Confronting hydrodynamic predictions with Xe-Xe data

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Abstract

Comparing collision systems of different size, at near the same collision energy, offers us the opportunity to probe the scaling behavior and therefore the nature of the system itself. Recently, we made predictions for Xe-Xe collisions at 5.44 TeV using viscous hydrodynamic simulations, noting that the scaling from the larger Pb-Pb system is rather generic, and arguing that robust predictions can be made that do not depend on details of the model. Here we confront our predictions with measurements that were subsequently made in a short Xe-Xe run at the LHC by the ALICE, ATLAS, and CMS collaborations. We find that the predictions are largely confirmed. Of particular interest is a strong indication of a non-spherical shape for the ^{129}Xe nucleus.

Keywords: Quark-Gluon Plasma, Hydrodynamics, Flow

1. Introduction

In the standard picture of a heavy-ion collision, the system evolves as a relativistic fluid for a significant part of its lifetime. Experimental data show many generic (qualitative and quantitative) features supporting this picture, and hydrodynamic simulations have successfully described and predicted a large set of observables. Nevertheless, it is important to take advantage of every opportunity to test this standard picture as strictly as possible. This can be accomplished by changing aspects of the system, such as selecting events for collision centrality and changing the collision energy.

Of particular interest is the scaling of results with system size. Recent measurements from small collision systems (such as p-p, p-A, d-A, and ^{3}He-A) show many features that are similar to the largest collision systems. This has lead to a vigorous debate about the nature of small collision systems as well as large, and the limits of validity of the equations of hydrodynamics.

A natural way to address these questions is to perform collisions of intermediate size and verify whether the scaling is as predicted from the generic properties of hydrodynamic evolution. To this end a short run was performed at the Large Hadron Collider using ^{129}Xe beams at $\sqrt{s_{NN}} = 5.44$ TeV, bridging the gap between the larger system of ^{208}Pb-^{208}Pb and smaller systems p-p and p-^{208}Pb, which have been studied at almost the same energy (5.02 TeV).

In Ref. [1] we made predictions for the upcoming Xe-Xe results, focusing on observables that probe generic scaling properties of the standard hydrodynamic picture (rather than those which depend on unknown parameters and model details), to test the nature of the collision system and whether system size scaling deviates from hydrodynamic expectations.

Additional predictions and comparisons were made using another hydrodynamic model in Refs. [2, 3].

2. Hydrodynamic scaling predictions and comparison to measurement

Simulations were carried out for both Pb-Pb and Xe-Xe collisions using the 2+1 dimensional code v-USPhydro [4, 5], assuming longitudinal boost invariance. Initial conditions are given by the T$_R$ENTo [6] model with parameters $p = 0$, $k = 1.6$, $\sigma = 0.51$ fm, which provide the initial entropy density at an initial time of $\tau = 0.6$ fm. The initial transverse flow and viscous tensor are assumed to vanish. Hydrodynamic evolution is carried out with shear viscosity $\eta/s = 0.047$ and lattice QCD equation of state PDG16+/2+1[WB] [7] until freeze out at $T = 150$ MeV, followed by the decay of unstable resonances. Nuclear shape parameters for the ^{129}Xe nucleus taken from Ref. [8].

A baseline expectation is scale-invariance, due to the scale invariance of the equations of ideal hydrodynamics. In this baseline picture, intensive quantities such as the mean transverse momentum and the various integrated flow observables v_n should be equal in the larger (Pb) an smaller (Xe) systems. Various effects break this scaling, but they can be understood as corrections to the scale-invariant baseline. The mean transverse momentum, for example, is expected to change very little (less than 2%)[1] [1]. Flow measurements are instead expected to change more, due to the following effects.

Fluctuations in the initial state, instead of being scale invariant, are expected to scale as $A^{-1/2}$. This results in an expected *increase* in the smaller system of $(129/208)^{-1/2} \sim 1.27$, which is verified in calculations of triangularity ϵ_3[1]. However, the hydro response to the initial spatial anisotropy v_3/ϵ_3 is also modified due to viscous effects, which are greater in the smaller system[2]. Overall, these effects combine for a predicted increase in v_3 in Xe-Xe collisions of approximately 15% in central collisions, and a *decrease* of ~10% in collisions at 50–60% centrality. Measurements of $v_3\{2\}$ were made subsequently by the three major LHC experiments and are presented along with our prediction in Fig. 1b. There is some disagreement between experimental measurements, but overall the prediction is quantitatively validated, indicating that the expected hydrodynamic scaling is present and also that the viscous effects in our calculation are of a realistic size. A similar prediction was made for v_4, which is compared to preliminary results from the CMS and ATLAS collaborations in Fig. 1c.

Elliptic flow is generated not only from fluctuations in the initial stages of a collision, but also by the average geometry of the nuclear overlap region. In non-central collisions, the latter is the dominant effect, and so a significant increase in eccentricity ϵ_2 is not expected. Instead, increased viscous effects (plus a slightly less sharp nuclear skin) predict a small decrease of v_2, in agreement with subsequent measurements, as seen in Fig. 1a. In contrast fluctuations are important for central collisions. Besides increased fluctuations due to the smaller size, the Xe system may exhibit additional elliptic flow fluctuations because of a non-spherical nuclear shape. Such a deformation has not yet been observed in this isotope, but interpolation from nearby isotopes and theoretical calculations suggest that it should be present. An observation of nuclear structure properties such as this in a heavy-ion collision would be very interesting. Indeed, measurements of $v_2\{2\}$ indicate a strong increase for central collisions (see Fig. 1a), as predicted for a deformed nucleus (but not for a spherical nucleus) [1]. We know of no other explanation for this distinct dependence on centrality, and given the overall agreement with other harmonics and other centralities, we take it as strong evidence of a deformed ^{129}Xe nucleus.

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[1]A measurement of $\langle p_T \rangle$ was presented by the ALICE collaboration in Ref. [9], but the result is under revision and we were asked not to compare to the current result.

[2]Note that here, "viscous effects" refers not only to the value of viscosity in the Quark-Gluon-Plasma phase of hydrodynamic evolution, but also effects such as freeze out that are present even when viscosity is negligible near the transition temperature. All such effects are expected to be larger for systems of smaller size
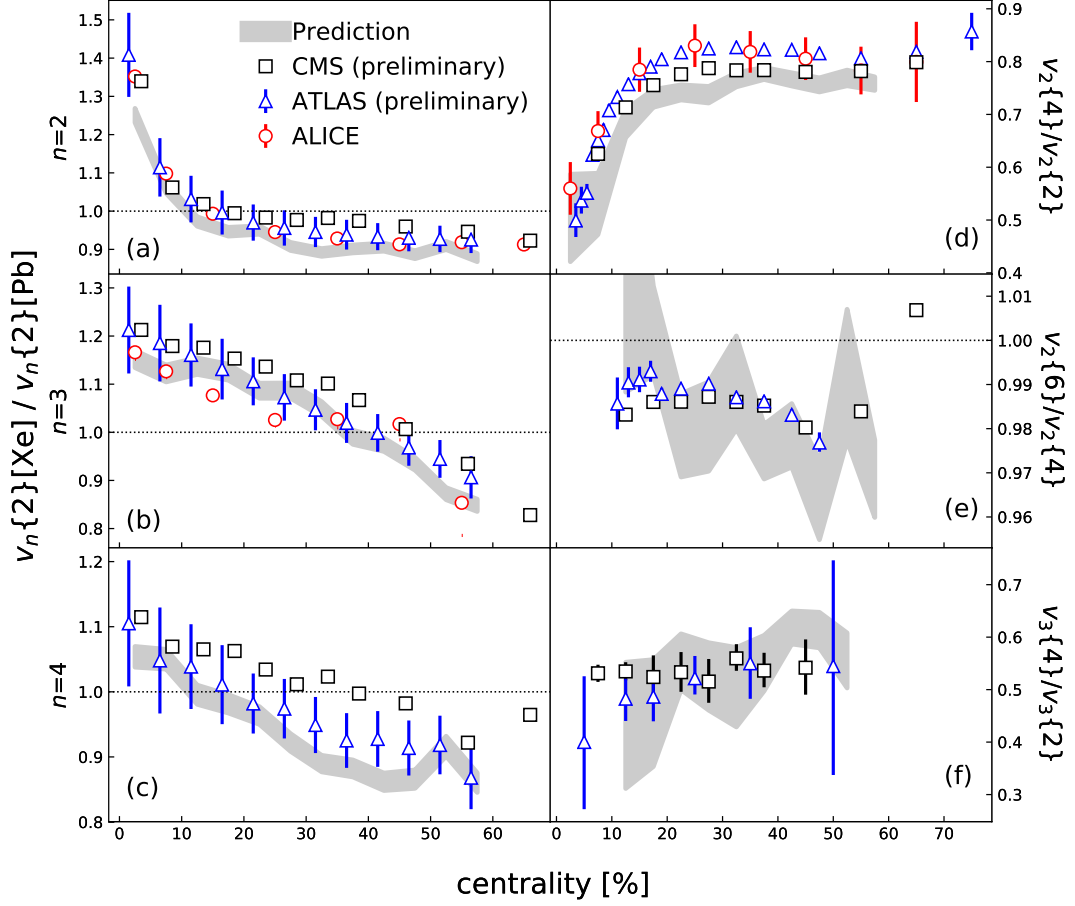
Fig. 1. Hydrodynamic predictions (gray bands) compared to measurements from ALICE (circles) [10] and preliminary measurements from ATLAS (triangles) [11], and CMS (squares) [12]. Shown on the left is the ratio of charged hadron $v_n\{2\}$ as measured in Xe-Xe collisions divided by that in Pb-Pb collisions for v_2 (a), v_3 (b), and v_4 (c). For readability CMS points are shifted to the right 1% and ATLAS to the left 1%. On the right are the ratio of charged hadron cumulants $v_2\{4\}/v_2\{2\}$ (d), $v_2\{6\}/v_2\{4\}$ (e), and $v_3\{4\}/v_3\{2\}$ (f) in Xe-Xe collisions

Cumulants of more than 2 particles are also of interest. These observables provide additional information about fluctuations in the system. For example, the ratio $v_2\{4\}/v_2\{2\}$ is directly related to the variance of the event-by-event distribution of v_2^2 — when there are no event-by-event fluctuations, the ratio is 1, but is reduced as the magnitude of fluctuations is increased. As such, we expect this ratio to be smaller in the Xe system compared to the Pb system. This prediction was also verified by recent measurements, as seen in Fig. 1d. (Note that our model has a ratio that is slightly too small in both systems, but the predicted change with system size is expected to be more robust, and is indeed correct). Similarly, preliminary data for the ratio $v_2\{6\}/v_2\{4\}$, shown in Fig. 1e, are in excellent agreement with our predictions, and they satisfy the expected scaling between Pb-Pb and Xe-Xe, in the sense that the deviation of this ratio from unity is larger in Xe-Xe systems. Since the degeneracy of higher-order cumulants is driven by nearly Gaussian v_2 fluctuations in presence of an almond shape of the collision zone [13], one naturally expects Xe-Xe collisions, where

fluctuations are larger and geometry is less sharp, to present a coarser splitting of higher-order cumulants. Finally, our prediction for the ratio $v_3\{4\}/v_3\{2\}$, shown in Fig. 1f, is in good agreement with preliminary data, though with larger error bars. No significant difference between Pb-Pb and Xe-Xe is observed for this observable.

3. Conclusions

Hydrodynamic calculations were made for Pb-Pb and Xe-Xe collision systems, in order to make predictions for the smaller Xe system and systematically test the hydrodynamic paradigm via the scaling of observables with system size. Here we compare to subsequent measurements, showing good agreement and a validation of the standard hydrodynamic picture across both systems.

A particular interesting result is the strong increase of $v_2\{2\}$ in central collisions in the Xe system compared to the Pb system, which is a distinct indication of non-spherical shape for the ^{129}Xe nucleus. Though a deformed shape was expected, LHC data provide the first experimental evidence, and this is arguably one of the most interesting and important results from the Xe-Xe run.

4. Acknowledgments

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