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Initial State fluctuations from midperipheral to ultracentral collisions in a transport approach

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Abstract. We study the build up of the anisotropic flows v_n for a fluid at fixed $\eta/s(T)$ by means of an event-by-event transport approach. Usually in the partonic approach are used massless partons implying a $\epsilon = 3p$ Equation of State (EoS). In this paper we extend previous studies to finite partonic masses tuned to simulate a fluid with an EoS close to the recent IQCD results. In particular we study the role of the equation of state and the effect of the η/s ratio and its T dependence on the build up of the $v_n(p_T)$ for Au+Au collisions at $\sqrt{s} = 200 \text{ GeV}$ and for Pb + Pb collisions at $\sqrt{s} = 2.76 \text{ TeV}$. We find that the sensitivity to the EoS of the $v_n(p_T)$ increase with the order of the harmonics n . In particular we find a mass ordering for the elliptic flow at low p_T . We find that for the two different beam energies considered the suppression of the $v_n(p_T)$ due to the viscosity of the medium have different contributions coming from the cross over or QGP phase depending on the collision energies. The study reveals that in ultra-central collisions (0 – 0.2%) the $v_n(p_T)$ have a stronger sensitivity to the T dependence of η/s in the QGP phase and this sensitivity increases with the order of the harmonic n .

1. Introduction

Ultra-relativistic heavy-ion collisions (uRHICs) experiments, conducted first at the Relativistic Heavy-Ion Collider (RHIC) and in the recent years at Large Hadron Collider (LHC), are the only way to access experimentally the properties of hot strongly interacting matter. In the last decades it has been reached a general consensus confirmed by several experimental signatures that the matter created in these collisions consists of a strongly interacting quark-gluon plasma (QGP). One of the most important discoveries was the large elliptic flow $v_2 = \langle (p_x^2 - p_y^2) / (p_x^2 + p_y^2) \rangle$ observed [1, 2]. The elliptic flow is a measurement of the anisotropy in momentum space of the emitted particles and it is an observable that encodes information about the Equation of State (EoS) and transport properties of the matter created in these collisions[3, 4]. Theoretical calculations first within the viscous hydrodynamics framework [5, 6] and in the recent years also within kinetic transport approach [7, 8] have shown that the large value of v_2 is consistent with a matter with a very low shear viscosity to entropy density ratio $4\pi\eta/s \sim 1 - 2$ close to the conjectured lower bound for a strongly interacting system [9].

Moreover, in the recent years experimentally it has been possible to measure the event-by-event angular distribution of emitted particles and it has been possible to extend this analysis to higher order harmonics $v_n = \langle \cos(n \varphi_p) \rangle$ [10, 11]. The origin of these high order harmonics



flows can be attributed to the fluctuations in the initial geometry [12, 13, 14]. In the recent years most of the theoretical efforts has been focused on the development of the event-by-event viscous hydrodynamics simulations. The comparison with the experimental results for $v_n(p_T)$ seems to confirm a finite but not too large average value of η/s with $4\pi\langle\eta/s\rangle \sim 1-3$ [14]. However, a small value of $\langle\eta/s\rangle$ is not an evidence of the creation of a QGP phase. Moreover it is well known that the η/s of the QGP is expected to have a temperature dependence with a minimum close to the cross over region. The collection of several different theoretical calculations show the evidence of this picture [15, 16, 17, 18, 19], see Fig.1. A phenomenological estimation of $\eta/s(T)$ could give further information if the matter created in these collisions undergoes a phase transition [20, 21, 22]. However due to the large error bars in the IQCD results for η/s at moment it is not possible to infer a clear temperature dependence in the QGP phase. Recently, the CMS, ATLAS, and ALICE collaborations have been able to measure the anisotropic flow coefficients $\langle v_n \rangle$ in ultra-central heavy ion collisions [23, 11, 24]. In particular the experimental results have shown that the triangular flow $n = 3$ appears to be comparable or even larger of the elliptic flow $n = 2$. Such a result poses a problem to hydrodynamical approach that predict a significantly larger $\langle v_2 \rangle$ w.r.t. $\langle v_3 \rangle$. Very recently it has been pointed-out that at LHC energies and for ultra-central collisions a quite large correlation between $\langle \epsilon_n \rangle$ and $\langle v_n \rangle$ is present up to $n = 5$ at variance with RHIC energies and/or other centralities [25]. At the same time a much larger sensitivity to $\eta/s(T)$ has been spot. Therefore the study of the anisotropic flows in ultra-central collision offer a powerfull tool infer information about the initial geometry of the fireball.

In this paper we extend the analysis to high order harmonics studying the role of the Equation of State and $\eta/s(T)$ on the build up of $v_n(p_T)$ using a kinetic transport approach with initial state fluctuations. In the transport calculations shown in this paper we use massive particles which supply the possibility of having a soften equation of state with a decreasing speed of sound when the crossover region is approached similar to the one of IQCD calculations [26, 27]. We will show results on $v_n(p_T)$ for $n = 2, \dots, 5$ for two different systems: $Au + Au$ collisions at $\sqrt{s} = 200 \text{ GeV}$ and $Pb + Pb$ collisions at $\sqrt{s} = 2.76 \text{ TeV}$ at different centralities.

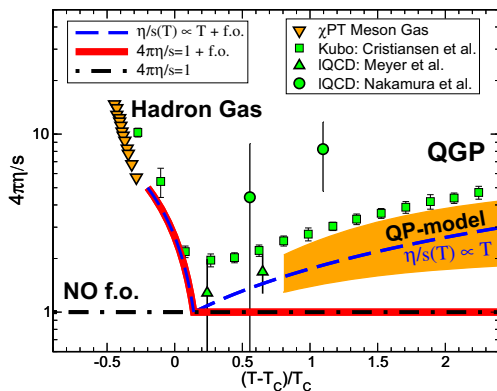


Figure 1. Different parametrizations for the temperature dependence of η/s . The orange area refers to the quasi-particle model predictions for η/s [28] while up-triangles, circles and squares are IQCD calculation on pure gauge [17, 18, 19]. The orange down-triangles are calculation in chiral perturbation theory for a meson gas [15, 16]. Finally the three different lines indicate different possible T dependencies used in this paper.

2. Transport approach at fixed η/s

In this work the fireball evolution is studied employing a transport code developed to perform studies of the dynamics of heavy-ion collisions for different energies [7, 29, 30, 31, 32, 33]. Recently this transport code has been extended to include the initial state fluctuations in order to study the harmonics $v_n(p_T)$ with $n \geq 2$. For a more detailed discussion about the implementation of the initial state fluctuations in transport approach see [25]. In this paper we extend the solution of the Relativistic Boltzmann Transport (RBT) equation to finite mass partons which allows to simulate a fluid with an EoS similar to the recent IQCD calculations

[26, 27]. This implies that the fluid has an equation of state that exhibit a large trace anomaly ($T_\mu^\mu = \epsilon - 3p \neq 0$) and consequently a sound velocity $c_s^2(T)$ that is significantly smaller than $1/3$ and reaching about $1/10$ at $T \approx T_C = 155 \text{ MeV}$.

The evolution of the phase-space distribution function $f(x, p, t)$ is given by solving the RBT equation:

$$p^\mu \partial_\mu f(x, p) = \int_{2,1',2'} (f_{1'} f_{2'} - f f_2) |\mathcal{M}|^2 \delta^4(p + p_2 - p_{1'} - p_{2'}) \quad (1)$$

with $\int_{2,1',2'} = \int \Pi_{k=2,1',2'} d^3 p_k / 2E_k (2\pi)^3$ while \mathcal{M} denotes the transition amplitude for the elastic processes. \mathcal{M} is directly related to the differential cross section $|\mathcal{M}|^2 = 16\pi s (s - 4M^2) d\sigma/dt$ with s the Mandelstam invariant. For the results shown in this paper we have considered an isotropic cross section. To study the expansion dynamics of the fireball 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 [34]. The motivation of this approach is inspired by the success of the hydrodynamical approach that has shown the key role played by the η/s to describe the experimental data [35, 14]. Therefore on one hand we use the RBT equation as an approach converging to hydrodynamics for small scattering relaxation time $\tau \sim \sigma\rho$ (or small η/s) [36, 37]. Furthermore it permits to study directly the impact of a T dependence of η/s on observables like the anisotropic flows $v_2(p_T)$ and $v_3(p_T)$ which is the main focus of this paper. On the other hand, this approach it is not based on an ansatz for the viscous corrections for the phase-space distribution function δf and it is naturally valid also at large η/s or for $p_T \gg T$ and it is possible to include initial non equilibrium effects to the distribution function $f(x, p)$ (see [31, 32]). As shown in [34] for a massive gas in the Chapmann-Enskog approximation at the first order η is given by

$$\eta = f(z) \frac{T}{\sigma_{tot}} \quad (2)$$

with $z = m/T$ while the function $f(z)$ is given by

$$f(z) = \frac{15}{16} \frac{[z^2 K_3(z)]^2}{(15z^2 + 2)K_2(2z) + (3z^3 + 49z)K_3(2z)} \quad (3)$$

where K_n -s are the modified Bessel functions. While the entropy density for a massive system is given by $s = \rho(4 + zK_1(z)/K_2(z))$. Notice that in the ultra-relativistic limit $z \rightarrow 0$ the $f(z) \rightarrow 1.2$ and we recover the massless limit for the η . As shown in [30] the expression for η in Eq.(2) is in quite good agreement at level of 3 – 5% with the Green-Kubo formula and it describes correctly the η/s of the system in the range of interest of HIC.

In Fig.1 we show the three different T dependencies of η/s studied: one of constant $4\pi\eta/s = 1$ during all the evolution of the system shown by dot dashed line another one of $4\pi\eta/s = 1$ at higher temperature in the QGP phase and an increasing η/s in the cross over region towards the estimated value for hadronic matter $4\pi\eta/s \approx 6$ [16, 38] and shown by solid line. Finally the third one shown by the dashed line in Fig.1 where we consider the increase of η/s at higher temperature with a linear temperature dependence and a minimum close to the critical temperature with a temperature dependence similar to that expected from general considerations as suggested by quasi particle models [28] or by recent calculations on pure gauge [19]. Notice that in our approach an increase of η/s at lower temperature $0.8T_C \leq T \leq 1.2T_C$ permits to account for a smooth realistic kinetic freeze-out (f.o.) because at lower T the mean free path λ goes like $\lambda \propto \frac{T}{s} \frac{1}{T}$. In the following discussion the term f.o. means to take into account the increase of η/s at $T < 1.2T_C$.

3. Role of the Equation of State on the v_n

In the following we will consider two systems at different centralities: $Au + Au$ collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ produced at RHIC and $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ at LHC. To generate an event by event initial profile we use the Monte-Carlo Glauber model. We employ the geometrical method to determine if the initial nucleons distribution. Within this method two nucleons collide each other if the relative distance in the transverse plane is $d_T \leq \sqrt{\sigma_{NN}/\pi}$ where σ_{NN} is the nucleon-nucleon cross section. In our calculation $\sigma_{NN} = 4.2 \text{ fm}^2$ is taken for RHIC at $\sqrt{s_{NN}} = 200 \text{ GeV}$ and $\sigma_{NN} = 7.0 \text{ fm}^2$ for LHC at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$. The resulting initial nucleon distribution is converted in a smooth one by assuming a Gaussian distribution centered in the nucleon position as done in several hydrodynamics calculations. In the results shown in this paper we have fixed the Gaussian width of the fluctuations to $\sigma_{xy} = 0.5 \text{ fm}$. In our calculation we assume a longitudinal boost invariant distribution from $y = -2.5$ to $y = 2.5$. For the initialization in momentum space at RHIC (LHC) energies we have considered for partons with transverse momentum $p_T \leq p_0 = 2 \text{ GeV}$ (3 GeV) a thermalized spectrum in the transverse plane. The initial local temperature in the transverse plane $T(x, y)$ is related to the local density in the transverse plane $\rho_T(x, y)$ by using the standard thermodynamical relation for massive particles $\rho_T(x, y) = \gamma T^3 z^2 K_2(z)/(2\pi^2)$ with $z = m/T$ and $\gamma = 40$ for $N_c = 3$ colors and $N_f = 2$ flavours. While for partons with $p_T > p_0$ we have assumed the spectrum of non-quenched minijets according to standard NLO-pQCD calculations with a power law shape [39]. The initial transverse momentum of the particles is distributed uniformly in the azimuthal angle. We fix the starting time of the simulation to $\tau_0 = 0.6 \text{ fm}/c$ for RHIC and $\tau_0 = 0.3 \text{ fm}/c$ for LHC as commonly done also in hydrodynamical approaches.

As well known the anisotropic flow coefficients are observable sensitive to the bulk properties of the created matter. In particular the $v_n(p_T)$ encode information about the Equation of State (EoS) and transport properties of the medium like the η/s ratio. To extract information about the EoS we have evaluated the average energy-momentum tensor $\langle T^{\mu\nu} \rangle$.

$$\langle T^{\mu\nu} \rangle = \frac{1}{V N_{test}} \sum_{i=1}^{N_{tot}} \frac{p_i^\mu p_i^\nu}{p_i^0} \quad (4)$$

$\langle T^{\mu\nu} \rangle$ is evaluated in a cylinder of radius $r_T = 1.5 \text{ fm}$ and in longitudinal direction $|\eta| < 0.3$. We evaluate the energy density by $\epsilon = \langle T^{00} \rangle$ and the pressure by assuming that $p = \frac{1}{3} \sum_i \langle T^{ii} \rangle$.

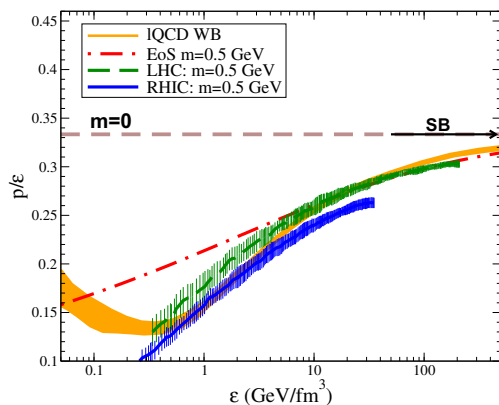


Figure 2. p/ϵ ratio as a function of the energy density. The orange band are the IQCD data taken from the Wuppertal-Budapest collaboration [40]. The solid green and dashed blue lines are respectively for LHC and RHIC energies for central collisions and mid rapidity.

In Fig.2 we compare the p/ϵ ratio obtained during the dynamical evolution in our simulations with the one of IQCD for both $Au + Au$ collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ and $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$. The results shown are for a fireball in central collisions. As shown we get a reasonably agreement with IQCD data for both energies. In these calculation we have fixed

$m = 0.5 \text{ GeV}$ and these values of masses are in agreement with the masses extracted within quasi-particle models [28]. Due to the initial fluctuations in density and therefore in energy density the corresponding value of p/ϵ can fluctuate event-by-event the blue and green bands show the possible range of trajectories covered in our simulations. This is quite interesting that such an effect is small and the bands follows closely the lQCD calculations. The band is due to the fact that locally the relation between pressure and energy density can be modified by non equilibrium effects.

The elliptic flow $v_2(p_T)$ and the high order harmonics $v_3(p_T)$, $v_4(p_T)$ and $v_5(p_T)$ have been calculated using the event plane method as

$$v_n = \langle \cos [n(\phi - \Psi_n)] \rangle \quad (5)$$

where the momentum space angles Ψ_n are given by

$$\Psi_n = \frac{1}{n} \arctan \frac{\langle \sin(n\phi) \rangle}{\langle \cos(n\phi) \rangle} \quad (6)$$

As a first step in our analysis we study the time evolution of the final anisotropic flows $\langle v_n \rangle$. Where the average $\langle \dots \rangle$ is over all the events. In our simulation we have performed 1000 events for each centrality class.

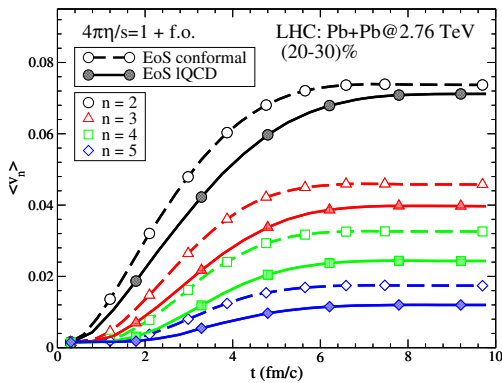


Figure 3. Time evolution of $\langle v_n \rangle$ at mid rapidity respectively for (20 – 30)% centrality collisions. Results for $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ and for the case $4\pi\eta/s = 1$ and the kinetic freeze out (f.o.). Different symbols are for different harmonics, solid lines are for the massive case (lQCD EoS) while dashed lines are for massless case (conformal limit).

In Fig.3 we plot the time evolution of the final anisotropic flow coefficients $\langle v_n \rangle$ for both cases massless (dashed lines) and massive case (solid lines). These calculation are for LHC energies at mid rapidity and for (20 – 30)% centrality collisions. Results show that in general for both massless and massive case for all harmonics the $v_n(p_T)$ are built-up within the first few fm/c and for both cases different harmonics have a different formation time with the following ordering $t_{v_2} < t_{v_3} < t_{v_4} \dots$. This was noted in Ref.[25], but here we consider the impact of the EoS. Moreover we observe that for massless case the system is more efficient to convert the initial anisotropy in coordinate space into final anisotropy in momentum space where the effect of a realistic EoS is to reduce the $\langle v_n \rangle$. This effect as shown in Fig.3 increase with the increasing of the order of the harmonics. The increasing sensitivity to the EoS for larger n is related to the different formation time of the harmonics where for example the second coefficient $\langle v_2 \rangle$ is almost completely developed within $3 - 4 \text{ fm/c}$ where the $p/\epsilon \approx 0.3$ and close to the conformal limit. The effect increases for large n because higher harmonics develop later at lower temperature where $p/\epsilon < 0.3$ and the system is less efficient in converting the initial anisotropy in coordinate in the final $\langle v_n \rangle$.

In Fig.4 we compare the final $v_n(p_T)$ for both massless (dashed lines) and massive case (solid lines). These results are for $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ and for (20 – 30)% centrality collisions. We observe for the elliptic flow v_2 a mass ordering where larger is the mass

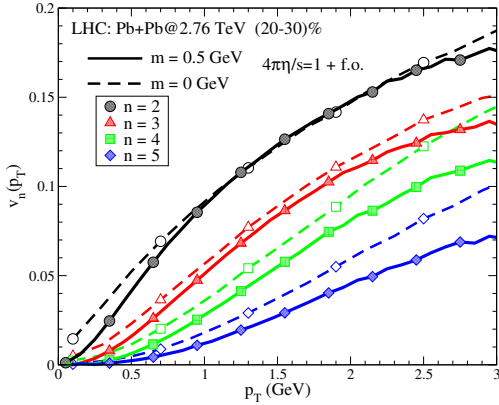


Figure 4. Differential $v_n(p_T)$ for $Pb+Pb$ collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ for (20 – 30)% centrality collisions and for the case $4\pi\eta/s = 1$ and the kinetic freeze out (f.o.). Different symbols are for different harmonics n . Solid lines are for the massive case while the dashed lines are for the massless case.

and smaller is the corresponding elliptic flow and this is typical of hydrodynamic expansion that boost strongly massive particles [41, 3]. This ordering can be explained by the fact that at low p_T the elliptic flow is $v_2(p_T) \propto p_T - \langle \beta_T \rangle m_T$ therefore for light particles $m_T = \sqrt{p_T^2 + m^2} \approx p_T$ and $v_2(p_T) \propto p_T$ while for massive particle the coupling of m_T with the radial flow gives at the same p_T a smaller $v_2(p_T)$ and it is translated in a non linear behavior at low p_T . A similar mass ordering we observe also for higher harmonics $v_n(p_T)$. In particular at low p_T the effect of the mass is to give a non linear behavior for the second and third coefficients. Moreover we observe that the sensitivity to the EoS of the $v_n(p_T)$ increases with the increasing of the harmonic n where for example a reduction of about 15% for $v_4(p_T)$ and of about 25% for $v_5(p_T)$ is observed. The enhancement of the sensitivity with the increase of the order of the harmonic is again related to the different formation time of the harmonics. In fact for large n the corresponding $v_n(p_T)$ develops later where the speed of sound c_s^2 or the p/ϵ is smaller then the one of conformal limit, see Fig.2.

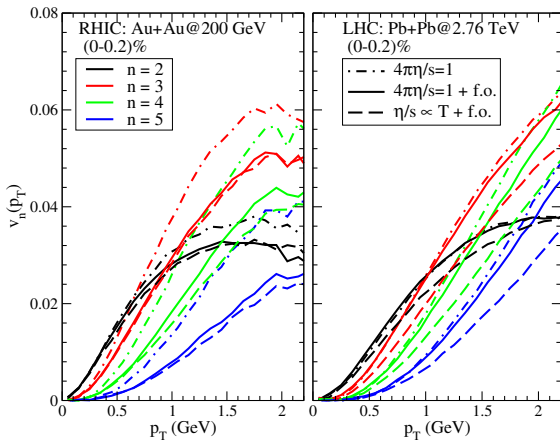


Figure 5. Differential $v_n(p_T)$ at mid rapidity and for ultra-central collisions. The comparison is between the two systems: $Au + Au$ at $\sqrt{s} = 200 \text{ GeV}$ (left panel) and $Pb + Pb$ at $\sqrt{s} = 2.76 \text{ TeV}$ (right panel). Different colors are for different harmonics n . The dot dashed lines refer to the case with a constant $\eta/s = (4\pi)^{-1}$ during all the evolution. The solid lines refer to the case with $\eta/s = (4\pi)^{-1}$ at higher temperature and kinetic f.o. while the dashed lines refer to the case with $\eta/s \propto T$ at higher temperature and the kinetic f.o. at lower temperature.

Recently it has been possible to access experimentally the ultra-central collisions. In ultra-central collisions the initial asymmetry in coordinate space measured by ϵ_n comes completely from the fluctuations in the initial geometry and there is no coupling with the global overlap shape that has a circular symmetry. Moreover as shown by the event-by-event ideal and viscous hydrodynamics calculations [42, 43] and recently also in event-by-event transport approach [25] for these collision centralities the final integrated anisotropic flows coefficient $\langle v_n \rangle$ are strongly correlated to the initial eccentricities $\langle \epsilon_n \rangle$ with a linear correlation coefficient $C(\epsilon_n, v_n) \approx 1$. In

Fig.5 it is shown the comparison of $v_n(p_T)$ produced in $Au + Au$ collisions at $\sqrt{s} = 200 \text{ GeV}$ (left panel) with the one produced in $Pb + Pb$ collisions at $\sqrt{s} = 2.76 \text{ TeV}$ (right panel) for ultra-central collisions. Comparing both panel of Fig.5 we observe that at low p_T for both energies the $v_n(p_T) \propto p_T^n$. On the other hand at high p_T we observe that the elliptic flow $v_2(p_T)$ shows a saturation while $v_n(p_T)$ for $n \geq 3$ have an almost linear p_T dependence. This is in qualitative agreement with what has been observed experimentally.

Similarly to what has been obtained in viscous hydrodynamical calculations the increase of the viscosity of the medium has the effect to reduce the produced $v_n(p_T)$. These results are qualitatively in agreement with previous results within kinetic transport approach and in the conformal limit [25]. Comparing the dot dashed lines with the solid lines in the left panel of Fig.5, we observe that at RHIC energies the $v_n(p_T)$ are sensitive to the increase of the η/s at lower temperature close to the cross over region. This sensitivity increase with the order of the harmonics. In particular for $n \geq 3$ the reduction for central collisions is about 30 – 35%. On contrary at LHC energies right panel of Fig.5 the $v_n(p_T)$ are more sensitive to the increase of η/s at high temperature as shown by a larger suppression of the $v_n(p_T)$ for the case where $\eta/s \propto T$ in the QGP phase (dashed lines). Notice that the 30% effect is determined by a slowly linear rising of η/s with T and with a minimum close T_C of $\eta/s \approx 1/(4\pi)$ as the dashed lines in Fig.1.

4. Conclusions

We have investigated the build up of the anisotropic flows $v_n(p_T)$ for $n = 2, 3, 4$ and 5 within an event-by-event transport approach. In particular we have studied the role of the EoS (by a finite mass) and the the role of a temperature dependent η/s , on the time evolution of $\langle v_n \rangle$ and on the differential $v_n(p_T)$. Our calculations show that the effect of the mass is to reduce the $v_n(p_T)$ with a sensitivity that increase with the order of the harmonics. Finally, we have studied the effect of η/s ratio on $v_n(p_T)$ for two different beam energies: at RHIC for $Au + Au$ collisions at $\sqrt{s} = 200 \text{ GeV}$ and at LHC for $Pb + Pb$ collisions at $\sqrt{s} = 2.76 \text{ TeV}$. We have found that at RHIC the $v_n(p_T)$ are more affected by the value of η/s in the cross over region ($T < 1.2T_C$) with an enhancement of the sensitivity for larger harmonics. On contrary, at LHC energies we get that almost all the $v_n(p_T)$ are more affected by the η/s of the QGP. However the sensitivity to the T dependence of the η/s is quite weak. These results are in qualitative agreement with the results obtained for the massless case. In general we found an enhancement of the sensitivity of the $v_n(p_T)$ that for $n = 2, \dots, 5$ reaches about a 30 – 35%.

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