Elliptic Flow from fKLN Initial Conditions

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Abstract. A current goal of ultra-relativistic heavy ion collisions experiments is to verify a picture in which the two colliding nuclei can be described as two tiny disks of a Color Glass Condensate (CGC) that is the limiting state of QCD matter at very high density and energy. The searching of CGC in uRHIC experiments is strongly related to the evaluation of the η/s. In fact in viscous hydrodynamics simulations a standard Glauber initial condition leads to estimate $\eta/s \sim 1/4\pi$, while the fKLN initialization, which model the melting of Color Glass Condensate, leads to at least a factor of 2 larger η/s. We have found in the framework of kinetic theory that the out-of-equilibrium initial distribution described by the fKLN reduces the efficiency in building-up the elliptic flow. In particular from our work emerges that the available data on v_2 are in agreement with a $\eta/s \sim 1/4\pi$ also for fKLN initial conditions.

1. Introduction

The experiments of Ultra-relativistic heavy-ion collisions (uRHICs) performed at the Relativistic Heavy-Ion Collider (RHIC) and at the Large Hadron Collider (LHC) offer the possibility to create a strongly interacting quark-gluon plasma (QGP) [1, 2]. For non central collisions the overlap region between the two colliding nuclei is strongly deformed in the transverse plane and a measure of such a deformation is given by the spatial eccentricity. As a consequence of this spatial deformation the pressure gradient in the x direction of the transverse plane is larger than the pressure gradient in the y direction and this leads to a deformation into the momentum space. Such a deformation can be evaluated in terms of a fourier expansion of the transverse momentum spectra. The second coefficient, who accounts for the largest contribution, is the elliptic flow v_2. The elliptic flow is both sensitive to the initial condition in the overlap region and to the ratio between the shear viscosity and the entropy density (η/s) of the expanding fireball [3, 4]. The smaller is η/s the larger is the elliptic flow. Therefore measuring the v_2 gives the possibility to know the viscosity of the plasma [3, 4]. However there is a source of uncertainty in the determination of η/s due to the lack of knowledge regarding the initial spatial eccentricity, for which one does not have a direct experimentally access and that can only be estimated using theoretical models.

A widely used model to describe the initial condition is the Glauber model in which the initial profile of the fireball is given by the geometrical superposition of the profiles of the two colliding nuclei. However the heavy ion collisions at very high energies offer the possibility to verify the picture in which the two colliding nuclei can be described as two tiny disks of a Color Glass Condensate [5, 6]. In this proceedings we discuss the results obtained for the elliptic flow using these two different initial conditions [7].

2. The factorized KLN model

One model widely used to describe the distribution of particle ($dN_g/dyd^2\boldsymbol{x}_\perp$) created after the collisions of the two nuclei consisting of color glass condensate is the factorized KLN model (fKLN) [5, 8, 6] in which:

$$\frac{dN_g}{dyd^2\boldsymbol{x}_\perp} = \int d^2\boldsymbol{p}_T\, p_A(\boldsymbol{x}_\perp)p_B(\boldsymbol{x}_\perp)\Phi(\boldsymbol{p}_T,\boldsymbol{x}_\perp,y) \ , \tag{1}$$

where Φ rapresent the momentum space distribution

$$\Phi(\boldsymbol{p}_T,\boldsymbol{x}_\perp,y) \quad = \quad \frac{4\pi^2 N_c}{N_c^2-1}\frac{1}{p_T^2}\int^{p_T} d^2\boldsymbol{k}_T\alpha_S(Q^2)\times\phi_A(x_1,k_T^2;\boldsymbol{x}_\perp)\times\phi_B(x_2,(\boldsymbol{p}_T-\boldsymbol{k}_T)^2;\boldsymbol{x}_\perp) \tag{2}$$

here $x_{1,2} = p_T\exp(\pm y)/\sqrt{s}$ and the ultraviolet cutoff p_T is assumed to be equal to 3 GeV/c; α_S is the strong coupling constant and $p_{A,B}$ appearing in Eq.1 denotes the probability to find one nucleon at a given transverse coordinate, $p_A(\boldsymbol{x}_\perp) = 1-(1-\sigma_{in}T_A(\boldsymbol{x}_\perp)/A)^A$, in which σ_{in} is the inelastic cross section and T_A corresponds to the usual thickness function of the Glauber model. The saturation behaviour is built in the unintegrated gluon distribution functions (uGDF) $\phi_A(x_1,k_T^2;\boldsymbol{x}_\perp)$ and $\phi_B(x_1,k_T^2;\boldsymbol{x}_\perp)$ which refer respectively to nucleus A and B that can be written as follows

$$\phi_A(x_1,k_T^2;\boldsymbol{x}_\perp) = \frac{\kappa\, Q_s^2}{\alpha_s(Q_s^2)}\left[\frac{\theta(Q_s-k_T)}{Q_s^2+\Lambda^2}+\frac{\theta(k_T-Q_s)}{k_T^2+\Lambda^2}\right] \tag{3}$$

a similar equation holding for partons belonging to nucleus B. Following [8] we take the saturation scale for the nucleus A as

$$Q_{s,A}^2(x,\boldsymbol{x}_\perp) = Q_0^2\left(\frac{T_A(\boldsymbol{x}_\perp)}{1.53p_A(\boldsymbol{x}_\perp)}\right)\left(\frac{0.01}{x}\right)^\lambda \ , \tag{4}$$

and similarly for nucleus B, with $\lambda = 0.28$ and $Q_0^2 = 2\ GeV^2$. This choice is the one adopted in fKLN or MC-KLN and in hydro simulations [8, 3] to study the dependence of $v_2(p_T)$ on η/s.

3. Dynamical evolution of the QGP

We employ transport theory to describe the evolution of the QGP created in relativistic heavy-ion collisions. [9, 10, 11], The time evolution of the gluons distribution function $f(\boldsymbol{x},\boldsymbol{p},t)$ is governed by the Boltzmann equation:

$$\begin{aligned} p_\mu\partial^\mu f_1 \quad &= \quad \int d\Gamma_2 d\Gamma_{1'}d\Gamma_{2'}(f_{1'}f_{2'}-f_1f_2) \\ &\qquad \times|\mathcal{M}|^2\delta^4(p_1+p_2-p_{1'}-p_{2'}) \ , \end{aligned} \tag{5}$$

where $d^3\boldsymbol{p}_k = 2E_k(2\pi)^3 d\Gamma_k$ and $\mathcal{M}$ corresponds to the transition amplitude. Usually a key input ingredient of a transport approach is the knowledge of the cross section; here we reverse it and, with the aim of creating a more direct link with viscous hydrodynamics, we determine $|\mathcal{M}|^2$ in order to have a fixed η/s, for more details see [12, 13, 7]. We have carried out simulations of the QGP created in $Au+Au$ collision at $\sqrt{s} = 200\,AGeV$ with $b = 7.5\,\text{fm}$, belonging to the $20-30\%$ centrality class. The standard initial condition for simulations of the plasma fireball created at RHIC is a $\boldsymbol{x}$-space distribution given by the Glauber model and a $\boldsymbol{p}$-space thermalized spectrum in the transverse plane at a time $\tau = 0.6\,\text{fm/c}$ with a maximum initial temperature $\text{T}_0 = 340\text{MeV}$. In this case, for a standard mixture of N_{part} and N_{coll} we find

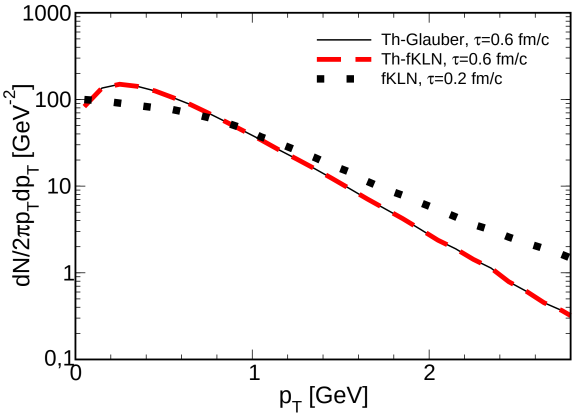

Figure 1. Transverse momentum distributions within $|y| \leq 0.5$ for the different initial conditions as in the legend for Au+Au at $\sqrt{s} = 200GeV$ and $b = 7.5\ fm$

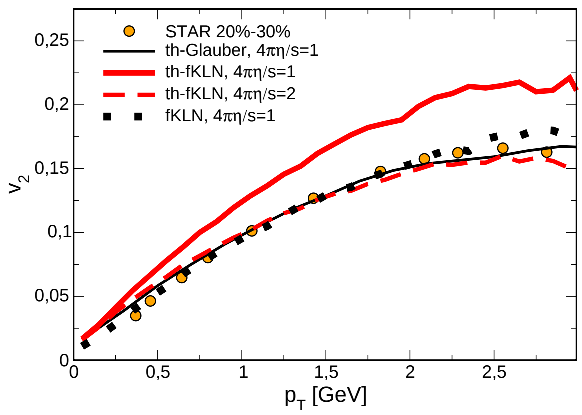

Figure 2. Elliptic flow for the different initial conditions at RHIC (Au+Au collisions at $\sqrt{s} = 200GeV$), with $b = 7.5$

$\epsilon_x = 0.284$. We will refer to this case as *Th-Glauber* and it is indicated by the thin line in Fig. 1. Instead the study of the impact of an initial CGC state has been performed considering an $\boldsymbol{x}$-space distribution given by the fKLN and a thermalized p_T distribution at $\tau_0 \sim 0.6 fm/c$ and $\mathrm{T}_0 = 340\mathrm{MeV}$, henceforth we will refer to it as *Th-fKLN* and it is shown by the dashed line in Fig.1. In this case we have an initial spatial eccentricity equal to 0.357. It represents the case implemented in hydrodynamics, that has lead to the conclusion that the CGC suggests a $\eta/s \sim 2/4\pi$ [8, 3, 14]. The third initial conditions is the full fKLN initial conditions where both the coordinate space and the momenta space are implemented according to fKLN model and it is indicated by the dotted line in Fig. 1. We notice that initially this last spectrum is quite far from thermalization reflecting the saturation behaviour typical of the melted CGC; however it thermalizes in approximatelly $1 fm/c$ [7]. As initial time we take $\tau_0 = 0.2\ fm/c$ because in this case there is no pre-assumption of thermalization. This is not usually considered in hydrodynamics because there it is implicitly assumed a distribution function in $\boldsymbol{p}$-space in local equilibrium, at least in the transverse plane. For all the previous cases, as usually done, a Bjorken scaling at the initial time is assumed and the particle multiplicity, dN/dy, is fixed to correctly reproduce the experimental data.

In figure 2 the v_2 for the cases *Th-Glauber* and *Th-fKLN* is shown for a fixed $\eta/s \sim 1/4\pi$ respectively by the thin line and by the thick line. Using the *Th-Glauber* initial conditions we get results very close to the data, indicated by the circle, instead if we use the *Th-fKLN* case we get an higher v_2. For such initial conditions the agreement with the data is achieved only if the η/s is increased by a factor of two as indicated by the dashed line in the same figure. Our result are in agreement with hydrodynamics calculations [14, 3, 15, 4] and this indicates the validity of our approach in the limit where hydrodynamics is applicable. Instead the dotted line in Fig. 2 shows the full KLN initialization. In this case the data are reproduced with a viscosity $4\pi\eta/s \sim 1$ because the larger eccentricity is compensated by the non equilibrium distribution that is less efficient in converting the initial spatial anisotropy in the momentum space. This is the novelty of our work which shows that the build-up of the elliptic flow can be affected also by off-equilibrium features of the distribution function in $\boldsymbol{p}$-space.

We have found a similar effect also at LHC energies ($\sqrt{s} = 2.7\ ATeV$) as shown in Fig.3. In this case the starting time for the simulation, when the termalized initial conditions are considered, is $\tau = 0.3\ fm/c$ with maximum initial temperature $\mathrm{T}_0 = 510\ MeV$, while the Q_0^2 is equal to 4.5

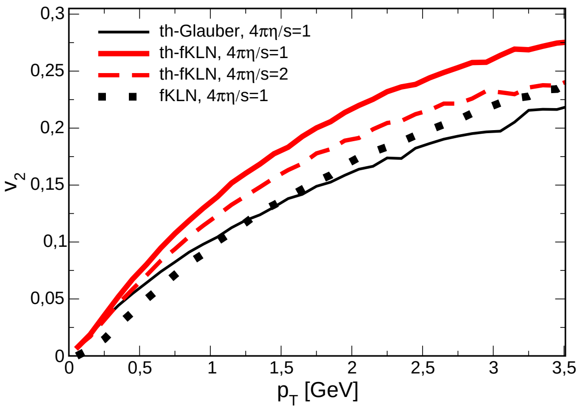

Figure 3. Elliptic flow for the different initial conditions as described in the legend. All the calculations refer to Pb+Pb collisions at $\sqrt{s} = 2.76TeV$, with $b = 7.5$

GeV^2. We observe that when the *Th-fKLN* initial conditions are considered we get an elliptic flow quite higher compared to the v_2 that we get with the *Th-Glauber* initial conditions even using η/s a factor two larger η/s, nevertheless the full KLN initialization gives a v_2 quite similar to that obtained with *Th-Glauber* with $\eta/s \sim 1/4\pi$.

4. Conclusions

In the framework of kinetic theory at fixed η/s we have found that the amount of elliptic flow produced in heavy ion collisions depends not only on the pressure gradients and on the ratio η/s of the system, but also on the initial distribution in momentum space. In particular a momentum distributions with a saturated behavior generates smaller v_2 respect to the thermal one. Using the fKLN distribution we have found that the effect of the initial non equilibrium distribution affects the estimate of η/s of about a factor two. Our results open the way to study the effect of initial momentum distribution on higher harmonics $v_n = \langle cos(n\varphi_p)\rangle$ offering a promising tool to further narrow the evaluation of the η/s of the plasma. Moreover we are setting our code in such way to include also the initial state fluctuations in order to study the impact of non-equilibrium initial conditions on the v_3. This should be very interesting since the hydrodinamics results show that the Th-fKLN with $\eta/s = 2/4\pi$ would generate a low v_3 respect to the available data leading to the conclusion that Th-fKLN is not able to describe for the experimental observations [14]. On the light of our results this last conclusion may be revised.
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