Vol. 5 (2012) *Acta Physica Polonica B Proceedings Supplement* No 2

EFFECT OF TEMPERATURE-DEPENDENT η/s ON FLOW ANISOTROPIES*

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(Received December 30, 2011)

We investigate the effects of a temperature-dependent shear viscosity over entropy density ratio η/s on the flow anisotropy coefficients v_2 and v_4 in ultrarelativistic heavy-ion collisions at RHIC and LHC. We find that v_4 is more sensitive to the viscosity at low temperatures than v_2. At RHIC v_2 is mostly affected by the viscosity around the phase transition, but the larger the collision energy, the more the quark-gluon plasma viscosity affects v_2.

DOI:10.5506/APhysPolBSupp.5.305
PACS numbers: 25.75.Ld, 12.38.Mh, 24.10.Nz

1. Introduction

Presently, most works aiming at the determination of the shear viscosity of strongly interacting matter assume a constant shear viscosity over entropy density ratio, η/s. However, this ratio can be a strongly varying function of temperature both in hadronic matter and in the quark-gluon plasma. In this work we study consequences of such a temperature dependence [1].

We model the space-time evolution of matter formed in heavy-ion collisions using relativistic dissipative hydrodynamics [2]. We assume longitudinal boost invariance and neglect the net-baryon number. Essential inputs to the model are the equation of state, the initial state and the transport coefficients. We consider here only the shear viscosity.

* Presented at the Conference "Strangeness in Quark Matter 2011", Kraków, Poland, September 18–24, 2011.

As equation of state, we use a recent lattice parametrisation [3] with chemical freeze-out at $T = 150\,\mathrm{MeV}$. The initial energy density at $\tau_0 = 1.0\,\mathrm{fm}$ is proportional to the density of binary nucleon–nucleon collisions in the transverse plane. The maximum energy density is fixed to reproduce the measured multiplicity in the most central collisions [4, 5]. For $\sqrt{s_{NN}} = 5.5\,\mathrm{TeV}$ Pb+Pb collisions we use the multiplicity predicted by the minijet + saturation model [6]. To compensate for different entropy production for different parametrizations of the shear viscosity, the initial energy-density profiles are normalised differently for each parametrization. Freeze-out is implemented using the Cooper–Frye formula [7] on a $T_{\mathrm{dec}} = 100\,\mathrm{MeV}$ hypersurface including the dissipative correction δf to the thermal distributions.

For η/s, we consider the four different parametrizations shown in Fig. 1. The minimum value of η/s is fixed to be $\eta/s = 0.08$ at $T = 180\,\mathrm{MeV}$ for all parametrizations. The shear relaxation time [2] is taken to be $\tau_{\mathrm{R}} = 5\eta/(e+p)$, where e and p are energy density and pressure, respectively.

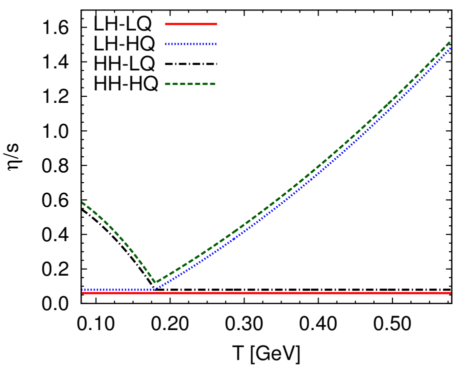

Fig. 1. η/s parametrizations.

2. Results

The elliptic flow coefficient, $v_2(p_{\mathrm{T}})$, for charged hadrons in the 20–30% most central collisions at RHIC, at the present LHC energy, and at the full LHC collision energy is shown in the left panels of Figs. 2–4, respectively. We note that at RHIC, the high-temperature part of η/s has practically no effect on the results. On the other hand, the viscous suppression of $v_2(p_{\mathrm{T}})$ is strongly enhanced if we increase the hadronic η/s. In low-energy LHC collisions, both hadronic and QGP viscosity have a similar effect, whereas at the full LHC energy the behaviour is opposite to that seen at RHIC: $v_2(p_{\mathrm{T}})$ is almost independent of the hadronic η/s, but sensitive to the high-temperature viscosity.

The anisotropy coefficient $v_4(p_{\mathrm{T}})$ (right panels of Figs. 2–4) exhibits a similar pattern, where the sensitivity to the low-temperature viscosity decreases, and the sensitivity to the high-temperature viscosity increases with increasing collision energy. However, in general, $v_4(p_\mathrm{T})$ is more sensitive to the shear viscosity in the low-temperature region than $v_2(p_\mathrm{T})$. At the low LHC energy $v_4(p_\mathrm{T})$ behaves like $v_2(p_\mathrm{T})$ at RHIC, and at the full LHC energy $v_4(p_\mathrm{T})$ behaves like $v_2(p_\mathrm{T})$ at low LHC energy.

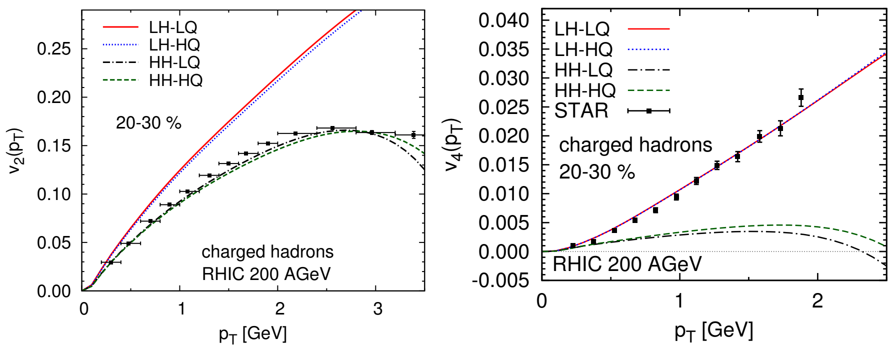

Fig. 2. $v_2(p_\mathrm{T})$ (left) and $v_4(p_\mathrm{T})$ (right) of charged hadrons in the 20–30% most central Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ (RHIC). Data are from Refs. [8,9].

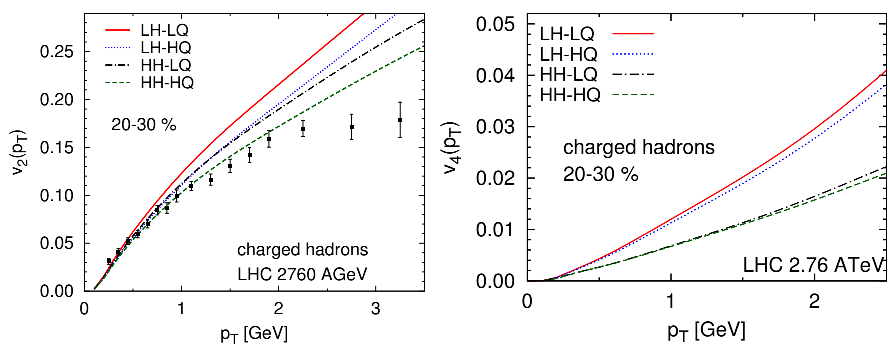

Fig. 3. $v_2(p_\mathrm{T})$ (left) and $v_4(p_\mathrm{T})$ (right) of charged hadrons in the 20–30% most central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ (LHC). Data are from Ref. [10].

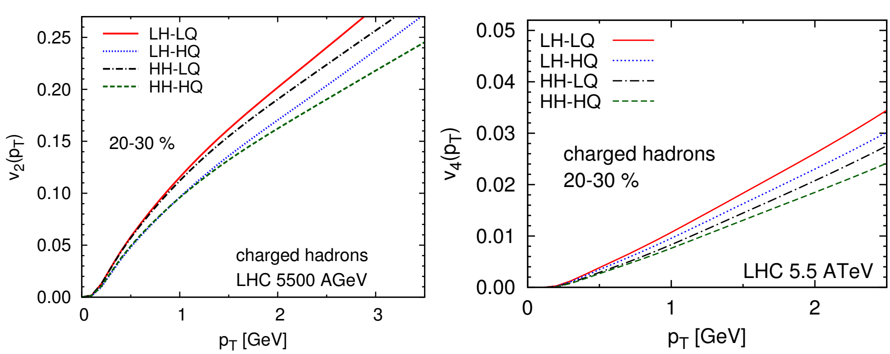

Fig. 4. $v_2(p_\mathrm{T})$ (left) and $v_4(p_\mathrm{T})$ (right) of charged hadrons in the 20–30% most central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5\,\mathrm{TeV}$ (LHC).

To further investigate the sensitivity of v_2 and v_4 to viscosity at different temperatures, we devised a set of simple parametrizations for $\eta/s(T)$, see Fig. 5. We take $\eta/s = 0.08$, except in the vicinity of a temperature $T_{\rm peak}$, where $\eta/s(T_{\rm peak}) = 0.24$, and the width of the peak is 10 MeV. By varying $T_{\rm peak}$, we can study at what temperature η/s affects v_2 and v_4 most.

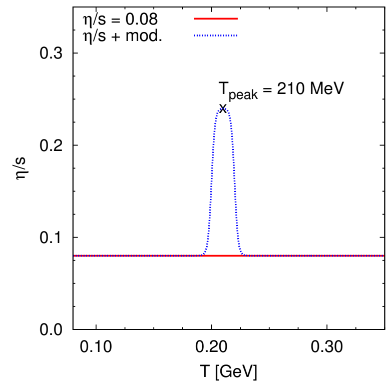

Fig. 5. One of the η/s parametrizations to find when flow anisotropies are most sensitive to η/s.

The results are shown in Fig. 6 as the relative change with respect to v_2 and v_4 evaluated using a constant $\eta/s = 0.08$ during the entire evolution. It is seen that at RHIC, the viscosity around $T = 170$ MeV has the largest effect on v_2, but the region of strongest sensitivity moves to larger temper-

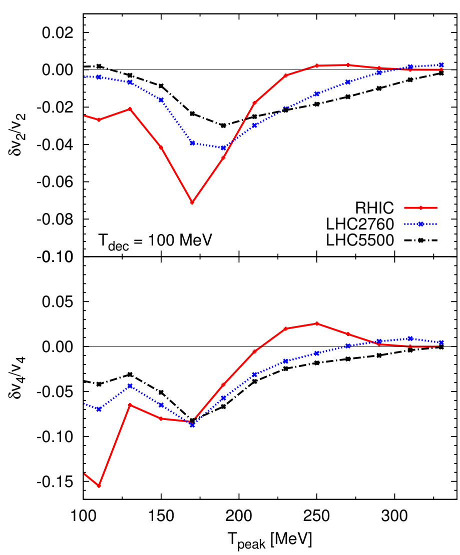

Fig. 6. The change in the $p_{\rm T}$-averaged v_2 and v_4 when there is a peak in the η/s ratio at $T_{\rm peak}$.

atures and becomes wider with increasing collision energy. If we ignore the point at $T = 110\,\mathrm{MeV}$ (because its main effect is via δf), the behaviour of v_4 is slightly different: With increasing collision energy the suppression at large temperatures increases, and at low temperatures decreases, but the temperature where η/s suppresses v_4 most hardly changes.

An interesting feature is that there is a region where η/s does not suppress flow anisotropies, but the larger the η/s the larger the anisotropy! This can be understood in the following way: At early times the main effect of shear viscosity is to inhibit the longitudinal expansion, and enhance the transverse expansion, instead of reducing the difference between the expansion in in-plane and out-of-plane directions. Thus, shear viscosity leads to larger transverse flow velocity. A simple blast-wave model [11] demonstrates that if nothing else changes, a larger transverse flow velocity leads to a larger $v_2(p_\mathrm{T})$ of light particles. At RHIC a similar reasoning leads to the insensitivity to the plasma viscosity, since the effects of increasing flow velocity and smaller difference between in-plane and out-of-plane directions cancel each other.

All this does not mean that v_2 would not be formed early. To take into account the thermal motion during the evolution, we characterise the time-evolution of v_2 by evaluating the v_2 of fictitious $m = 140\,\mathrm{MeV}$ bosons at different times τ_i. We use the Cooper–Frye formula on a hypersurface consisting of two parts: A constant temperature hypersurface with $T = T_\mathrm{dec} = 100\,\mathrm{MeV}$ and $\tau < \tau_i$, and a constant time hypersurface with $\tau = \tau_i$ and $T > 100\,\mathrm{MeV}$. This approach has the advantage that at the end of the evolution it matches the v_2 of thermal pions without any adjustment.

As seen in Fig. 7, v_2 is built up early, but the effect of η/s at early times is relatively small. The left panel depicts the evolution at RHIC, and one can see that at $\tau = 2\,\mathrm{fm}$, the larger η/s above the transition region

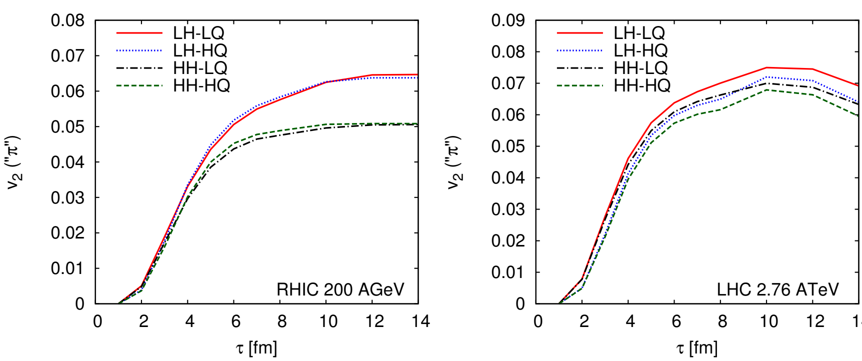

Fig. 7. Time-evolution of the p_T-averaged v_2 of fictitious $m = 140\,\mathrm{MeV}$ bosons ("π") in 20–30% most central Au+Au (left) and Pb+Pb (right) collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ (RHIC) and $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ (LHC), respectively.

has reduced the v_2 somewhat, but this difference is soon erased and the low-temperature viscosity dominates the evolution from $\tau \sim 3\,\mathrm{fm}$ on. The situation is different in the evolution at the lower LHC energy depicted in the right panel. Now, the plasma viscosity causes a clear difference at $\tau \sim 2\,\mathrm{fm}$, and this difference persists to much later times than at RHIC. Eventually, the hadronic viscosity takes over and reorders the curves, but it cannot completely compensate the differences built up earlier.

In summary, we have investigated how the temperature dependence of η/s affects the flow anisotropy coefficients v_2 and v_4. We found that the temperature, where v_n is most sensitive to viscosity varies with the collision energy — the larger the collision energy, the larger the temperature where the suppression is strongest. We also saw that v_4 is most sensitive to the viscosity at a lower temperature than v_2. It remains to be seen whether this is a general trend: the larger the n, the lower the temperature where v_n is most sensitive to the value of η/s.

This work was supported by the Helmholtz International Center for FAIR within the framework of the LOEWE program launched by the State of Hesse. The work of H.N. was supported by the ExtreMe Matter Institute (EMMI). P.H. is supported by BMBF under contract No. 06FY9092. E.M. is supported by OTKA/NKTH 81655.

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