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Nuclear coalescence and collective behaviour in small interacting systems

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The production of light nuclei in particle collisions can be described as the coalescence of nucleons into nuclei. In most coalescence models used in heavy ion collisions, the probability for coalescence is controlled predominantly by the size of the interaction region, while nucleon momentum correlations may be treated as collective flow or even neglected. Interestingly, recent experimental data on *pp* collisions at LHC have been interpreted as evidence for such collective behaviour even in small interacting systems. This is in contradiction to the standard approach of imposing the coalescence condition only in momentum space for small interacting systems, such as e^+e^- and dark matter annihilations or *pp* collisions. We argue however that these data are naturally explained using QCD inspired event generators when taking into account both nucleon momentum correlations and the size of the hadronic emission volume. To consider both effects, we use a per-event coalescence model based on the Wigner function representation of the produced nuclei states. This model reproduces well the size of baryon-emitting source as well as the coalescence factor B_2 recently measured in *pp* collisions by the ALICE collaboration. Finally, we comment on the generalization to larger interacting systems.

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PoS(EPS-HEP2021)318

1. Introduction

Light clusters of nucleons, such as deuteron, helium-3, tritium and their antiparticles, are sensitive probes for nucleon correlations and density fluctuations in particle collisions due to their composite structure and small binding energies. This makes them ideal probes for the QCD phase diagram in particle collisions [1]. Simultaneously, these particles are of interest in the search for exotic physics in cosmic ray studies due to their suppressed background at low energies [2, 3]. To interpret the results of collider data and cosmic ray experiments correctly, however, one needs a firm understanding of the production mechanisms for light nuclei.[1]

In Ref. [4], we developed a new coalescence model based on the Wigner function representation of the produced nucleon and nucleus states, for which we will be using the abbreviation WiFunC—short for Wigner Functions with Correlations. This model imposes the coalescence condition in phase space on an event-by-event basis, thus taking into account nucleon correlations. The model was later refined and applied in a cosmic ray study and discussed in relation to recent collider data in Refs. [5, 6] (see Ref. [7] for a recent summary). For concreteness, the focus here will be on antideuterons, but the same considerations apply to all kind of light nuclei with small binding energies, such at helium-3 and tritium, or even more exotic states like hypertriton.

2. The WiFunC model

The WiFunC model is based on the non-relativistic quantum mechanical description of coalescence, as reviewed in e.g. Refs. [8, 9]. In this approach, the deuteron spectrum can be found in the sudden approximation by projecting the two-nucleon density matrix onto the deuteron density matrix, $\mathrm{d}^3N_d/\mathrm{d}^3P_d = \mathrm{tr}\{\rho_d\rho_{\text{nucl}}\}$. The main differences in existing quantum-mechanical phase space coalescence models lie in the treatment of the phase space distribution of nucleons. In the WiFunC model, two-nucleon momentum correlations obtained from QCD inspired event generators are combined with a simple analytical ansatz for the spatial nucleon distribution: $h(r_i) = (2\pi\sigma^2)^{-3/2}\exp\{-r^2/2\sigma^2\}$. The deuteron spectrum can then be written as

$$\frac{\mathrm{d}^3N_d}{\mathrm{d}P_d^3} = \frac{3\zeta}{(2\pi)^6}\int \mathrm{d}q\ \mathrm{e}^{-q^2d^2}G(\mathbf{q},-\mathbf{q}), \tag{1}$$

where

$$\zeta(\sigma_\parallel,\sigma_\perp) = \sqrt{\frac{d^2}{d^2+4\sigma_\perp^2 m_\mathrm{T}^2/m^2}}\sqrt{\frac{d^2}{d^2+4\sigma_\perp^2}}\sqrt{\frac{d^2}{d^2+4\sigma_\parallel^2}}. \tag{2}$$

Here, G is the two-nucleon momentum distribution, q the nucleon momentum and m_T the transverse mass, all of which must be obtained on an event-by-event basis in the deuteron frame.The Gaussian suppression in Eq. (1) arises from approximating the deuteron wave function as a Gaussian such that its Wigner function becomes $\mathcal{D}(\mathbf{r},\ \mathbf{q}) = 8\exp\{-r^2/d - q^2d^2\}$ with $d \simeq 3.2$ fm. In general, however, a more accurate wave function should be used, such as the two-Gaussian fit to the Hulthen wave function introduced for the WiFunC model in Ref. [4]. The numerical implementation of the model is thoroughly described in Refs. [4, 7].

[1]The discussions apply equally well to particles and antiparticles, and the prescription "anti" will therefore be omitted.

PoS(EPS-HEP2021)318

The physical interpretation of the parameters $\sigma_\parallel$ and $\sigma_\perp$ is the size of the nucleon formation length in respectively the parallel and perpendicular direction relative to the particle collision. They will in general have a point-like contribution from the spread in single parton-parton interactions, and a geometrical contribution from the extension of the parton clouds. In the particular case of pp collisions and e^+e^- annihilations, they are of the same size and expected to be close to 1 fm. Therefore, one can reduce the number of free parameters by fixing $\sigma_\parallel \simeq \sigma_\perp$ and $\sigma \equiv \sigma_{(e^+e^-)} \simeq \sigma_{(pp)}/\sqrt{2} \simeq 1$ fm. When fitting the model to various collider data on deuteron and helium-3 production in e^+e^-, pp and pN collisions, one finds a good agreement with the spectral shapes, and obtains $\sigma = (1.0 \pm 0.1)$ fm in agreement with the physical interpretation [6].

Ideally also the two-nucleon position correlations should be evaluated event by event. This can be achieved by replacing the analytical ansatz by the semi-classical trajectories implemented in some event generators like PYTHIA 8 [10] and UrQMD [11]. In such cases, one can instead directly evaluate

$$\frac{\mathrm{d}^3 N_d}{\mathrm{d}P_d^3} = 3 \int \frac{\mathrm{d}^3 r\, \mathrm{d}^3 q}{(2\pi)^6}\, \mathrm{e}^{-r^2/d^2 - q^2 d^2} W_{np}(\,\mathbf{p}_p,\, \mathbf{p}_n,\, \mathbf{r}_p,\, \mathbf{r}_n), \tag{3}$$

where W_{np} is the two-nucleon Wigner function [5].

Even though coalescence models are arguably the best motivated nucleus production models, especially for small interacting systems, alternative models exist. In the competing statistical thermal models [12] that often are used in heavy ion collisions, it is assumed that the hadronisation and the formation of the light nuclei occurs in an expanding "fireball" of quark–gluon plasma. These models are well motivated by the observation that the spectra of light nuclei in heavy ion collisions are consistent with a thermal spectrum with a freeze-out temperature similar to mesons and nucleons. However, even in the coalescence picture, one expects the energy spectrum to be inherited by the nucleons up to a quantum mechanical correction factor [13]. Furthermore, their low binding energies make it challenging to justify how the nuclei can survive the freeze-out process. Curiously, data on small interacting systems have recently been shown to contain characteristic features for collective flows and the formation of a quark–gluon plasma [14]. This has motivated the suggestion that the production of light nuclei can be attributed to thermal production even in small interacting systems, such as pp and pPb collisions [3, 9, 15]. However, many of these—including the cases that will be discussed in the next section—are naturally described by the WiFunC model [5].

3. Multiplicity dependence and baryon emission volume in pp collisions

The ALICE collaboration measured recently the common baryon emission volume in pp collisions at 13 TeV [16]. In Fig. 1, we compare the source size r_0 estimated for proton-proton pairs to that predicted by the WiFunC model [5]. Additionally, we show the source size obtained in the limit $\sigma_\parallel \gg \sigma_\perp$, which corresponds to the steepest slope $r_0(m_T)$ possible in our model. It is worth noticing that the data tend to give better fits for $\sigma_\parallel > \sigma_\perp$, as expected from their physical interpretations. Even so, we find not yet any need to fit them separately due to the relatively large experimental uncertainties. From Fig. 1 one can infer $\sigma = (1.0 \pm 0.1)$ fm, completely independent of the event generator. The success of similar femtoscopy experiments is an important indication that coalescence is a major production mechanism for light nuclei [17].

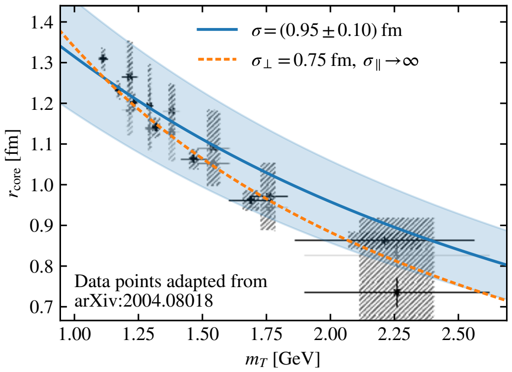

Figure 1: The Gaussian emission size predicted by the WiFunC model is compared to experimental data; figure adapted from Ref. [5].

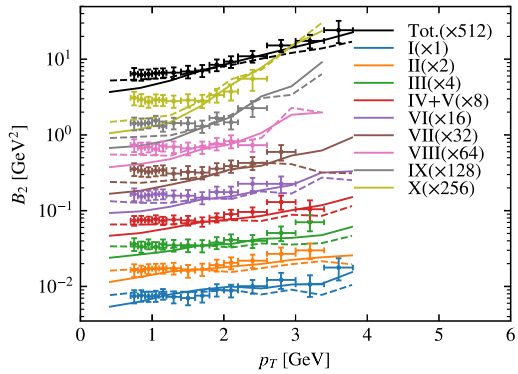

Figure 2: The coalescence factor B_2 for different multiplicity classes is compared to the predictions by QGSJET using the WiFunC model (solid lines) and a per-event model in momentum space (dashed lines); figure adapted from Ref. [5].

In Fig. 2 we compare the coalescence factor B_2 measured by the ALICE collaboration in pp collisions at 13 TeV to the predictions of the WiFunC model using QGSJET II [18] with $\sigma = 0.9$ fm. The results are split into different multiplicity classes. For comparison, we show also the results using the standard per-event coalescence model with only a hard cut-off in momentum space. The qualitative data are well described by the WiFunC model: There is an increase in B_2 with increasing transverse momentum, p_T, and the slope becomes stronger for increasing multiplicity. Care must however be taken when quantitatively comparing the model to experimental data, since the data are often only available at specific kinematical regions outside the range of validity of the event generators. In the WiFunC model, the increase in slope at increasing p_T is due to a non-trivial combination of the decrease in source size and two-particle correlations. Moreover, the increase of the slope for increasing multiplicity comes from the decrease in the available phase space.

4. Comment on the process dependence

Up to now, we have focused on nuclei production in small interacting systems. However, as long as the event generators are able to describe the underlying interaction process, the WiFunC model can also be applied to processes involving larger nuclei. The geometrical contribution to the spreads $\sigma_\parallel$ and $\sigma_\perp$ will generally vary event-by-event. In particular, it should depend on the centrality of the event, and thus on the corresponding rate of multiple scatterings. These variations are expected to be small for proton-proton interactions, which is supported by the data presented in the previous section. In interactions of larger systems, such as pPb and PbPb, we expect on the other hand a considerable multiplicity dependence on the size of the source region on an event-by-event basis. This dependence is strongly correlated with the number of spectator nucleons, which can be extracted from QGSJET.

The ALICE collaboration has measured the deuteron-to-nucleon ratio and the coalescence factor B_2 as a function of multiplicity for pp, pPb and PbPb interactions (see Figs. 4 and 5 in Ref. [15]). These results suggest that B_2 behaves as a smooth function of multiplicity, independent on the interaction type. In particular, the results for pPb and pp are, within experimental uncertainties, overlapping. This is at first sight in contradiction to the WiFunC approach: At large multiplicities

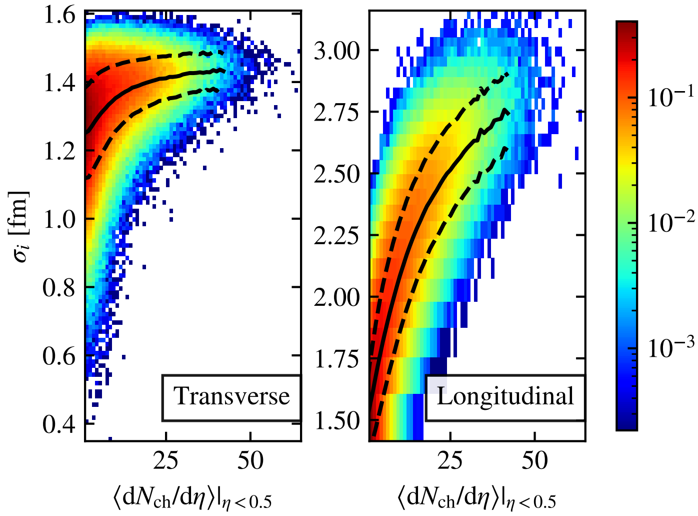

Figure 3: Spread of $\tilde{\sigma}_\perp = \sigma_\perp m_T/m$ (left) and $\sigma_\parallel$ (right) in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of the number of charged particles in the central pseudorapidity region for QGSJET. The mean value at each N_{ch} and its standard deviation is shown in solid and dashed lines, respectively. The colour code shows the probability density.

we expect a distinct difference in the nuclei yields in different interacting processes. The data from the ALICE collaboration therefore suggest that the bulk of measured antinuclei originate from peripheral interactions with $\sigma_{geom} \simeq R_p$.

In order to check this suggestion, we plot in Fig. 3 the distribution of the spatial spreads, $\sigma_\perp$ and $\sigma_\parallel$, for the produced nucleons in pPb interactions at 5.02 TeV using QGSJET. The number of nucleons that participate in the interaction is extracted from QGSJET event-by-event and the corresponding process dependence in the spread in the WiFunC model is taken into account using the dependence introduced in Ref. [6]. As expected, the spread increases in both the transverse and longitudinal directions with increasing multiplicities. In Fig. 4, we plot the resulting distribution in the spatial distribution factors ζ, cf. with Eq. (2). While the ζ-factor in pp collisions is almost symmetrically distributed around 0.5, the increase in the number of participating particles leads to a distinct "banana shape" in the spread in the case of pPb collisions. Thus, at large multiplicities, we expect a distinct difference between the yields of light nuclei in pp and pPb interactions. However, these differences are only sizeable above $\langle dN_{ch}/d\eta\rangle|_{\eta<0.5} \gtrsim 20$, for which there are currently no data. Such multiplicities will hopefully be probed in future LHC runs with increased luminosity. Interestingly, similar data on the hypertriton production may already show signs of this effect [19].

We emphasize that we show in Fig. 4 only the spatial distribution factor [Eq. (2)] obtained for the produced nucleons. This means that the two-nucleon correlations important in the deuteron production [via the integral in Eq. (1)] have not been taken into account in the discussions in this section. For increasing multiplicity, the phase space available for single nucleons will on average decrease, which implies an increased coalescence probability according to Eq. (1). This multiplicity dependence is, however, expected to only depend weakly on the interaction process.

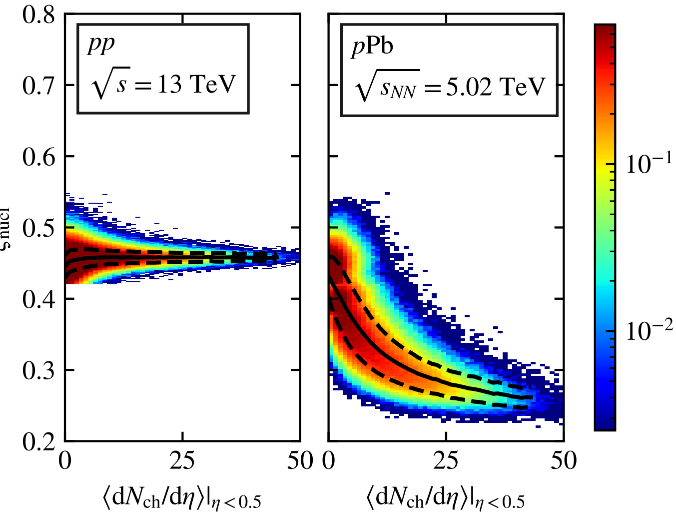

Figure 4: Spread of ζ in pp collisions at $\sqrt{s} = 13$ TeV (left) and pPb (right) collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of the number of charged particles in the central pseudorapidity region for QGSJET. The mean value at each $N_{\rm ch}$ and its standard deviation is shown in solid and dashed lines, respectively. The colour code shows the probability density.

5. Summary

Recent experimental data shows signs characteristic for collective motion and the production of a quark–gluon plasma in small interacting systems. This includes, for example, the baryon emission source size and the coalescence factor B_2 measured recently by the ALICE collaboration. However, using the WiFunC model—a per-event coalescence model based on the Wigner function representation of the nucleons and produced nuclei—we showed that the same properties are well reproduced by conventional QCD inspired event generators when both the source volume and momentum correlations are taken into account. Finally, we commented on the generalization of the model to larger interacting nuclei, and argued that it predicts that at large multiplicities, $\langle dN_{\rm ch}/d\eta \rangle|_{\eta<0.5} \gtrsim 20$, the yields of produced nuclei in pp and pPb interactions as function of multiplicity should differ distinctly.

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