The impact of nuclear deformation on relativistic heavy-ion collisions: assessing consistency in nuclear physics across energy scales

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In the hydrodynamic framework of heavy-ion collisions, elliptic flow, $v_2$, is sensitive to the quadrupole deformation, $\beta$ of the colliding ions. This enables one to test whether the established knowledge on the low-energy structure of nuclei is consistent with collider data from high-energy experiments. We derive a formula based on generic scaling laws of hydrodynamics to relate the difference in $v_2$ measured between collision systems that are close in size to the value of $\beta$ of the respective species. We validate our formula in simulations of $^{238}\text{U}+^{238}\text{U}$ and $^{197}\text{Au}+^{197}\text{Au}$ collisions at top Relativistic Heavy Ion Collider (RHIC) energy, and subsequently apply it to experimental data. Using the deformation of $^{238}\text{U}$ from low-energy experiments, we find that RHIC $v_2$ data implies $0.16 \lesssim |\beta| \lesssim 0.20$ for $^{197}\text{Au}$ nuclei, i.e., significantly more deformed than reported in the literature, posing an interesting issue in nuclear phenomenology.

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a. Introduction. The hydrodynamic modeling of the quark-gluon plasma (QGP) formed in relativistic heavy-ion collisions is a precision tool to understand the wealth of measurements obtained at the BNL Relativistic Heavy Ion collider (RHIC) and at the CERN Large Hadron Hadron Collider (LHC) [1–7]. The success of this framework is largely based upon a correct description of the initial condition of the QGP prior to its dynamical expansion [8]. One does in general expect that such initial condition is impacted by the quadrupole deformation of the colliding ions [9–12]. This has been demonstrated in particular by recent flow data in $^{238}\text{U}+^{238}\text{U}$ collisions at RHIC [13]. In principle, the uncertainty brought by this observation to the overall picture should be under control, as the structure of nuclear ground states is well constrained by nuclear experiments at low energy, and one may assume that the structure probed at colliders on ultra-short time scales of order $10^{-24}\text{s}$ is the same. For an unbiased interpretation of high-energy data, it is crucial to check whether this is indeed the case, i.e., that the manifestations of nuclear deformation at high energy are consistent with the expectations from low-energy physics.

The majority of nuclei are deformed in their ground state, presenting an intrinsic quadrupole moment in their mass distribution, $\int |\beta|^2 Y_{20}\rho(r) \neq 0$. Experimentally [14, 15], the deformation of an (even-even) nucleus of mass number $A$ and charge $Ze$ is quantified by $\beta = \frac{4\pi}{3ZeR_0^3}\sqrt{B(E2)}/f$, where $R_0 = 1.2A^{1/3}$, and $B(E2)$ is the isospin transition probability of the electric quadrupole operator from the ground state to the first $2^+$ state. Nearly spherical nuclei, such as $^{208}\text{Pb}$, have $\beta \approx 0$, while well-deformed nuclei, like $^{238}\text{U}$, have $\beta \approx 0.3$.

In heavy-ion collisions, deformed nuclei are modeled through 2-parameter Fermi (2pF) mass densities: $\rho(r) \propto (1 + \exp[(r - R_0(1 + \beta Y_{20}))/\omega_0])^{-1}$, with the value of $\beta$ taken (up to small corrections [16]) from low-energy experiments. Colliding randomly oriented deformed nuclei impacts the initial state of the QGP, enhancing in particular the fluctuations of its ellipticity [12], $\varepsilon_2$, determined by the transverse positions $(r, \phi)$ of the participant nucleons $\varepsilon_2 = \sum r^2 \cos^2(\theta)/\sum r^2$ [17]. In hydrodynamics, $\varepsilon_2 = 0$ yields an elliptical imbalance in the pressure-gradient forces [18] that drive the expansion of the QGP. This pressure imbalance results in a $\cos(2\phi)$ modulation of the azimuthal distribution of detected hadrons, $dN/d\phi \propto 1 + 2v_2 \cos(2\phi)$, where $v_2$ is the elliptic flow coefficient [19]. In hydrodynamic calculations [20], $v_2$ emerges indeed as a response to the initial eccentricity, $v_2 = k_2\varepsilon_2$, so that $\beta = 0$ in the colliding nuclei leads to enhanced fluctuations of the observed $v_2$.

In this Letter, we address the question of whether the values of $\beta$ found in low-energy literature are consistent with $v_2$ data at high energy. We introduce a simple method to do so, and argue that, at present, the sought consistency of nuclear experiments across energy scales is not achieved.

b. Relating $v_2^2$ to the quadrupole deformation. The idea is to compare systems that are close in size. As we show in the next section, the dependence of the mean squared (ms) elliptic flow on $\beta$ is the following:

$$v_2 \{2\}^2 \equiv \langle v_2^2 \rangle = a + b\beta^2. \tag{1}$$

where averages are performed over events in a narrow centrality class, and the physical meaning of the coefficients $a$ and $b$ will be clarified below. Given two collision systems $X+X$ and $Y+Y$, we introduce the following quantities [the subscript $X(Y)$ indicates a quantity evaluated in $X+X(Y+Y)$ collisions]:

$$r_{x}\equiv \langle v_2^2 \rangle_x, \quad r_{y} = \frac{b_{y}}{b_{x}}, \quad r_{a} = \frac{a_{x}}{a_{y}}, \quad r_{y} = \frac{b_{y}}{a_{y}}. \tag{2}$$

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With these definitions and Eq. (1), we can express the quadrupole deformation parameter of species \( Y \), \( \beta_X^2 \), as a linear function of \( \beta_X^2 \),

\[
\beta_X^2 = \left( \frac{r_X^2 r_a - 1}{r_Y} \right) + \left( r_X r_b \right) \beta_X^2.
\]  

(3)

The ratios \( r_b, r_a, r_Y \) can be reliably predicted in hydrodynamics, so that Eq. (3) can be used to verify the consistency of data from nuclear experiments at different energy scales. Specifically, in hydrodynamics we expect:

- The coefficient \( b \) in Eq. (1) quantifies how efficiently the fluctuations in the global geometry due to the deformed, randomly oriented nuclear shapes are converted into fluctuations of elliptic flow. The contribution of the term \( b \beta^2 \) to the ms \( \nu_2 \) in Eq. (1) is thus of the same nature as the contribution from the so-called elliptic flow in the reaction plane \( \nu_2, \nu_3 \) to the ms \( \nu_2 \) in collisions of spherical nuclei. At a given collision centrality, the relative contribution of \( \nu_2, \nu_3 \) to the ms \( \nu_2 \) varies very slowly with the mass number, therefore, if \( X \) and \( Y \) are large systems, we expect \( r_b \approx 1 \).

- The coefficient \( a \) in Eq. (1) corresponds to ms \( \nu_2 \) in the absence of deformation. Therefore, \( a \) in central collisions is the \( \nu_2 \) originating solely from fluctuations, e.g., in the positions of the participant nucleons. This quantity scales with the inverse mass number, \( 1/A \), and an additional factor from viscous damping. Considering \( \beta_X = \beta_Y = 0 \) and \( \nu_2 / \nu_3 \) is an even function of \( \eta \), where \( \eta \) is an even function of \( \frac{\nu_2}{\nu_3} \), \( \eta \approx \frac{\nu_2}{\nu_3} \).

Recent state-of-the-art hydrodynamic simulations [25] report however a slightly smaller damping, reflected by a larger coefficient, \( 0.57 \sim 5/9 \), in the rhs of Eq. (5). Now, since \( \nu_2 \) is not affected by the deformation of the colliding ions [see Fig. 1(b)], we can estimate the variation of the \( a \) coefficient in Eq. (1) (i.e., the variation of \( \nu_2 \) in the case \( \beta = 0 \)) from the variation of the mass number and the experimentally measured variation of \( \nu_2 / \nu_3 \):

\[
r_b - 1 = \frac{\Delta a}{a} = (1 - x) \frac{\Delta (1/A)}{1/A} + x \frac{\Delta \nu_2^2}{\nu_2^2}, \quad x \approx \frac{4}{9},
\]  

(6)

- The ratio \( r_Y \) is a property of a single collision system, and has to be evaluated through an explicit calculation. Its value is however largely model-independent, as we explain in the next section.

Wrapping up, Eq. (3) relates the deformation parameters of two ions close in size to the ratio of elliptic flow coefficients. The ratios \( r_b, r_a, r_Y \) are properties of the hydrodynamic description, and can be predicted by generic scaling laws, as we now demonstrate through numerical calculations.

**c. Numerical validation.** To gather the huge statistics of events required to constrain observables in central collisions, we employ the multi-phase transport model (AMPT) as a proxy for hydrodynamics. This model has proven successful in describing collective flow data in small and large collision systems at RHIC and LHC [26–29]. AMPT starts with a Glauber Monte Carlo calculation [30], which determines event-to-event the collision impact parameter and participant nucleons, \( N_{\text{part}} \). The system evolution is modeled with strings that first melt into partons, followed by elastic partonic scatterings, which engender the hydrodynamic collectivity, followed by parton coalescence and hadronic rescattering. We use AMPT v2.5.6 in string-melting mode, and a partonic cross section of 3.0 mb [29, 28], which gives a reasonable description of \( ^{197}\text{Au}+^{197}\text{Au} \) \( \nu_2 \) data at RHIC. We simulate 238\text{U}+238\text{U} collisions at \( \sqrt{s_{\text{NN}}} = 193 \text{ GeV} \) with \( \beta = 0, 0.15, 0.22, 0.5, 0.34, 0.4 \), as well as \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \) \( ^{197}\text{Au}+^{197}\text{Au} \) collisions implementing \( \beta = 0, -0.13 \). We emphasize that this is the first such calculation, where one systematically scans over several \( \beta \) values, ever performed. The 2pF parameters for the colliding ions are taken from the fits of their nuclear charge densities [31]. We use hadrons with \( 0.2 < p_T < 2 \text{ GeV} \) and \( |y| < 2 \), and define the event centrality from either \( N_{\text{part}} \) or the charged hadron multiplicity, \( N_{\text{ch}} \), in the window \( |y| < 1 \).

Figure 1 shows \( \nu_2^2 \) and \( \nu_3^2 \) as functions of \( N_{\text{part}}/2A \), as well as the corresponding \( \nu_2^2 \) and \( \nu_3^2 \) in the inset panels. We note a strong dependence of \( \nu_2 / \nu_3 \) on the value of \( \beta \) in central collisions, whereas \( \nu_2 / \nu_3 \) is independent of \( \beta \). The \( \nu_2 \) values are similar between \( \beta = 0.28 \) and \( \beta = -0.28 \), confirming that \( \nu_2 \) is an even function of \( \beta \).

1 Although in extremely central collisions, say \( 0-0.2\% \), we found \( \nu_2(\beta = -0.28) > \nu_2(\beta = 0.28) \) and \( \nu_2(\beta = -0.28) < \nu_2(\beta = 0.28) \).
These features are present as well in the curves of the $\la v_2^2 \ra$, demonstrating the geometric origin of $v_2$ in our simulations. We note that the value of $\la v_2^2 \ra$ is larger in $^{197}$Au+$^{197}$Au collisions, due to the smaller A.

Figure 2 shows that $\la v_2^2 \ra$ is indeed linear in $\beta^2$, in agreement with Eq. (1). The calculation is performed for different centrality classes (defined from the distribution of $N_{ch}$), showing that the linear relation is valid even in non-central collisions. To emphasize the geometric origin of this result, we show that $\la v_2^2 \ra$ is also linear in $\beta^2$:

$$\langle v_2^2 \rangle = a' + b' \beta^2.$$  \hspace{0.5cm} (7)

Figure 3 shows the centrality dependence of $r_b$, $r_n$, and $r_Y$ ($X = ^{197}$Au, $Y = ^{238}$U), and demonstrates explicitly the points made in the previous section.

Figure 3(a) shows $r_b = b_X/b_Y$, and confirms the expectation that this quantity should be close to unity. This is a geometric effect. We find indeed that plotting $r_b'$, obtained from the linear fits of $\langle v_2^2 \rangle$ across centrality, yields a dependence which is essentially identical to that of $r_b$, implying a minor role of the hydrodynamic response.

Figure 3(b) shows $r_n = a_X/a_Y$ as a function of centrality. The hydrodynamic expectation given by Eq. (6), is shown as a line for the most central bins. The agreement with the calculated $r_n$ is excellent in the 0–1% bin, confirming our arguments. The result is $r_n = 1.18$ with $\Delta(1/A) / 1/A = 0.21$, $x = 4/9$ in Eq. (6) and $\Delta \langle v_2^2 \rangle / \langle v_2^2 \rangle = 0.136$ from AMPT in the 0–1% bin. We have checked that the estimated value of $r_n$ reduces only by $\sim 1\%$ if a larger coefficient $x = 5/9$ is used, showing that the uncertainty on the precise magnitude of the viscous correction does not affect our analysis. Once more, $r_n'$ in Fig. 3(b) calculated from the eccentricity shows the same centrality dependence, indicating that the hydrodynamic response yields only a global rescaling factor close to unity.

Figure 3(c) shows $r_U = a_{U}/a_{Y}$, which is 25.6 in the 0–1% bin. We argue that this is a generic prediction of hydrodynamics, and not of our specific setup. From Eq. (1), and considering $v_2 U \{2\}^2 = \kappa_2^2 v_2 U \{2\}^2$ at fixed centrality, one can write

$$r_U = \frac{d \ln v_2 U \{2\}^2}{d \beta^2} \bigg|_{\beta^2=0} = \frac{1}{\kappa_2^2(\beta^2 = 0)} \frac{d \ln v_2 U \{2\}^2}{d \beta^2}$$

$$+ \frac{1}{\varepsilon_2 U \{2\}^2(\beta^2 = 0)} \frac{d \varepsilon_2 U \{2\}^2}{d \beta^2}.$$  \hspace{0.5cm} (8)

Now, $d \ln \beta^2 / d \beta^2$ is determined by how an increase in system size due to $\beta$ modifies the hydrodynamic response. This is dictated by generic scaling laws, irrespective of the chosen setup. Similarly, from explicit calculations within different initial-state models we find that the variation $d \varepsilon_2 U \{2\}^2 / d \beta^2$ is essentially model-independent. The values of $\kappa_2^2$ and $\varepsilon_2 U \{2\}^2$ evaluated at $\beta^2 = 0$ are, on the other hand, model-dependent. However, if models are tuned such to return the same $v_2 U \{2\}^2$, i.e., the same product $\kappa_2^2 \varepsilon_2 U \{2\}^2$ after hydrodynamics, then any such model dependence would disappear in Eq. (8). The value of $r_U$ appears to be, hence, a solid prediction. That said, Eq. (8) contains $1 / \varepsilon_2 U \{2\}^2(\beta^2 = 0)$, therefore, one expects $r_U$ to present a strong centrality dependence, confirmed by the trends in Fig. 3(c). This engenders an uncertainty from the centrality definition. In particular, repeating these calculations with the centrality defined according to $N_{part}$ instead of $N_{ch}$, we find that $r_U$ increases by about 20%.

In summary, the hydrodynamic expectations on the ratios $r_b$, $r_n$, and $r_Y$ pointed out in the previous section are confirmed by our numerical results. We can thus move on and apply Eq. (3) to existing data from nuclear structure and heavy ion experiments.

\textit{d. Application to RHIC data.} We apply Eq. (3), with $X = ^{197}$Au and $Y = ^{238}$U, to the 0–1% most central
The situation for the odd-even \(208\text{Pb}+\text{U} \) collisions (at the same centralities) by \( \beta \) bigger than in \( 238\text{U}+\text{U} \) collisions, ii) lower than measured in \( 208\text{Pb}+208\text{Pb} \) collisions (at the same centralities) by the ALICE collaboration [38] with nearly identical kinematic cuts. This ordering among systems is naturally explained by \( 197\text{Au} \) being more deformed than \( 208\text{Pb} \) and less deformed than \( 238\text{U} \). However, taking \( \beta = 0.29 \) and \( \beta_B = 0.06 \) from low-energy data [14], we have checked in initial-state calculations that capture well the ratios of \( v_n/\langle p_T \rangle \) correlations between different systems [39] that the magnitude of the deviations observed experimentally cannot be explained with \( |\beta| = 0.1 \), while implementing \( |\beta| = 0.2 \) improves dramatically the agreement with data. These results will be reported in future work.
Conclusion and outlook. Anisotropic flow in high-energy nuclear collisions emerges as a dynamical response of the QGP to its initial spatial anisotropy. The latter is affected by the geometric shape of the colliding nuclei, leading to an intrinsic connection between the phenomenology of heavy-ion collisions and the structure of atomic nuclei. Matching high-energy data to low-energy expectations, we assess if our knowledge of nuclear physics across energy scales leads to consistent results.

We have attempted to do so for 0–1% Au + Au data points to a deformation of 197Au larger than found in low-energy literature.

Further efforts are required to elucidate this issue. At low energy, what is missing is the evaluation of the structure properties of 197Au in a state-of-art theoretical framework, such as that of Ref. [42]. This would reduce the spread of the $\beta_{\mathrm{Au}}$ interval in Fig. 4. At high energy, one should repeat our analysis on more collision systems. We do not have yet AMPT results for 129Xe + 129Xe collisions. The ALICE Collaboration reports [40] a large ratio $v_2^a = \langle v_2^a \rangle_{Xe}/\langle v_2^a \rangle_{Pb} \approx 2.56$. We do not have yet AMPT results for 129Xe + 129Xe collisions, however, we have checked via the initial-state calculations of Ref. [12] that $b_{Xe} \approx b_{Pb}$ and $\alpha_{Xe} \approx (238/129) \alpha_{Pb}$. The logic of the present discussion should apply, i.e., $\beta_{Xe} \approx \beta_{Pb}$, $\delta_{Xe} \approx (238/129) \delta_{Pb}$, so that $\gamma_{Xe} \approx (238/129) \gamma_{Pb}$. Using $v_3 \langle v_2 \rangle_{Xe}/\langle v_2 \rangle_{Pb} = 1.22$ from the CMS Collaboration [41], we obtain $\gamma_{Xe} = \alpha_{Pb}/\alpha_{Xe} \approx 0.64$ from Eq. (6) (increases to 0.65 if $x = 5/9$ is used). With $r_b = 1$ and $\beta_{Pb} = 0.06$ [14] this leads to $\beta_{Xe} \approx 0.24$ via Eq. (3).

Arguably, though, the most efficient way to do so would be collecting data from collisions of even-even species that are close in size but have different and experimentally measured deformation. The ideal candidates for such a study are the stable samarium isotopes, which present a remarkable transition from spherical to well-deformed shapes [43]. One could collide, for instance, $^{144}$Sm, which is essentially as spherical as $^{208}$Pb, $^{148}$Sm, mildly deformed with a triaxial ground state, much as $^{129}$Xe and $^{197}$Au, and $^{154}$Sm, which is a well-deformed nucleus like $^{238}$U. With the ideas introduced in this paper, it would thus be possible to assess from high-energy data if the evolution of $\beta$ along the isotope chain is consistent with the low-energy expectations. Systematic deviations would eventually open deeper physics questions.

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