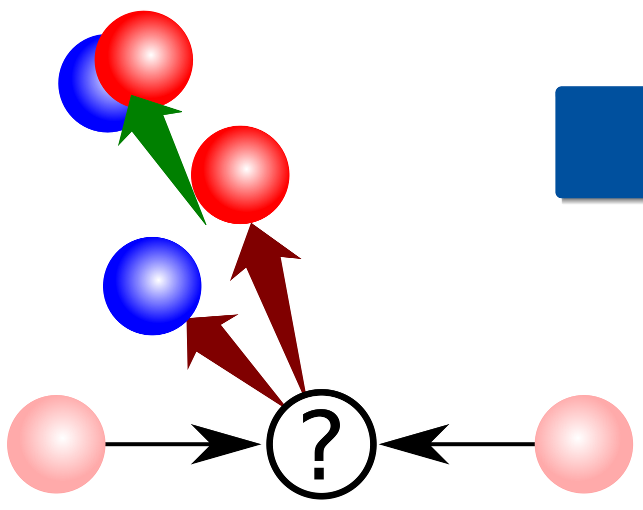

Nuclear coalescence in small interacting systems

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Motivation

Light (anti-)nuclei, like (anti-)deuteron, (anti-)helion and (anti-)tritium, are sensitive probes for the QCD phase diagram due to their composite structure and small binding energies. At the same time, light antinuclei are of immense interest for the astroparticle community since they are ideal probes for new and exotic physics. In order to correctly interpret experimental results, a solid description of the formation process is needed.

Coalescence models

In the *coalescence model*, final state nucleons merge into a nucleus if they are sufficiently close in *phase space*. Traditionally, the yield was parametrised as

$$E_A\frac{\mathrm{d}^3N_A}{\mathrm{d}P_A^3} = B_A\left(E_p\frac{\mathrm{d}^3N_p}{\mathrm{d}P_p^3}\right)^Z\left(E_n\frac{\mathrm{d}^3N_n}{\mathrm{d}P_n^3}\right)^N\Bigg|_{P_p=P_n=P_A/A},$$

where B_A is known as the *coalescence factor*.

In *small interacting systems* (e.g. e^+e^-, pp, and dark matter), the model is usually considered in momentum space: $B_A \propto p_0^{3(A-1)}$. In *heavy ion collisions*, one usually only consider the emission volume: $B_A \propto V^{A-1}$.

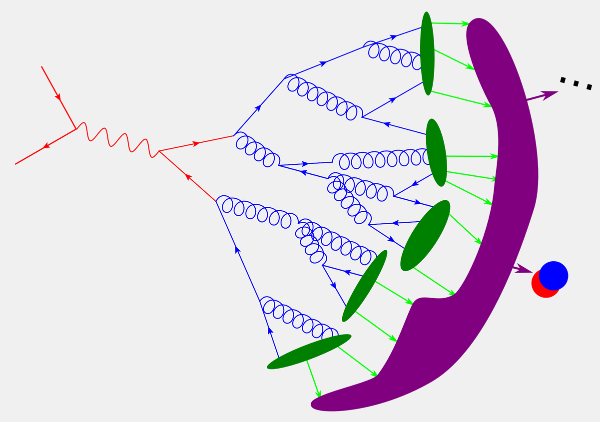
We demonstrate below that these models are inaccurate.

Timescales

There are three characteristic timescales in *point-like interactions*:

1. Hard process:
   $t_{\text{ann}} \sim 1/\sqrt{s}$
2. Perturbative cascade:
   $\Lambda_{\text{QCD}}^2 \ll |q^2| \ll s$
3. Hadronisation:
   $L_{\text{had}} \simeq \gamma L_0,\ L_0 \sim R_p \simeq 1\ \text{fm}$

$\Rightarrow$ The emission length of nucleons are dominated by the hadronisation length.



One therefore expects an emission length $\sigma_{\text{(point-like)}} \sim$ fm even in point-like interactions.

In *extended processes*, the emission length obtains a geometrical contribution from multiple parton-parton interactions: $\sigma_{\text{(geom)}} \sim R_N \sim$ fm.

In the particular case of pp and e^+e^- collisions, the transverse and longitudinal emission lengths are of the same order, and

$$\sigma \equiv \sigma_{e^\pm} \simeq \sigma_{pp}/\sqrt{2} \simeq 1\ \text{fm}.$$

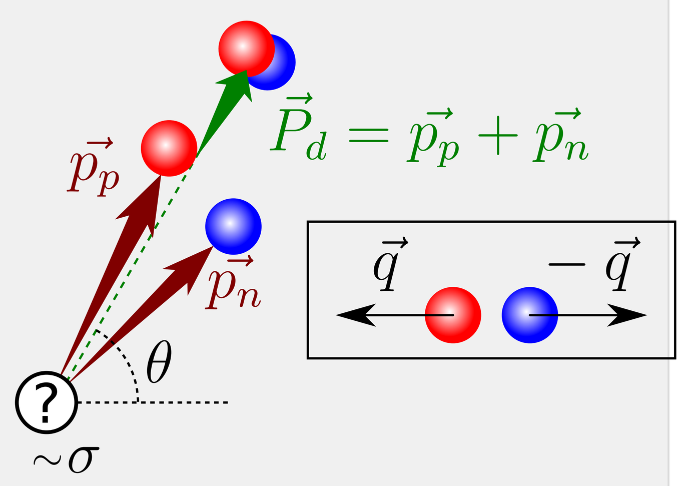
The size of the deuteron and helion wave functions are of the same order as the emission length, $r_{\text{rms}}^d \sim 2$ fm. This means that one must take into account both the size of the formation region and momentum correlations!

The WiFunC model

Momentum correlations and the emission volume are simultaneously considered in the WiFunC (Wigner Functions with Correlations) model. Here, the nucleus spectrum is found by projecting the (anti-)nucleon density matrix onto the (anti-)nucleus density matrix and assuming a Gaussian distribution for the nucleon emission. The (anti-)deuteron yield can then be written as

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

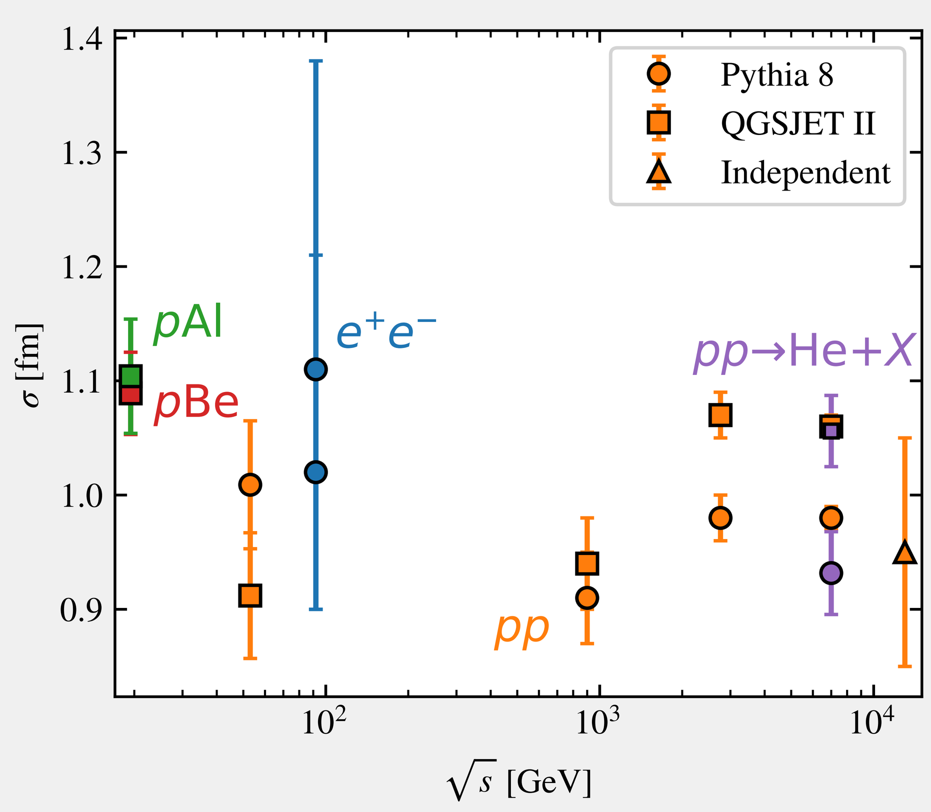
$$\zeta = \left(\frac{d^2}{d^2+4\sigma^2 m_T^2/m^2}\right)^{1/2}\frac{d^2}{d^2+4\sigma^2}.$$



The model can be added to any Monte Carlo event generator by using a weight

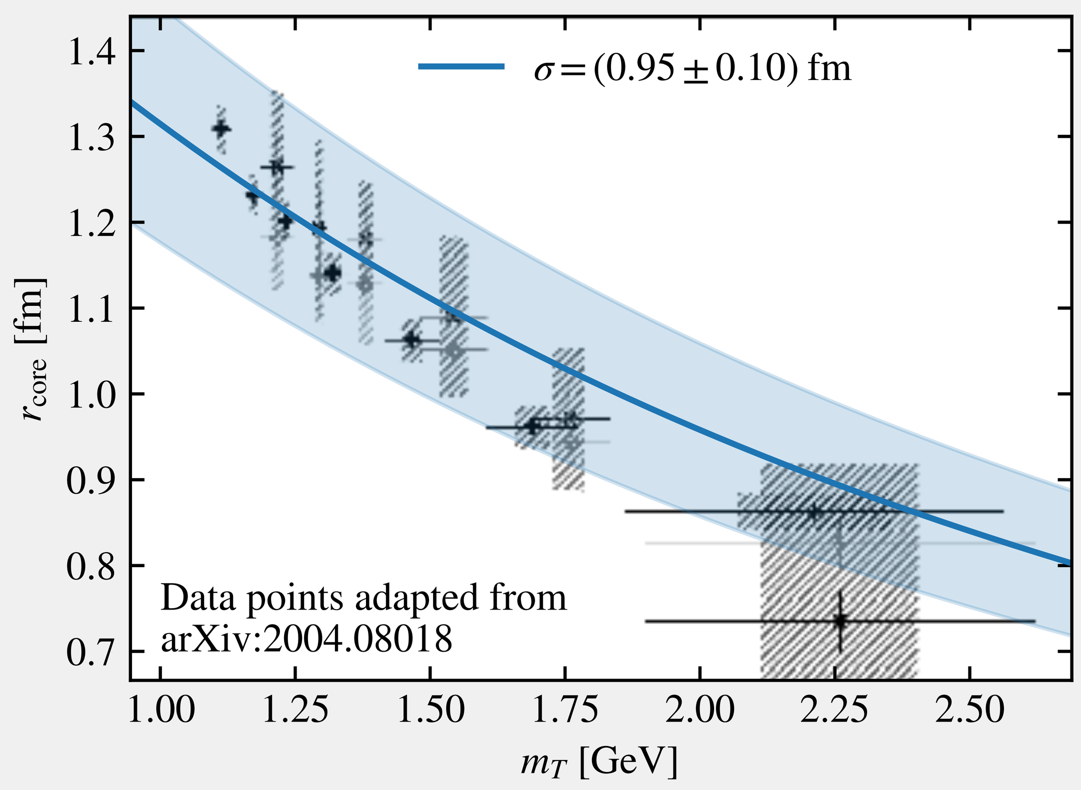
$$w = 3\Delta\zeta(d_1)\mathrm{e}^{-d_1^2q^2} + 3(1-\Delta)\zeta(d_2)\mathrm{e}^{-d_2^2q^2},$$

where $\Delta = 0.581$, $d_1 = 3.979$ fm, $d_2 = 0.890$ fm are fixed by fitting a two-Gaussian wave function to the Hulthen wave function describing the deuteron. A similar expression has been derived for (anti-)helion and (anti-)tritium.



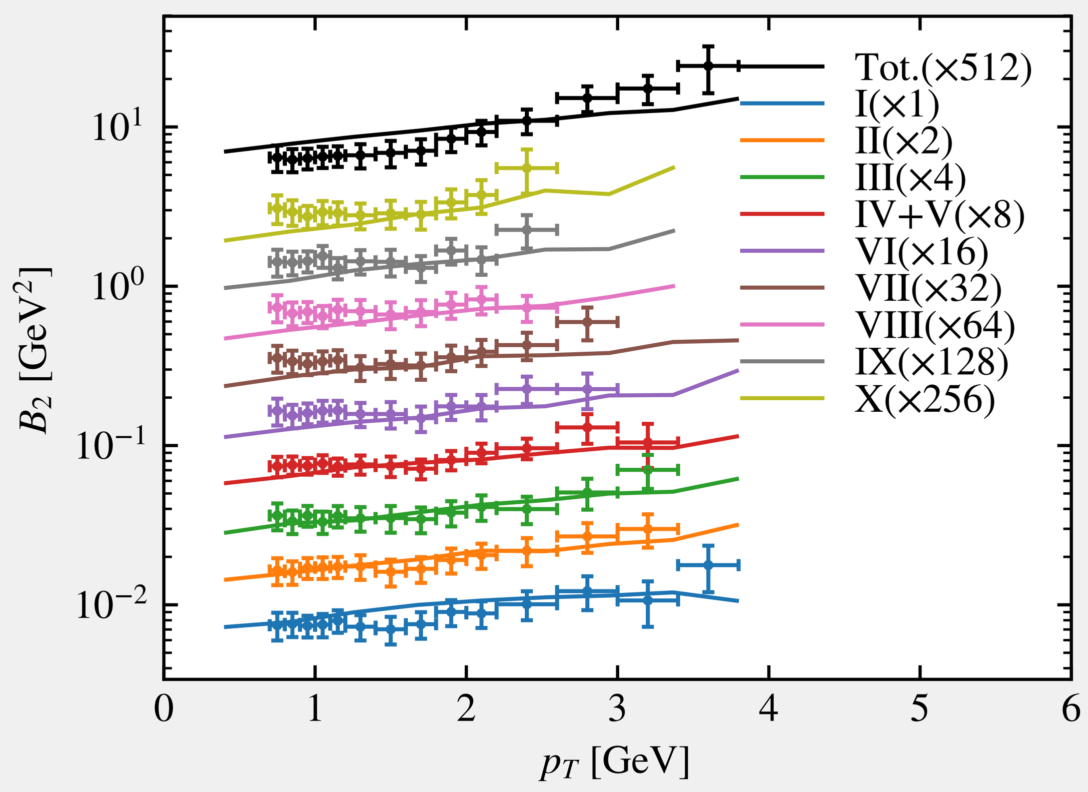
Femtoscopy experiments and emission volume

The emission size σ can be directly and independently measured in femtoscopy experiments using only data on baryon production. The agreement with the WiFunC model supports the validity of the basic model assumptions. Moreover, it implies that the WiFunC model contains no free parameters.



The coalescence factor

The main characteristics of the experimental data by the ALICE collaboration on the B_2 factor in pp collisions at 13 TeV is reproduced despite that the event generator (in this case QGSJET II) has neither been tuned to two-particle correlations nor to the kinematics of the experiment.



The steepening at large p_T which increases with multiplicity is in the WiFunC model explained by a combination of the non-trivial source function and two-particle correlations.

Space-time correlations

Some event generators, like Pythia 8 and UrQMD, have implemented a (semi) classical description of the space-time of the cascade. One can thus in principle take into account space-time correlations by evaluating

$$\frac{\mathrm{d}^3N_d}{\mathrm{d}P_d^3} = \frac{3}{8(2\pi)^3}\int \mathrm{d}^3q\,\mathrm{d}^3r\,\mathrm{e}^{-r^2/d^2-q^2d^2}W_{np}(q,r), \tag{1}$$

if one assumes that the Wigner function can be interpreted as a probability distribution.

The framework underlying the Wigner function approaches to coalescence and femtoscopy experiments rely on the equal time approximation, i.e. it is assumed that the particles are produced at the same time. More concretely, it is assumed that $q \ll m\sigma/t \sim$ GeV (Lednický 2009). Since the bulk of (anti-)nuclei are produced by nucleons with $q \sim \mathcal{O}(0.1)$ GeV, this condition is in general not satisfied for small interacting systems.

Conclusions

- One must consider both momentum correlations and the emission volume when describing the production of (anti-)nuclei in small interacting systems. This is achieved by using the WiFunC model.
- The m_T scaling of the emission volume and the properties of the B_2 factor can be described by conventional QCD inspired event generators.
- The equal time approximation is in general not satisfied for small interacting system.

Further readings

The WiFunC model and its application to collider physics and astrophysics are discussed in more detail in:

- M. Kachelriess, S. Ostapchenko and J. Tjemsland, [arXiv:2206.00998].
- J. Tjemsland, "Formation of light (anti)nuclei," PoS **TOOLS2020** (2021), 006 [arXiv:2012.12252].
- M. Kachelriess, S. Ostapchenko and J. Tjemsland, Eur. Phys. J. A **57** (2021) no.5, 167 [arXiv:2012.04352].
- M. Kachelrieß, S. Ostapchenko and J. Tjemsland, JCAP **08** (2020), 048 [arXiv:2002.10481].
- M. Kachelrieß, S. Ostapchenko and J. Tjemsland, Eur. Phys. J. A **56** (2020) no.1, 4 [arXiv:1905.01192].

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Questions?
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