Initial indications for the production of a strongly coupled plasma in Pb+Pb collisions at sqrt[s_{NN}]=2.76 TeV

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Initial indications for the production of a strongly coupled plasma 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 (cent) 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 $v_2(p_T, \text{cent})$. Analysis indicates that the averaged 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 in these Pb+Pb collisions is ~ 1584 (or 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 [3–7], 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 in this collision-zone 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 [8–17], 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 (cent) and hadron transverse momentum p_T, in Au+Au collisions at RHIC ($\sqrt{s_{NN}} = 0.06 - 0.2$ TeV) [18–26]. 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 [16, 17, 27–34], transport model calculations [14, 15, 35] and hybrid approaches which involve the parametrization of scaling deviations from ideal hydrodynamic behavior [7, 10, 13, 36, 37].

With the advent of detailed $v_2(\text{cent}, p_T)$ 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 multiplicity 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 flow coefficient scaled by the initial eccentricity of the collision zone $\frac{v_2(N_{\rm part}, p_T)}{\varepsilon_2(N_{\rm part})}$, as illustrated in Fig. 1. Here, results from hydrodynamic simulations (with the code of Dusling and Teaney [38]) 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 [37]. It shows eccentricity-scaled values of $v_{2,4}(p_T, N_{\rm part})$ (obtained with factorized Kharzeev-Levin-Nardi [MC-KLN] model eccentricities [39, 40]) 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

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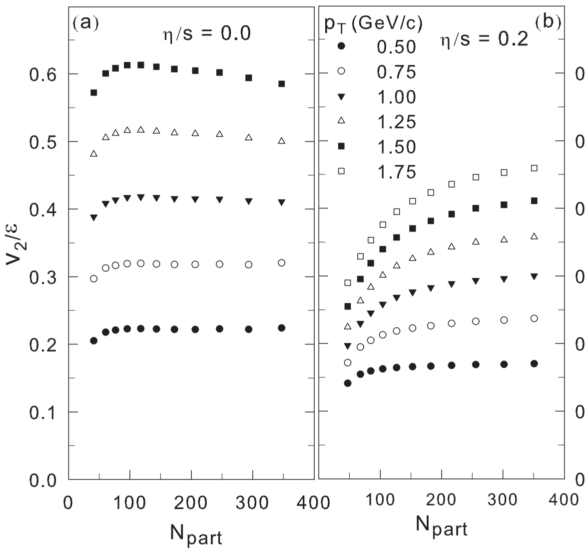

FIG. 1. (color online) Comparison of v_2/ε_2 vs. $N_{\rm part}$ for several p_T selections, obtained from perfect fluid (a) and viscous (b) hydrodynamic simulations of Au+Au collisions. For these calculation, a Glauber initial eccentricities are use in conjunction with a lattice-based equation of state [38].

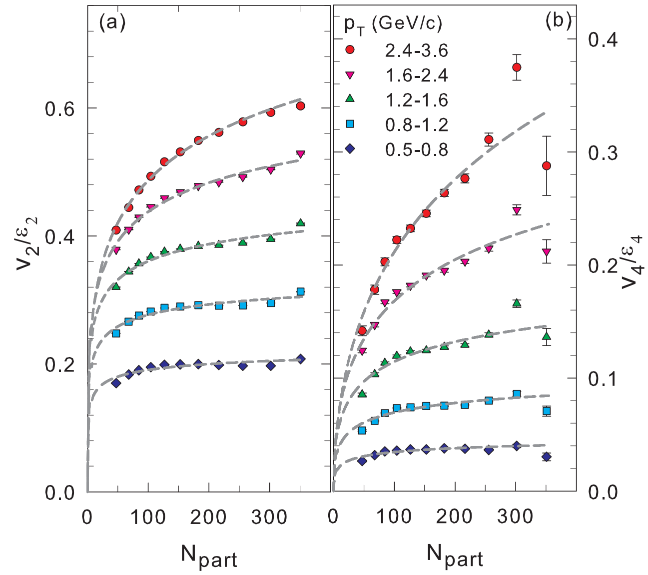

FIG. 2. (color online) Comparison of v_2/ε_2 vs. $N_{\rm part}$ (a) and v_4/ε_4 vs. $N_{\rm part}$ (b) for several p_T selections as indicated. The dashed curves indicate a simultaneous fit to the data in (a) and (b) [for each p_T] [37]. The $v_{2,4}$ data are from Ref. [26].

progressively (from low to high $N_{\rm part}$) as the $\langle p_T\rangle$ is increased, reflecting an increase in the scaling deviations 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 [9, 38];

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

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 [37]; 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 [38]. 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 show that a simple way to test for a change in $\frac{\eta}{s}$ for two different data sets, is 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 $v_2({\rm cent}, p_T)$. Indeed, the calculated MC-KLN initial eccentricities for the two reactions are very similar as shown in Fig. 3 (b). The same trend is observed for Glauber initial eccentricities which are smaller than the MC-KLN values. The ratios in Fig. 3 (b) are a little larger than unity due to the larger size of the Pb nucleus. However, for the same centrality, they are ≈ 1 as also noted in Ref. [2].

The flow results recently reported in Ref. [2] have also indicated a strong similarity between the elliptic flow coefficients $v_2({\rm cent}, p_T)$ 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. Given that the differences between the Glauber-based initial eccentricities for Au+Au and Pb+Pb collisions are small for the same centrality selection (cf. Fig. 3 and Ref. [2]), the measured flow coefficients for both data sets can be directly compared to test for a viscosity difference.

A comparison of $v_2(p_T)$ for several centrality selections from the PHENIX [26] and ALICE [2] data sets, is shown in Fig. 3 (a). The comparison shows good agreement between the magnitudes and trends for both data sets, indicating 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 [41]. Parenthetically, 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 [42] 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 [26]. These different measuring techniques re-

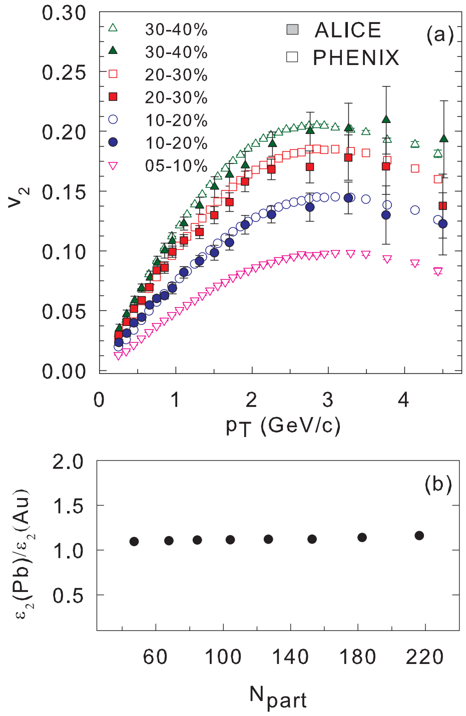

FIG. 3. (color online) Comparison of v_2 vs. p_T for several centrality selections as indicated (a). The ALICE and PHENIX data are from Refs. [2] and [26] respectively. The ratio of the initial eccentricity for Pb+Pb and Au+Au collisions is shown as a function of $N_{\rm part}$ in panel (b).

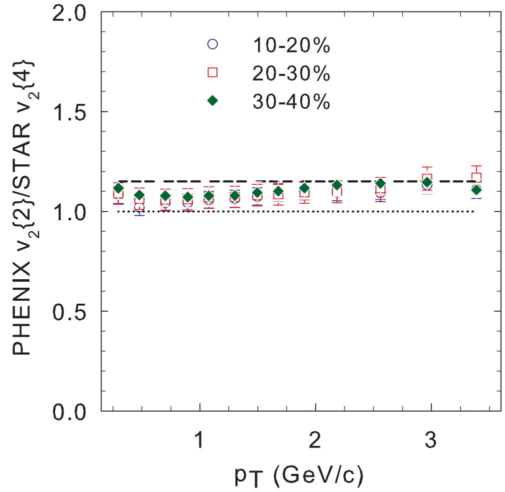

FIG. 4. (color online) Comparison of PHENIX's $v_2\{2\}$ vs. p_T and STAR's $v_2\{4\}$ vs. p_T for several centrality selections as indicated. The STAR and PHENIX data are from Refs. [2] and [26] respectively. The dotted and dashed lines indicate ratios of 1.0 and 1.15 respectively.

flect different associated eccentricity fluctuations which manifest as a small difference in the magnitudes of the two data sets. This difference is illustrated in Fig. 4 where we show the ratio of the PHENIX $v_2\{2\}$ measurements to STAR's four particle $v_2\{4\}$ measurements. The ratios show the expected 9-12% difference(esentially independent of p_T) due to the larger inherent fluctations for the $v_2\{2\}$ measurements [43, 44]. This difference does not alter the arguments nor the conclusions which follow. The observed agreement between the $v_2(p_T)$ data from both the LHC and RHIC implies that the observed increase of the p_T-integrated v_2 (from RHIC to the LHC) [2], can be simply explained by an increase in the $\langle p_T \rangle$.

As in Refs. [7, 37] the deviations from eccentricity-scaling have been used to characterize the magnitude of the viscous corrections to $\frac{v_2(N_{\rm part},p_T)}{\varepsilon_2(N_{\rm part})}$ and $\frac{v_2(N_{\rm part})}{\varepsilon_2(N_{\rm part})}$ [10, 13, 36, 45] by a Knudsen number ($K = \lambda/\bar{R}$) parametrization, where λ is the mean free path and $\bar{R}$ is the transverse size of the system obtained from the same Glauber-based calculations used to determine $\varepsilon_2(N_{\rm part})$. In turn, the extracted Knudsen number provides an estimate for the specific viscosity of the QGP;

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

where c_s is the sound speed estimated from lattice calculations [46] for the mean temperature T. The agreement between the LHC and RHIC data shown in Fig. 3 (a) and in Fig. 2 of Ref. [2], indicate very similar viscous corrections and thus, a similar $\frac{\eta}{s}$ range for the plasma produced at higher temperatures in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In Ref. [37] 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 [47].

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 [48, 49];

$$K = \left(\frac{\beta}{\bar{R}T}\right), \tag{3}$$

where the magnitude of β depends primarily on whether the plasma is strongly or weakly coupled (for a weakly couple plasma, $\beta \sim 36/8.144 g^4$). Substitution of the estimate for K into Eq. 2 shows that very little change in $\frac{\eta}{s}$ would result 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 the range of interest. Note that a similar argument applies for the comparison of RHIC differential v_2 data over the beam collision energy range $\sqrt{s_{NN}} = 0.062 - 0.2$ TeV, where $v_2(p_T, {\rm cent})$ has been observed to be approximately constant for Au+Au collisions [21]. Here, an important difference is that the associated temperature change is relatively small.

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 $v_2(p_T, \text{cent})$. Our analysis indicates that the averaged specific viscosity of the QGP produced in LHC collisions is similar to that for the strongly coupled QGP produced in RHIC collisions. Therefore, a strong indication for an evolution toward a more weakly interacting plasma has not been exhibited. It will be most interesting to investigate whether or not this conclusion is further supported by detailed viscous hydrodynamic calculations, as well as more detailed differential flow measurements at the LHC.

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