

Anisotropic Hydrodynamics for Au-Au Collisions at 200 GeV[†]

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Abstract: In this proceedings, we review the basics of quasiparticle anisotropic hydrodynamics (aHydroQP). Then we present phenomenological comparisons between 3+1d quasiparticle anisotropic hydrodynamics and experimental data from RHIC experiments at 200 GeV Au-Au collisions. We show that 3+1d aHydroQP model is able to describe the experimental results quite well using smooth Glauber initial conditions for many heavy-ion collision observables.

Keywords: quark-gluon plasma; relativistic heavy-ion collisions; anisotropic hydrodynamics

1. Introduction

Heavy-ion collision experiments at the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) create and study the quark-gluon plasma (QGP). In the early years after confirming the existence of QGP, ideal hydrodynamics was used to describe the collective behavior seen in these experiments [1]. Later on, viscous hydrodynamics was used to take into account the dissipative effects [2–4]. However, the QGP is a highly momentum anisotropic plasma at early times after the impact which motivates introducing anisotropic hydrodynamics [5–11]. Recently, the 3+1d quasiparticle anisotropic hydrodynamics model was introduced and compared to experimental data at different energies [12–14]. For more details about anisotropic hydrodynamics, we refer the reader to [15,16].

In this proceedings contribution, we will first introduce 3+1d quasiparticle anisotropic hydrodynamics (aHydroQP) [17,18]. Then, we will present some phenomenological comparisons between 3+1d aHydroQP and some heavy-ion observables for Au-Au collisions at 200 GeV from different RHIC experiments. We show the spectra, multiplicity, and elliptic flow for charged particles for which aHydroQP shows good agreement with data [14].

2. 3+1d Quasiparticle Anisotropic Hydrodynamics

In anisotropic hydrodynamics, the one-particle distribution function is assumed to be of the form

$$f(x, p) = f_{\text{iso}} \left(\frac{1}{\lambda} \sqrt{p_{\mu} \Xi^{\mu\nu} p_{\nu}} \right), \quad (1)$$

where λ can be identified with the temperature in the isotropic equilibrium limit and $\Xi^{\mu\nu}$ is the anisotropy tensor [10]

$$\Xi^{\mu\nu} = u^{\mu} u^{\nu} + \zeta^{\mu\nu} - \Delta^{\mu\nu} \Phi, \quad (2)$$

Here, u^μ is the fluid four-velocity, $\zeta^{\mu\nu}$ is a symmetric and traceless anisotropy tensor, and Φ is the degree of freedom associated with the bulk pressure [16].

Ignoring the off-diagonal components, in the local rest frame the distribution function in Equation (1) can be written compactly in the following form

$$f(x, p) = f_{\text{eq}} \left(\frac{1}{\lambda} \sqrt{\sum_i \frac{p_i^2}{\alpha_i^2} + m^2} \right), \quad (3)$$

where $i \in \{x, y, z\}$ and $\alpha_i \equiv (1 + \zeta_i + \Phi)^{-1/2}$. We note that by taking $\alpha_x = \alpha_y = \alpha_z = 1$ and $\lambda = T$ one recovers the isotropic equilibrium distribution function. We also note that $m(T)$ is a single effective mass which is a function of temperature and tuned to match the equation of state of QCD.

To obtain, the dynamical equations for 3+1d aHydroQP one can take moments of the Boltzmann equation [17].

$$p^\mu \partial_\mu f(x, p) + \frac{1}{2} \partial_i m^2 \partial_{(p)}^i f(x, p) = -C[f(x, p)], \quad (4)$$

where $C[f(x, p)]$ is the collisional kernel which is taken to be in the relaxation time approximation [17].

3. Phenomenological Results

Next, we turn to presenting comparisons between 3+1d quasiparticle anisotropic hydrodynamics and experimental data from 200 GeV Au-Au collisions. In Ref. [14], we presented a number of observables: spectra, identified particle multiplicities as a function of centrality, multiplicity, elliptic flow for charged and identified particles, and the pseudorapidity dependence of the integrated elliptic flow. In this proceedings, we will present only the spectra, the multiplicity, and the elliptic flow for charged particles due to the space limitation. For more centrality classes or other observables, we refer the reader to Ref. [14].

In Figure 1, we show the spectra of pions, kaons, and protons as a function of the transverse momentum p_T . In the left panel, we show the 0–5% centrality class while in the right panel we show the 30–40% centrality class. From both panels, we see that aHydroQP agrees with the data quite well.

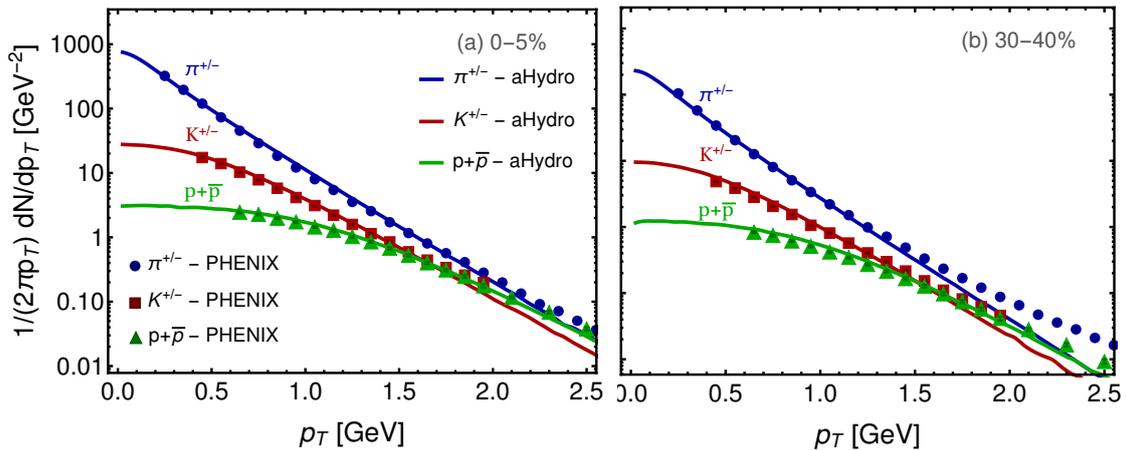


Figure 1. Pion, kaon, and proton spectra predicted by aHydroQP compared to experimental observations by the PHENIX collaboration [19]. The panels show the centrality classes (a) 0–5% and (b) 30–40%.

Next, in Figure 2a, we show comparisons of the charged particle multiplicity as a function of pseudorapidity predicted by 3+1d aHydroQP and experimental data. As can be seen from the figure, in a wide range of centrality classes, the agreement between aHydroQP and the experimental results is quite good. In Figure 2b, we present the elliptic flow for charged particles as a function of transverse

momentum in the 20–30% centrality class. We find that our model shows good agreement with the experimental results. The data in the left and right panels are from the PHOBOS collaboration [20] and the PHENIX collaboration [21], respectively.

The extracted fitting parameters that were used in the above phenomenological comparisons are $T_0(\tau_0 = 0.25 \text{ fm}/c) = 455 \text{ MeV}$, $\eta/s = 0.179$, and the freeze-out temperature used was $T_{FO} = 130 \text{ MeV}$.

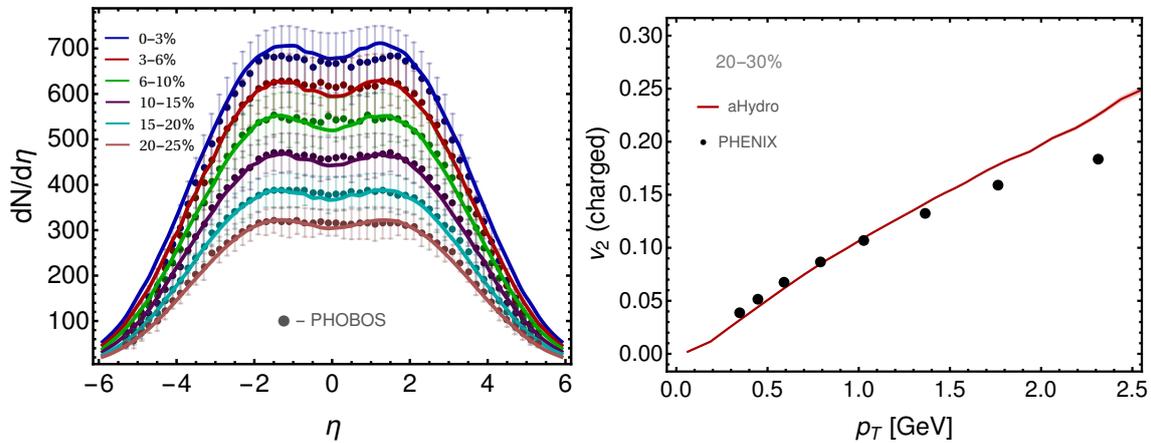


Figure 2. In panel (a), a comparison of the charged particle multiplicity in different centrality classes (0–25%) is shown between aHydroQP and experimental data which is taken from the PHOBOS collaboration [20]. In panel (b), the elliptic flow for charged particles in 20–30% centrality class is shown where 3+1d aHydroQP predictions is compared to data taken from the PHENIX collaboration [21]. Figure is taken from [14].

4. Conclusions

In this proceedings contribution, we presented phenomenological comparisons between 3+1d quasiparticle anisotropic hydrodynamics and Au-Au collisions at 200 GeV. We showed the spectra, multiplicity, and elliptic flow for charged particles in some centrality classes. We demonstrated that aHydroQP agrees with the data quite well for many observables. Finally, we listed the extracted fitting parameters that were used in these comparisons.

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References

1. Huovinen, P.; Kolb, P.F.; Heinz, U.W.; Ruuskanen, P.V.; Voloshin, S.A. Radial and elliptic flow at RHIC: further predictions. *Phys. Lett.* **2001**, *B503*, 58–64, [[hep-ph/0101136](#)]. doi:10.1016/S0370-2693(01)00219-2.
2. Romatschke, P.; Romatschke, U. Viscosity Information from Relativistic Nuclear Collisions: How Perfect is the Fluid Observed at RHIC? *Phys. Rev. Lett.* **2007**, *99*, 172301, [[arXiv:nucl-th/0706.1522](#)]. doi:10.1103/PhysRevLett.99.172301.
3. 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, [[arXiv:nucl-th/1502.01675](#)]. doi:10.1103/PhysRevLett.115.132301.

4. Niemi, H.; Denicol, G.S.; Huovinen, P.; Molnár, E.; Rischke, D.H. Influence of the shear viscosity of the quark-gluon plasma on elliptic flow in ultrarelativistic heavy-ion collisions. *Phys. Rev. Lett.* **2011**, *106*, 212302, [[arXiv:nucl-th/1101.2442](#)]. doi:10.1103/PhysRevLett.106.212302.
5. Florkowski, W.; Ryblewski, R. Highly-anisotropic and strongly-dissipative hydrodynamics for early stages of relativistic heavy-ion collisions. *Phys. Rev.* **2011**, *C83*, 034907, [[arXiv:nucl-th/1007.0130](#)]. doi:10.1103/PhysRevC.83.034907.
6. Martinez, M.; Strickland, M. Dissipative Dynamics of Highly Anisotropic Systems. *Nucl. Phys.* **2010**, *A848*, 183–197, [[arXiv:nucl-th/1007.0889](#)]. doi:10.1016/j.nuclphysa.2010.08.011.
7. Martinez, M.; Ryblewski, R.; Strickland, M. Boost-Invariant (2+1)-dimensional Anisotropic Hydrodynamics. *Phys. Rev.* **2012**, *C85*, 064913, [[arXiv:nucl-th/1204.1473](#)].
8. Ryblewski, R.; Florkowski, W. Highly-anisotropic hydrodynamics in 3+1 space-time dimensions. *Phys. Rev.* **2012**, *C85*, 064901, [[arXiv:nucl-th/1204.2624](#)]. doi:10.1103/PhysRevC.85.064901.
9. Bazow, D.; Heinz, U.W.; Strickland, M. Second-order (2+1)-dimensional anisotropic hydrodynamics. *Phys. Rev.* **2014**, *C90*, 054910, [[arXiv:nucl-th/1311.6720](#)]. doi:10.1103/PhysRevC.90.054910.
10. Nopoush, M.; Ryblewski, R.; Strickland, M. Bulk viscous evolution within anisotropic hydrodynamics. *Phys. Rev.* **2014**, *C90*, 014908, [[arXiv:hep-ph/1405.1355](#)]. doi:10.1103/PhysRevC.90.014908.
11. Nopoush, M.; Ryblewski, R.; Strickland, M. Anisotropic hydrodynamics for conformal Gubser flow. *Phys. Rev.* **2015**, *D91*, 045007, [[arXiv:nucl-th/1410.6790](#)]. doi:10.1103/PhysRevD.91.045007.
12. Alqahtani, M.; Nopoush, M.; Ryblewski, R.; Strickland, M. 3+1d quasiparticle anisotropic hydrodynamics for ultrarelativistic heavy-ion collisions. *Phys. Rev. Lett.* **2017**, *119*, 042301, [[arXiv:nucl-th/1703.05808](#)]. doi:10.1103/PhysRevLett.119.042301.
13. Alqahtani, M.; Nopoush, M.; Ryblewski, R.; Strickland, M. Anisotropic hydrodynamic modeling of 2.76 TeV Pb-Pb collisions. *Phys. Rev.* **2017**, *C96*, 044910, [[arXiv:nucl-th/1705.10191](#)]. doi:10.1103/PhysRevC.96.044910.
14. Almaalol, D.; Alqahtani, M.; Strickland, M. Anisotropic hydrodynamic modeling of 200 GeV Au-Au collisions. *arXiv* **2018**, arXiv:1807.04337. [[arXiv:nucl-th/1807.04337](#)].
15. Strickland, M. Anisotropic Hydrodynamics: Three lectures. *Acta Phys. Polon.* **2014**, *B45*, 2355–2394, [[arXiv:nucl-th/1410.5786](#)]. doi:10.5506/APhysPolB.45.2355.
16. Alqahtani, M.; Nopoush, M.; Strickland, M. Relativistic anisotropic hydrodynamics. *Prog. Part. Nucl. Phys.* **2018**, *101*, 204–248, [[arXiv:nucl-th/1712.03282](#)]. doi:10.1016/j.pnpnp.2018.05.004.
17. Alqahtani, M.; Nopoush, M.; Strickland, M. Quasiparticle equation of state for anisotropic hydrodynamics. *Phys. Rev.* **2015**, *C92*, 054910, [[arXiv:hep-ph/1509.02913](#)]. doi:10.1103/PhysRevC.92.054910.
18. Alqahtani, M.; Nopoush, M.; Strickland, M. Quasiparticle anisotropic hydrodynamics for central collisions. *Phys. Rev.* **2017**, *C95*, 034906, [[arXiv:nucl-th/1605.02101](#)]. doi:10.1103/PhysRevC.95.034906.
19. Adler, S.S.; Afanasiev, S.; Aidala, C.; Ajitanand, N.N.; Akiba, Y.; Alexander, J.; Amirkas, R.; Aphecetche, L.; Aronson, S.H.; Auerbeck, R.; et al. Identified charged particle spectra and yields in Au+Au collisions at $\sqrt{s(NN)} = 200$ -GeV. *Phys. Rev.* **2004**, *C69*, 034909, [[arXiv:nucl-ex/nucl-ex/0307022](#)]. doi:10.1103/PhysRevC.69.034909.
20. Alver, B.; Back, B.B.; Baker, M.D.; Ballintijn, M.; Barton, D.S.; Betts, R.R.; Bickley, A.A.; Bindel, R.; Budzanowski, A.; Busza, W.; et al. Phobos results on charged particle multiplicity and pseudorapidity distributions in Au+Au, Cu+Cu, d+Au, and p+p collisions at ultra-relativistic energies. *Phys. Rev.* **2011**, *C83*, 024913, [[arXiv:nucl-ex/1011.1940](#)]. doi:10.1103/PhysRevC.83.024913.
21. Adare, A.; Afanasiev, S.; Aidala, C.; Ajitanand, N.N.; Akiba, Y.; Al-Bataineh, H.; Alexander, J.; Al-Jamel, A.; Aoki, K.; Aphecetche, L.; et al. Scaling properties of azimuthal anisotropy in Au+Au and Cu+Cu collisions at $\sqrt{s(NN)} = 200$ -GeV. *Phys. Rev. Lett.* **2007**, *98*, 162301, [[arXiv:nucl-ex/nucl-ex/0608033](#)]. doi:10.1103/PhysRevLett.98.162301.

