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Flow in small and large quark-gluon plasma droplets: the role of nucleon substructure

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Abstract

We study the effects of nucleon substructure on bulk observables in proton-lead collisions at the LHC using Bayesian methodology. Substructure is added to the TRENTo parametric initial condition model using Gaussian nucleons with a variable number of Gaussian partons. We vary the number and width of these partons while recovering the desired inelastic proton-proton cross section and ensemble averaged proton density. We then run the model through a large number of minimum bias hydrodynamic simulations and measure the response of final particle production and azimuthal particle correlations to initial state properties. Once these response functions are determined, we calibrate free parameters of the model using established Bayesian methodology. We comment on the implied viability of the partonic model for describing hydrodynamic behavior in small systems.

Keywords: Bayesian, Flow, Initial conditions, Quark-gluon plasma, Small systems

1. Introduction

Recent measurements of azimuthal particle correlations in small collision systems show striking similarities to flow signatures observed in gold-gold and lead-lead collisions, leading many to question if the origin of small system correlations is hydrodynamic in nature. A key difficulty in assessing the model-to-data consistency of hydrodynamic models in light-light and light-heavy collisions is theoretical uncertainty in the QGP initial conditions. In this work, we use established Bayesian methodology [1] to parametrize and constrain the QGP initial conditions in small collision systems in order to infer initial state properties with reduced bias.

The TRENTo initial condition model [2] used in this work parametrizes local nuclear entropy deposition at midrapidity according to a reduced thickness function

$$\left.\frac{dS}{d^2x\,\tau_0\,d\eta}\right|_{\eta=0} \propto \left(\frac{\tilde{T}_A^p + \tilde{T}_B^p}{2}\right)^{1/p}. \tag{1}$$

Here $\tilde{T}$ is the modified participant thickness function $\tilde{T}(\mathbf{x}) \equiv \sum_{i=1}^{N_\text{part}} \gamma_i\, T_p(\mathbf{x}-\mathbf{x}_i)$, where γ_i is a random weight factor sampled from a Gamma distribution with unit mean and fluctuation standard deviation σ_fluct, while T_p denotes the proton thickness function described by a normalized Gaussian distribution with nucleon

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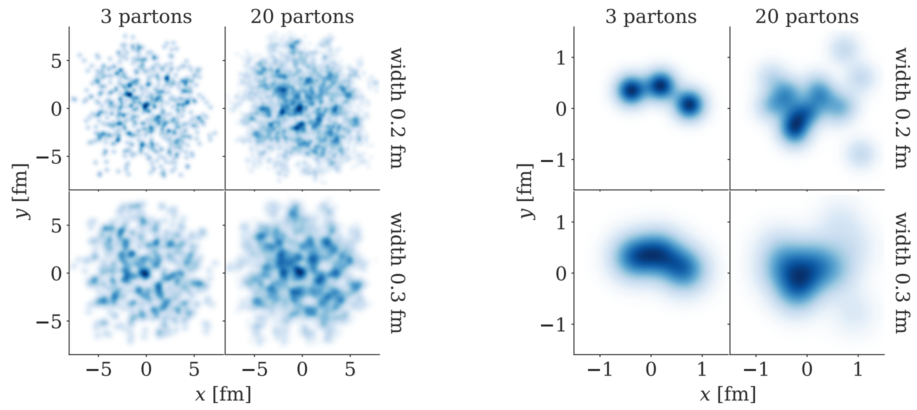

Fig. 1. Nuclear thickness functions T with nucleon substructure for a single lead nucleus (left panel) and proton (right panel) for parton widths $v = 0.2, 0.3$ fm (rows) and parton numbers $m = 3, 20$ (columns).

width w. The exponent p in Eq. (1) is a tunable entropy deposition factor which takes continuous values $p \in (-\infty, \infty)$ and allows the model to mimic various theory calculations [3].

Participant nucleons in the colliding nuclei are first determined according to the pairwise collision probability

$$P_{\rm coll}(b) = 1 - \exp[-\sigma_{gg} T_{pp}(b)], \tag{2}$$

where T_{pp} denotes the proton-proton overlap function, and the cross section parameter σ_{gg} is determined to satisfy the experimentally measured proton-proton cross section $\sigma_{pp}^{\rm inel} = \int d^2b\, P_{\rm coll}(b)$. The participant nucleons in each nucleus are then used to construct the participant thickness functions $\tilde{T}_A$ and $\tilde{T}_B$ which are subsequently passed through the generalized mean in Eq. (1) to furnish the initial transverse entropy density.

2. Nucleon substructure

The generalized mean parameter $p = 0$, which optimally describes charged particle yields and flows in heavy nuclei [3], predicts perfectly Gaussian QGP entropy profiles in high energy proton-proton collisions when the interacting protons are modeled as Gaussians. By construction, such profiles will never drive anisotropic transverse flow and hence could not be used to investigate hydrodynamic behavior in small collision systems where the system size approaches the proton length scale.

One possible solution to resolve the apparent conflict is to replace Gaussian protons with deformed or lumpy protons [4]. In this work, we extend the TRENTo formalism and replace each nucleon with a fixed number of Gaussian partons. The new proton thickness function T_p becomes

$$T_p(\mathbf{x}) = \gamma_i \sum_{i=1}^{N_{\rm partons}} \frac{1}{2\pi v^2} \exp\left[-\frac{(\mathbf{x} - \mathbf{x}_i)^2}{2v^2}\right], \tag{3}$$

where $N_{\rm partons}$ is the number of partons, v is their width, and $\mathbf{x}_i$ the partons' positions which are sampled from a Gaussian distribution of width $r_{\rm parton} = \sqrt{w^2 - v^2}$. The factor γ_i is a Gamma random weight factor as before. Once the nucleon width, parton number, and parton width are specified, we apply Eq. (2) to each pair of partons and flag each corresponding nucleon as a participant if one or more of its partons collide. If any parton in a given nucleon participates, *all* partons in that nucleon contribute to the participant thickness function. Finally, we numerically tune the cross section parameter σ_{gg} which now modulates the parton-parton interaction probability in order to recover the desired p+p inelastic cross section. Figure 1 shows several examples of the nucleon substructure effect on proton and lead nuclear thickness functions.