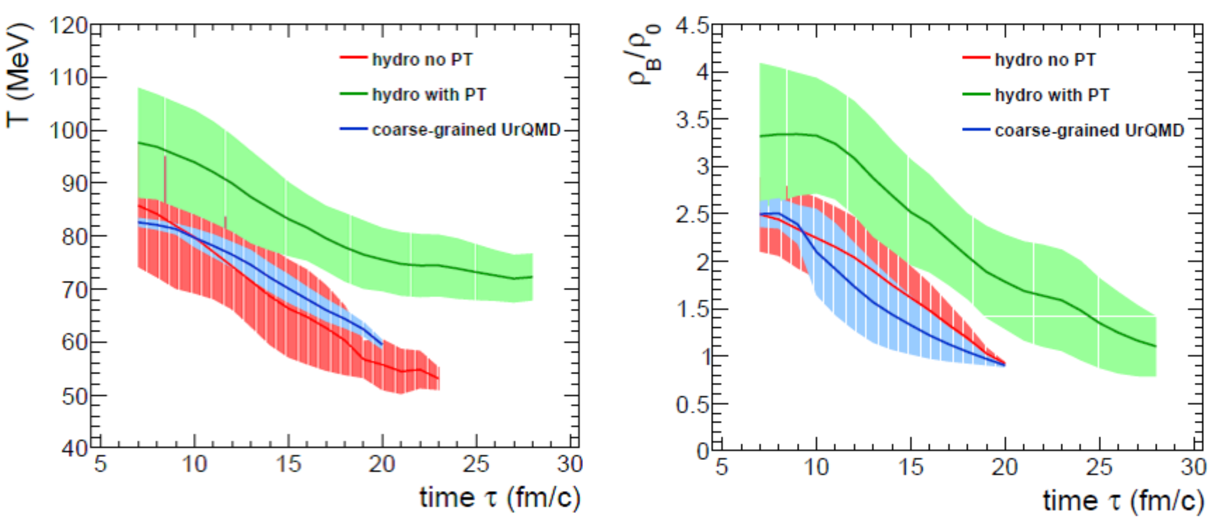

Fig. 1. Time evolution of average temperature (T, left panel) and baryon density (ρ_B, right panel) in hydrodynamic simulations of central Au+Au (1.23AGeV) collisions employing an EoS with (green lines) and without (red lines) a 1st-order phase transition (PT). For comparison, the coarse-graining results of hadronic transport calculations [3] are also shown (blue lines). The bands correspond to the second moment of the distributions in T and ρ_B.

This motivated us to search for signatures of a 1st-order transition in the spectra of electromagnetic radiation, which is emitted throughout the entire 4-volume of the fireball evolution. For the invariant-mass spectra of dileptons (e^+e^- pairs) one has

$$dN_{ee}/dM = \int (M/q_0)\, d^3q\, d^3x\, dt\, R_{ee} \ ,$$

where the integration is over space-time and 3-momentum, and R_{ee} is the 8-differential thermal production rate (with $M^2 = q_0^2 - \mathbf{q}^2$). We have employed hadronic emission rates including in-medium vector-meson spectral functions which have been well tested in heavy-ion collisions at the SPS and RHIC [4]. The invariant-mass spectra obtained from integrating the rates over the hydrodynamic simulations of central Au+Au collision at a lab energy of 1.23 AGeV are shown in Fig. 2. The main result is that the 1st-order scenario indeed produces significantly larger radiation yields than the cross-over one, by about a factor of 2 over most of the invariant-mass range from 0-1.5 GeV. At low masses, M < 1 GeV, this is mostly due to the longer lifetime, while at higher masses the larger temperatures also play an important role. We also show results from our previous work using coarse-grained hadronic transport calculations for the convolution with thermal dilepton rates [3]. The pertinent temperature and density evolution (Fig. 1), and the resulting dilepton spectra are quite similar to the hydrodynamic results without phase transition, which essentially reflects the systematic uncertainty in describing the medium evolution within the limits of small (hydrodynamics) and large (transport) mean-free-path approximations.

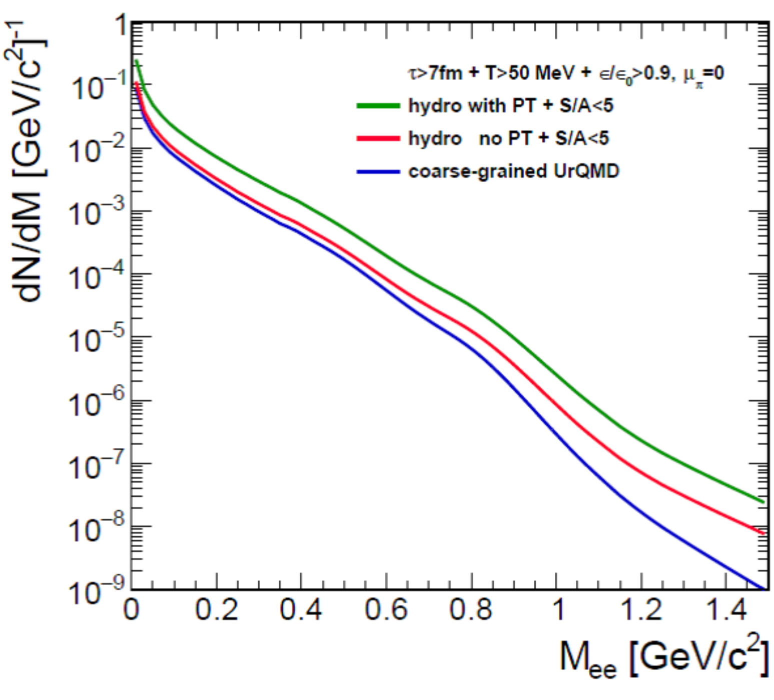

Fig. 2. Thermal dilepton spectra calculated for central Au+Au (1.23AGeV) collisions using hydrodynamic medium evolutions with an equation of state with 1st-order phase transition (green line) or with a cross-over transition (red line), as well as for a coarse-grained hadronic transport simulation using the UrQMD model (blue line).

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[3] R. Rapp and J. Wambach, Eur. Phys. J. A **6**, 415 (1999); H. van Hees and R. Rapp, Nucl. Phys. A **806**, 339 (2008); R. Rapp, Adv. High Energy Phys. **201**3, 148253 (2013).
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