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Latest predictions from the EbyE NLO EKRT model

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Abstract

We present the latest results from the NLO pQCD + saturation + viscous hydrodynamics (EbyE NLO EKRT) model. The parameters in the EKRT saturation model are fixed by the charged hadron multiplicity in the 0-5 % 2.76 TeV Pb+Pb collisions. The $\sqrt{s}$, A and centrality dependence of the initial particle production follows then from the QCD dynamics of the model. This allows us to predict the $\sqrt{s}$ and A dependence of the particle production. We show that our results are in an excellent agreement with the low-p_T data from 2.76 TeV and 5.02 TeV Pb+Pb collisions at the LHC as well as with the data from the 200 GeV Au+Au collisions at RHIC. In particular, we study the centrality dependences of hadronic multiplicities, flow coefficients, and various flow correlations. Furthermore, the nuclear mass number dependence of the initial particle production and hydrodynamic evolution can be tested in the 5.44 TeV Xe+Xe collisions at the LHC. To this end, we show our predictions for charged particle multiplicities, and in particular, show how the deformations of the Xe nuclei reflect into the flow coefficients.

Keywords: heavy-ion collisions, perturbative QCD calculations, saturation, dissipative fluid dynamic

1. Introduction

In the EKRT framework the initial conditions for hydrodynamical evolution in heavy-ion collisions are calculated by using NLO perturbative QCD and collinear factorization together with a saturation conjecture that controls the transverse energy production through a semi-hard scale $p_{\rm sat}$ [1, 2]. The saturation momentum is a function of $\sqrt{s}$ and the nuclear mass number, and depends on the transverse coordinate through the product of nuclar thickness functions T_A [3, 4], $p_{\rm sat} = p_{\rm sat}(T_A T_A,\ \sqrt{s}, A, K_{\rm sat})$, where $K_{\rm sat}$ is fixed by the charged particle multiplicity in $0-5$ % 2.76 TeV Pb+Pb collisions. Once $K_{\rm sat}$ is fixed, the initial conditions can be computed for any $\sqrt{s}$ and A, as long as they are sufficiently large, so that the $p_{\rm sat}$ remains perturbative.

The local formation time can be estimated as $\tau_s(\mathbf{r}) = 1/p_{\rm sat}(\mathbf{r})$ and the local energy density at the formation time is then given by $e(\mathbf{r}, \tau_s(\mathbf{r})) = \frac{K_{\rm sat}}{\pi}[p_{\rm sat}(\mathbf{r})]^4$ [5]. This profile is then evolved to a common time $\tau_0 = 1/p_{\rm sat}^{\rm min} = 0.2$ fm by using 0+1D Bjorken hydrodynamics. The evolved energy density profile can then be used as an initial condition for the full fluid dynamical evolution.

The subsequent evolution of the system is described by a boost-invariant Israel-Stewart type of dissipative fluid dynamics with the coefficients of the non-linear terms from Refs. [6, 7]. The kinetic freeze-out is

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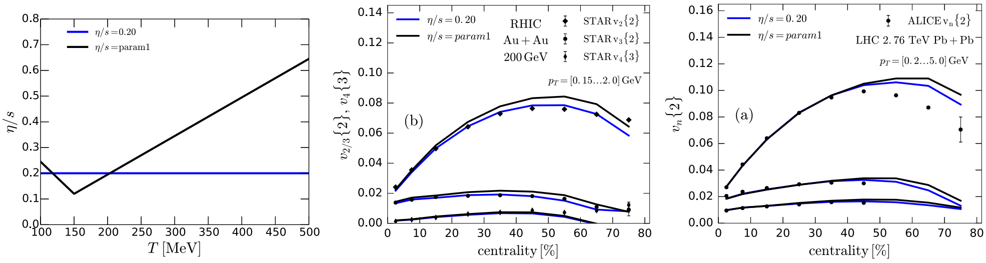

Fig. 1. The tested temperature dependencies of η/s (Left). The centrality dependence of v_n in 200 GeV Au+Au collisions (Middle), and 2.76 TeV Pb+Pb collisions (Right). The experimental data are from ALICE [13] and STAR [14, 15, 16].

$T_{\rm dec}$ = 100 MeV. The chemical freeze-out at $T_{\rm chem}$ = 175 MeV is encoded into the equation state, for which we use the $s95p$-PCE-v1 parametrization [8, 9]. We neglect the bulk viscosity and set the initial values of shear-stress tensor and transverse velocity to zero. The remaining free input is the parametrization of the temperature dependence of the shear viscosity to entropy density ratio, $\eta/s(T)$.

As discussed in detail in Ref. [10], the nuclear shapes and the event-by-event fluctuations enter the calculation through T_A. The event-by-event T_A is computed by sampling the nucleon positions from the Woods-Saxon parametrization of the nucleon density. For each nucleon we then set a gaussian transverse density profile, and the nuclear T_A is the sum of these nucleon thickness functions. We take the Pb and Au nuclei to be spherically symmetric, but as in Ref. [11], for the Xe nuclei we take into account the nuclear shape deformation, described by the parameters $\beta_2 = 0.163$ and $\beta_4 = -0.003$ from Ref. [12].

2. Results

The parametrizations of $\eta/s(T)$ are constrained by the flow coefficients v_n and various flow correlators in 200 GeV Au+Au and 2.76 TeV Pb+Pb collisions [10]. The $\eta/s(T)$ parametrizations that give the overall best agreement with these data are shown in Fig. 1 (Left), and the corresponding v_n are shown in Figs. 1 (Middle) and 1 (Right), respectively.

In Fig. 2 we show various correlation measures between v_n and v_m, defined through so called normalized symmetric cumulants, $nsc(n,m) = \langle v_n^2 v_m^2\rangle/\langle v_n^2\rangle\langle v_m^2\rangle - 1$, where the angular brackets denote the event averaging, accounting the proper weights of the event multiplicity [17]. The best agreement with the correlators is obtained with the same $\eta/s(T)$ parametrizations as the v_n themselves, thus the consistency between the experimental data and the fluid dynamical behavior is excellent.

Armed with the $\eta/s(T)$ parametrizations and the corresponding values of $K_{\rm sat}$ that were fixed in Ref. [10] our framework is closed, and we can predict the low-p_T hadronic observables for 5.023 TeV Pb+Pb [18] and 5.44 TeV Xe+Xe [19] collisions that were measured recently. In Fig. 3 we show the centrality dependence of the charged hadron multiplicity for all the systems we are considering. The predictions are in excellent agreement with the measured multiplicities. The predicted v_n in 5.023 TeV Pb+Pb collisions are shown in Fig. 4 as the ratios to v_n in the 2.76 TeV Pb+Pb collisions. The data is from the ALICE Collaboration [25]. The predicted slight increase of v_n is consistent with the measurement.

Finally, in Fig. 5 we show the ratio of our predicted v_n for the 5.44 Xe+Xe collisions to v_n in 5.023 TeV Pb+Pb collisions compared to the ALICE data [26]. The Xe nuclei are not spherically symmetric, and as a result the initial conditions are modified compared to the spherical case, especially in more central collisions, and moreover the modified initial densities then reflect through the fluid dynamical evolution to the final flow coefficients [11]. In the figure we show both the cases: with and without accounting for the nuclear deformation. As can be seen from the figure, v_n in central collisions are enhanced compared to the v_n in 5.023 TeV Pb+Pb collisions regardless of whether we include the Xe deformation or not. However, with the deformation the enhancement of the elliptic flow, v_2, is much stronger, and it is clearly necessary to include the deformation in order to describe the experimental data. For larger n the effect of deformation is much weaker.

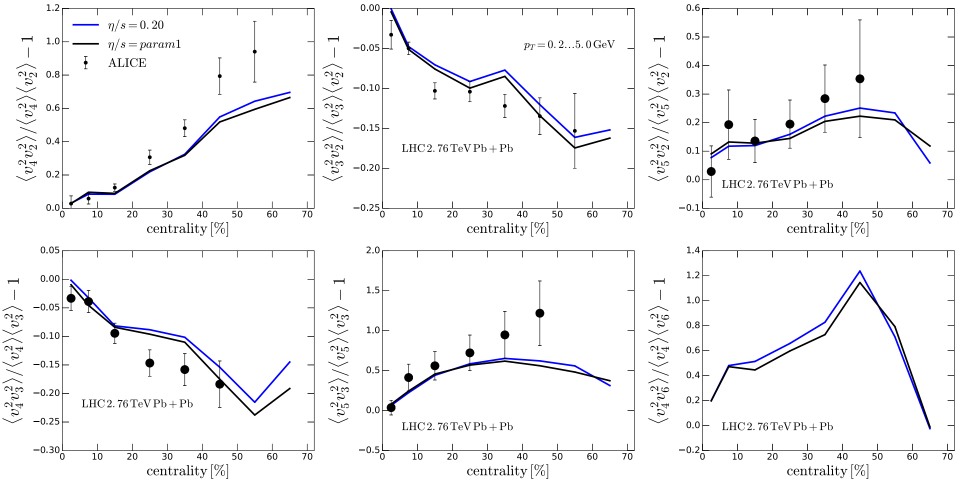

Fig. 2. The normalized symmetric cumulants in 2.76 TeV Pb+Pb collisions. The data are from Ref. [17].

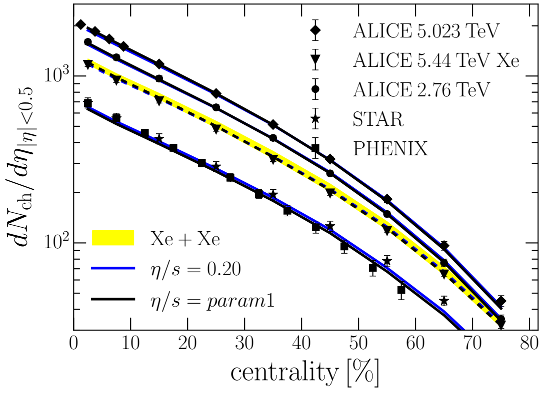

Fig. 3. Centrality dependence of the charged hadron multiplicity. The experimental data are from ALICE [20, 21, 22], STAR [23] and PHENIX [24].

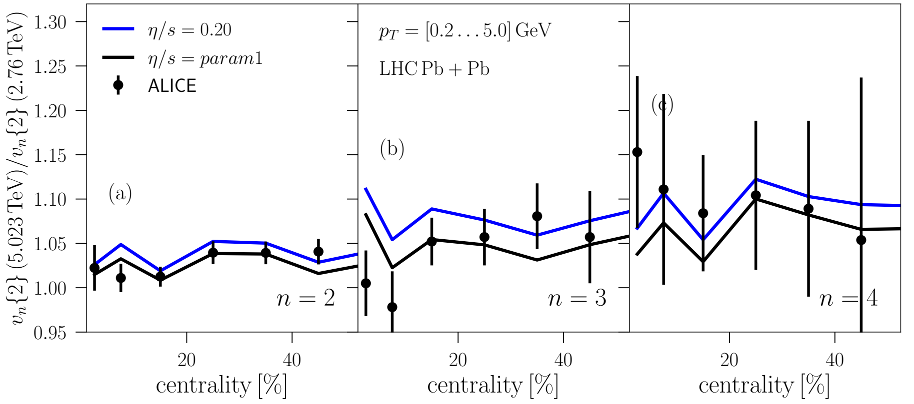

Fig. 4. The ratio of v_n between 2.76 TeV and 5.023 TeV Pb+Pb collisions. The data are from Ref. [25].

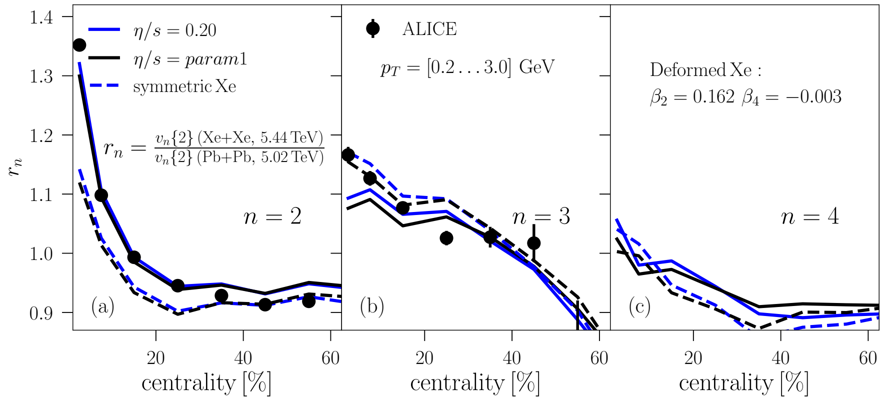

Fig. 5. The ratio of v_n between 5.023 TeV Pb+Pb and 5.44 TeV Xe+Xe collisions. The data are from Ref. [26].

As a conclusion, we have demonstrated that our framework of EKRT initial conditions together with the dissipative fluid dynamical evolution describes a large class of low-p_T observables in a wide range of collision energies. Especially, we have shown that once the framework is fixed at 200 GeV Au+Au and 2.76 TeV Pb+Pb collisions, we can predict the $\sqrt{s}$ and A dependence of the soft observables and describe all these systems with the same $\eta/s(T)$, which is a necessary requirement to demonstrate a fluid dynamical behavior. In particular, the measurement of the Xe+Xe collisions is a very good test of the A dependence of the initial particle production and fluid dynamical behaviour. The measured v_n show exactly the behaviour we expect from the fluid dynamical response to the modified geometry due to the nuclear deformations.

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