Constraining the Nucleon Size with Relativistic Nuclear Collisions

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Phys. Rev. Lett. **128**, 042301 — Published 27 January 2022

DOI: 10.1103/PhysRevLett.128.042301

Constraining the nucleon size with relativistic nuclear collisions

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The notion of the "size" of nucleons and their constituents plays a pivotal role in the current paradigm of the formation and the fluctuations of the quark-gluon plasma produced in high-energy nuclear collision experiments. We report on state-of-the-art hydrodynamic results showing that the correlation between anisotropic flow, v_n^2, and the mean transverse momentum of hadrons, $[p_t]$, possesses a unique sensitivity to the nucleon size in off-central heavy-ion collisions. We argue that existing experimental measurements of this observable support a picture where the relevant length scale characterizing the colliding nucleons is of order 0.5 fm or smaller, and we discuss the broad implications of this finding for future global Bayesian analyses aimed at extracting initial-state and medium properties from nucleus-nucleus collision data, including v_n^2-$[p_t]$ correlations. Determinations of the nucleon size in heavy-ion collisions will provide a solid independent constraint on the initial state of small system collisions, and will establish a deep connection between collective flow data in nucleus-nucleus experiments and data on deep inelastic scattering on protons and nuclei.

Fluctuations in the energy density distribution of the quark-gluon plasma (QGP) formed in relativistic nuclear collisions originate mainly from the random position of the nucleons populating the colliding ions at the time of scattering. Model incarnations of such processes require turning the distributions of nucleons participating in the collisions into continuous density profiles serving as initial conditions for the subsequent hydrodynamic expansion of the QGP. To this aim, a nucleon *size* is introduced, describing the transverse extent of nucleons (or their constituents) relevant for high-energy experiments.

Determining the nucleon size is an important experimental problem as the structure of hadrons, shaped by the non-perturbative dynamics of the strong interaction, remains poorly known. The rest-frame proton *charge radius* is precisely measured, and is approximately 0.84 fm [1]. Inelastic scattering at high energy should instead probe a smaller *strong radius*. Analysis of diffractive J/Ψ photoproduction in e^-p collisions suggests that the scale relevant for these processes is a gluon radius of order 0.50 fm [2]. A recent study [3] estimates in addition a proton mass radius around 0.55 fm from the threshold photoproduction of vector mesons.

For about 15 years following the discovery of the importance of initial-state fluctuations in the phenomenology of heavy-ion collisions [4], hydrodynamic simulations of the QGP have modeled the transverse profiles of the boosted nucleons via two-dimensional Gaussians of width $w \approx 0.4$ fm. The corresponding root mean square radius is $\sqrt{\langle r^2 \rangle} = \sqrt{2}w \approx 0.56$ fm, consistent with the above estimates. These calculations culminated in the first global Bayesian analysis of Pb+Pb data performed by the Duke group in 2016 [5], implementing the T$_\text{R}$ENTo model [6] for the entropy density of the QGP at the beginning of hydrodynamics, which returns a high-probability [or Maximum A Posteriori (MAP)] nucleon width parameter around 0.45 fm. In addition, a quantitative description of experimental data has been achieved over the past decade from hydrodynamic simulations implementing the IP-Glasma initial condition model based on the color glass condensate effective theory [7]. IP-Glasma employs nucleon sizes consistent with the gluon radius constrained from HERA data [2, 8], namely, a nucleon width of 0.4 fm, albeit with sub-nucleonic constituents of width $w_q = 0.11$ fm, inferred from incoherent J/Ψ production [9, 10].

This consistent state of affairs took a sudden turn in 2019. The second analysis of the Duke group [11], where the T$_\text{R}$ENTo model is used for the QGP energy density (as opposed to the entropy density) at $\tau = 0^+$, returns a MAP $w = 0.96$ fm, doubling the previous estimate. The origin of such finding is, at present, unknown. It has been confirmed recently by the Bayesian analyses of the JETSCAPE collaboration [12, 13] and of Parkkila *et al.* [14, 15], which return $w = 0.8$-1.1 fm from Pb+Pb data. Furthermore, global analyses of Pb+Pb and also p+Pb data have been performed with the inclusion of sub-nucleonic constituents, characterized by an auxiliary width, w_q, in the T$_\text{R}$ENTo model, both by the Duke group [16], and within the Trajectum framework [17–19]. These calculations also find diffuse nucleons, $w = 0.8$-0.9 fm, albeit with $w_q \approx 0.4$ fm.

Hydrodynamic results within the above-mentioned frameworks return similar final-state observables, meaning that there are stark inconsistencies in current implementations of the nucleon size. While observables that probe the initial condition of the QGP, such as relative flow fluctuations [20, 21], are known and routinely employed in hydrodynamic studies, obtaining a focused sensitivity to nucleon size is a more difficult problem. Flow coefficients, v_n, offer the largest sensitivity to the nucleon width parameter [13, 19], however, other parameters affect v_n in a similar way, most notably QGP transport coefficients. Apart from improving existing constraints on the initial condition, and permitting us to use heavy-ion collisions to probe hadron structure, finding an observable strongly sensitive to the nucleon size, and only weakly to medium parameters, would, thus, overcome the degenerate impact on v_n of nucleon width and transport coefficients, leading to improved constraints on the temperature dependence of the latter. In the literature there are, in particular, inconsistent implementations of the specific bulk viscosity, ζ/s, whose magnitude (at its peak) ranges from close to zero [19] to values similar to those characterizing the specific shear viscosity, η/s [7]. The bulk viscous effects developed during the hydrodynamic phase should be connected with the size and the lumpiness of the initial condition, therefore, our understanding of ζ/s may largely benefit from an improved knowledge of the nucleon size.

In this Letter, we show that these goals may be achieved by means of straightforward experimental measurements, as we point out that the correlation between v_n^2 and the mean transverse momentum of the detected hadrons, $[p_t]$, presents a unique sensitivity to the nucleon width in off-central nucleus-nucleus collisions. We argue, in particular, that existing data on this observable constrains the relevant length scales.

We illustrate our point through a simple calculation. We simulate 5.02 TeV Pb+Pb collisions by means of the T$_\mathrm{R}$ENTo model of initial conditions, with an entropy density of the form

$$s(x) \propto \left(\frac{t_A^p(x) + t_B^p(x)}{2} \right)^{1/p} \Bigg|_{p=0} = \sqrt{t_A(x) t_B(x)}, \quad (1)$$

where x is a transverse coordinate and $t_{A(B)}$ is defined by a superposition of participant densities

$$t_A(x) = \sum_j \lambda_j g(x; x_j, w), \quad (2)$$

where g is a Gaussian centered on the jth participant nucleon, and λ_j is drawn randomly from a Γ distribution of unit mean and variance $1/k$, where k is a positive coefficient. In each event we evaluate also the energy density from the equation of state of high-temperature QCD, $e \propto s^{4/3}$. Centrality classes of width 1% are defined for the simulated events from their entropy. For each centrality, we calculate the correlation between v_n^2 and $[p_t]$ through the Pearson coefficient [22]

$$\rho_n \equiv \rho(v_n^2, [p_t]) = \frac{\langle \delta v_n^2 \delta [p_t] \rangle}{\sqrt{\langle (\delta v_n^2)^2 \rangle \langle (\delta [p_t])^2 \rangle}}, \quad (3)$$

where $\delta O = O - \langle O \rangle$ for any observable O. To estimate Eq. (3) from initial-state quantities, we assume that, on an event-by-event basis, v_n is proportional to the corresponding initial-state anisotropy, ε_n, while $[p_t]$ is proportional to the energy of the system [23]. We leave a default

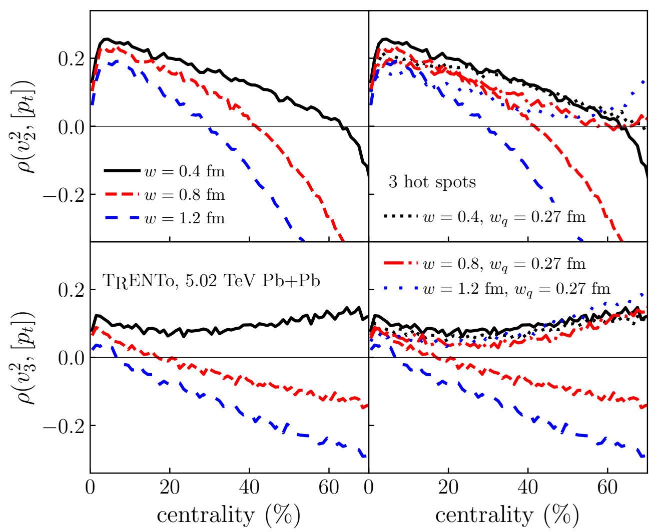

FIG. 1. Estimated $\rho(v_n^2, [p_t])$ in the T$_\mathrm{R}$ENTo model. Left: results for smooth nucleons. Right: results for smooth nucleons, and composite nucleons with 3 hot spots with $w_q = 0.27$ fm. Different line styles correspond to different parametrizations of nucleon structure. Top: $n = 2$. Bottom: $n = 3$.

parameter $k = 1$ (close to that found in Ref. [12]), and choose $w = 0.4,\ 0.8,\ 1.2$ fm.

Our results are displayed in Fig. 1. The panels on the left show dramatic qualitative differences concerning the sign and the centrality dependence of the correlators, depending on the value of w. We note that the same observable has been studied at fixed w and fixed p but varying k in Ref. [24], as well as at fixed w and fixed k but varying p in Ref. [23]. In both cases, effects as dramatic as those found in Fig. 1 are not observed. The panels on the right of the figure present results with the inclusion of nucleon constituents (or hot spots). This amounts to replacing the right hand side of Eq. (2) with $\sum_j \sum_q \lambda_q g(x; x_q, w_q)$, i.e., a sum of Gaussians of width w_q (set to 0.27 fm) centered at x_q, which is the coordinate, within the jth participant, of the qth constituent, sampled from a Gaussian distribution whose width is chosen such that the nucleon is on average a Gaussian of width w. We sample 3 hot spots per participant, and we have checked that using 9 does not change our results significantly. Figure 1 shows, then, that in presence of hot spots it is the scale w_q that determines ρ_n. Note that the results for $w = 0.4$ fm depend only marginally on the nucleon structure, suggesting that reducing further the relevant size has little impact on these observables.

The T$_\mathrm{R}$ENTo estimators capture ρ_n at the end of hydrodynamics, up to a correction induced by the upper p_t cut of the particles from which the observable is evaluated, that resembles a global rescaling of ρ_n across centralities [25–27]. Therefore, we have indeed exhibited an observable with a unique sensitivity to the nucleon (or sub-nucleon) size in nucleus-nucleus collisions.

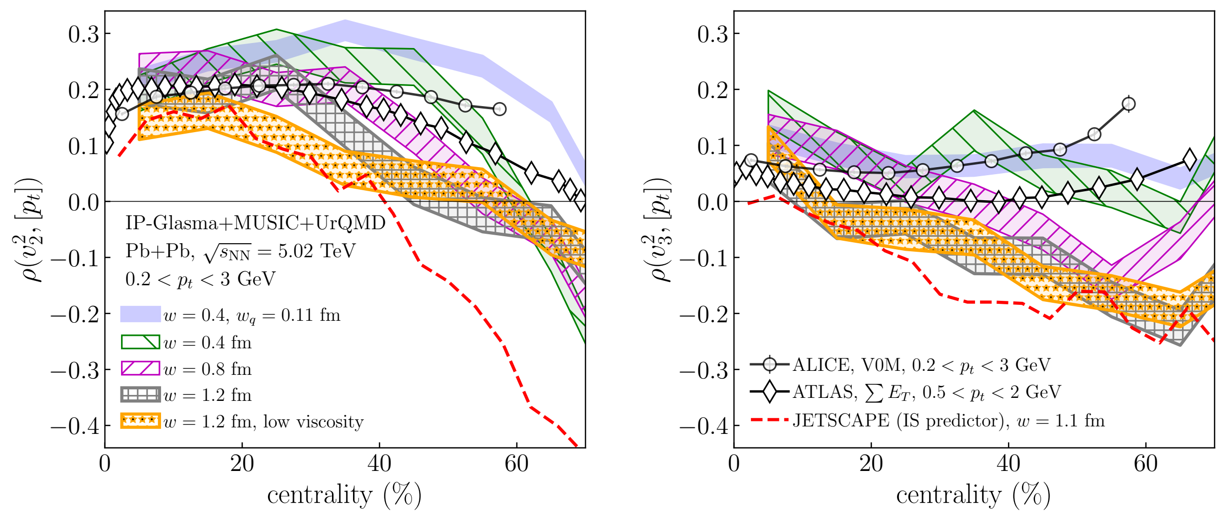

FIG. 2. Results of the IP-Glasma+MUSIC+UrQMD framework for $\rho(v_2^2, [p_t])$ (left) and $\rho(v_3^2, [p_t])$ (right). Different shaded bands correspond to different values of the nucleon width. The orange band with starry hatches corresponds to a calculation with reduced viscosities. The dashed lines are estimators using JETSCAPE initial conditions. Symbols are preliminary ATLAS data [26] (diamonds) for charged particles with $0.5 < p_t < 2$ GeV, $|\eta| < 2.5$ and the centrality defined via $\sum E_T$, and ALICE data [27] (circles) for charged particles with $0.2 < p_t < 3$ GeV, $|\eta| < 0.8$, and the centrality defined via V0M amplitude. We note that the theoretical calculations implement the same p_t cut used by the ALICE collaboration, and that the larger upper p_t cut in the ALICE analysis explains partly the larger ρ_n compared to ATLAS data for non-central collisions.

We demonstrate now that the same conclusion holds in fully-comprehensive hydrodynamic simulations. We perform simulations of Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV in a framework [7] that includes *i*) the pre-hydrodynamic evolution of the created system within the IP-Glasma model [7], *ii*) viscous relativistic hydroydnamic evolution (including shear and bulk viscous corrections) performed with the MUSIC code [28–30], *iii*) a post-hydrodnamic phase of hadron decays and rescattering simulated via UrQMD [31, 32]. Different choices of nucleon structure are implemented. The standard scenario implements nucleons composed of three hot spots of width $w_q = 0.11$ fm [9] whose positions are randomly distributed following a Gaussian of width $w = 0.4$ fm. We have run, in addition, simulations for elementary nucleons with $w = 0.4$, 0.8, and 1.2 fm, rescaling the initial profiles (by a factor 1.2) to yield comparable multiplicities across centralities, as entropy production and the nucleus-nucleus cross section are sensitive to w. Centrality classes of width 1% are defined from the minimum bias midrapidity charged multiplicity, however, as we are limited by statistics we average our results over 10% bins.

Our results are in Fig. 2. They confirm the trends of Fig. 1. For central collisions, the ρ_n coefficients show little sensitivity to the choice of w, while in peripheral collisions they are visibly ordered, following the ordering of the implemented w parameters. This gives a strong indication that these observables are driven by the nucleon size even in fully-comprehensive calculations. We note that ρ_2 for a smooth nucleon with $w = 0.4$ fm differs above 50% centrality from the result including three hot spots, highlighting the impact of the sub-nucleonic structure. The figure reports as symbols experimental data by the ALICE [27] and the ATLAS [26] collaborations. In experiments $\rho_n > 0$ across the considered range of centrality. ALICE data is in fair agreement with the IP-Glasma+MUSIC+UrQMD result implementing $w_q = 0.11$ fm. For peripheral collisions, data is in qualitative disagreement with the calculations implementing $w = 0.8$ fm or larger, and suggests that it is indeed possible to constrain the size of nucleons (or their constituents) from such observations.

To corroborate this point, Fig. 2 shows the initial-state predictor of Fig. 1 where the energy and the entropy of the system are computed following the phase of free streaming of JETSCAPE MAP initial conditions with $w = 1.1$ fm [12]. As expected, this calculation yields a result similar to our $w = 1.2$ fm curve, with the residual differences possibly coming from the different energy-density scaling, namely, $t_A t_B$ in IP-Glasma, and $\sqrt{t_A t_B}$ in TRENTo. This result shows explicitly that, while both the JETSCAPE calculations and IP-Glasma+MUSIC+UrQMD give comparable results for v_n^2 and $[p_t]$, the current JETSCAPE MAP initial condition model leads to v_n^2-$[p_t]$ correlations after hydrodynamics that are quantitatively and qualitatively different from the measured ones. According to our findings, this is due to the large nucleon width inferred by the JETSCAPE collaboration, which is a consequence of considering only up to two-particle correlation observables in the Bayesian analysis. Figure 2 shows as well

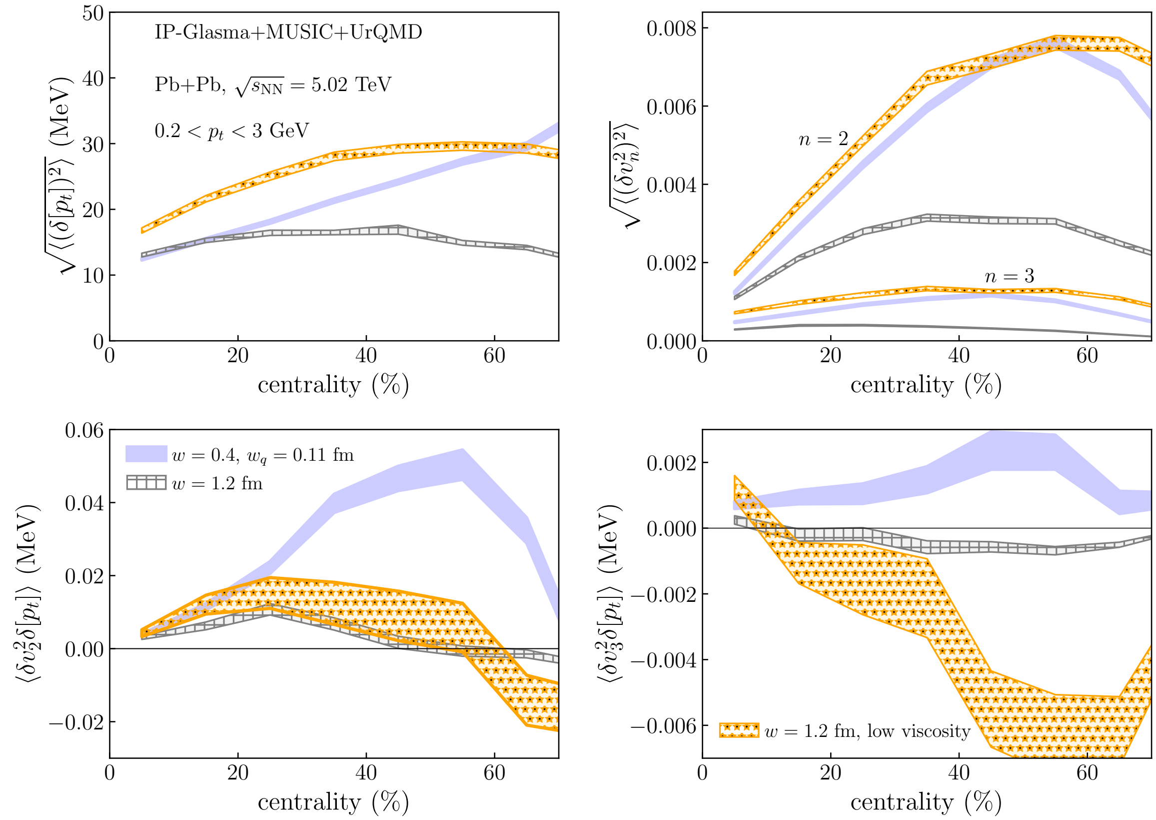

FIG. 3. IP-Glasma+MUSIC+UrQMD results for the components of $\rho(v_n^2, [p_t])$. We show results for composite nucleons with $w = 0.4$ fm plus three hot spots with $w_q = 0.11$ fm (blue shaded band), and smooth nucleons with $w = 1.2$ fm (gray hatched band or orange starry-hatched band for low viscosities). Top-left: standard deviation of $[p_t]$ fluctuations. Top-right: standard deviation of v_n^2 fluctuations. Bottom-left: covariance of v_2^2 and $[p_t]$. Bottom-right: covariance of v_3^2 and $[p_t]$.

results from a low-viscosity run where we set $\zeta/s = 0$ and $\eta/s = 0.02$ (and rescale the initial profiles to account for the loss of viscous entropy production). We find that the ρ_n are largely insensitive to medium effects (see also [33]). Their inclusion in future Bayesian analyses will provide a focused sensitivity to initial-state properties, leading to improved estimates of w (or w_q). On a side note, the ALICE collaboration [27] has recently measured the correlation of three flow observables [34, 35], namely of $[p_t]$, v_2^2, and v_3^2, dubbed $\rho(v_2^2, v_3^2, [p_t])$ [36]. Remarkably, this generalization of ρ_n proves insensitive to initial-state features such as the nucleon size.

To further clarify the results of Fig. 2, we plot in Fig. 3 the components of Eq. (3) for extreme scenarios of nucleon structure, namely, the IP-Glasma model with $w = 0.4$ fm and $w_q = 0.11$ fm, and with diffuse nucleons, $w = 1.2$ fm. The upper panels of Fig. 3 show the quantities in the denominator of Eq. (3). A strong depletion of both v_n^2 and $[p_t]$ fluctuations is observed as one sets $w = 1.2$ fm. Such dependence is however not as spectacular as that found in the bottom panels of the figure, showing the numerator of Eq. (3). Increasing w reduces $\langle \delta v_2^2 \delta[p_t]\rangle$ by orders of magnitude in peripheral collisions, and flips the sign of $\langle \delta v_3^2 \delta[p_t]\rangle$. As argued in Ref. [37], the sign of ρ_2 should turn from positive to negative at large centrality, as soon as the almond shape of the system, induced by the collision impact parameter, is lost, and the geometry is dictated by clusters of participant nucleons. Larger nucleon widths reduce the reaction plane eccentricity of the QGP, therefore, ρ_2 should indeed change sign earlier in centrality if w increases. However, the great impact of w on ρ_3 does not have a clear interpretation. Nucleon structure properties affect two-particle correlation observables, but mainly in peripheral collisions [19]. Our finding that ρ_3 flips sign depending on w for centralities as low as 10% points, thus, to a new type of sensitivity. Results for $w = 1.2$ fm and reduced viscosities are also shown in Fig 3 to highlight the remarkable cancellation of viscous effects in ρ_n.

In summary, ρ_n coefficients represent powerful probes of the nucleon size in nucleus-nucleus collisions. The experimental observation that $\rho_n > 0$ up to 70% centrality suggests a size of order 0.5 fm, in contrast with the findings of state-of-the-art Bayesian analyses. In addition, these observables are remarkably insensitive to viscous corrections, such that their inclusion in future global analyses will constrain both the initial state of the QGP and its transport properties. Computationally, this requires a nontrivial effort. The blue shaded bands in Fig. 2 are obtained from 30k minimum bias collisions, a very high number in the context of Bayesian analyses, though not prohibitively high. We note, in particular, that the analyses of Refs. [14, 15] include symmetric cumulants, i.e., more statistics-hungry 4-particle correlations.

In addition, our results indicate that as soon as nucleons are described in terms of their constituents, the ρ_n coefficients become fully sensitive to the size of such constituents. Therefore, even if the notion of nucleon size in heavy-ion collisions will be replaced in the future by a more fundamental sub-nucleonic scale, the relevance of our analysis will endure. The possibility of exploiting the hydrodynamic framework of heavy-ion collisions to constrain nucleon structure has two far-reaching implications. First, it allows one to gauge the geometry of small systems, e.g. p+Pb collisions, from the analysis of large systems alone, which are more robustly understood [19]. Second, it permits one to assess the consistency of different determinations of the nucleon and sub-nucleon scales relevant to inelastic processes at high energy in different kinds of experiments, such as electron-ion collisions at the future Electron-Ion Collider.

We thank Wilke van der Schee and You Zhou for useful discussions related to the present topic. G.G. is funded by DFG (German Research Foundation) Project-ID 273811115 SFB 1225 ISOQUANT. B.P.S. and C.S. are supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under DOE Contract Nos. DE-SC0012704 and DE-SC0021969, respectively. C.S. acknowledges a DOE Office of Science Early Career Award. This work is in part supported within the framework of the Beam Energy Scan Theory (BEST) Topical Collaboration, and under contract number DE-SC0013460. This research was done using resources provided by the Open Science Grid (OSG) [38, 39], which is supported by the National Science Foundation award #2030508.

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