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IL NUOVO CIMENTO Vol. 37 C, N. 1 Gennaio-Febbraio 2014
DOI 10.1393/ncc/i2014-11667-8

Colloquia: IFAE 2013

Elliptic flow and shear viscosity from a beam energy scan

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ricevuto l'1 Ottobre 2013

Summary. — We study within a relativistic transport approach the impact of a temperature dependent shear viscosity to entropy density ratio, $\eta/s(T)$, on the build-up of the elliptic flow, v_2, a measure of the angular anisotropy in the particle production. Beam Energy Scan from $\sqrt{s_{NN}} = 62.4\,\text{GeV}$ at RHIC up to $2.76\,\text{TeV}$ at LHC has shown that the $v_2(p_T)$ as a function of the transverse momentum p_T appears to be nearly invariant with energy. We show that such a surprising behavior is determined by a rise and fall of $\eta/s(T)$ with a minimum at $T \sim T_c$, as one would expect if the matter undergoes a phase transition or a cross-over.

PACS 24.85.+p – Quarks, gluons, and QCD in nuclear reactions.
PACS 25.75.Nq – Quark deconfinement, quark-gluon plasma production, and phase transitions.
PACS 25.75.-q – Relativistic heavy-ion collisions.

1. – Introduction

The main motivation for the ultra-relativistic heavy-ion collisions (uRHICs) program is to create a transient state of a quark-gluon plasma (QGP) [1]. The experimental results accumulated in these decades at the RHIC program at BNL and more recently at the LHC program at CERN have shown that the elliptic flow $v_2 = \langle \cos(2\,\varphi_p)\rangle = \langle (p_x^2 - p_y^2)/(p_x^2 + p_y^2)\rangle$, which is a measure of the anisotropy in the angular distribution of the emitted particle, is the largest ever seen in uRHICs [1, 2]. The comparison of the experimental measured v_2 and theoretical calculations within viscous hydrodynamics [3] or transport approach [4-6] have shown that such a matter has a very low shear viscosity to entropy density ratio η/s close the conjectured lower bound for a strongly interacting system in the limit of infinite coupling, $\eta/s = 1/4\pi$ [7]. On the other hand, recent measurements of higher harmonics $v_n = \langle \cos(n\,\varphi_p)\rangle$ with $n > 2$ have found results which are compatible with a finite but not too large value of $\eta/s \sim 1$–3 [8, 9]. However, a low value of $\eta/s \sim 0.1$ in itself is not a direct signature of the creation of a QGP

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indeed from perturbative calculation one expects to have an η/s about one order of magnitude larger [10]. It is known from atomic and molecular physics that a minimum in η/s is expected close to the transition temperature as emphasized in the context of QGP in refs. [11, 12]. For this reason not an average value for η/s, but rather a phenomenological estimate of its temperature dependence can give an information about the phase transition of the matter created.

It has been emphasized by both the STAR Collaboration at RHIC [13] and the ALICE at LHC [2] (in agreement with the measurements done also by CMS [14] and ATLAS [15]) that surprisingly the $v_2(p_T)$ appears to be invariant in the very wide colliding energy range of $62.4\,\mathrm{GeV} \le \sqrt{s_{\mathrm{NN}}} \le 2.76\,\mathrm{TeV}$. It therefore appears a key question to answer the reason for the invariance of $v_2(p_T)$. We show that the invariance of $v_2(p_T)$ in the energy range $62.4\,\mathrm{GeV} \le \sqrt{s_{\mathrm{NN}}} \le 2.76\,\mathrm{TeV}$ is caused by a fall and rise of the $\eta/s(T)$ as one would expect if the created matter undergoes a phase transition.

2. – Transport approach at fixed η/s

In this section we introduce a Relativistic Boltzmann Transport (RBT) at fixed η/s ratio. The motivation to introduce this approach is twofold, on one hand it is possible to make a direct comparison to viscous hydrodynamics and on the other hand we have a tool to directly estimate the viscosity of the plasma in a wider range of η/s and p_T and compare it to hydrodynamics.

To study the dynamics with a certain $\eta/s(T)$, we determine locally in space and time the total cross section σ_{tot} according to the Chapmann-Enskog theory. For a pQCD inspired cross section, $\mathrm{d}\sigma/\mathrm{d}t \sim \alpha_s^2/(t-m_D^2)^2$, typically used in parton cascade approaches [4, 16, 5], this gives:

$$\eta/s = \frac{1}{15}\langle p\rangle\,\tau_\eta = \frac{1}{15}\frac{\langle p\rangle}{g(a)\sigma_{tot}\rho}\,, \tag{1}$$

where $a = m_D/2T$, with m_D being the screening mass regulating the angular dependence of the cross section σ_{tot}, while $g(a)$ is the proper function accounting for the pertinent relaxation time $\tau_\eta^{-1} = g(a)\sigma_{tot}\rho$ associated to the shear transport coefficient and given by $g(a) = 50^{-1}\int \mathrm{d}y y^6[(y^2+3^{-1})K_3(2y) - yK_2(2y)]h(a^2y^{-2})$ with K_n-s being the Bessel functions and the function h is relating the transport cross section to the total one $\sigma_{tr}(s) = \sigma_{tot}\,h(m_D^2/s)$ and $h(\zeta) = 4\zeta(1+\zeta)[(2\zeta+1)ln(1+1/\zeta)-2]$. We have shown in ref. [17] that eq. (1) correctly describes the η/s of the system.

In this approach we solve the RBT equation with the constraint that $\eta/s(T)$ is fixed during the dynamics of the collisions by means of eq. (1) in a way similar to [18], but with an exact local implementation as described in detail in [4].

3. – Effect of $\eta/s(T)$ on the elliptic flow

In our calculation the initial condition is longitudinal boost invariant flow. The initial $\mathrm{d}N/\mathrm{d}\eta$ have been chosen in order to reproduce the final $\mathrm{d}N_{ch}/\mathrm{d}\eta(b)$ at mid rapidity as observed in the experiments at RHIC and LHC energies. The partons are initially distributed according to the Glauber model in coordinate space. In the momentum space the distribution is thermal up to $p_T = 2\,\mathrm{GeV}$ and at larger p_T we include the spectrum of non-quenched minijets according to standard NLO-pQCD calculations. The maximum temperature, T_{m0}, in the center of the fireball is fixed by assuming that it

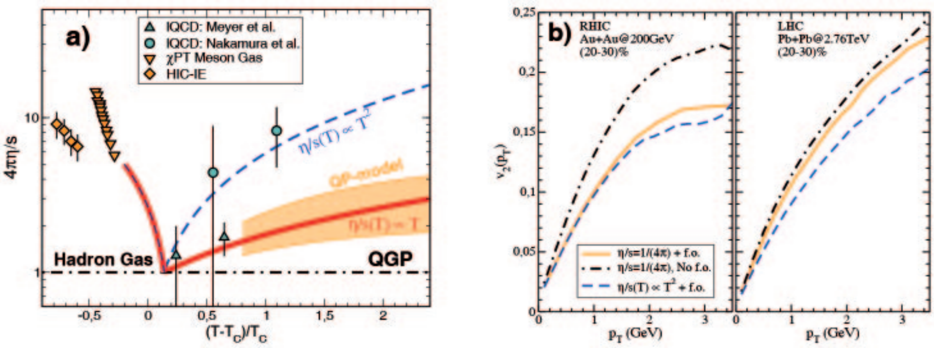

Fig. 1. – a) Different parametrizations for η/s. See the text for more details. b) $v_2(p_T)$ at mid rapidity for 20%–30% collision centrality. In the left panel it is shown the RHIC result for Au + Au at $\sqrt{s} = 200\,\mathrm{GeV}$ while in the right panel it is shown the LHC result for Pb + Pb at $\sqrt{s} = 2.76\,\mathrm{TeV}$. The black dot dashed lines refer to $4\pi\eta/s = 1$ during all the evolution of the fireball and without the freeze out condition while the orange solid lines are the calculations with the inclusion of the kinetic freeze out and with $4\pi\eta/s = 1$ in the QGP phase and finally the blue dashed lines are the calculations with $\eta/s(T) \propto T^2$ in the QGP phase.

scales with the collision energy according to the relation $(\tau A_T)^{-1} \mathrm{d}N_{ch}/\mathrm{d}\eta \propto T^3$. For the initial time, τ_0, we ensure that it satisfies the uncertainty relation between the initial average thermal energy and the initial time by $T_{m0}\tau_0 \approx 1$, and we fix $\tau_0 = 0.6\,\mathrm{fm}/c$ for Au + Au at $\sqrt{s} = 200\,\mathrm{GeV}$ as usually done in hydrodynamics. Thus we found that the maximum initial temperature is $T_{m0} = 290\,\mathrm{MeV}$, $340\,\mathrm{MeV}$ and $560\,\mathrm{MeV}$ respectively for $\sqrt{s} = 62.4\,\mathrm{GeV}$, $200\,\mathrm{GeV}$ and $2.76\,\mathrm{TeV}$. The local temperature scale according to the energy density profile $T(\vec{r}) = T_{m0}(\epsilon(\vec{r})/\epsilon(0))^{1/4}$.

In the following we will discuss the impact of the temperature dependence of η/s, see fig. 1a. In the cross-over region that we identify as the region just below the knee in the ϵ/T^4 curve [19], *i.e.* at $\epsilon < 1.5\,\mathrm{GeV/fm}^3$ and/or $T < T_0 = 1.2T_c$, the η/s increases linearly at decreasing T matching the estimates from chiral perturbation theory for a high temperature meson gas [20] (triangles in fig. 1a). In fig. 1a it is also shown a comparison with the estimate of η/s extrapolated from heavy-ion collisions at intermediate energies [21] (HIC-IE diamonds). At higher temperature due to the large error bars in the lQCD results for η/s it is not possible to infer a clear temperature dependence in the QGP phase. Therefore for $T > 1.2T_c$ we have considered two cases: one with a linear dependence $4\pi\eta/s = T/T_0$ (red solid line in fig. 1a) in agreement with the indication of lQCD calculation in ref. [22] (up-triangles) and quasi-particle model prediction (orange band) where $\eta/s \sim T^\alpha$ with $\alpha \approx 1$–1.5 [23]. The other one with a quadratic dependence $4\pi\eta/s = 3.64(T/T_0 - 1) + (T/T_0)^2$ (blue dashed line) resembling the lQCD in quenched approximation in ref. [24] as given also in [25]. We also consider a common case of a constant η/s at its conjectured minimum value $1/4\pi$. In order to discuss the different effects on the $v_2(p_T)$ of an $\eta/s(T)$ at different collision energies we compare the $v_2(p_T)$ obtanined using three different temperature parametrizations of $\eta/s(T)$ for Au + Au at $\sqrt{s} = 200\,\mathrm{GeV}$ (left panel) and Pb + Pb at $\sqrt{s} = 2.76\,\mathrm{TeV}$ (right panel). As shown in the left panel of fig. 1b, at RHIC the v_2 is sensitive to the value of η/s in the cross over region and the effect of the freeze out (the increase of η/s at low temperature) is to reduce the v_2 of about of 20%, from black dot dashed line to orange solid line. At LHC energies, right panel of fig. 1b, the scenario is different, we have that v_2 is less sensitive to the

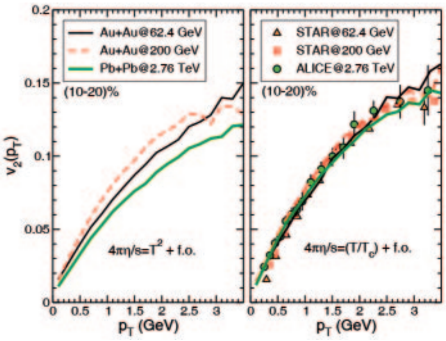

Fig. 2. – $v_2(p_T)$ at mid rapidity for 10%–20% collision centrality. The thin solid line, the dashed line and the thick solid line refer to: Au + Au at $\sqrt{s} = 62.4\,\text{GeV}$ and $\sqrt{s} = 200\,\text{GeV}$ and Pb + Pb at $\sqrt{s} = 2.76\,\text{TeV}$, respectively. On the left panel, it is shown the result for an $\eta/s(T)$ with a quadratic dependence, (blue dashed line in fig. 1a), while on the right panel it is shown the result for a linear dependence, (red solid line in fig. 1a). In the right panel symbols refers to data for $v_2[4]$ measured by STAR and ALICE collaborations [2, 13].

increase of η/s at low temperature in the cross over region. The effect of large η/s in the cross over region at LHC energies is to reduce the v_2 by less than 5% in the low p_T region, from black dot dashed line to orange solid line. Therefore, in general the effect of the kinetic f.o. is to reduce the elliptic flow and for decresing collision energy the $v_2(p_T)$ becomes more sensitive of the value of η/s at low temperature. As we can see comparing the blue dashed lines with the orange solid one in the left panel and in the right panel of fig. 1b the increase of η/s in the QGP phase affects more the system created at LHC. This means that the v_2 developed at LHC energies is more sensitive to the value of η/s in the QGP phase.

The different impact of $\eta/s(T)$ on $v_2(p_T)$ is determined by the different initial temperature and consequent lifetime of the stage at $T > T_c$. In fact at RHIC energies such a lifetime is about 4–6 fm/c in contrast to about 10 fm/c at LHC. Therefore at RHIC the elliptic flow has not enough time to fully develop in the QGP phase, while at LHC the lifetime is long enough to let the v_2 develop almost completely in the QGP phase and the increase of $\eta/s(T)$ at low T becomes irrelevant, see fig. 1b. From this observation one has the hint that an invariant $v_2(p_T)$ with the collision energy as shown in the experiments can be caused by the specific T-dependence of η/s that balances the suppression due to the viscosity above and below T_c where a minimum in η/s should occur. In fig. 2 we show that it is possible to discriminate the T-dependence of η/s in the QGP phase ($T > T_C$). As we can see in the left panel of fig. 2 the rapidly increasing $\eta/s(T)$ in the QGP phase affects the system created at LHC and this generates again a larger splitting of the $v_2(p_T)$ among the different energies. This means that also a strong T-dependence in the QGP phase is in contrast with the observed $v_2(p_T)$ invariance, essentially it would make the system at LHC too much viscous. Finally we consider $4\pi\eta/s = T/T_0$, according to the solid red line in fig. 1a. The results in the right panel of fig. 2 are also compared with the experimental results for the $v_2[4]$ measured at RHIC and LHC energy, data taken by [2, 13]. We can see that in such case there is an almost perfect invariance of $v_2(p_T)$ (within a 5%) in agreement with what is observed in the experimental data shown by the different symbols in fig. 2 (right panel). The main effect is that with a mild increase of $\eta/s(T)$ at $T > T_0$ the elliptic flow at LHC energies goes up reaching the higher $v_2(p_T)$ obtained at lower energies.

Therefore a comparative analysis at different beam energies is able to reveal an information on the $\eta/s(T)$, namely the necessity of a "U" shape of $\eta/s(T)$ with a minimum slightly above T_C which is tyical when the matter undergoes a cross-over [11].

4. – Conclusions

We have investigated within a transport approach the effect of a temperature dependence $\eta/s(T)$ on the build up of v_2 from RHIC to LHC energies. We find that for the different beam energies considered the suppression of the elliptic flow due to the viscosity of the medium has a different damping coming from the hadronic or QGP phases depending on the average energy of the system. As shown the elliptic flow at LHC is less affected by the hadronic phase and it becomes more sensitive to the QGP properties. In our analysis, we have shown that going from RHIC to LHC energies it is possible to have a nearly invariant $v_2(p_T)$ only if the η/s has a fall and rise with a minimum around the transition which is a typical behaviour of a phase transition or a cross-over. For details see [26].

REFERENCES

[1] Adams J. *et al.*, *Nucl. Phys. A*, **757** (2005) 102.
[2] Aamodt K. *et al.*, *Phys. Rev. Lett.*, **105** (2010) 252302.
[3] Romatschke P. and Romatschke U., *Phys. Rev. Lett.*, **99** (2007) 172301.
[4] Ferini G., Colonna M., Di Toro M. and Greco V., *Phys. Lett. B*, **670** (2009) 325.
[5] Xu Z. and Greiner C., *Phys. Rev. C*, **79** (2009) 014904.
[6] Plumari S. and Greco V., *AIP Conf. Proc.*, **1422** (2012) 56.
[7] Kovtun P., Son D. and Starinets A., *Phys. Rev. Lett.*, **94** (2005) 111601.
[8] Cifarelli L., Csernai L. P. and Stocker H., *Europhys. News*, **43N2** (2012) 29.
[9] Staig P. and Shuryak E., *Phys. Rev. C*, **84** (2011) 044912.
[10] Arnold P. B., Moore G. D. and Yaffe L. G., *JHEP*, **05** (2003) 051.
[11] Csernai L. P., Kapusta J. and McLerran L. D., *Phys. Rev. Lett.*, **97** (2006) 152303.
[12] Lacey R. A., Ajitanand N., Alexander J., Chung P., Holzmann W. *et al.*, *Phys. Rev. Lett.*, **98** (2007) 092301.
[13] Adamczyk L. *et al.*, *Phys. Rev. C*, **86** (2012) 054908.
[14] Chatrchyan S. *et al.*, *Phys. Rev. C*, **87** (2013) 014902.
[15] Aad G. *et al.*, *Phys. Lett. B*, **707** (2012) 330.
[16] Plumari S., Baran V., Di Toro M., Ferini G. and Greco V., *Phys. Lett. B*, **689** (2010) 18.
[17] Plumari S., Puglisi A., Scardina F. and Greco V., *Phys. Rev. C*, **86** (2012) 054902.
[18] Molnar D., arXiv:0806.0026 [nucl-th].
[19] Borsanyi S., Endrodi G., Fodor Z., Jakovac A., Katz S. D. *et al.*, *JHEP*, **11** (2010) 077.
[20] Chen J.-W., Li Y.-H., Liu Y.-F. and Nakano E., *Phys. Rev. D*, **76** (2007) 114011.
[21] Danielewicz P., Barker B. and Shi L., *AIP Conf. Proc.*, **1128** (2009) 104.
[22] Meyer H. B., *Phys. Rev. D*, **76** (2007) 101701.
[23] Plumari S., Alberico W. M., Greco V. and Ratti C., *Phys. Rev. D*, **84** (2011) 094004.
[24] Nakamura A. and Sakai S., *Phys. Rev. Lett.*, **94** (2005) 072305.
[25] Niemi H., Denicol G., Huovinen P., Molnar E. and Rischke D., *Phys. Rev. C*, **86** (2012) 014909.
[26] Plumari S., Greco V. and Csernai L., arXiv:1304.6566 [nucl-th].