Light nuclei formation
Insights with femto

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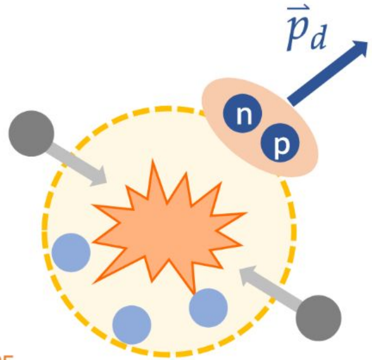
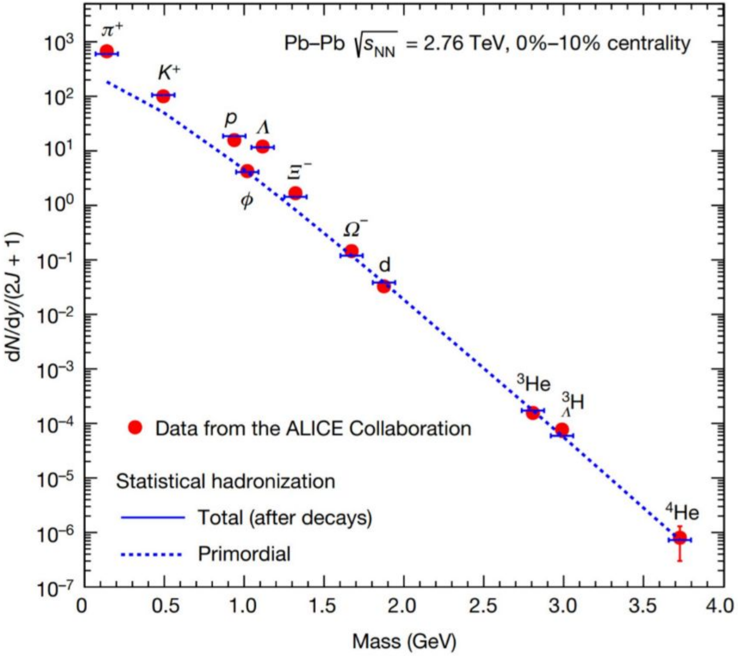
Nuclei formation mechanism: Thermal model

- 3 parameters: Temperature T, baryo-chemical potential μ_B, Volume V
- Small systems: Canonical SHM, correlation volume V_C
- Successful over 10 orders of magnitude in yield with common freeze-out parameter T_c~156 MeV (at LHC energies)
- Survival problem: How do nuclei survive the hadronic phase?





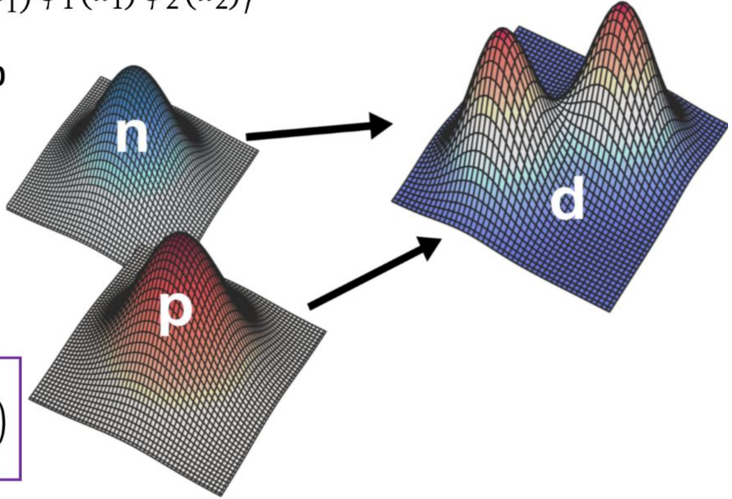
A. Andronic et al., Nature, 561, p. 321–330 (2018)

The Density matrix formalism of coalescence

- QM description of the formation process

$$\frac{\mathrm{d}^3 N_d}{\mathrm{d}P^3} = S_d \int d^3x_1 d^3x_2 d^3x_1' d^3x_2' \psi_d^*\left(\vec{x}_1',\vec{x}_2'\right) \psi_d\left(\vec{x}_1,\vec{x}_2\right) \left\langle \psi_2^\dagger\left(\vec{x}_2'\right) \psi_1^\dagger\left(\vec{x}_1'\right) \psi_1\left(\vec{x}_1\right) \psi_2\left(\vec{x}_2\right) \right\rangle$$

- In this framework we can calculate the coalescence prob



$$\mathscr{P}(\vec{q},r_0) = \mathrm{S_d} \int d^3r\, d^3r_d H_{pn}(\vec{r},\vec{r}_d; r_0) D(\vec{q},\vec{r})$$

$$H_{pn}(\vec{r},\vec{r}_d; r_0) = \frac{1}{\left(2\pi r_0^2\right)^3} exp\left(-\frac{\vec{r}_n^2+\vec{r}_p^2}{2r_0^2}\right) \qquad D(\vec{q},\vec{r}) = \int d^3\xi\, \psi_d^*\left(\vec{r}-\vec{\xi}/2\right) \psi_d\left(\vec{r}+\vec{\xi}/2\right) exp\left(i\vec{q}\cdot\vec{\xi}\right)$$

Source size

Nucleus wave function

Nucleon relative momentum

The Density matrix formalism of coalescence

- QM description of the formation process

$$\frac{d^3N_d}{dP^3} = S_d \int d^3r d^3r_d d^3q\, D(\vec{q},\vec{r}) H_{pn}(\vec{r},\vec{r}_d; r_0) G_{pn}\left(\vec{P}_d/2 + \vec{q}\right.$$

- In this framework we can calculate the coalescence probability

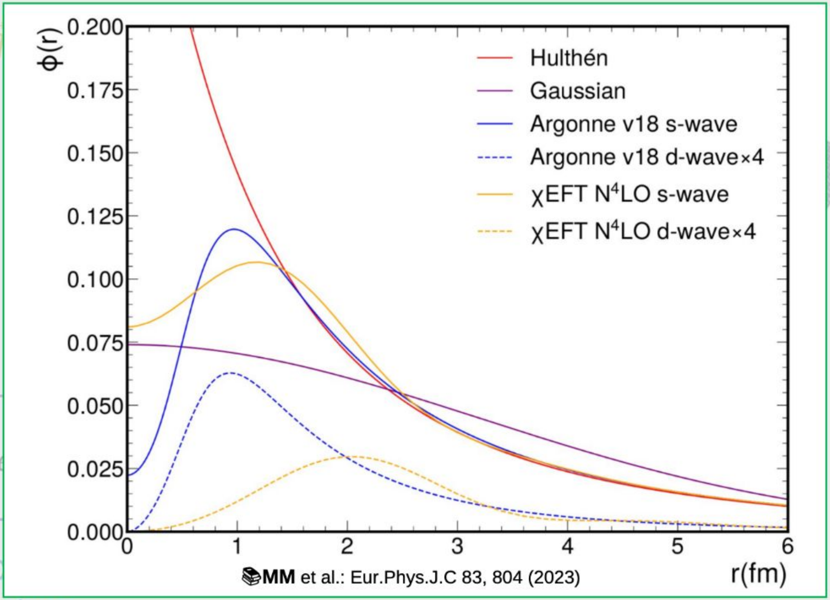
$$\mathscr{P}(\vec{q},r_0) = S_d \int d^3r\, d^3r_d H_{pn}(\vec{r},\vec{r}_d; r_0) D(\vec{q},\vec{r})$$

$$= \frac{1}{(2\pi r_0^2)^3} exp\left(-\frac{\vec{r}_n^2 + \vec{r}_p^2}{2r_0^2}\right) \qquad = \int d^3\xi\, \psi_d^*\left(\vec{r} - \vec{\xi}/2\right) \psi_d\left(\vec{r} + \vec{\xi}/2\right)$$

Source size

Deuteron wave function

Nucle momentum



The Density matrix formalism of coalescence

- QM description of the formation process

$$\frac{d^3N_d}{dP^3} = S_d \int d^3r d^3r_d d^3q \, D(\vec{q},\vec{r}) H_{pn}(\vec{r},\vec{r}_d;\, r_0) G_{pn}\left(\vec{P}_d/2+\vec{q},\vec{P}_d/2-\vec{q}\right)$$

- In this framework we can calculate the coalescence probability

$$\mathscr{P}(\vec{q},r_0) = S_d \int d^3r \, d^3r_d H_{pn}(\vec{r},\vec{r}_d;\, r_0) D(\vec{q},\vec{r})$$

$$= \frac{1}{\left(2\pi r_0^2\right)^3} exp\left(-\frac{\vec{r}_n^2+\vec{r}_p^2}{2r_0^2}\right)$$

$$= \int d^3\xi \, \psi_d^*\left(\vec{r}-\vec{\xi}/2\right) \psi_d\left(\vec{r}+\vec{\xi}/2\right) exp\left(i\vec{q}\cdot\vec{\xi}\right)$$

Source size

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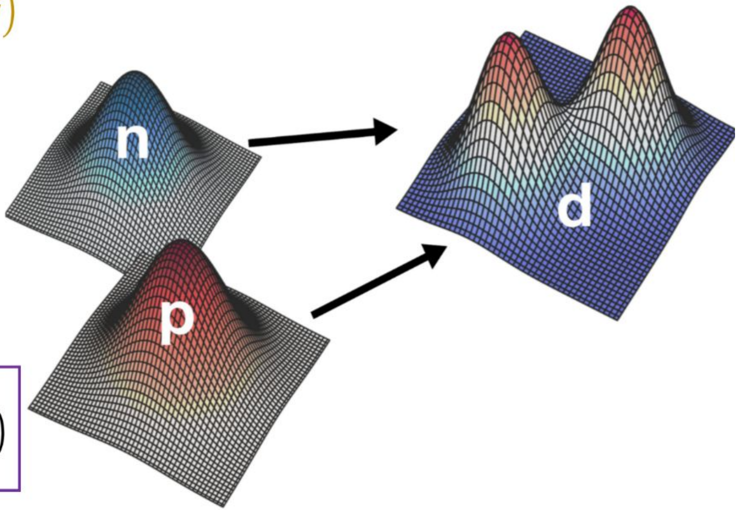


A = 3 calculation in backup

The Density matrix formalism of coalescence

- QM description of the formation process

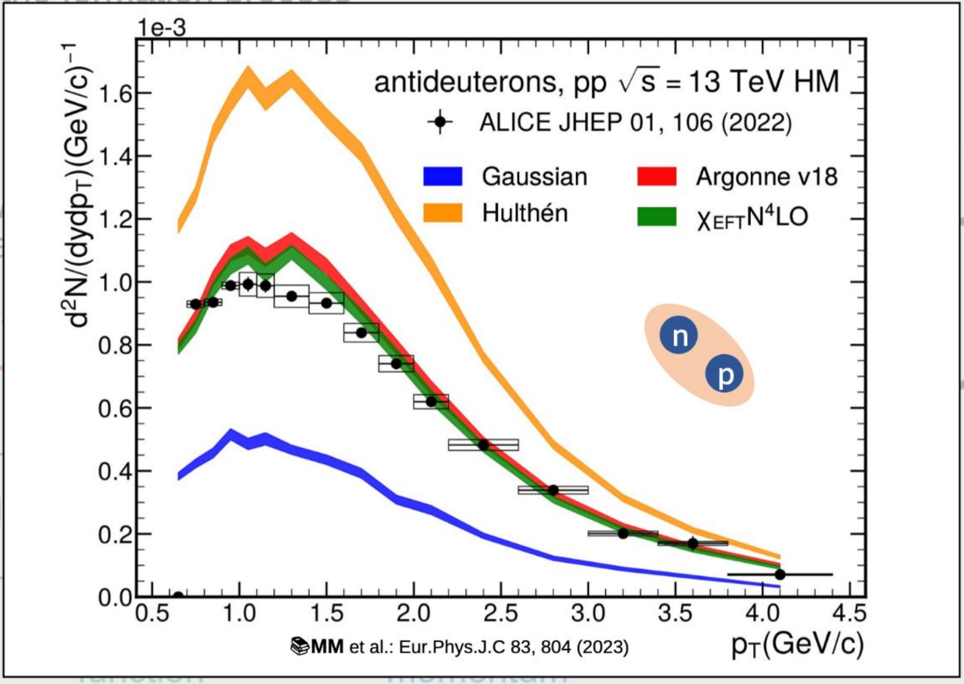
$$\boxed{\frac{d^3N_d}{dP^3}} = S_d \int d^3r d^3r_d$$

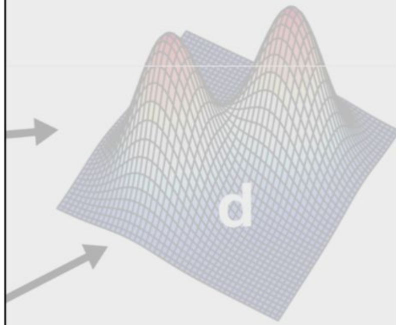
- In this framework w
coalescence proba

$$\mathscr{P}(\vec{q}, r_0) = S_d \int d^3r\, d$$

$$= \frac{1}{(2\pi r_0^2)^3} exp\left(-\frac{\vec{r}_n^2 + \vec{r}_p^2}{2r_0^2}\right)$$

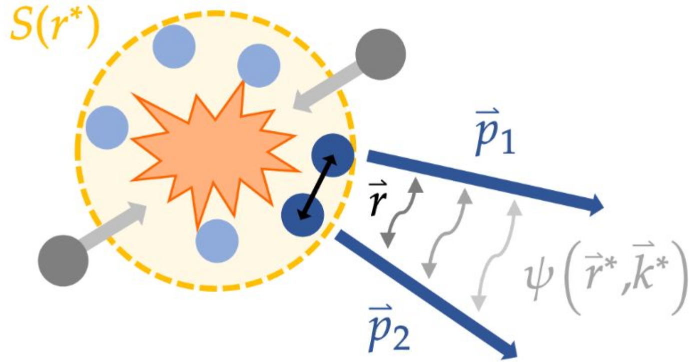
Source size



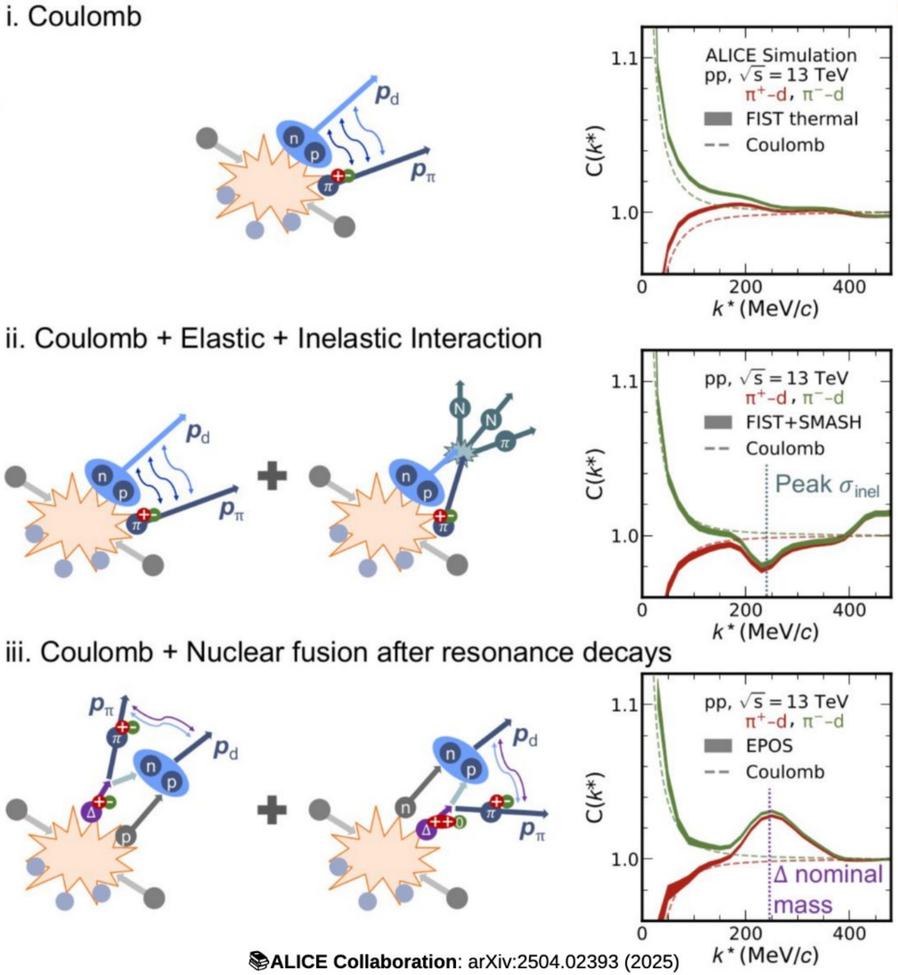


π-d Femtoscopy

- Studies the momentum correlations between particles



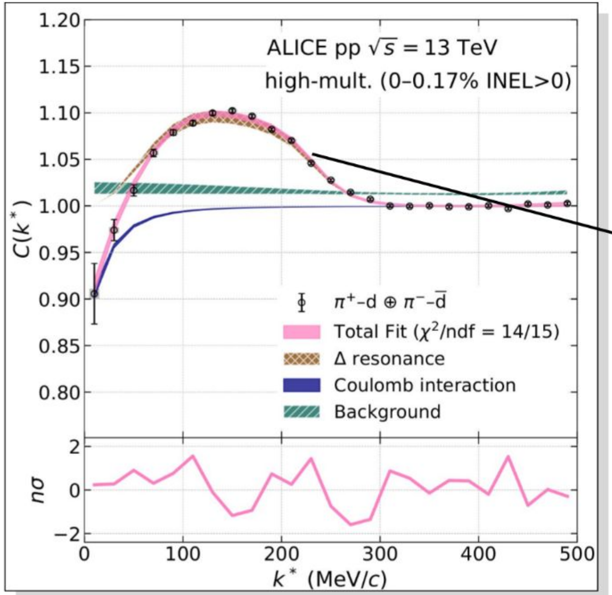
$$C(k^*) = \mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

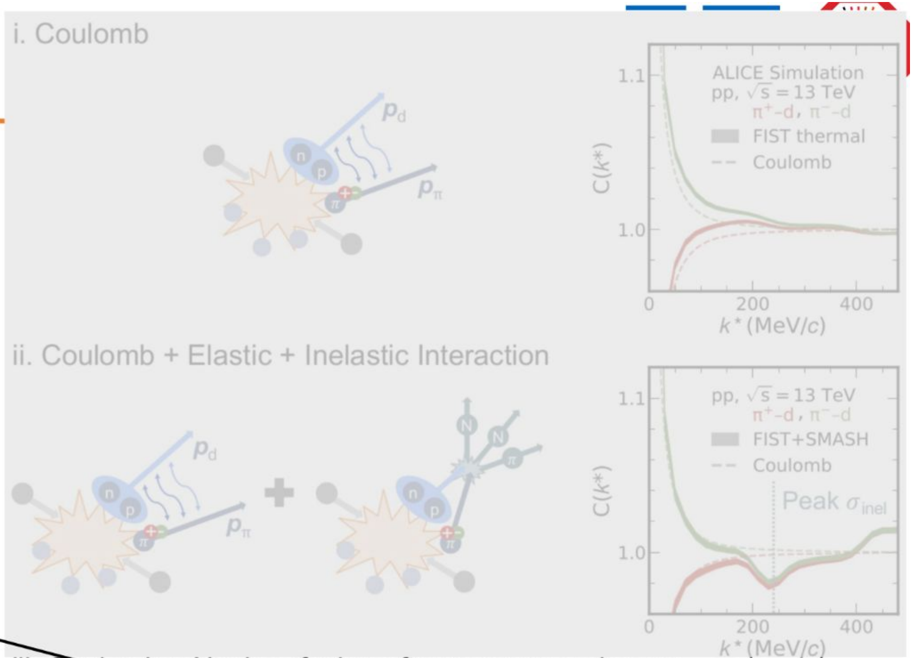


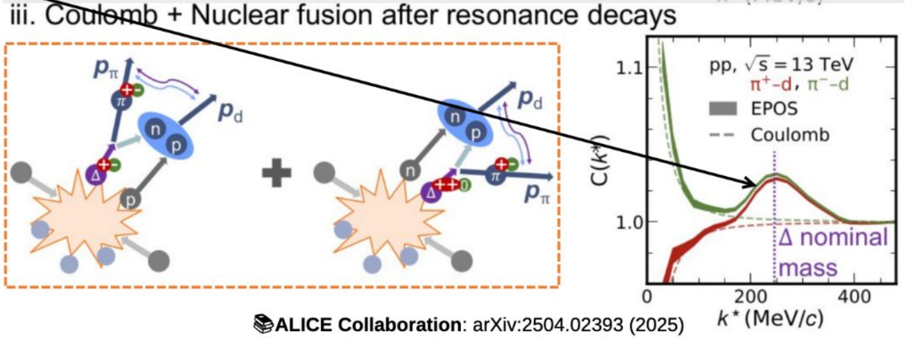
ALICE Collaboration: arXiv:2504.02393 (2025)

π-d Femtoscopy

Nuclei must be produced after the decay of resonances via coalescence processes!







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Two-particle correlation function of $p\pi^+$