The Viscosity of Quark-Gluon Plasma at RHIC and the LHC

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Abstract. The specific shear viscosity \((\eta/s)_{\text{QGP}}\) of quark-gluon plasma (QGP) can be extracted from elliptic flow data in heavy-ion collisions by comparing them with the dynamical model VISHNU which couples a viscous fluid dynamic description of the QGP with a microscopic kinetic description of the late hadronic rescattering and freeze-out stage. A robust method for fixing \((\eta/s)_{\text{QGP}}\) from the collision centrality dependence of the eccentricity-scaled charged hadron elliptic flow is presented. The systematic uncertainties associated with this extraction method are discussed, with specific attention to our presently restricted knowledge of initial conditions. With the \((\eta/s)_{\text{QGP}}\) extracted in this way, VISHNU yields an excellent description of all soft-hadron data from Au+Au collisions at top RHIC energy. Extrapolations to Pb+Pb collisions at the LHC, using both a purely hydrodynamic approach and VISHNU, are presented and compared with recent experimental results from the ALICE Collaboration. The LHC data are again well described by VISHNU, with the same \((\eta/s)_{\text{QGP}}\) value as at RHIC energies.

Keywords: Hydrodynamics, quark-gluon plasma, heavy-ion collisions, eccentricity, shear viscosity, elliptic flow, hybrid approach

PACS: 25.75.-q, 12.38.Mh, 25.75.Ld, 24.10.Nz

HOW TO MEASURE \((\eta/s)_{\text{QGP}}\)

Relativistic heavy-ion collisions create spatially deformed fireballs of hot, dense matter – in both non-central and (due to event-by-event shape fluctuations) central collisions. Hydrodynamics converts this initial spatial deformation into final state momentum anisotropies. Viscosity degrades the conversion efficiency \(\varepsilon_x = \langle (\mathbf{s}^2 - \mathbf{v}_x^2) \rangle / \langle (\mathbf{v}_y^2 + \mathbf{v}_z^2) \rangle \rightarrow \varepsilon_p = \langle (\mathbf{T}_{xx} - \mathbf{T}_{yy}) \rangle / \langle (\mathbf{T}_{xx} + \mathbf{T}_{yy}) \rangle\)

of the fluid (\(x\) and \(y\) are the directions transverse to the beam direction \(z\)); for given initial fireball ellipticity \(\varepsilon_x\), the viscous suppression of the dynamically generated total momentum anisotropy \(\varepsilon_p\) is monotonically related to the specific shear viscosity \(\eta/s\). The observable most directly related to \(\varepsilon_p\) is the total charged hadron elliptic flow \(v_{2,\text{ch}}\) [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]) \(\varepsilon_p\) fully saturates in the QGP phase. When (as it happens at RHIC energies) \(\varepsilon_p\) does not reach saturation before hadronization, dissipative hadronic dynamics [3] affects not only the distribution of \(\varepsilon_p\) over hadron species and \(p_T\), but even the final value of \(\varepsilon_p\) itself, and thus \(v_{2,\text{ch}}\) from which we want to extract \(\eta/s\). To isolate the QGP viscosity \((\eta/s)_{\text{QGP}}\) 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], a hybrid of VISH2+1 (Viscous Israel-Stewart Hydrodynamics in 2+1 dimensions [6]) and UrQMD, is such a code.

\((\eta/s)_{\text{QGP}}\) 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, \(v_{2,\text{ch}}/\varepsilon_x\), on the charged hadron multiplicity density per overlap area, \((1/S)(dN_{\text{ch}}/dy)\), that depends only on \((\eta/s)_{\text{QGP}}\) but not on the details of the initial state model that provides \(\varepsilon_x\) and \(S\) [7]. Pre-equilibrium flow and bulk viscous effects on these curves are small [7].

The QGP viscosity can be extracted from experimental \(v_{2,\text{ch}}\) 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 (please see [7] and references therein for a description of these models). In both cases the slope of the data [8] is correctly reproduced; this is not the case for ideal nor for viscous hydrodynamics with constant \(\eta/s\). Due to the \(\sim 20\%\) larger ellipticity of the MC-KLN fireballs, the magnitude of \(v_{2,\text{exp}}/\varepsilon_x\) differs between the two models. Consequently, the value of \((\eta/s)_{\text{QGP}}\) 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 \(\varepsilon_x\) more precisely, \((\eta/s)_{\text{QGP}}\) cannot be determined to better
It has been suggested [9, 10, 11, 12] that the ambiguity between the MC-Glauber and MC-KLN ellipticities which lies at the origin of this uncertainty can be resolved by simultaneously analyzing elliptic and triangular flow, \( v_2 \) and \( v_3 \).

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protons (resonance decay contributions are included). Such a level of theoretical control is unprecedented.²

\((\eta/s)_{\text{QGP}}\) AT THE LHC

The successful comprehensive fit of soft hadron spectra and elliptic flow in Au+Au collisions at RHIC shown in Fig. 2 and elaborated on in more detail in Refs. [14, 15] allows for tightly constrained LHC predictions. Fig. 3 shows such predictions for both pure viscous hydrodynamics VISH2+1 [15] and VISHNU [16]. A straightforward extrapolation with fixed \((\eta/s)_{\text{QGP}}\) overpredicts the LHC \(v_2^{ch}\) values by 10-15%; a slight increase of \((\eta/s)_{\text{QGP}}\) from 0.16 to 0.20 (for MC-KLN) gives better agreement with the ALICE data [17]. However, at LHC energies \(v_2\) becomes sensitive to details of the initial shear stress profile [15], and no firm conclusion can be drawn yet whether the QGP turns more viscous (i.e. less strongly coupled) at higher temperatures. Furthermore, ALICE [18] has noted a discrepancy between the \(\bar{p}/p^-\) ratio measured in Pb+Pb collisions at the LHC and the value observed by STAR in Au+Au collisions at RHIC. The latter has a strong influence on the value of the chemical decoupling temperature implemented in the model. We use \(T_{\text{chem}}=165\) MeV which nicely fits the normalization of the proton spectra from STAR but overpredicts those from PHENIX by a factor \(~1.5-2\) (left panel in Fig. 2). The \(\bar{p}/p^-\) ratio measured by ALICE at the LHC agrees with the PHENIX value measured at RHIC (see Fig. 7 in [18]) but is smaller by a factor \(~1.5-2\) than what is implemented in the LHC predictions from Refs. [15, 16]. Correspondingly, our predictions of the \(\bar{p}\) spectra for Pb+Pb@LHC [15] overpredict the measured spectra by this factor [18]. Reducing the \(\bar{p}/p^-\) ratio to the measured value will reduce the charged hadron elliptic flow [19]. To go to the larger radial flow, this reduces is stronger at the LHC than at RHIC. This may account for the \(~15\%\) overprediction of \(v_2^{ch}\) for \((\eta/s)_{\text{QGP}}=0.16\) at the LHC seen in the left panel of Fig. 3.

The right panel of this figure 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 \(v_2(p_T)\) the sum of all charged hadrons noted in Ref. [17] thus appears accidental. As a result of this shift of the elliptic flow to larger \(p_T\) for heavier particles, which is caused by the stronger radial flow at the LHC, the mass-splitting between the \(v_2(p_T)\) curves for different mass hadrons grows from RHIC to LHC. This predicted growth has been confirmed by ALICE (see Fig. 6 in [20]).

As mentioned in footnote 2, the purely hydrodynamic simulations based on VISH2+1 with constant \(\eta/s=0.2\) fail to correctly reproduce the centrality dependence of the proton elliptic flow \(v_2(p_T)\). Especially in central collisions, \(v_2(p_T)\) is overpredicted at small \(p_T\) (see Fig. 2 in [21]), i.e. the radial flow pushing the elliptic flow to higher \(p_T\) and

² We note that the purely hydrodynamic model VISH2+1 does almost equally well, with \((\eta/s)_{\text{QGP}}=0.2\) for MC-KLN initial conditions [15], except for the centrality dependence of the differential elliptic flow \(v_2(p_T)\) for protons. We will see a similar failure of VISH2+1 for Pb+Pb collisions at the LHC further below. The main difference to VISHNU is that, in order to generate enough radial flow at freeze-out, VISH2+1 must be started earlier \((\tau_0=0.6\) instead of 1.05 fm/c\) because it lacks the highly dissipative hadronic phase that generates additional radial flow in VISHNU at late times (in the VISH2+1 simulations \(\eta/s\) is held constant at 0.2 until hadronic freeze-out). The variation with collision centrality of the final balance between radial and elliptic flow turns out to be correct in VISHNU (where more of the radial flow develops later) but incorrect in VISH2+1 (where more of it is created early).
The hybrid model are in progress. created in relativistic heavy-ion collisions at RHIC and LHC. Transverse momentum spectra and elliptic flow of stage microscopically using a kinetic approach, provides a comprehensive quantitative description of the bulk matter after reducing lead to an underprediction of elliptic flow from shown in Fig. 5 were done primarily to understand systematic differences between the predictions for spectra and preference for the smaller value QGP phase, even though the hadronic phase with low \( \eta/s \) will \( \eta/s \) will almost perfectly, for all three particle species. Looking closely, one observes a slight (6%) underprediction of \( v_2(p_T) \) for all three particle species. This underprediction gets stronger in more peripheral collisions (reaching 9% at 50%-60% centrality) – a clear sign that we have slightly overestimated \( (\eta/s)_{QGP} \). (Since, for fixed \( \eta/s \), viscous effects increase in inverse proportion to the fireball size [6], an overestimate of \( \eta/s \) will lead to an underprediction of \( v_2(p_T) \) that grows with the impact parameter of the collisions.) We are confident that, after reducing \( (\eta/s)_{QGP} \) to 0.16, the data will be well described at all collision centralities. Corresponding simulations are in progress.

**CONCLUSIONS**

The hybrid model VISHNU, which describes the evolution of the dense and strongly coupled quark-gluon plasma phase macroscopically using viscous fluid dynamics and that of the dilute late hadronic rescattering and freeze-out stage microscopically using a kinetic approach, provides a comprehensive quantitative description of the bulk matter created in relativistic heavy-ion collisions at RHIC and LHC. Transverse momentum spectra and elliptic flow of soft charged hadrons, pions, kaons, and protons are well reproduced at all collision centralities, with a QGP shear...
viscosity \((\eta/s)_{QGP} = \frac{\pi}{16} = 0.16\) if MC-KLN initial conditions are used. So far the data yield no evidence for a change of \((\eta/s)_{QGP}\) between RHIC and LHC that would reflect the different temperature ranges probed. Overall, the QGP liquid created in heavy-ion collisions at the LHC appears to be as strongly coupled as at RHIC energies.

**FIGURE 5.** (Color online) Same preliminary data from ALICE [20, 21] as in Fig. 4, but now compared with VISHNU calculations with \((\eta/s)_{QGP} = 0.2\), using the same MC-KLN initial conditions as in Fig. 3. Shown is the eccentricity-scaled elliptic flow, i.e. \(v_2^2/\varepsilon\) for the experimental data and \(\langle v_2^2 \rangle/\langle \varepsilon \rangle\) for the theoretical curves.

**Acknowledgments:** This work was supported by the U.S. Department of Energy under grants No. DE-AC02-05CH11231, DE-SC0004286 and (within the framework of the JET Collaboration) No. DE-SC0004104. Extensive computing resources provided by the Ohio Supercomputing Center are gratefully acknowledged.

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