TEMPERATURE AND NET BARYOCHEMICAL POTENTIAL DEPENDENCE OF η/s IN A HYBRID APPROACH*

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In this proceedings contribution, the qualitative effect of a net baryochemical potential dependence of the shear viscosity to entropy density ratio η/s in hybrid approach simulations is investigated. The influence of a net baryochemical potential dependence of the shear viscosity over entropy ratio on the observables of heavy-ion collisions has been subject of only few investigations in hydrodynamic simulations. In this work, a generalized $\eta/s(T, \mu_B)$ is tested within the hybrid approach SMASH-vHLLE-hybrid, combining the hadronic transport approach SMASH and the (3+1)D viscous hydrodynamic code vHLLE. It is shown that the proposed parameterization approximates the shear viscosity in the late stage non-equilibrium hadronic transport stage.

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1. Introduction

There is increasing interest in the theoretical description of heavy-ion collisions at finite baryon densities using hybrid approaches, which combine hadronic transport for the simulation of the early and late stages with relativistic hydrodynamics for the hot and dense stage. Apart from the initial condition, viscous hydrodynamic calculations need as an input an equation of state of the nuclear matter as well as the transport coefficients.

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Many theoretical predictions support a non-constant shear viscosity over entropy ratio η/s, with a minimum close to the phase transition [1–4]. Additionally, there exist also theoretical predictions of a dependence on the net baryochemical potential [5–7]. Existing studies focus mainly on a temperature dependence or even only a constant effective shear viscosity. Therefore, in the following, the effects of including both a temperature and a baryochemical potential dependence in the shear viscosity on the evolution and observables of a hybrid simulation will be investigated. A more in-depth examination of the dependence of the shear viscosity on the net baryon chemical potential can be found in [8].

2. Setup and parametrization of η/s

The following results were calculated from the hybrid approach SMASH-vHLLE-hybrid [9]. The hadronic transport approach is run until the geometrical overlap time of the two nuclei. At that eigentime, the energy-momentum tensor and net charge currents are calculated. The smearing parameters for the transition from transport to hydrodynamic evolution are taken from Table 1 of [10]. From the resulting freezeout hypersurface, 1000 events are sampled for the hadronic afterburner evolution, in order to allow for on-average quantum number conservation. The transition to the late stage rescattering is governed by the switching energy density $\epsilon_{\rm sw}$. When this value is reached, the fluid element is removed from the hydrodynamic evolution. $\epsilon_{\rm sw}$ is a free technical parameter and does only control the application of the hybrid and transport approach, but does not determine which degrees of freedom are realized in the QCD matter. Whereas the bulk viscosity is set to zero for all runs, the choice of the shear viscosity will be discussed in the following.

In contrast to adding terms proportional to μ_B to $\eta/s(T)$, parameterizing instead in the local rest frame energy density ϵ and the net baryon number ρ has the advantage that these are evolved throughout the hydrodynamic simulation, and therefore reduces the dependency of results on the choice of the equation of state.

Several simplifications are performed for this qualitative study. We use η/s as the measure of fluidity even at finite μ_B and restrict ourselves to a linear dependence of the shear viscosity both in the region of high- and low-energy densities, with a minimum near transition. This already implies an implicit μ_B-dependence. Additionally, we study a linear term proportional to the net baryon number density ρ. This results in the following functional form:

$$\eta/s(\epsilon,\rho) = \max\left(0, (\eta/s)_{\rm kink} + \begin{cases} S_{\epsilon,H}(\epsilon-\epsilon_{\rm kink}) + S_\rho\rho, & \epsilon < \epsilon_{\rm kink} \\ S_{\epsilon,Q}(\epsilon-\epsilon_{\rm kink}) + S_\rho\rho & \epsilon > \epsilon_{\rm kink}\end{cases}\right). \quad (1)$$

According to lattice QCD [11] and experimental results [12], we set the position of the minimum at vanishing net baryochemical potential to 1 GeV/fm^3, and the value of the shear viscosity at this point is set to the KSS-bound [13]. For high-energy densities, the steepness is motivated by matching pQCD results [2] at a temperature of 400 MeV and vanishing net baryochemical potential, whereas at low-energy density, we match the shear viscosity extracted from box calculations in SMASH at the particlization temperature.

The remaining free parameter is S_ρ, which we are going to vary in order to investigate its effect on the observables. The parameterization for the choice of $S_\rho = 0.05$ fm^3 can be seen in Fig. 1.

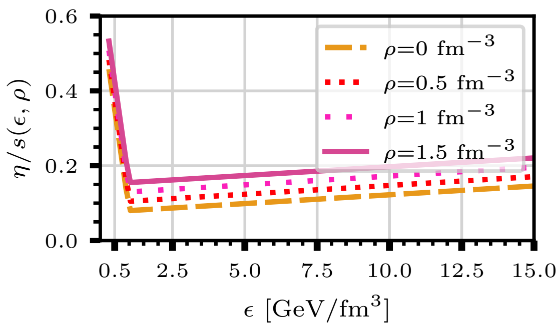

Fig. 1. $\eta/s(\epsilon,\rho)$ for $S_\rho = 0.05$ fm^3. From [8].

This parameterization is compared to other existing choices for constant or temperature-dependent η/s. The first choice is a constant value for η/s, with values depending on collision energies [10]. The second choice is representative for results from the Bayesian analysis. For this, we use the parameterization in [14] and choose parameters which lie centrally in the 60% confidence interval of the posterior.

3. Results

The anisotropic flow coefficients are very sensitive to the shear viscosity. The values of the elliptic flow for different choices of parameterizations can be found in Fig. 2. The ϵ-dependent parameterization leads to a significantly reduced elliptic flow in comparison to the alternative parameterizations due to an increased effective shear viscosity. In contrast, the different choices of S_ρ have only minimal effects on the flow. These effects are mostly restricted to low collision energies, as they lead to higher net baryon densities.

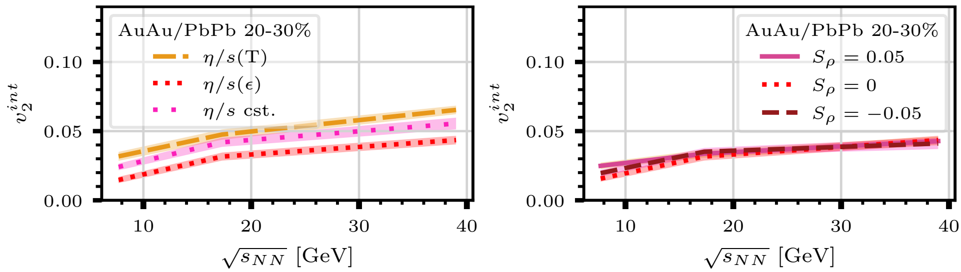

Fig. 2. Integrated event plane elliptic flow of charged hadrons at midrapidity ($|y| < 0.5$) for different parametrization strategies (left) and different values of the net baryon number density dependence (right). From [8].

The duration of the hydrodynamic evolution, defined by the point when the last fluid element reaches an energy density smaller than ϵ_{sw}, has an important effect on the role of the parameterization of η/s for the observables. Depending on the value of ϵ_{sw}, the system stays longer in the hydrodynamic evolution and shorter in the transport calculation, or *vice versa*. The effect of a different choice of the switching energy density on the integrated elliptic flow of charged hadrons is plotted in Fig. 3 at all three investigated values for ϵ_{sw} for the default choice of η/s as well as the parameterizations in T and ϵ. We see that the lines for constant η/s and $\eta/s(T)$ show significant changes when varying ϵ_{sw}, as the flow increases when reducing ϵ_{sw}. In contrast, for $\eta/s(\epsilon)$, the lines stay close to each other, which in turn means that the flow is, for this range of ϵ_{sw}, almost independent of $\eta/s(\epsilon)$.

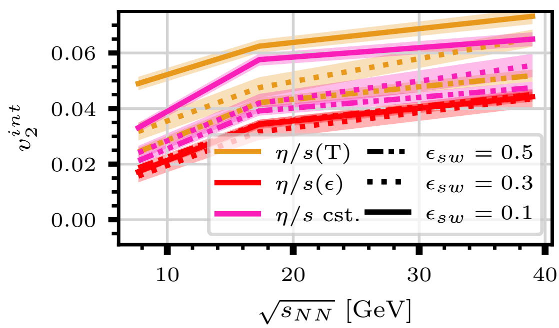

Fig. 3. Integrated event plane elliptic flow of charged hadrons at midrapidity ($|y| < 0.5$) for different parametrization strategies and values of ϵ_{sw}. From [8].

By increasing ϵ_{sw}, regions which were evolved in the hydrodynamic evolution are then evolved in hadronic transport, where the shear viscosity is not directly accessible. This means that the independence of the integrated flow from the value of ϵ_{sw} for $\eta/s(\epsilon)$ is a strong sign that $\eta/s(\epsilon)$ approximates the shear viscosity in the non-equilibrium hadronic transport stage.

The effect is however not limited to the elliptic flow. Bulk observables, such as the midrapidity yield and mean transverse momentum, are also sensitive to a change of the shear viscosity. This can be seen in Fig. 4. Varying the switching energy density strongly affects the yield, which decreases with decreasing the time of hadronic transport evolution after the hydrodynamic phase for all parameterizations in a similar way. In return, with decreasing yield, the mean transverse momentum increases with decreasing switching energy density. The strength of the effect in comparison to the change in the elliptic flow shows that both observables are more dependent on the evolution in hadronic transport or hydrodynamics than on the underlying shear viscosity.

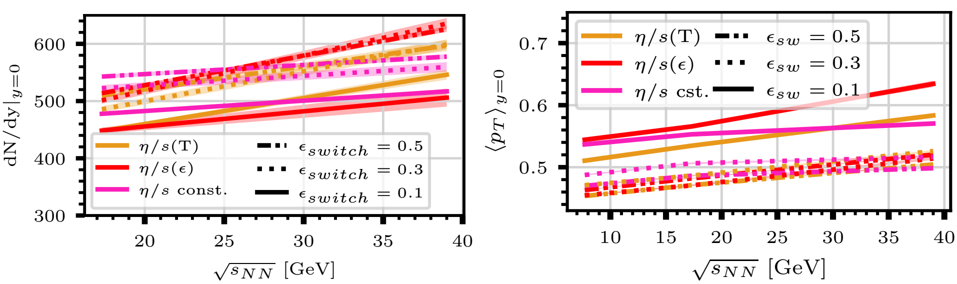

Fig. 4. Charged hadron yield (left) and mean transverse momentum (right) at midrapidity ($|y| < 0.5$) for different parametrization strategies and values of $\epsilon_{\rm sw}$.

4. Conclusions

In this work, a new parameterization of the shear viscosity over entropy ratio as a function of energy density and net baryon number density, $\eta/s(\epsilon, \rho)$ based on known constraints is tested within the hybrid approach SMASH-vHLLE-hybrid. The parameterization is compared to a temperature-dependent parameterization extracted from the Bayesian inference as well as with the default setting of SMASH-vHLLE-hybrid, a constant value of η/s. Additionally, the impact of a ρ dependence was investigated. The dependence on the net baryon number does have no significant effect on the flow as its effect on the shear viscosity is limited to the early stages of the hydrodynamic evolution. The flow is sensitive to the switching energy density when using constant or temperature-dependent η/s, but stays at the same values for $\eta/s(\epsilon)$. This shows that the parameterization in the energy density approximates the shear viscosity in non-equilibrium hadronic transport within the region of $\epsilon = 0.1$–0.5 GeV/fm^3. The yield and mean transverse momentum, on the other hand, are strongly affected by a change in the switching energy density, which shows that they are more sensitive to the choice of the model than the value of the shear viscosity.

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REFERENCES

[1] D. Everett *et al.*, *Phys. Rev. Lett.* **126**, 242301 (2021).
[2] J. Ghiglieri, G.D. Moore, D. Teaney, *J. High Energy Phys.* **1803**, 179 (2018).
[3] J. Auvinen *et al.*, *Phys. Rev. C* **102**, 044911 (2020).
[4] C. Greiner, J. Noronha-Hostler, J. Noronha, arXiv:1105.1756 [ucl-th].
[5] G.S. Denicol, C. Gale, S. Jeon, J. Noronha, *Phys. Rev. C* **88**, 064901 (2013).
[6] G.P. Kadam, H. Mishra, *Phys. Rev. C* **92**, 035203 (2015).
[7] N. Demir, S.A. Bass, *Phys. Rev. Lett.* **102**, 172302 (2009).
[8] N. Götz, H. Elfner, arXiv:2207.05778 [hep-ph].
[9] N. Götz, https://github.com/smash-transport/smash-vhlle-hybrid
[10] A. Schäfer *et al.*, arXiv:2112.08724 [hep-ph].
[11] S. Borsányi *et al.*, *Phys. Lett. B* **730**, 99 (2014).
[12] J. Cleymans, H. Oeschler, K. Redlich, S. Wheaton, *J. Phys. G: Nucl. Part. Phys.* **32**, S165 (2006).
[13] P. Kovtun, D.T. Son, A.O. Starinets, *Phys. Rev. Lett.* **94**, 111601 (2005).
[14] JETSCAPE Collaboration (D. Everett *et al.*), *Phys. Rev. C* **103**, 054904 (2021).