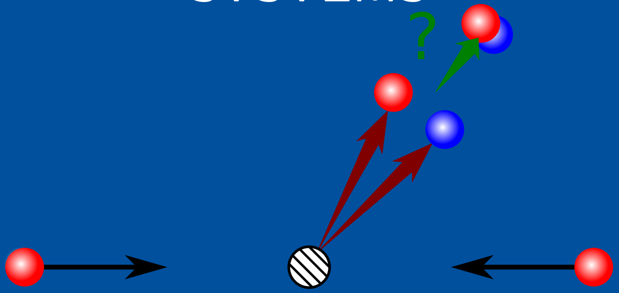
NUCLEAR COALESCENCE IN SMALL INTERACTING SYSTEMS



Based on Kachelrieß, Ostapchenko, JT [2012.04352]

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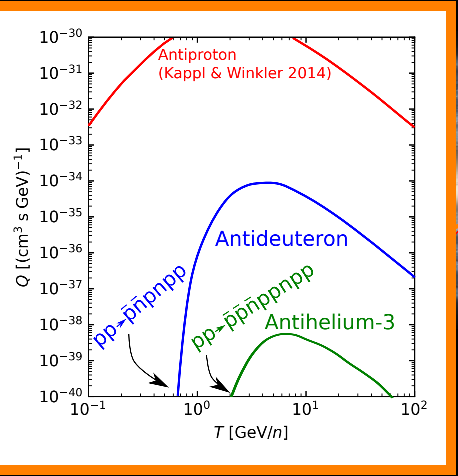
Why coalescence of light (anti)nuclei?

1. Composite structure
2. Small binding energy

$\Rightarrow$ Sensitive probe for the QCD phase diagram

Motivation: Cosmic ray antinuclei



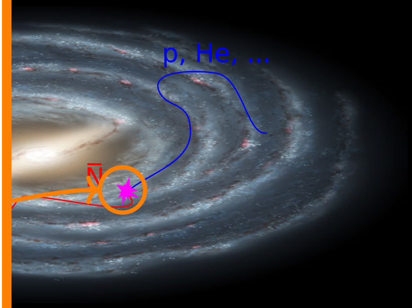
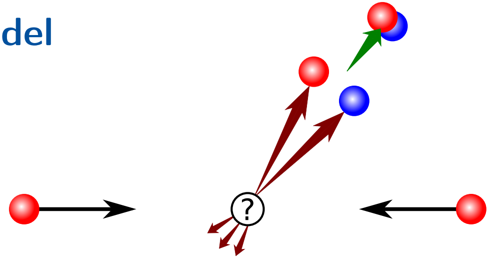


Image credit: NASA JPL; NASA AMS

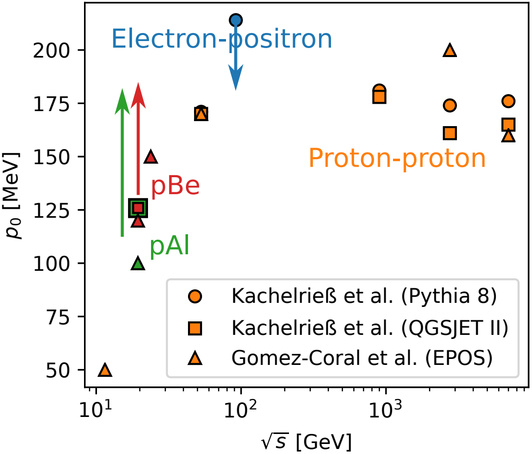
The coalescence model



- Nucleon capture process $p + n \to d^*$
- $E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}P_A^3} = B_A \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}P_p^3} \right)^Z \left(E_n \frac{\mathrm{d}^3 N_n}{\mathrm{d}P_n^3} \right)^N \Bigg|_{P_p = P_n = P_A/A}$
- Small interacting systems: $B_A \propto p_0^{3(A-1)}$
- Large interacting systems: $B_A \propto V^{A-1}$

  Both momentum correlations and the emission volume should be taken into account

The coalescence model in momentum space



(Tjemsland [2012.12252])

The quantum mechanics of coalescence

$$\frac{\mathrm{d}^3 N_d}{\mathrm{d}p_d^3} = \mathsf{tr}\,\rho_d \rho_{\mathrm{nucl}}$$ (Scheibl and Heinz [nucl-th/9809092])

$$\Rightarrow \frac{\mathrm{d}^3 N_d}{\mathrm{d}P_d^3} = \frac{3}{8(2\pi)^3} \int \mathrm{d}^3 r_d \int \frac{\mathrm{d}^3 q\, \mathrm{d}^3 r}{(2\pi)^3} \mathcal{D}(\vec{r}, \vec{q})\, W_{np}(\vec{p}_p, \vec{p}_n, \vec{r}_p, \vec{r}_n)$$

- Internal deuteron Wigner function → $\mathcal{D}(\vec{r}, \vec{q})$
- Two-nucleon Wigner function → $W_{np}(\vec{p}_p, \vec{p}_n, \vec{r}_p, \vec{r}_n)$

The two-nucleon Wigner function

- **Example: thermal nucleons** (Sun et al. [1812.05175])

$$W_{np} = f_n f_p; \quad f(p, r) \sim \exp\left(-\frac{p^2}{2mT_K} - \frac{r^2}{2\sigma^2}\right)$$

$$\frac{N_d}{N_p N_n} \sim \left(\frac{mT_K d^2}{mT_K d^2 + 1}\right)^{3/2} \left(\frac{d^2}{d^2 + 4\sigma^2}\right)^{3/2}$$

- **The WiFunC model** (Kachelriess et al. [1905.01192])

$$W_{np} = H_{np}(\vec{r}_n, \vec{r}_p) G_{np}(\vec{p}_n, \vec{p}_p)$$

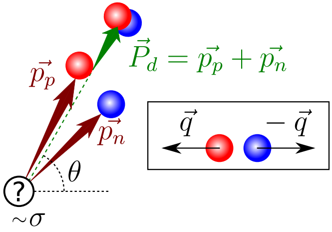
$$H_{np}(\vec{r}_n, \vec{r}_p) = h(\vec{r}_n) h(\vec{r}_p) \qquad h(\vec{r}) = (2\pi\sigma^2)^{-3/2} \exp\left\{-\frac{r^2}{2\sigma^2}\right\}$$

The WiFunC model for (anti)deuteron

Coalescence probability

$$w = 3\zeta \mathrm{e}^{-d^2 q^2}$$

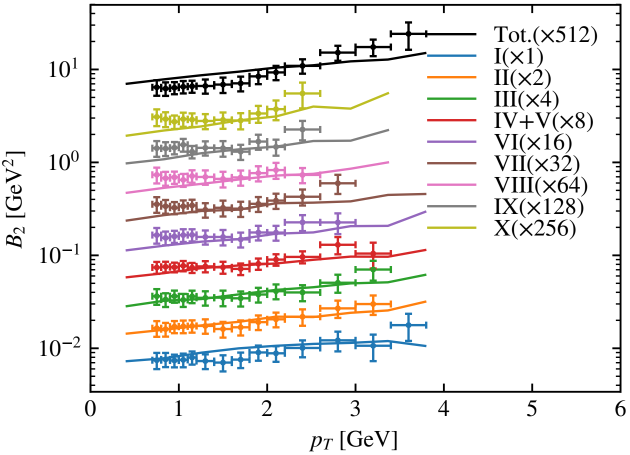
$$\zeta = \sqrt{\frac{d^2}{d^2 + 4\sigma^2 m_T^2/m^2} \frac{d^2}{d^2 + 4\sigma^2}}$$



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

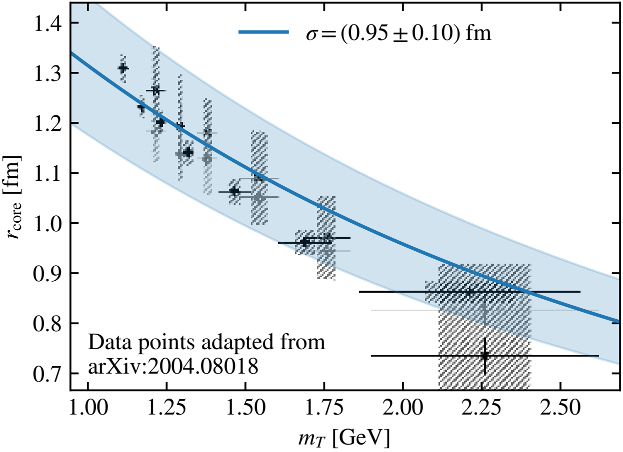
Can be added to nearly any event generator to describe the production of light (anti)nuclei in small interacting systems

Coalescence factor, $B_2(p_T)$



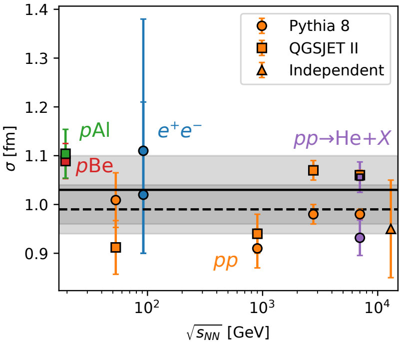
QGSJET II, ALICE *pp* 13 TeV

Experimental data: baryon emission source



ALICE *pp* 13 TeV

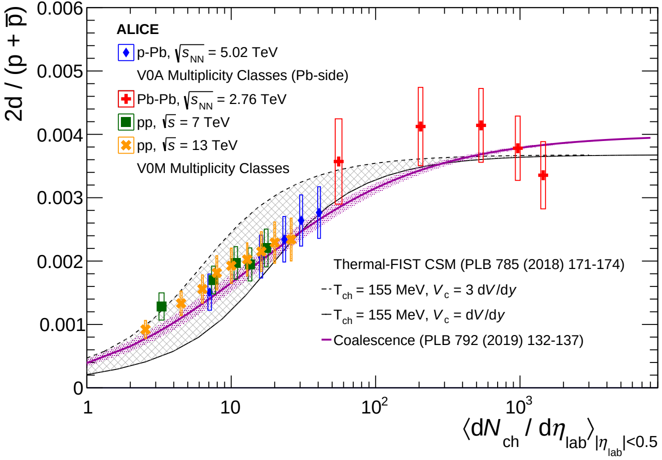
Experimental data: the coalescence parameter



(Tjemsland [2012.12252])

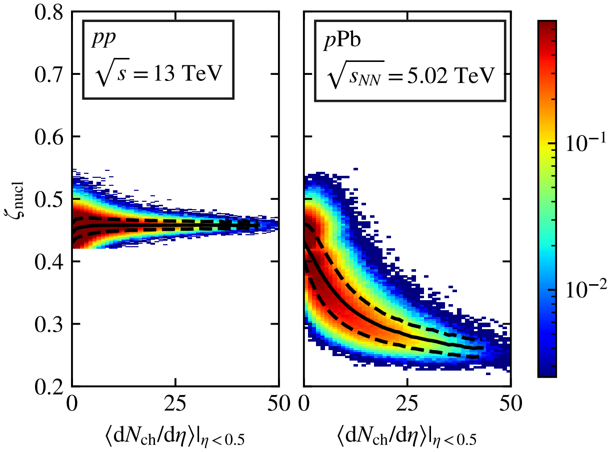
The success of femtoscopy studies indicates coalescence being a major production mechanism of (anti)nuclei (Bellini et al. [2007.01750])

Larger interacting systems



(Acharya [2003.03184])

Larger interacting systems



QGSJET II, σ determined by # spectators

Alternative descriptions of the emission volumes

Some event generators have implemented a description of the space-time structure:

- Pythia 8 (Ferreres-Solé and Sjöstrand [1808.04619])
- UrQMD (Bleicher [hep-ph/9909407])

Simple coalescence model (UrQMD):
$\Delta p < p_0$ and $\Delta r < r_0$ (Sombun et al. 2019)

Can instead use:

$$w = 3 \exp\left\{ -\frac{r^2}{d^2} - q^2 d^2 \right\}$$

Summary

- The production of (anti)nuclei in small interacting systems (e.g. e^+e^-, pp, pN and peripheral NN) collisions should be considered on an event-by-event basis taking into account both momentum correlations and the nucleon emission volume
- Recent hadron correlation experiments are consistent with QCD inspired event generator and coalescence without any need for invoking collective flow
- An improved coalescence model for light (anti)nuclei

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

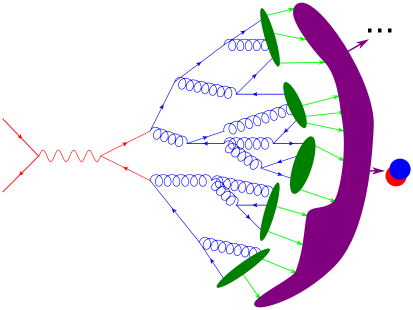
BACKUP SLIDES

Timescales

Point-like process

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

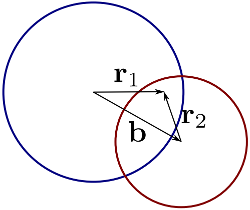
$\Rightarrow \sigma_{(\text{point-like})} \sim \text{ fm}$



Geometrical contribution

- Multiple parton-parton interactions

$\Rightarrow \sigma_{(\text{geom})} \sim R_N \sim \text{ fm}$

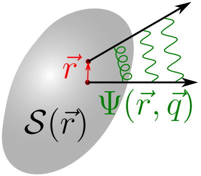


$r^d_{\text{rms}} \sim 2\text{ fm} \sim L_0 \Longrightarrow$ The size of the formation region and momentum correlations must be taken into account!

Femtoscopy experiments

- Measurable quantity:

$$\mathcal{C}(\vec{q}) = \int \mathrm{d}^3 r\, \mathcal{S}(\vec{r}) |\Psi(\vec{r}, \vec{q})|^2$$



- A Gaussian source if often assumed in experiments

$$\mathcal{S}(\vec{r}) \sim \exp\left\{-\frac{r^2}{4r_0^2}\right\}$$

- The nucleon Wigner functions predict the baryon source

$$W_{np} \sim \exp\left\{-\frac{r_z^2}{4\sigma_\parallel^2} - \frac{r_y^2}{4\sigma_\perp^2} - \frac{r_\perp^2}{4\sigma_\perp^2}\frac{m_T^2}{m^2}\right\}$$

Improving the deuteron wave function

The ground state of the deuteron is well described by the Hulthen wave function,

$$\varphi_d(\vec{r}) = \sqrt{\frac{\alpha\beta(\alpha+\beta)}{2\pi(\alpha-\beta)^2}}\,\frac{\mathrm{e}^{-\alpha r} - \mathrm{e}^{-\beta r}}{r},$$

with $\alpha = 0.23\mathrm{fm}^{-1}$ and $\beta = 1.61\mathrm{fm}^{-1}$ (Zhaba 2017).

Two-Gaussian wave function:

$$\varphi_d(\vec{r}) = \pi^{-3/4}\left(\mathrm{i}\sqrt{\frac{\Delta}{d_1^3}}\mathrm{e}^{-r^2/2d_1^2} + \sqrt{\frac{1-\Delta}{d_2^3}}\mathrm{e}^{-r^2/2d_2^2}\right).$$

The new coalescence model for (anti)deuteron

Coalescence probability

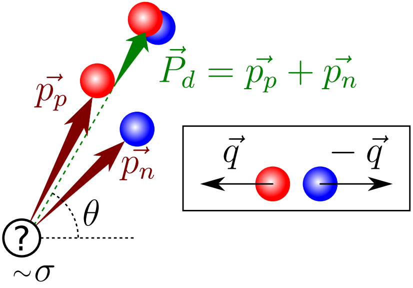
$$w = 3\Delta\zeta_1 \mathrm{e}^{-d_1^2 q^2} + 3(1-\Delta)\zeta_2 \mathrm{e}^{-d_2^2 q^2}$$

$$\zeta_i = \frac{d_i^2}{d_i^2 + 4\tilde{\sigma}^2}\sqrt{\frac{d_i^2}{d_i^2 + 4\sigma^2}}$$

$$\tilde{\sigma}^2 = \sigma^2/(\cos^2\theta + \gamma^2 \sin^2\theta)$$

$\Delta = 0.581$, $d_1 = 3.979\ \mathrm{fm}$,

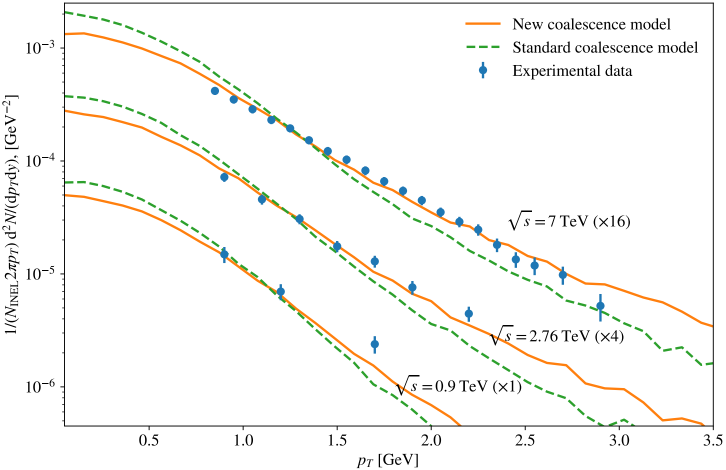
$d_2 = 0.890\ \mathrm{fm}$



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

Can be added to nearly any event generator to describe the production of light (anti)nuclei in small interacting systems

Experimental data: antideuteron spectrum



Proton-proton collisions, ALICE [1709.08522]   MC: Pythia 8.2

Coalescence of helium-3 and tritium

Helium-3 and tritium formation model

$$\frac{\mathrm{d}^3 N_{\mathrm{He}}}{\mathrm{d}P_{\mathrm{He}}^3} = \frac{64 s\zeta}{\gamma(2\pi)^3} \int \frac{\mathrm{d}^3 p_1}{(2\pi)^3} \frac{\mathrm{d}^3 p_2}{(2\pi)^3} G_{N_1 N_2 N_3}(-\vec{p}_2 - \vec{p}_3, \vec{p}_2, \vec{p}_3) \mathrm{e}^{-b^2 P^2},$$

$$\zeta = \left(\frac{2b^2}{2b^2 + 4\sigma^2} \right)^3,$$

$$P^2 = \frac{1}{3} \left[(\vec{p}_1 - \vec{p}_2)^2 + (\vec{p}_2 - \vec{p}_3)^2 + (\vec{p}_2 - \vec{p}_3)^2 \right]$$

$$= \frac{2}{3} \left[\vec{p}_2^2 + \vec{p}_3^2 + \vec{p}_1 \cdot \vec{p}_2 \right].$$

$b_{^3\mathrm{He}} = 1.96$ fm; $b_t = 1.76$ fm; $s = 1/12$