INITIAL-STATE ANISOTROPIES AND THEIR UNCERTAINTIES IN ULTRARELATIVISTIC HEAVY-ION COLLISIONS FROM THE MCG MODEL

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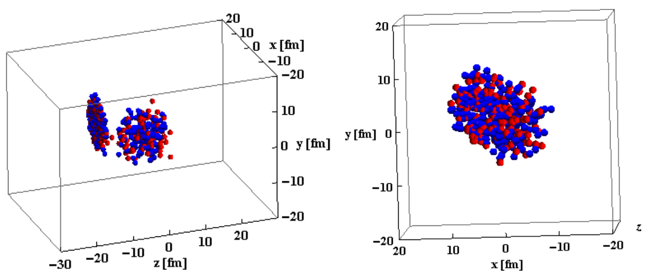
ABSTRACT

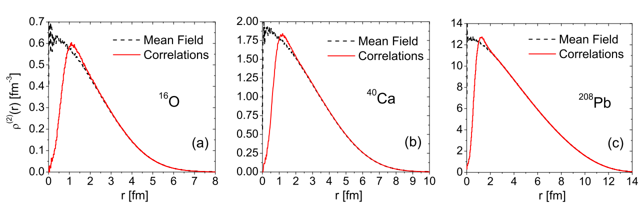
In hydrodynamical modeling of heavy-ion collisions, the initial-state spatial anisotropies are translated into momentum anisotropies of the final-state particle distributions [1, 2]. Thus, understanding the origin of the initial-state anisotropies and their uncertainties is important before extracting specific QCD matter properties [3], such as viscosity, from the experimental data. In this work [4] we review the wounded nucleon approach based on the Monte Carlo Glauber model, charting in particular the uncertainties arising from modeling of the nucleon-nucleon interactions between the colliding nucleon pairs and nucleon-nucleon correlations inside the colliding nuclei [5]. We discuss the differences between the black disk model and a probabilistic profile function approach for the inelastic nucleon-nucleon interactions, and investigate the influence of initial-state correlations using state-of-the-art modeling of these [6, 7, 8, 9].

1 - NUCLEON CONFIGURATIONS

- In the Monte Carlo Glauber (MCG) modeling one needs to know the positions of the initial state nucleon configurations
- We developed a Metropolis code to include *nucleon-nucleon* correlations [5] in the initial state of the colliding nuclei



- The method is constructed to reproduce the same nucleon density distribution as the usual one and, in addition, to reproduce the basic features of the two-nucleon density in the presence of the NN correlations; the figure shows the MC two-body radial nucleon density for various nuclei [10, 11, 12, 13, 14]:



- The Metropolis procedure uses a model wave function $|\psi|^2$ as probability weight function [6]
- The many-body wave function is taken in the form

$$\psi(\boldsymbol{x}_1, ..., \boldsymbol{x}_A) = \prod_{i<j}^{A} \hat{f}_{ij}\, \phi(\boldsymbol{x}_1, ..., \boldsymbol{x}_A)\,, \tag{1}$$

where ϕ is the uncorrelated wave function and $\hat{f}_{ij}$ are correlation operators; here, $\boldsymbol{x}_i$ denotes the position, spin and isospin projection of the i-th nucleon.

- The correlation operator contains a detailed spin-isospin dependence, which is as follows

$$\begin{aligned}\hat{f}_{ij} \;=\;& f^c(r_{ij}) + f^\sigma(r_{ij})\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j + f^\tau(r_{ij})\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j \\ & + f^{\sigma\tau}(r_{ij})\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j + f^t(r_{ij})\hat{\boldsymbol{S}}_{ij} \\ & + f^{t\tau}(r_{ij})\hat{\boldsymbol{S}}_{ij}\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j + ...\,,\end{aligned} \tag{2}$$

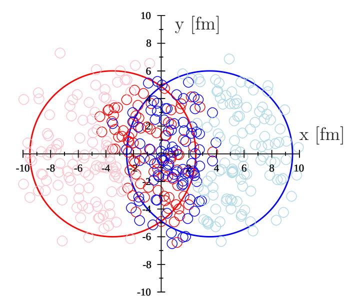
where radial-dependent correlation functions $f^{(\alpha)}$ obtained variationally

- Given the non-commutative nature of the state-dependent correlation operator, they full correlation case will be treated to a given degree

⟹ We will refer as *Central* to the approximation in which only the $f^{(c)}(r_{ij})$ is present; as *Full (2b)* to the two-body approximation with state dependent operators and as *Full (3b)* to three-body chains of such non-commutative operators; most notably, the *tensor* operator, which is needed to account for most of the binding in any realistic many-body description of nuclei and is responsible of the proton-neutron dominance of NN correlations over proton-proton correlations [10, 11, 12].

2 - MODELING THE INELASTIC INTERACTIONS

- In each Monte Carlo Glauber event, after the initial states are determined, the two nuclei collide at a given impact parameter $\boldsymbol{b}$



- We work in the Glauber model framework, neglecting the effects of inelastic diffraction that lead to fluctuations of the strength of the NN interactions
- To generate the inelastic NN collisions of interest here, we use the following two different approximations for deciding whether a collision between the nucleons i and j from different nuclei takes place:

⟹ *Black disk* approximation, where one assumes the two nucleons to interact inelastically with a probability one if their transverse separation b_{ij} is within a radius defined by the inelastic NN cross section σ^{in}_{NN},

$$\boldsymbol{b}^2_{ij} \leq \frac{\sigma^{in}_{NN}}{\pi}\,; \tag{3}$$

⟹ *Profile function approach*, where the probability of an inelastic interaction between the nucleons i and j is given by

$$P(\boldsymbol{b}_{ij}) = 1 - |1 - \Gamma(\boldsymbol{b}_{ij})|^2\,, \tag{4}$$

and that is commonly used in modeling of the NN inelastic interaction;

- The profile function Γ in Eq. (4) is expressed in terms of the total and elastic NN cross sections as follows:

$$\Gamma(\boldsymbol{b}_{ij}) = \frac{\sigma^{tot}_{NN}}{4\pi B}\, e^{-b^2_{ij}/(2\,B)}\,, \tag{5}$$

with $B = (\sigma^{tot}_{NN})^2/(16\pi\sigma^{el}_{NN})$.

- The probability distribution $P(\boldsymbol{b}_{ij})$ can be derived in the Born approximation of the potential-scattering formalism, by parametrizing the NN elastic scattering amplitude as

$$f(\boldsymbol{q}) = \frac{C(i+k)}{4\pi}\, e^{-\frac{1}{2}Bq^2} \tag{6}$$

and using the optical theorem,

$$\sigma^{tot}_{NN} = \frac{4\pi}{k} Im[f(\boldsymbol{0})]. \tag{7}$$

- One finally arrives at the probability function of Eq. (4), whose integral over the transverse separation gives the inelastic NN cross section:

$$\begin{aligned}\sigma^{in}_{NN} &= \int d^2\boldsymbol{b}_{ij}\, \left(2\,Re\,\Gamma(\boldsymbol{b}_{ij}) - |\Gamma(\boldsymbol{b}_{ij})|^2\right) \\ &= \int d^2\boldsymbol{b}_{ij}\, \left(1 - |1 - \Gamma(\boldsymbol{b}_{ij})|^2\right).\end{aligned} \tag{8}$$

- The parameters B and σ^{tot}_{NN} can be fixed on the basis of measured cross sections. For the current set-up at $\sqrt{s_{NN}} = 200$ GeV, we take $B = 14$ GeV^{-2} and $\sigma^{tot}_{NN} = 52$ mb, which correspond to $\sigma^{in}_{NN} = 42$ mb and $\sigma^{el}_{NN} = 9.9$ mb.

3.1 - SPATIAL ASSYMMETRIES AND THEIR FLUCTUATIONS

- In ultrarelativistic heavy ion collisions performed at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) elliptic flow – the second Fourier coefficient v_2 that quantifies the azimuthal anisotropy in the measured particle distributions – has been found to be large. The appearance of a significant v_2 is a clear signature of pressure formation in the system [2, 3]
- The spatial anisotropy is translated first into a flow-velocity anisotropy during the hydrodynamical evolution and, finally, at the decoupling of the system, into a measurable momentum-anisotropy of final-state particle distributions. Experiments at RHIC and LHC have been able to measure non zero flow coefficients up to v_6
- Studies based on event-by-event hydrodinamical modeling have shown that all initial-state anisotropies are transferred to the final measurable flow values in a similar way as eccentricity is translated to elliptic flow
- In this work we focus on the first three harmonics $n = 1, 2, 3$: dipole asymmetry, eccentricity, and triangularity. We know from the experimental results that the second and third harmonics are the largest ones.
- We calculate the asymmetries from the wounded nucleon positions which are obtained from the MCG model. In the following, the angle brackets denote an average over wounded, or participant, nucleons. The asymmetries are defined as

$$\epsilon_n = -\frac{\langle w(r)\cos(n(\phi - \psi_n))\rangle}{\langle w(r)\rangle}, \tag{9}$$

where $w(r)$ is a weight and ψ_n is an orientation angle that is obtained as

$$\psi_n = \frac{1}{n}\arctan\frac{\langle w(r)\sin(n\phi)\rangle}{\langle w(r)\cos(n\phi)\rangle} + \frac{\pi}{n}, \tag{10}$$

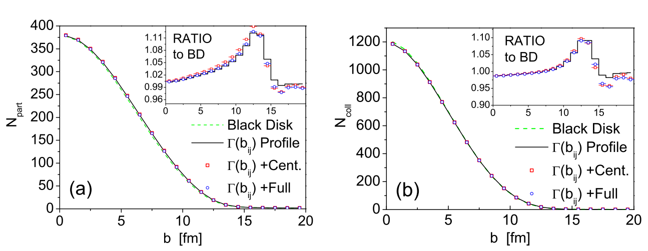
We choose to use $w(r) = r^3$ for $n = 1$, $w(r) = r^2$ for $n = 2$, and $w(r) = r^3$ for $n = 3$

- We also study the fluctuations of the initial-state asymmetries since the current flow analysis methods are sensitive to the fluctuations of the flow coefficients. Since final flow values reflect the initial-state asymmetries, the fluctuations of the flow coefficients should follow the initial-state fluctuations. We define the fluctuations of the anisotropies as

$$\Delta\epsilon_n = \sqrt{\frac{\sum(\epsilon^i_n - \langle\epsilon_n\rangle)^2}{N}}, \tag{11}$$

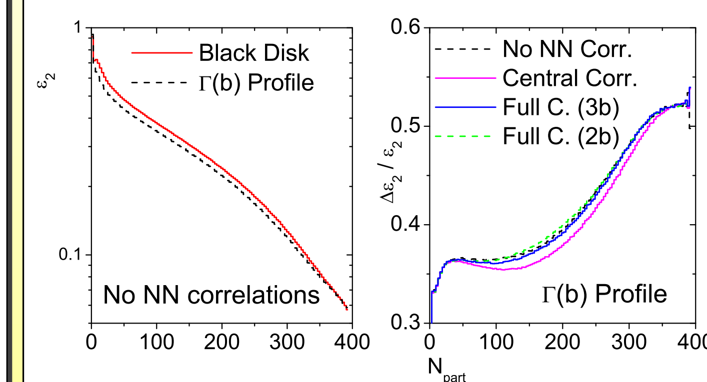
where ϵ^i_n is the asymmetry in event i and $\langle\epsilon_n\rangle$ denotes the average over N events.

- We first show the effect of $i)$ NN correlations and $ii)$ different interaction models on the average number of participants



- We have then investigated the effects of the same two sources of uncertainty on the first three harmonics of the distribution of participant matter

3.2 - RESULTS for ECCENTRICITY



CONCLUSIONS

In this paper we studied two sources of additional uncertainty in the Monte Carlo model calculations for the initial state anisotropies, *i.e.* NN correlations and nucleon-nucleon interaction models. The uncertainty caused by the studied effects to these anisotropies was found to be maximally of the order of 10%. Thanks to the recent developments in event-by-event hydrodynamics, more precise comparisons of flow coefficients between the data and the theory are becoming possible, thus it is important to chart all the relevant uncertainties to this precision, so that the QCD matter properties could eventually be determined from the measured particle spectra and their azimuthal asymmetries. As far as the NN correlation effects are concerned, whose effect on various scattering processes involving nuclei have been established, in this case they seem to play a minor role; we have a hint that multibody-correlations may play an additional role. For a detailed discussion and additional results, see Ref. [4].

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M. Alvioli is supported by the project HadronPhysics2 of the EC and ECT*/FBK; we also thank the HPC-Europa2 consortium for computational resources.