The QGP shear viscosity – elusive goal or just around the corner?

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Abstract. With the new viscous hydrodynamic + hadron cascade hybrid code `VISHNU`, a rather precise ($\mathcal{O}(25\%)$) extraction of the QGP shear viscosity $(\eta/s)_{\rm QGP}$ from heavy-ion elliptic flow data is possible *if* the initial eccentricity of the collision fireball is known with $< 5\%$ accuracy. At this point, eccentricities from initial state models differ by up to 20%, leading to an $\mathcal{O}(100\%)$ uncertainty for $(\eta/s)_{\rm QGP}$. It is shown that a simultaneous comparison of elliptic and triangular flow, v_2 and v_3, puts strong constraints on initial state models and can largely eliminate the present uncertainty in $(\eta/s)_{\rm QGP}$. The variation of the differential elliptic flow $v_2(p_T)$ for identified hadrons between RHIC and LHC energies provides additional tests of the evolution model.

Prologue – how to measure $(\eta/s)_{\rm QGP}$: Hydrodynamics converts the initial spatial deformation of the fireball created in relativistic heavy-ion collisions into final state momentum anisotropies. Viscosity degrades the conversion efficiency $\varepsilon_x = \frac{\langle\langle y^2-x^2\rangle\rangle}{\langle\langle y^2+x^2\rangle\rangle} \to \varepsilon_p = \frac{\langle T^{xx}-T^{yy}\rangle}{\langle T^{xx}+T^{yy}\rangle}$ of the fluid; for given initial fireball ellipticity ε_x, the viscous suppression of the dynamically generated total momentum anisotropy ε_p is monotonically related to the specific shear viscosity η/s. The observable most directly related to ε_p is the total charged hadron elliptic flow $v_2^{\rm ch}$ [1]. Its distribution in p_T depends on the chemical composition and p_T-spectra of the various hadron species; the latter evolve in the hadronic stage due to continuously increasing radial flow (and so does $v_2(p_T)$), even if (as expected at top LHC energy [2]) ε_p fully saturates in the QGP phase. When (as happens at RHIC energies) ε_p does not reach saturation before hadronization, dissipative hadronic dynamics [3] affects not only the distribution of ε_p over hadron species and p_T, but even the final value of ε_p itself, and thus of $v_2^{\rm ch}$ from which we want to extract η/s. To isolate the QGP viscosity $(\eta/s)_{\rm QGP}$ we therefore need a hybrid code that couples viscous hydrodynamics of the QGP to a realistic model of the late hadronic stage, such as `UrQMD` [4], that describes its dynamics microscopically. `VISHNU` [5] is such a code.

Extraction of $(\eta/s)_{\rm QGP}$ from 200 A GeV Au+Au collisions at RHIC: The left panel in Fig. 1 shows that such an approach yields a universal dependence of the ellipticity-scaled total charged hadron elliptic flow, $v_2^{\rm ch}/\varepsilon_x$, on the charged hadron multiplicity density per overlap area, $(1/S)(dN_{\rm ch}/dy)$, that depends only on $(\eta/s)_{\rm QGP}$ but not on the details of the initial state model that provides ε_x and S [6]. Pre-equilibrium flow and bulk viscous effects on these curves are small [6].

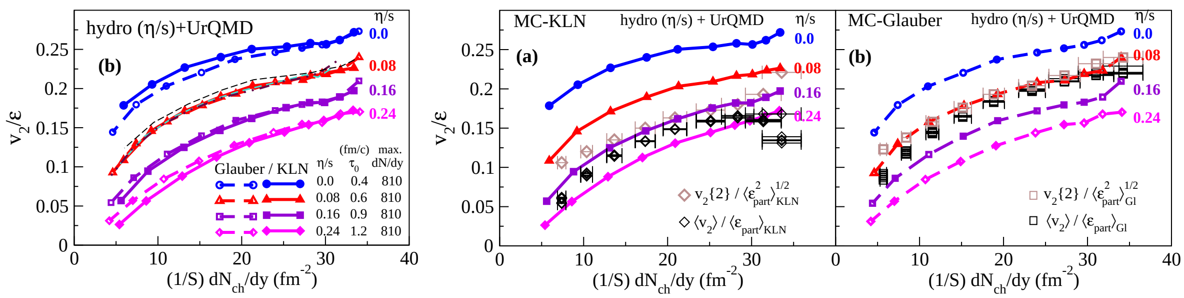

Figure 1. (Color online) Centrality dependence of eccentricity-scaled elliptic flow [6].

The QGP viscosity can be extracted from experimental $v_2^{\rm ch}$ data by comparing them with these universal curves. The right panels of Fig. 1 show this for MC-Glauber and MC-KLN initial state models [6]. In both cases the slope of the data [7] is correctly reproduced (not true for ideal nor viscous hydrodynamics with constant η/s). Due to the $\sim$20% larger ellipticity of the MC-KLN fireballs, the magnitude of $v_{2,\rm exp}^{\rm ch}/\varepsilon_x$ differs between the two models. Consequently, the value of $(\eta/s)_{\rm QGP}$ extracted from this comparison changes by more than a factor 2 between them. Relative to the initial fireball ellipticity all other model uncertainties are negligible. Without constraining ε_x more precisely, $(\eta/s)_{\rm QGP}$ cannot be determined to better than a factor 2 from elliptic flow data alone, irrespective of any other model improvements. Taking the MC-Glauber and MC-KLN models to represent a reasonable range of initial ellipticities, Fig. 1 gives $1 < 4\pi(\eta/s)_{\rm QGP} < 2.5$ for temperatures $T_{\rm c} < T < 2T_{\rm c}$ probed at RHIC.

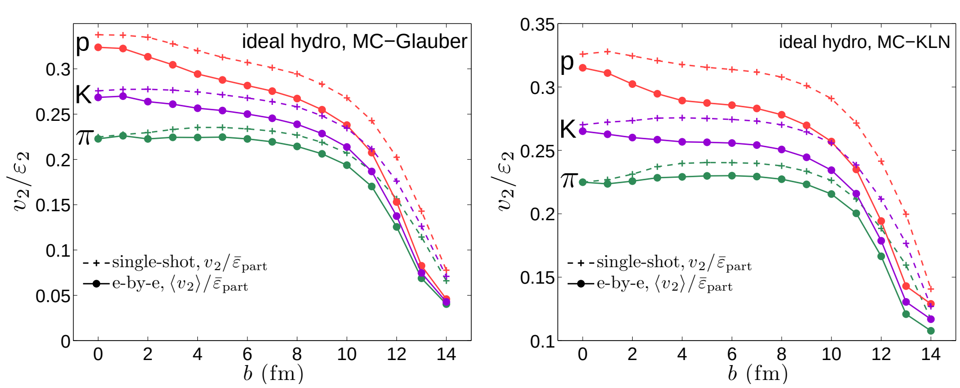

Figure 2. (Color online) Eccentricity-scaled elliptic flow as function of impact parameter for pions, kaons and protons from single-shot and event-by-event ideal fluid evolution of fluctuating initial conditions from the MC-Glauber (left) and MC-KLN (right) models.

`VISHNU` with $(\eta/s)_{\rm QGP} = \frac{1}{4\pi}$ for MC-Glauber and $\frac{2}{4\pi}$ for MC-KLN provides an excellent description of all aspects of soft ($p_T < 1.5\,\rm GeV$) hadron production (p_T-

spectra and differential $v_2(p_T)$ for all charged hadrons together as well as for individual identified species) in 200 A GeV Au+Au collisions at all but the most peripheral collision centralities [8]. Such a level of theoretical control is unprecedented.

Event-by-event hydrodynamics of fluctuating fireballs: In Fig. 1 we evolved a smooth averaged initial profile ("single-shot hydrodynamics"). This overestimates the conversion efficiency v_2/ε [9, 10]. Fig. 2 shows that event-by-event ideal fluid dynamical evolution of fluctuating fireballs reduces v_2/ε by a few percent [10]. The effect is only $\sim 5\%$ for pions but larger for heavier hadrons. We expect it to be less in viscous hydrodynamics which dynamically dampens large initial fluctuations. A reduced conversion efficiency v_2/ε from event-by-event evolution will reduce the value of $(\eta/s)_{\rm QGP}$ extracted from $v_2^{\rm ch}$; based on what we see in ideal fluid dynamics, the downward shift for $(\eta/s)_{\rm QGP}$ will at most be of order 0.02-0.03.

Predictions for spectra and flow at the LHC: The successful comprehensive fit of spectra and elliptic flow at RHIC [8] allows for tightly constrained LHC predictions. Fig. 3 shows such predictions for both pure viscous hydrodynamics `VISH2+1` [11] and `VISHNU` [12]. A straightforward extrapolation with fixed $(\eta/s)_{\rm QGP}$ overpredicts the LHC

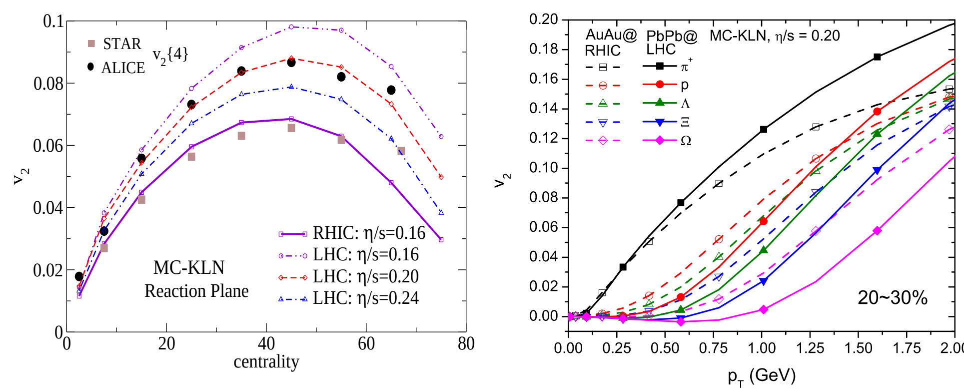

Figure 3. (Color online) Total charged hadron elliptic flow as function of centrality (`VISHNU`, left [12]) and differential elliptic flow for identified hadrons for 20-30% centrality (`VISH2+1`, right [11]) for 200 A GeV Au+Au collisions at RHIC and 2.76 A TeV Pb+Pb collisions at the LHC. Experimental data are from [13].

$v_2^{\rm ch}$ values by 10-15%; a slight increase of $(\eta/s)_{\rm QGP}$ from 0.16 to 0.20 (for MC-KLN) gives better agreement with the ALICE data [13]. However, at LHC energies v_2 becomes sensitive to details of the initial shear stress profile [11], and no firm conclusion can be drawn yet whether the QGP turns more viscous (i.e. less strongly coupled) at higher temperatures. The right panel shows that, at fixed $p_T < 1$ GeV, $v_2(p_T)$ increases from RHIC to LHC for pions but decreases for all heavier hadrons. The similarity at RHIC and LHC of $v_2^{\rm ch}(p_T)$ for the sum of all charged hadrons thus appears accidental.

Constraining initial state models by simultaneous measurement of v_2 and v_3: While the ellipticities ε_2 differ by about 20% between MC-KLN and MC-Glauber models, their triangularities ε_3 (which are entirely due to event-by-event fluctuations) are almost

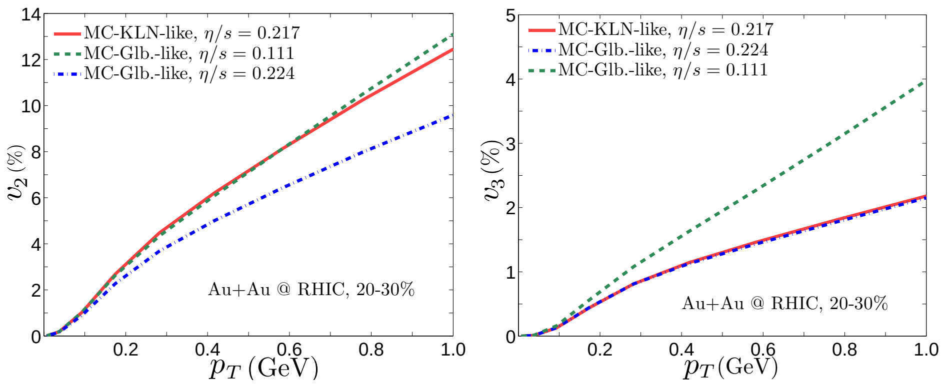

Figure 4. (Color online) p_T-differential elliptic and triangular flow from viscous hydrodynamics for initial eccentricities from the MC-KLN and MC-Glauber models.

identical [10]. This suggests to use triangular flow v_3 (which is almost entirely [10] driven by ε_3) to obtain a model-independent measurement of $(\eta/s)_{\mathrm{QGP}}$. Fig. 4 shows $v_2^\pi(p_T)$ and $v_3^\pi(p_T)$ for deformed Gaussian fireballs with average eccentricities ε_2 and ε_3 (with random relative angle) taken from the fluctuating Glauber ("MC-Glauber-like") and KLN ("MC-KLN-like") models. It demonstrates that a given set of flow data requires shear viscosities that differ by a factor 2 to reproduce $v_2(p_T)$ and but the same shear viscosities in both models to reproduce $v_3(p_T)$. A good fit by both models to $v_2(p_T)$ produces dramatically different curves for $v_3(p_T)$, and *vice versa*. The figure illustrates the strong discriminating power for such simultaneous studies and gives hope for a much more precise extraction of $(\eta/s)_{\mathrm{QGP}}$ in the near future.

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