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Bulk Observables within a Hybrid Approach for Heavy Ion Collisions with SMASH Afterburner †

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Abstract: We present a model of the dynamical evolution of relativistic heavy ion collisions, which combines second-order viscous hydrodynamics and microscopic transport. In particular, we present a hybrid approach with MUSIC hydrodynamics, and SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) afterburner. In this work, we focus on low-p_T hadronic observables—identified hadron p_T spectra and anisotropic flow coefficients. We also demonstrate how the hadronic chemistry is altered by the hadronic non-equilibrium dynamics, for example by baryon-antibaryon annihilation. The new MUSIC + SMASH hybrid approach is also compared to existing MUSIC + UrQMD results.

Keywords: relativistic heavy ion collisions; collective dynamics; hybrid approach

1. Introduction

For a few decades, high-energy nucleus-nucleus collisions have been carried out as a way to explore QCD matter at high temperature. One of the most important findings is that quark-gluon plasma (QGP) is created and behaves like a perfect fluid [1–7]. The hybrid framework, which combines viscous hydrodynamics and microscopic transport, has been successful in describing the low-p_T hadronic observables in heavy ion collisions [8–10]. It has been consensus that it is necessary to have hadronic and electromagnetic degrees of freedom within a single framework of microscopic transport. In addition, given that resonance excitations and decays dominate the low-p_T bulk dynamics in hadronic re-scattering, we are motivated to take the resonance mass distribution into account at the point of transition from hydrodynamics to microscopic transport. In this work, we present a hybrid approach with the IP-Glasma pre-thermalization dynamics [11], MUSIC hydrodynamics [12,13] with shear and bulk viscosities, Cooper-Frye particlization [14], and SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) [15] afterburner. In addition to the resonance mass sampling at particlization, we focus on how the hadronic chemistry is altered by the hadronic non-equilibrium dynamics, for example by baryon-antibaryon annihilation.

2. Materials and Methods

The pre-equilibrium dynamics in this work is described by the IP-Glasma model [11], where the low-x gluons with large multiplicity are characterized by a gluon field and their time evolution is governed by the classical Yang-Mills dynamics with color charges carried by colliding nuclei. The system is assumed to reach local thermal equilibrium at $\tau_0 = 0.4\,\mathrm{fm}$, until which the gluon field is evolved by the classical Yang-Mills equation. Once the energy-momentum tensor of gluon field is specified, the initial energy density and flow velocity for hydrodynamics are given by the eigenvalue equation $T^{\mu}{}_{\nu}u^{\nu} = \epsilon\, u^{\mu}$.

Time evolution of the fireball is handled by MUSIC viscous hydrodynamics [12,13] with shear and bulk viscosities. In addition to the energy-momentum conservation $\partial_\mu T^{\mu\nu} = 0$, the following equations determine time evolution of the shear stress tensor $\pi^{\mu\nu}$ and bulk pressure Π.

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\,\theta - \delta_{\Pi\Pi}\Pi\,\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} \tag{1}$$

$$\begin{aligned} \tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} &= 2\eta\,\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} \\ &\quad -\tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\,\sigma^{\mu\nu} \end{aligned} \tag{2}$$

where we have introduced the transport coefficients [16,17], which quantify how the system responds to spatial anisotropy and inhomogeneity. The equation of state, which provides a connection between energy density and pressure, has a cross-over phase transition between the hadronic resonance gas and lattice QCD [18].

The macroscopic degrees of freedom in hydrodynamics must be transformed into particles to simulate hadronic re-scatterings with microscopic transport. Based on the Cooper-Frye formalism [14], this transition is performed such that energy and momentum are conserved. The momentum-space distribution of particles is given by

$$\frac{dN}{d^3\mathbf{p}} = \frac{g}{(2\pi)^3}\int_\Sigma [f_0(x,\mathbf{p}) + \delta f_{\text{shear}} + \delta f_{\text{bulk}}]\,\frac{p^\mu d^3\Sigma_\mu}{E_\mathbf{p}} \tag{3}$$

where we have the shear [19] and bulk [20] viscous corrections to the distribution function. They are linearly proportional to $\pi^{\mu\nu}$ and Π, respectively. The isothermal hypersurface with temperature 165 MeV is chosen as the hypersurface Σ, at which particlization occurs. Introducing resonance mass sampling at particlization is work in progress. It must be pointed out that, in addition to the mass sampling of individual particle, the multiplicity integrations for sampling also have to take the mass distribution into account. Figure 1 shows the spectral functions being considered. It is expected that hadronic chemistry as well as kinematics will be altered by mass sampling. If higher masses are favored due to the asymmetric spectral functions, the p_T spectra will be shifted toward higher p_T and the multiplicity will be reduced.

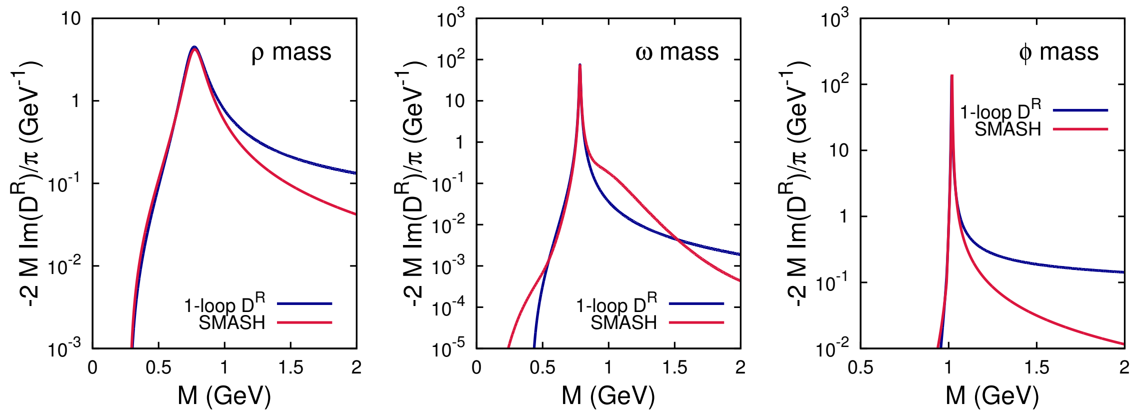

Figure 1. Spectral functions of the ρ meson (**left**), ω meson (**center**) and ϕ meson (**right**). Spectral functions from the retarded propagator, which is used in a dilepton study [21], are compared to the parametrization from Ref. [22], which is used in SMASH [15].

The hadronic re-scatterings are simulated by SMASH 1.5 [15], which is a microscopic transport approach incorporating hadronic degrees of freedom and a geometric collision criterion. The most significant hadronic interactions include elastic scatterings, resonance excitation and decay and baryon-antibaryon annihilations.

3. Results

In this work, we focus on the single-particle distribution, which is well captured by the identified hadron p_T-spectra and differential elliptic flow. They are presented in Figure 2 putting an emphasis on effects of hadronic re-scatterings. For the p_T-spectra, the PHENIX data [23] are shown for comparison. For the p_T-differential elliptic flows, the PHENIX [24] and STAR [25] data are shown. Note that in this calculation, all resonances are sampled with pole masses to allow for an apple-to-apple comparison to the existing MUSIC+UrQMD results [10].

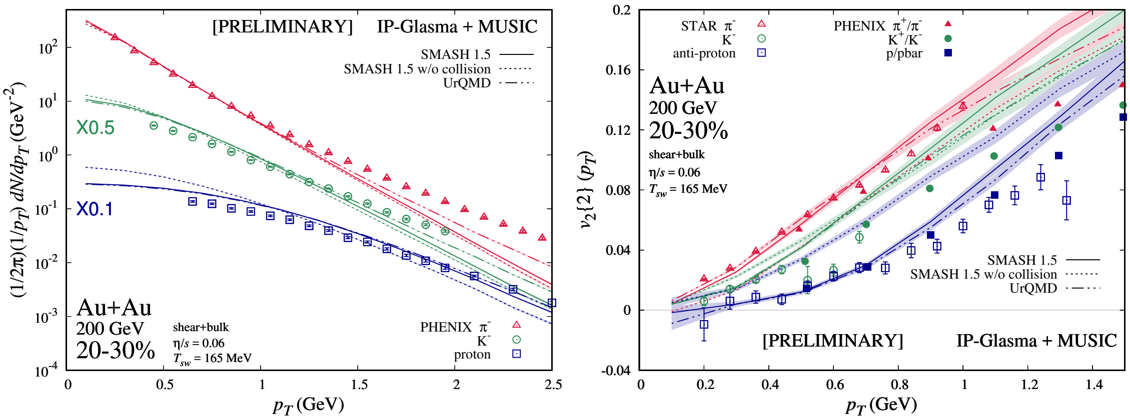

Figure 2. The identified hadron p_T-spectra (**left**) and differential elliptic flows (**right**).

The proton p_T spectrum and elliptic flow is shifted toward higher p_T, due to scatterings with lighter hadrons. The proton yield is also reduced by annihilation processes. While protons are affected in the similar way as in MUSIC + UrQMD hybrid, pions are less accelerated during the re-scattering phase. This is partially due to the difference between SMASH and UrQMD [26,27] in terms of pion-pion elastic scatterings.

4. Discussion

By comparing our simulations with and without collisions, it can be shown that protons are accelerated as a consequence of collisions with lighter hadrons, which are flowing faster in the radial direction. This observation is well consistent with the previous work based on a hybrid approach [10]. In addition, the presence of the baryon-antibaryon annihilation process reduces proton multiplicity. As discussed in Refs. [10,28], one can argue that the higher masses of baryons, in conjunction with the expansion of the system, make baryon-antibaryon creation less significant compared to annihilations. Therefore, our current treatment of baryon-antibaryon annihilation is still a good approximation to deal with the baryonic chemistry.

As mentioned earlier, the resonance excitation and decay are dominant processes in the hadronic re-scattering phase, and therefore the resonance mass sampling at the particlization is a crucial step. Future works include investigation of uncertainties such as different formulation or difference between vacuum and in-medium spectral functions. Lastly, even though we have been focusing on the single-particle distributions so far, multi-particle distributions and correlations certainly deserve attention in a study with the hybrid framework. In this case, we expect that conservation laws at the particlization play important roles.

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References

1. Arsene, I.; Bearden, I.G.; Beavis, D.; Besliu, C.; Budick, B.; Bøggild, H.; Chasman, C.; Christensen, C.H.; Christiansen, P.; Cibor, J.; et al. Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment. *Nucl. Phys. A* **2005**, *757*, 1–27, doi:10.1016/j.nuclphysa.2005.02.130.
2. Back, B.B.; Baker, M.D.; Ballintijn, M.; Barton, D.S.; Becker, B.; Betts, R.R.; Bickley, A.A.; Bindel, R.; Budzanowski, A.; Busza, W.; et al. The PHOBOS perspective on discoveries at RHIC. *Nucl. Phys. A* **2005**, *757*, 28–101, doi:10.1016/j.nuclphysa.2005.03.084.
3. Adams, J.; Aggarwal, M.M.; Ahammed, Z.; Amonett, J.; Anderson, B.D.; Arkhipkin, D.; Averichev, G.S.; Badyal, S.K.; Bai, Y.; Balewski, J.; et al. Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions. *Nucl. Phys. A* **2005**, *757*, 102–183, doi:10.1016/j.nuclphysa.2005.03.085.
4. Adcox, K.; Adler, S.S.; Afanasiev, S.; Aidala, C.; Ajitanand, N.N.; Akiba, Y.; Al-Jamel, A.; Alexander, J.; Amirikas, R.; Aoki, K.; et al. Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration. *Nucl. Phys. A* **2005**, *757*, 184–283, doi:10.1016/j.nuclphysa.2005.03.086.
5. Gyulassy, M.; McLerran, L. New forms of QCD matter discovered at RHIC. *Nucl. Phys. A* **2005**, *750*, 30–63, doi:10.1016/j.nuclphysa.2004.10.034.
6. Gale, C.; Jeon, S.; Schenke, B. Hydrodynamic Modeling of Heavy-Ion Collisions. *Int. J. Mod. Phys. A* **2013**, *28*, 1340011, doi:10.1142/S0217751X13400113.
7. De Souza, R.D.; Koide, T.; Kodama, T. Hydrodynamic Approaches in Relativistic Heavy Ion Reactions. *Prog. Part. Nucl. Phys.* **2016**, *86*, 35–85, doi:10.1016/j.ppnp.2015.09.002.
8. Petersen, H.; Steinheimer, J.; Burau, G.; Bleicher, M.; Stocker, H. A Fully Integrated Transport Approach to Heavy Ion Reactions with an Intermediate Hydrodynamic Stage. *Phys. Rev. C* **2008**, *78*, 044901, doi:10.1103/PhysRevC.78.044901.
9. Ryu, S.; Paquet, J.-F.; Shen, C.; Denicol, G.S.; Schenke, B.; Jeon, S.; Gale, C. Importance of the Bulk Viscosity of QCD in Ultrarelativistic Heavy-Ion Collisions. *Phys. Rev. Lett.* **2015**, *115*, 132301, doi:10.1103/PhysRevLett.115.132301.
10. Ryu, S.; Paquet, J.F.; Shen, C.; Denicol, G.; Schenke, B.; Jeon, S.; Gale, C. Effects of bulk viscosity and hadronic rescattering in heavy ion collisions at energies available at the BNL Relativistic Heavy Ion Collider and at the CERN Large Hadron Collider. *Phys. Rev. C* **2018**, *97*, 034910, doi:10.1103/PhysRevC.97.034910.
11. Schenke, B.; Tribedy, P.; Venugopalan, R. Fluctuating Glasma initial conditions and flow in heavy ion collisions. *Phys. Rev. Lett.* **2012**, *108*, 252301, doi:10.1103/PhysRevLett.108.252301.
12. Schenke, B.; Jeon, S.; Gale, C. (3+1)D hydrodynamic simulation of relativistic heavy-ion collisions. *Phys. Rev. C* **2010**, *82*, 014903, doi:10.1103/PhysRevC.82.014903.
13. Schenke, B.; Jeon, S.; Gale, C. Elliptic and triangular flow in event-by-event (3+1)D viscous hydrodynamics. *Phys. Rev. Lett.* **2011**, *106*, 042301, doi:10.1103/PhysRevLett.106.042301.
14. Cooper, F.; Frye, G. Comment on the Single Particle Distribution in the Hydrodynamic and Statistical Thermodynamic Models of Multiparticle Production. *Phys. Rev. D* **1974**, *10*, 186, doi:10.1103/PhysRevD.10.186.
15. Weil, J.; Steinberg, V.; Staudenmaier, J.; Pang, L.G.; Oliinychenko, D.; Mohs, J.; Kretz, M.; Kehrenberg, T.; Goldschmidt, A.; Bäuchle, B.; et al. Particle production and equilibrium properties within a new hadron transport approach for heavy-ion collisions. *Phys. Rev. C* **2016**, *94*, 054905, doi:10.1103/PhysRevC.94.054905.
16. Denicol, G.S.; Jeon, S.; Gale, C. Transport Coefficients of Bulk Viscous Pressure in the 14-moment approximation. *Phys. Rev. C* **2014**, *90*, 024912.

17. Denicol, G.S.; Niemi, H.; Molnar, E.; Rischke, D.H. Derivation of transient relativistic fluid dynamics from the Boltzmann equation. *Phys. Rev. D* **2012**, *85*, 114047, doi:10.1103/PhysRevD.85.114047. Erratum: [*Phys. Rev. D* **2015**, *91*, 039902, doi: 10.1103/PhysRevD.91.039902.]
18. Huovinen, P.; Petreczky, P. QCD Equation of State and Hadron Resonance Gas. *Nucl. Phys. A* **2010**, *827*, 26–53, doi:10.1016/j.nuclphysa.2010.02.015.
19. Dusling, K.; Moore, G.D.; Teaney, D. Radiative energy loss and v(2) spectra for viscous hydrodynamics. *Phys. Rev. C* **2010**, *81*, 034907, doi:10.1103/PhysRevC.81.034907.
20. Bozek, P. Bulk and shear viscosities of matter created in relativistic heavy-ion collisions. *Phys. Rev. C* **2010**, *81*, 034909, doi:10.1103/PhysRevC.81.034909.
21. Vujanovic, G.; Young, C.; Schenke, B.; Rapp, R.; Jeon, S.; Gale, C. Dilepton emission in high-energy heavy-ion collisions with viscous hydrodynamics. *Phys. Rev. C* **2014**, *89*, 034904, doi:10.1103/PhysRevC.89.034904.
22. Manley, D.M.; Saleski, E.M. Multichannel resonance parametrization of pi N scattering amplitudes. *Phys. Rev. D* **1992**, *45*, 4002, doi:10.1103/PhysRevD.45.4002.
23. Adler, S.S.; Afanasiev, S.; Aidala, C.; Ajitanand, N.N.; Akiba, Y.; Alexander, J.; Amirikas, R.; Aphecetche, L.; Aronson, S.H.; Averbeck, R.; et al. Identified charged particle spectra and yields in Au+Au collisions at S(NN)**1/2 = 200-GeV. *Phys. Rev. C* **2004**, *69*, 034909, doi:10.1103/PhysRevC.69.034909.
24. Adare, A.; Afanasiev, S.; Aidala, C.; Ajitanand, N.N.; Akiba, Y.; Al-Bataineh, H.; Alexander, J.; Aoki, K.; Aramaki, Y.; Atomssa, E.T.; et al. Measurement of the higher-order anisotropic flow coefficients for identified hadrons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. *Phys. Rev. C* **2016**, *93*, 051902, doi:10.1103/PhysRevC.93.051902.
25. Adams, J.; Aggarwal, M.M.; Ahammed, Z.; Amonett, J.; Anderson, B.D.; Arkhipkin, D.; Averichev, G.S.; Badyal, S.K.; Bai, Y.; Balewski, J.; et al. Azimuthal anisotropy in Au+Au collisions at s(NN)**(1/2) = 200-GeV. *Phys. Rev. C* **2005**, *72*, 014904, doi:10.1103/PhysRevC.72.014904.
26. Bass, S.A.; Belkacem, M.; Bleicher, M.; Brandstetter, M.; Bravina, L.; Ernst, C.; Gerland, L.; Hofmann, M.; Hofmann, S.; Konopka, J.; et al. Microscopic models for ultrarelativistic heavy ion collisions. *Prog. Part. Nucl. Phys.* **1998**, *41*, 255, doi:10.1016/S0146-6410(98)00058-1.
27. Bleicher, M.; Zabrodin, E.; Spieles, C.; Bass, S.A.; Ernst, C.; Soff, S.; Bravina, L.; Belkacem, M.; Weber, H.; Stöcker, H.; et al. Relativistic hadron hadron collisions in the ultrarelativistic quantum molecular dynamics model. *J. Phys. G* **1999**, *25*, 1859, doi:10.1088/0954-3899/25/9/308.
28. Pan, Y.; Pratt, S. Baryon annihilation and regeneration in heavy ion collisions. *Phys. Rev. C* **2014**, *89*, 044911, doi:10.1103/PhysRevC.89.044911.