Initial indications for the production of a strongly coupled plasma in Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

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Phys. Rev. C 83, 031901 — Published 25 March 2011

DOI: 10.1103/PhysRevC.83.031901
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 ($N_{\text{part}}$) 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.

PACS numbers: 25.75.Dw, 25.75.Ld

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 high temperature, high entropy density domain of the QCD phase diagram. At $\sim 14$ 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 $\sim 1584$ (or 8.3 per participating nucleon pair $N_{\text{part}}$) 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 QGP’s 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 $v_n = \langle e^{i n \Delta \phi} \rangle$, $n = 2, 4, \ldots$, 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 $v_2(N_{\text{part}})$, $v_2(p_T)\!$ and $v_2(N_{\text{part}}, p_T)$ 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) [18–20]. Indeed, considerable effort is currently being devoted to the quantitative extraction of the specific shear viscosity $\eta/s$ (i.e. the ratio of shear viscosity $\eta$ 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 $p_T$ on anisotropic flow is especially transparent in studies involving the flow coefficient scaled by the initial eccentricity of the collision zone $v_2(N_{\text{part}}, p_T)/v_2(N_{\text{part}})$, as illustrated in Fig. 1. Here, results from hydrodynamical simulations (with the code of Dusling and Teaney [38]) are shown for two different viscosity values. For $z = 0$, Fig. 1 (a) indicates an essentially flat dependence for $v_2(N_{\text{part}}, p_T)/v_2(N_{\text{part}})$ in line with the expected scale invariance of perfect fluid hydrodynamics. By contrast, Fig. 1 (b) shows that the introduction of a viscosity ($z = 0.2$) reduces the magnitude of $v_2(N_{\text{part}}, p_T)$ 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 $N_{\text{part}}$ 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 $v_2(4\langle p_T, N_{\text{part}} \rangle)$ (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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progressively (from low to high $N_{\text{part}}$) 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 \[\frac{dN}{dp_T dp_T d\phi} \sim f_0 + \delta f = f_0 \left( 1 + C \left( \frac{p_T}{T_f} \right)^{2-\alpha} \right), \] where $f_0$ is the equilibrium distribution, $T_f$ is the freeze-out temperature, $C \approx \frac{n}{\sigma \tau s N}$ and $\alpha$ is estimated to be 0 [37]; $\tau$ is the time scale of the expansion. Note that the factor $\delta f$ results [explicitly] from a finite shear viscosity and is known to dominate the calculated viscous corrections to $v_2(p_T)$ for $p_T \gtrsim 1 \text{ GeV/c}$ due to its strong $p_T^2$ dependence [38]. Thus, a significant increase in the value of $\frac{\Delta f}{f_2(N_{\text{part}}, \rho)}$ would not only serve to decrease the magnitude of $\frac{\Delta f}{f_2(N_{\text{part}}, \rho)}$, but would also magnify the eccentricity-scaling deviations, especially for $p_T \gtrsim 1 \text{ GeV/c}$.

Figures 1 and 2 show that a simple way to test for a change in $\frac{\Delta f}{f_2}$ for two different data sets, is to compare their respective eccentricity-scaled anisotropy coefficients $v_2(N_{\text{part}}, \rho)$ and $v_2(N_{\text{part}}, \rho)$, to see if they differ. That is, a significant $\frac{\Delta f}{f_2}$ 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 $N_{\text{part}}$ dependence of $v_2(N_{\text{part}}, \rho)$ is the same for both data sets, then the test can be made more simple by directly comparing the flow coefficients $v_2(\text{cent}, p_T)$.

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 $\approx 1$ 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 $v_2(\text{cent}, p_T)$ obtained by the ALICE collaboration for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ and those obtained by the STAR collaboration for Au+Au collisions at $\sqrt{s_{NN}} = 0.2 \text{ TeV}$. 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 ($\sqrt{s_{NN}} = 2.76 \text{ TeV}$) and Au+Au ($\sqrt{s_{NN}} = 0.2 \text{ TeV}$) 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 $\Delta p_T$-separation between the event plane and the detected hadrons [26]. These different measuring techniques re-
show that very little change in
v2 for the specific viscosity of the QGP;
In turn, the extracted Knudsen number provides an esti-
mate for the specific viscosity of the QGP; $\frac{\eta}{s} \approx \lambda T c_s \equiv (\bar{R}K T c_s),$

where $c_s$ is the sound speed estimated from lattice calcu-
lations [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 $\frac{2}{\lambda}$ range for the plasma
produced at higher temperatures in Pb+Pb collisions at
$\sqrt{s_{NN}} = 2.76$ TeV. In Ref. [37] the estimate $4\pi \frac{2}{\lambda} \sim 1 - 2$
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 $\frac{2}{\lambda}$ values for the plasma pro-
duced 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];

$$K = \left( \frac{\beta}{RT} \right),$$

where the magnitude of $\beta$ depends primarily on whether
the plasma is strongly or weakly coupled (for a weakly
couple plasma, $\beta \sim 36/8.144g^4$). Substitution of the esti-
mate for $K$ into Eq. 2 shows that very little change in
$\frac{2}{\lambda}$ would result if the coupling strength of the plasma re-
mains essentially the same for two different mean tempera-
tures, 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 $v_2(p_T, \text{cent})$ 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 be-
tween measurements of charged particle differential el-

FIG. 3. (color online) Comparison of $v_2$ vs. $p_T$ for several cen-
trality 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 $N_{\text{part}}$ 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.
 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 hydrodynamical calculations, as well as more detailed differential flow measurements at the LHC.

Acknowledgments: We thank R. Snellings for providing the ALICE experimental data. This research is supported by the US DOE under contract DE-FG02-07ER40331. A008.

[41] A recent manuscript, arXiv:1012.3955, indicates that a similarly small change in $v_2(p_T)$ as a function of beam energy, is indicated by hydrodynamical calculations.