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Modelling the formation of light (anti)nuclei via coalescence using Monte Carlo generators

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Coalescence is one of the main models used to describe the formation of light (anti)nuclei. It is based on the hypothesis that nucleons close in phase space can coalesce and form a nucleus. Coalescence has been successfully tested in hadronic collisions at colliders, from small (pp collisions) to large systems (A–A collisions). However, in Monte Carlo simulations (anti)nuclear production is not described by event generators. A possible solution is given by the implementation of coalescence afterburners, which can describe nuclear production on an event-by-event basis. This idea would find application in astroparticle studies, allowing for the description of (anti)nuclear fluxes in cosmic rays, which are crucial for indirect Dark Matter searches. In this work, the implementation of an event-by-event coalescence afterburner based on a state-of-the-art Wigner approach is discussed. The results here shown are obtained with the EPOS3 event generator and compared to the measurements performed in pp collisions at the LHC. In particular, the role of the emitting source in the coalescence process is discussed, comparing the results obtained using the direct measurement of the source size with the semi-classical traces implemented in EPOS3.

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1. Coalescence with the Wigner function formalism

The formation mechanism of light (anti)nuclei is still under debate. One of the models most commonly used to describe it is coalescence. The basic idea of the coalescence model is that an (anti)nucleus can be formed if their constituent nucleons are close enough in phase space.[1] However, this formulation is very vague and the exact implementation can vary. The most simplistic implementation of coalescence is the spherical approximation. Here a nucleus is formed when the nucleons lie within a sphere of radius p_0 in momentum space. The parameter p_0 is called coalescence momentum and it cannot be calculated ab initio. Instead, it needs to be fitted to existing data for each energy and collision system separately. This reveals the first weakness of this implementation: it cannot be used to make predictions at energies and in collision systems which have never been measured. However, such an extrapolation is required for example in cosmic ray studies, where light nuclei formation needs to be modeled over a wide range of collision energies and for different collision systems. A more sophisticated approach to coalescence is the Wigner function formalism. Such approach overcomes the shortcomings of the spherical approximation, by taking into account the spatial distance between the coalescing nucleons. Furthermore, it no longer requires a fit to existing data, hence it can be used to predict deuteron yields at all energies and collision systems. The full derivation of this implementation is given in Ref. [1]. The Wigner function formalism, as the name suggests, is based on the Wigner function, which is defined as:

$$W(\vec{r},\vec{q}) = \frac{1}{(2\pi)^3}\int \phi(\vec{x}+\vec{\xi}/2)\phi^*(\vec{x}-\vec{\xi}/2)\mathrm{e}^{i\vec{q}\cdot\vec{r}}\,d^3\xi\,, \tag{1}$$

where $\phi(\vec{x})$ is the wave function of the object of interest, in this case the deuteron. The yield of deuterons can be calculated by projecting the deuteron Wigner function $W_\mathrm{d}(\vec{q},\vec{r})$ onto the two-nucleon phase space $W_\mathrm{np}(\vec{p}_\mathrm{n},\vec{p}_\mathrm{p},\vec{r}_\mathrm{n},\vec{r}_\mathrm{p})$:

$$\frac{d^3N}{dP^3} = S\int d^3q\int d^3r_n\int d^3r_p W_\mathrm{d}(\vec{q},\vec{r})W_\mathrm{np}(\vec{p}_\mathrm{n},\vec{p}_\mathrm{p},\vec{r}_\mathrm{n},\vec{r}_\mathrm{p})\,. \tag{2}$$

Assuming that spatial and momentum coordinates of the nucleons are uncorrelated, as well as a Gaussian wave function for deuterons, one obtains:

$$\frac{d^3N}{dP^3} = S\frac{8\zeta}{(2\pi)^6}\int d^3q e^{-q^2d^2}G_\mathrm{np}(\vec{P}_d/2+\vec{q},\vec{P}_d/2-\vec{q})\,, \tag{3}$$

where

$$\zeta = \left(\frac{d^2}{d^2+4\sigma^2}\right)^{3/2} \tag{4}$$

includes the size σ of the emission source of nucleons and the characteristic size parameter of the deuteron $d = \sqrt{8/3}\,r_\mathrm{d} = 3.2\,\mathrm{fm}$ depends on the RMS radius r_d of deuterons. In Eq. 3 the term $8S\,\zeta e^{-q^2d^2}$ can be interpreted as the probability of a p-n pair, emitted from a source with size σ and with relative momentum 2q, to coalesce and form a deuteron. This probability can be used with an event generator like EPOS3 [2] to predict deuteron yields.

[1] Since the formation mechanism is expected to be the same for particles and antiparticles the (anti) will from now on be omitted.

2. Tuning the event generator

It is well-known that event generators cannot perfectly describe nature. Therefore, the event generator used for coalescence studies must be tuned to reproduce certain observables so that the final result is not biased by the shortcomings of the event generator but is only sensitive to the coalescence model itself. The observables with the highest impact on coalescence were determined to be the particle multiplicity, as it determines the number of p-n pairs in a single event, as well as the momentum and spatial distributions, since they are important for calculating the coalescence probability. The ALICE Collaboration measured the production of (anti)protons, (anti)deuterons and the emission source size in pp collisions at $\sqrt{s}$ = 13 TeV with a high multiplicity (HM) trigger. Hence, in this work we use this dataset as a reference to tune the EPOS3 event generator results. To limit biases the multiplicity estimation is done in a different kinematic region than the measurement. In ALICE the measurements are carried out at midrapidity (|y|<0.5), and the multiplicity estimation is done at forward and backward rapidity ($2.8 < \eta < 5.1$ and $-3.7 < \eta - 1.7$, respectively). In order to tune the event generator to the mean multiplicity of the dataset of interest [3] ($\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle_{|\eta|<0.5} = 35.8 \pm 0.5$), one requires a minimum number of charged particles in the forward and backward rapidity regions for each event and looks at the corresponding multiplicity distribution at midrapidity. Using this method one can very well reproduce the mean multiplicity of the ALICE measurement. The final midrapidity distribution in EPOS3, after the HM trigger selection, can be seen in Fig. 1 (left). The next step is to correct the momentum distributions of protons, assuming

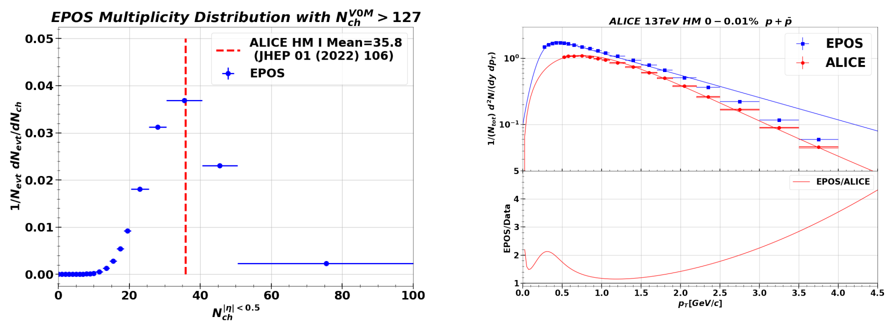

Figure 1: (Left) Charged particle distribution at midrapidity in EPOS3 when requiring 127 charged particles in the forward and backward rapidity region and comparison to the mean charged-particle multiplicity measured by ALICE [3]. (Right) Transverse momentum spectra of protons ($\mathrm{p} + \bar{\mathrm{p}}$) obtained from EPOS3 with a HM trigger compared to the measurements by ALICE [3]. Fits with an exponentially modified Gaussian function and a Lévy-Tsallis distribution are shown for EPOS3 and ALICE spectra, respectively.

isospin symmetry. In Fig. 1 (right) the $\mathrm{p} + \bar{\mathrm{p}}$ transverse momentum spectrum for EPOS3 with the HM trigger discussed above is compared to the corresponding measurement by ALICE. The EPOS3 spectrum is fitted using an exponentially modified Gaussian function. The ALICE spectra are fitted with a Lévy-Tsallis distribution. The predictions by EPOS3 fail to reproduce the ALICE measurement over the whole p_{T} range. Hence, the protons and neutrons are re-weighted according to the ratio of the fit function to data. Furthermore, in EPOS3 neutrons are produced in larger amounts with respect to protons, hence they are additionally re-weighted to reproduce proton yields (flat correction of ∼10 %). The last correction is the spatial distribution, specifically the source

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size σ, which is a measure of the distance among the particles created in the collision. Using femtoscopy techniques the source size in the same dataset of pp collisions at $\sqrt{s} = 13$ TeV with an HM trigger was measured by ALICE. The results of this measurement for p-p pairs are compared to the results from EPOS3 in Fig. 2 (left). It is evident that EPOS3 fails to reproduce the overall size as well as its scaling with the transverse mass ($m_{\mathrm{T}} = \sqrt{(p_{\mathrm{T},1}^2 + p_{\mathrm{T},2}^2)/2 + m_{\mathrm{p}}^2}$). As mentioned in Sect. 1, old simplistic models only considered the relative momenta between the nucleons, but not their distance. In order to test the validity of this hypothesis, these two source size scalings with m_{T} give a unique opportunity to study the dependence of the coalescence model on the source size. To do this, the Wigner function formalism is once used with the semi-classical traces natively implemented in EPOS3 and once with the measured source size. This is done by sampling random distances according to the measured source size as a function of m_{T} of each the p-n pairs for which a coalescence probability is calculated.

3. Results

Applying this probability to the output of EPOS3, which has been tuned as described above, one obtains the deuteron spectra shown in Fig. 2 (right). A clear difference is observed between the results obtained with the two different source models. Hence a description of coalescence using only the momentum correlations between nucleons, as assumed in the spherical approximation, is not sufficient. Since both models fail to reproduce the data, further investigations into more realistic wave functions are required.

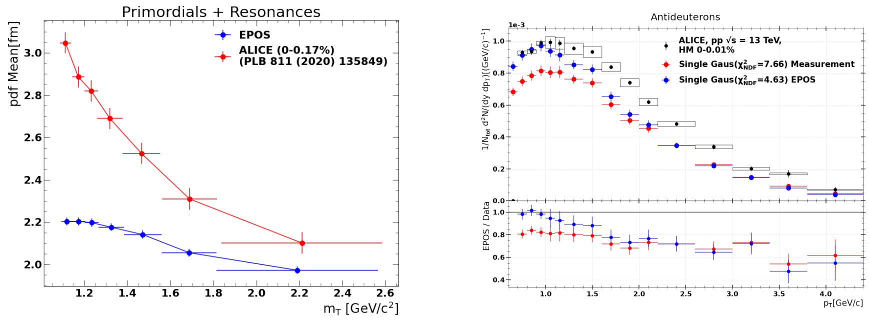

Figure 2: (Left) Comparison between the source size measured by ALICE [4] and that natively obtained from EPOS3, as a function of the average transverse mass $\langle m_{\mathrm{T}} \rangle$ of the proton-proton (antiproton-antiproton) pairs. (Right) Comparison between the deuteron yield predictions from EPOS3 using the Wigner function formalism with the two different source size scalings and the yields measured by ALICE [3].

References

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