A strongly coupled plasma is produced in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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Results from first measurements of charged particle differential elliptic flow obtained in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at CERN's Large Hadron Collider (LHC), are compared to those obtained for Au+Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV with the PHENIX detector at BNL's Relativistic Heavy Ion Collider (RHIC). The comparisons, made as a function of centrality or the number of participant pairs ($N_{\rm part}$) and particle transverse momentum p_T, indicate an excellent agreement between the magnitude and trends for the flow coefficients $v_2(p_T, N_{\rm part})$. This suggests that the specific viscosity of the quark gluon plasma (QGP) produced in LHC collisions is similar to that for the strongly coupled QGP produced in RHIC collisions.

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First results from Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, from CERN's Large Hadron Collider (LHC) [1, 2] have initiated the highly anticipated explorations of the the high temperature, high entropy density domain of the QCD phase diagram. At ~ 14 times the energy of RHIC collisions, these Pb+Pb collisions are expected to create a rapidly thermalized plasma of quarks and gluons (QGP) at temperatures higher than those currently accessible at RHIC. The reported hadron multiplicity density in these Pb+Pb collisions is $dN/d\eta \sim 1584$ (8.3 per participating nucleon pair $N_{\rm part}$) for the most central 5% of the hadronic cross section [1] – a factor of 2.2 increase over that observed in central Au+Au collisions at RHIC ($\sqrt{s_{NN}} = 0.2$ TeV). Thus, it appears that one now has a lever arm for probing the QGPs viscosity and other transport properties to determine if they evolve from the strongly coupled plasma observed at RHIC [3–5], towards the more weakly interacting, gaseous plasma state expected at asymptotically high temperatures.

In non-central heavy ion collisions, the spacial asymmetry of an initial "almond-shaped" collision-zone leads to *flow*. That is, partonic interactions drive uneven pressure gradients in- and out of the reaction plane and hence, a momentum anisotropy of the particles emitted about this plane. At mid-rapidity, the magnitude of this flow is frequently characterized with the even-order Fourier coefficients; $v_{\rm n} = \left\langle e^{in(\Delta\phi)} \right\rangle$, $n = 2, 4, ...$, where $\Delta\phi$ is the azimuth of an emitted hadron about the reaction plane, and brackets denote averaging over particles and events.

Because they are known to be sensitive to various transport properties of the expanding hot medium [6–15], the differential Fourier coefficients $v_2(N_{part})$, $v_2(p_T)$ and $v_2(N_{part}, p_T)$ have been extensively studied as a function of collision centrality and hadron transverse momentum p_T, in Au+Au collisions at RHIC ($\sqrt{s_{NN}} = 0.2$ TeV) [16–23]. Indeed, considerable effort is currently being devoted to the quantitative extraction of the specific shear viscosity η/s (*i.e.* the ratio of shear viscosity η to entropy density s) via comparisons to viscous relativistic hydrodynamic simulations [14, 15, 24–30], transport model calculations [12, 13, 31] and hybrid approaches which involve the parametrization of scaling deviations from ideal hydrodynamic behavior [5, 8, 11, 32, 33].

With the advent of detailed $v_2(N_{part}, p_T)$ data for Pb+Pb collisions at the LHC ($\sqrt{s_{NN}} = 2.76$ TeV), an important question is whether these new flow data give an early indication for a significant difference in the viscosity of the QGP produced in RHIC and LHC collisions? Such a difference might be expected because, relative to Au+Au collisions at RHIC, the measured $dN/d\eta$ for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, suggests an approximate 30% increase in the temperature of the QGP produced in LHC collisions.

The influence of $\frac{\eta}{s}$ on anisotropic flow is especially transparent in studies involving the eccentricity-scaled flow coefficient $\frac{v_2(N_{\rm part}, p_T)}{\varepsilon_2(N_{\rm part})}$ as illustrated in Fig. 1. Here, results from hydrodynamic simulations (with the code of Dusling and Teaney [34]) are shown for two different viscosity values. For $\frac{\eta}{s} = 0$, Fig. 1 (a) indicates an essentially flat dependence for $\frac{v_2(N_{\rm part}, p_T)}{\varepsilon_2(N_{\rm part})}$ in line with the expected scale invariance of perfect fluid hydrodynamics. By contrast, Fig. 1 (b) shows that the introduction of a viscosity ($\frac{\eta}{s} = 0.2$) reduces the magnitude of $v_2(N_{\rm part}, p_T)$ and breaks the scale invariance of ideal hydrodynamics evidenced in Fig. 1 (a). That is, there are substantial p_T-dependent deviations away from the essentially flat $N_{\rm part}$ dependence observed in Fig. 1 (a).

Figure 2 shows that these predicted scaling deviations are found in actual experimental data [33]. It shows eccentricity-scaled values of $v_{2,4}(p_T, N_{\rm part})$ (obtained with factorized Kharzeev-Levin-Nardi [MC-KLN] model eccentricities [35, 36]) for several p_T cuts. The low-p_T selections show small scaling deviations, *i.e.* they are almost flat. However, the data points slope upward progressively (from low to high $N_{\rm part}$) as the $\langle p_T \rangle$ is increased, reflecting an increase in the scaling deviations

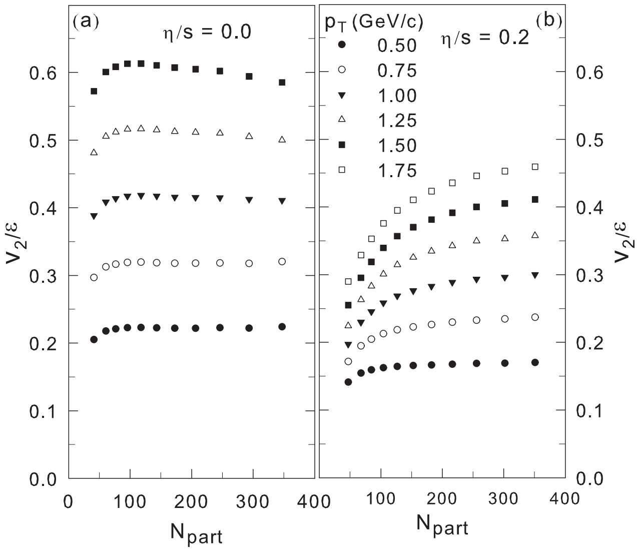

FIG. 1. (color online) Comparison of v_2/ε_2 vs. $N_{\rm part}$ for several p_T selections, obtained from perfect fluid (a) and viscous (b) hydrodynamic simulations [34] of Au+Au collisions.

with $\langle p_T \rangle$.

These eccentricity-scaling deviations reflect the effects of viscosity, as well as its attendant influence on the emission distribution (f) on the freeze-out surface. This distribution can be expressed as [7, 34];

$$\frac{dN}{dy p_T dp_T d\phi} \sim f_0 + \delta f \equiv f_0 \left(1 + C\left(\frac{p_T}{T_f}\right)^{2-\alpha}\right), \quad (1)$$

where f_0 is the equilibrium distribution, T_f is the freeze-out temperature, $C \approx \frac{\eta}{3\tau s T_f}$ and α is estimated to be 0 [33]; τ is the time scale of the expansion. Note that the factor δf results [explicitly] from a finite shear viscosity and is known to dominate the calculated viscous corrections to $v_2(p_T)$ for $p_T \gtrsim 1$ GeV/c due to its strong p_T^2 dependence [34]. Thus, a significant increase in the value of $\frac{\eta}{s}$ would not only serve to decrease the magnitude of $\frac{v_2(N_{\rm part}, p_T)}{\varepsilon_2(N_{\rm part})}$ but would also magnify the eccentricity-scaling deviations, especially for $p_T \gtrsim 1$ GeV/c.

Figures 1 and 2 shows that a simple way to test for a change in $\frac{\eta}{s}$ for two different data sets, it to compare their respective eccentricity-scaled anisotropy coefficients $\frac{v_2(N_{\rm part}, p_T)}{\varepsilon_2(N_{\rm part})}$ and $\frac{v_4(N_{\rm part}, p_T)}{\varepsilon_4(N_{\rm part})}$, to see if they differ. That is, a significant $\frac{\eta}{s}$ difference would not only lead to different magnitudes, but also to very different p_T-dependent curvatures for the eccentricity-scaled coefficients from each data set. If the $N_{\rm part}$ dependence of $\varepsilon_{2,4}$ is the same for both data sets, then the test can be made more simple by directly comparing the flow coefficients $v_2(N_{\rm part}, p_T)$.

The flow results recently reported in Ref. [2] have indicated a strong similarity between the elliptic flow coefficients $v_2(N_{\rm part}, p_T)$ obtained by the ALICE collaboration for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and those obtained by the STAR collaboration for Au+Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV. This similarity is especially striking because the difference between the Glauber-based initial eccentricities (MC-Glauber) for Au+Au and Pb+Pb collisions are reported to be ≈ 5% [2], *i.e.* the measured flow coefficients for both data sets can be directly compared to test for a viscosity difference.

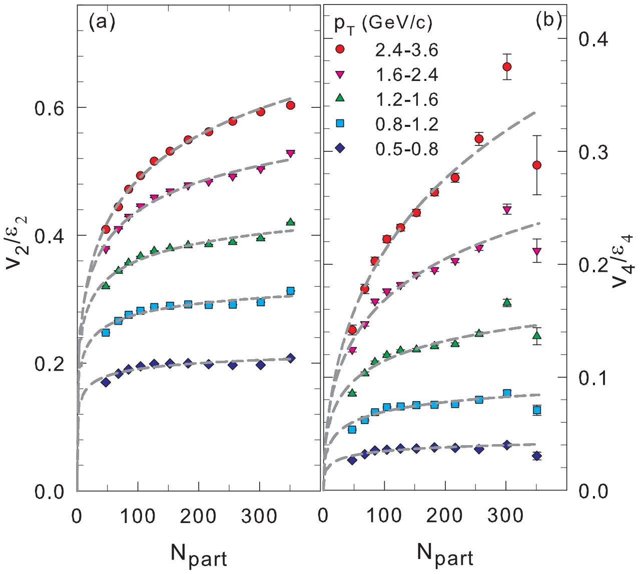

FIG. 2. (color online) Comparison of v_2/ε_2 vs. $N_{\rm part}$ (a) and v_4/ε_4 vs. $N_{\rm part}$ (b) for several p_T selections as indicated. The dashed curves indicate a simultaneous fit to the data in (a) and (b) [for each p_T] [33]. The $v_{2,4}$ data are from Ref. [23].

A similar comparison of $v_2(p_T)$ for several centrality selections from the PHENIX [23] and ALICE [2] data sets, is shown in Fig. 3 (a). Note that the $N_{\rm part}$ dependence of the ratios of the MC-FKLN initial eccentricities shown in Fig. 3 (b), is essentially flat over the centrality range of interest. The comparison shows an excellent agreement between the magnitudes and trends for both data sets, suggesting a strong similarity between the viscous corrections to $v_2(p_T)$ in Pb+Pb ($\sqrt{s_{NN}} = 2.76$ TeV) and Au+Au ($\sqrt{s_{NN}} = 0.2$ TeV) collisions. Here, it is noteworthy that an exact agreement between the magnitudes of both data sets is not to be expected because the ALICE measurements were obtained via the 4-particle cumulant method [37] while the PHENIX measurements were obtained via the event plane method, albeit with a sizable $\Delta\eta$-separation between the event plane and the detected hadrons [23]. These different measuring techniques are expected to reflect a small difference in the associated eccentricity fluctuations, which could manifest as a small difference in the magnitudes of the two data sets.

The deviations from eccentricity-scaling can be used to

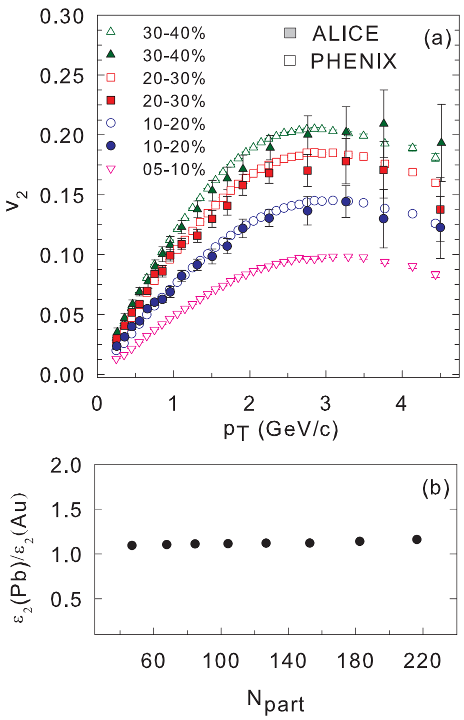

FIG. 3. (color online) Comparison of v_2 vs. p_T for several centrality selections as indicated (a). The ALICE and PHENIX data are from Refs. [2] and [23] respectively. The ratio of the initial eccentricity for Pb+Pb and Au+Au collisions is shown as a function of $N_{\rm part}$ in panel (b).

characterize the magnitude of the viscous corrections to $\frac{v_2(N_{\rm part})}{\varepsilon_2(N_{\rm part})}$ [8, 11, 32, 38] and $\frac{v_2(N_{\rm part},p_T)}{\varepsilon_2(N_{\rm part})}$ [5, 33] via a Knudsen number ($K = \lambda/\bar{R}$) parametrization ansatz, where λ is the mean free path and $\bar{R}$ is the transverse size of the system. In turn, the extracted Knudsen number provides an estimate for the specific viscosity of the QGP;

$$\frac{\eta}{s} \approx \lambda T c_s \equiv (\bar{R} K T c_s), \qquad (2)$$

where c_s is the sound speed estimated from lattice calculations [39] for the mean temperature T.

In Ref. [33] the estimate $4\pi\frac{\eta}{s} \sim 1-2$ was obtained for the K values extracted using MC-KLN and MC-Glauber eccentricities [respectively] in central and mid-central Au+Au collisions ($\sqrt{s_{NN}} = 0.2$ TeV) for the mean temperature $T = 220 \pm 20$ MeV [40]. Thus, the agreement between the LHC and RHIC data shown in Fig. 3, suggests a similar $\frac{\eta}{s}$ range for the plasma produced at higher temperatures in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

The similarity between the $\frac{\eta}{s}$ values for the plasma produced in RHIC and LHC collisions can be understood in the framework of Eq. 2, via the following simple estimate for the Knudsen number [41, 42];

$$K = \left(\frac{\beta}{\bar{R}T}\right),$$

where the magnitude of β depends primarily on whether the plasma is strongly or weakly coupled. Using this estimate for K, Eq. 2 shows that very little change in $\frac{\eta}{s}$ is to be expected if the coupling strength of the plasma remains essentially the same for two different mean temperatures, *i.e.* the mean sound speed does not show a strong temperature dependence over this temperature range. Note that a similar argument applies for comparisons involving RHIC differential v_2 data, obtained at several different beam energies [43].

In summary, we have made detailed comparisons between measurements of charged particle differential elliptic flow obtained in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, and those obtained for Au+Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV with the PHENIX detector at RHIC. The comparisons indicate an excellent agreement between the magnitude and trends for the flow coefficients $v_2(p_T, N_{\rm part})$, suggesting that the specific viscosity of the QGP produced in LHC collisions is similar to that for the strongly coupled QGP produced in RHIC collisions. It will be most interesting to investigate whether or not this conclusion is further supported by detailed viscous hydrodynamic calculations.

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