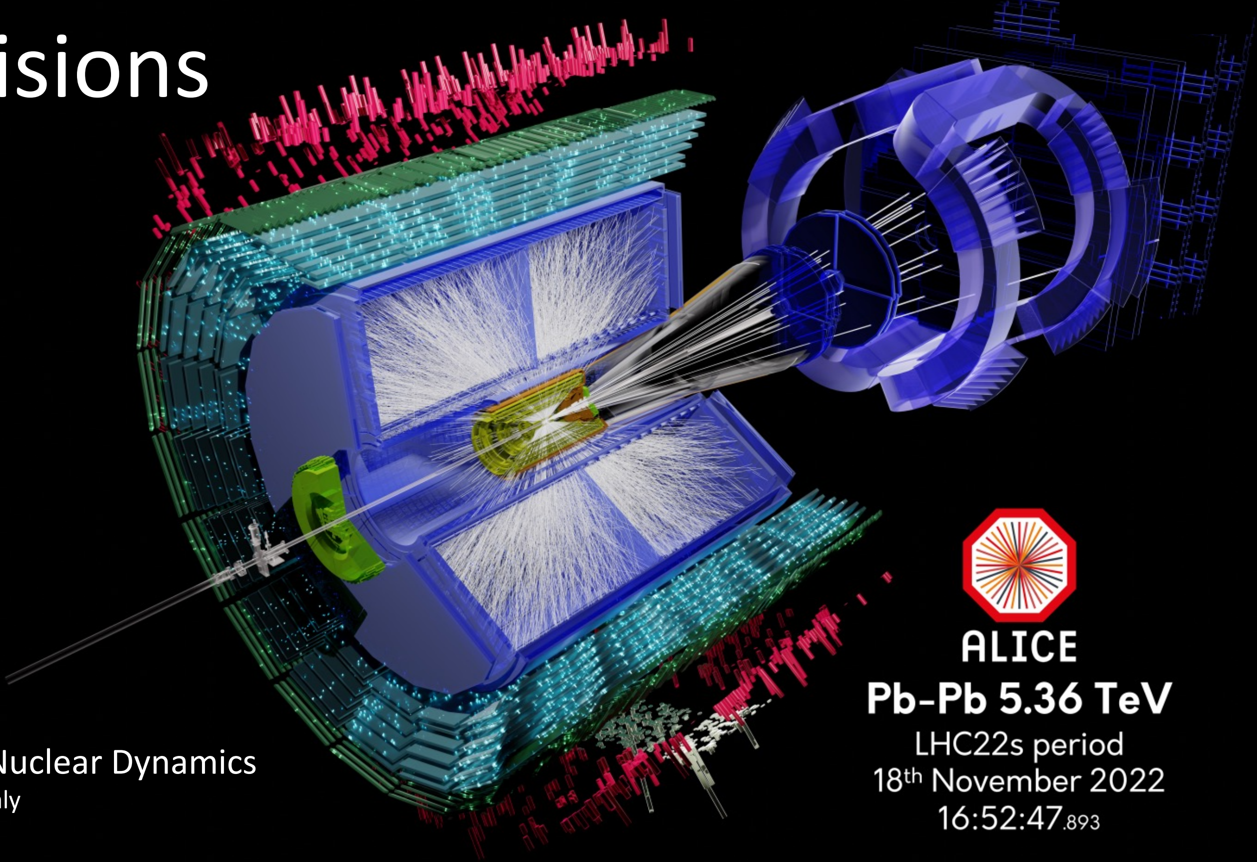
Synthesis of light nuclei in hadronic collisions

Harald Appelshäuser

Goethe Universität Frankfurt



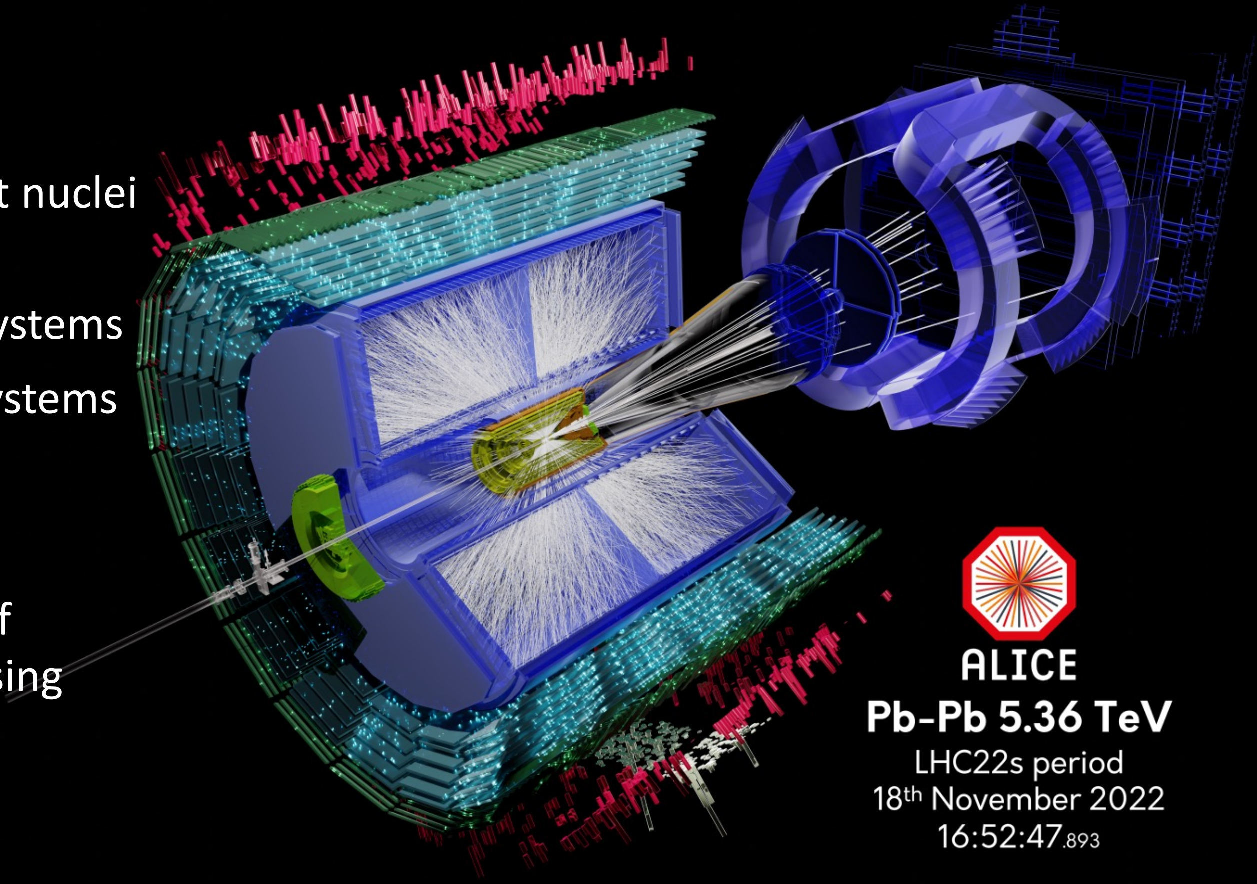
59th International Winter Meeting on Nuclear Dynamics

January 23 – 27 2023, Bormio, Italy

Outline

- Phenomenology of light nuclei production
  - in small collision systems
  - in large collision systems

- Outlook:
  - Dynamical study of nucleosynthesis using femtoscopy



Statistical hadronization

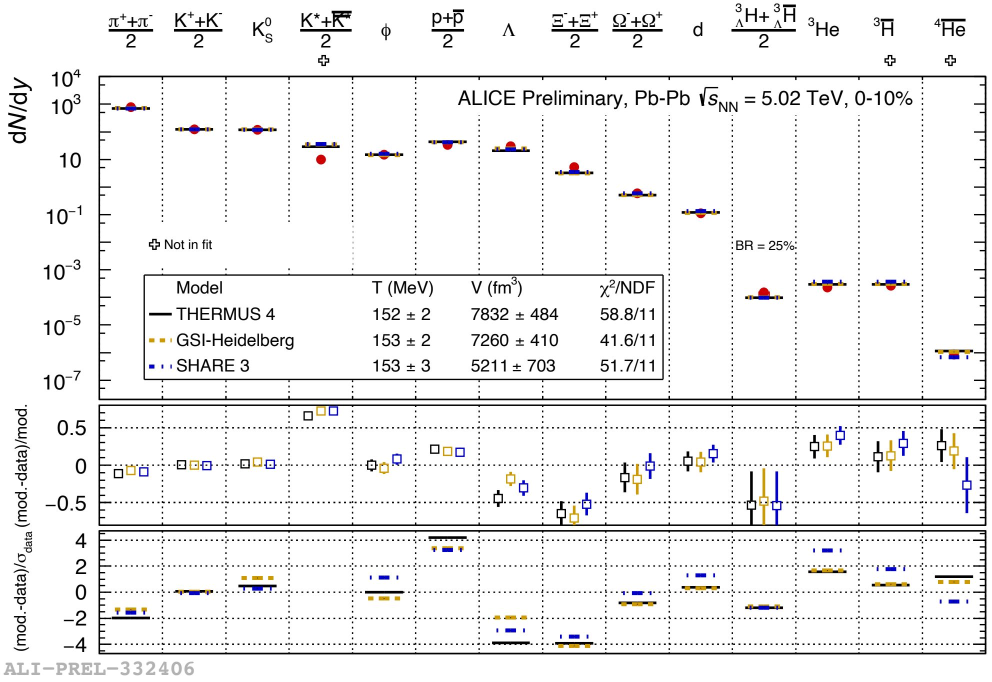
Statistical hadronization models (SHM) provide very good description of hadron production in central Pb-Pb collisions:

$$n_i = \frac{N}{V} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp\left((E_i-\mu_i)/T\right)\pm 1}$$

In the grandcanonical limit at LHC:

$$\mu_i \approx 0$$

- Production rate depends only on energy (mass) of the particle
- $T \equiv T_{ch} \approx T_c$

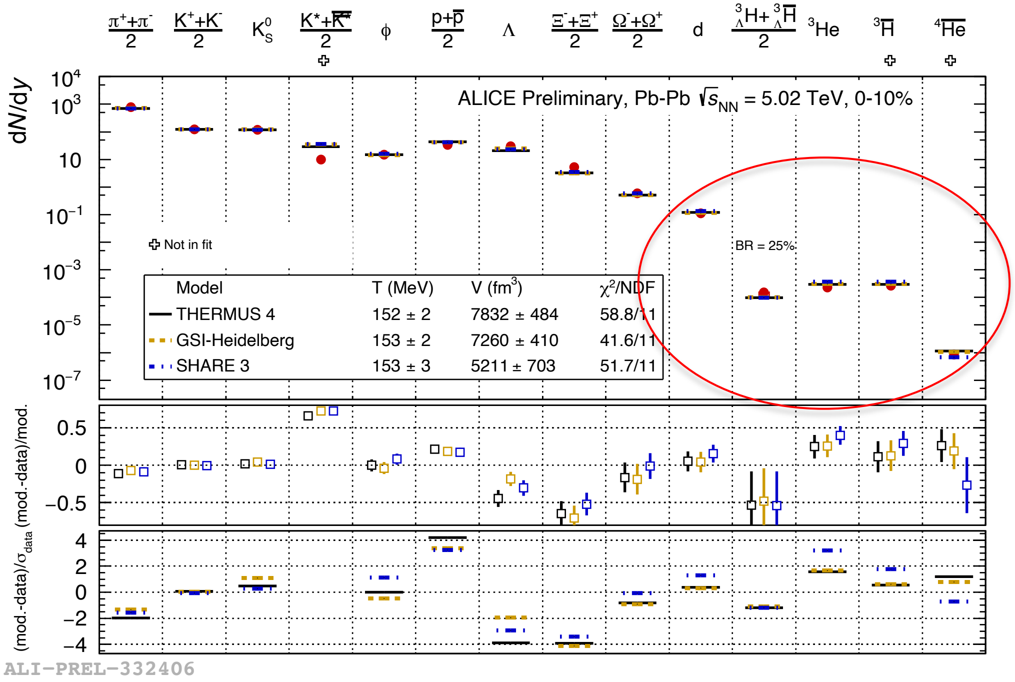


Statistical hadronization

Good description of light nuclei production is not easy to understand:

$$T_{ch} \gg E_{bind}$$

- How are nuclei produced at the phase boundary?
- How do weakly-bound objects survive a long-lived hadronic phase?



Coalescence

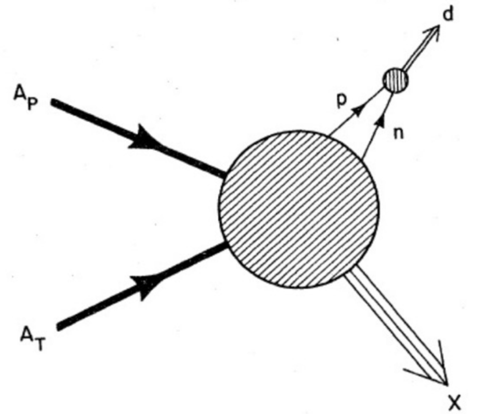
Nuclear clusters are formed after kinetic freeze-out if nucleons are close in phase space.

Coalescence into cluster A is determined by the momentum space density of n, p:

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \Big|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}$$

with coalescence parameter B_A:

$$B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{(A-1)} \frac{M}{m^A}$$



J. Kapusta, Phys. Rev. C 21 (1980) 1301

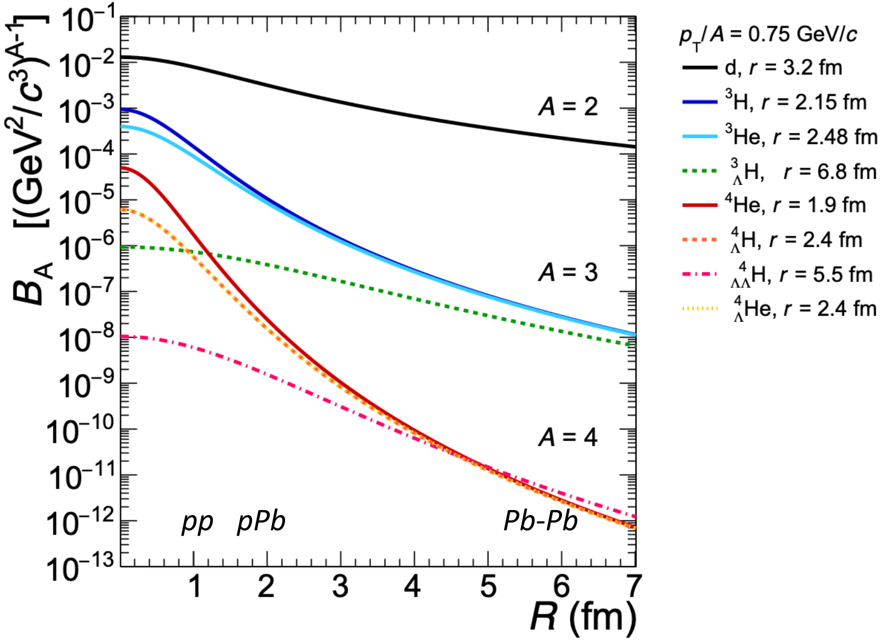
Coalescence

State-of-the-art approaches include source size R and finite size r_A of the cluster:

$$B_A = g_A \frac{1}{\sqrt{A}} \frac{1}{m_T^{A-1}} \left(\frac{2\pi}{R^2 + \left(\frac{r_A}{2}\right)^2} \right)^{\frac{3}{2}(A-1)}$$

F. Bellini, A. Kalweit, Phys. Rev. C99 (2019) 5, 054905
K.-J. Sun, C.M. Ko, B. Doenigus, PLB792 (2019)

→ System size dependence
→ Cluster size dependence
→ Momentum dependence

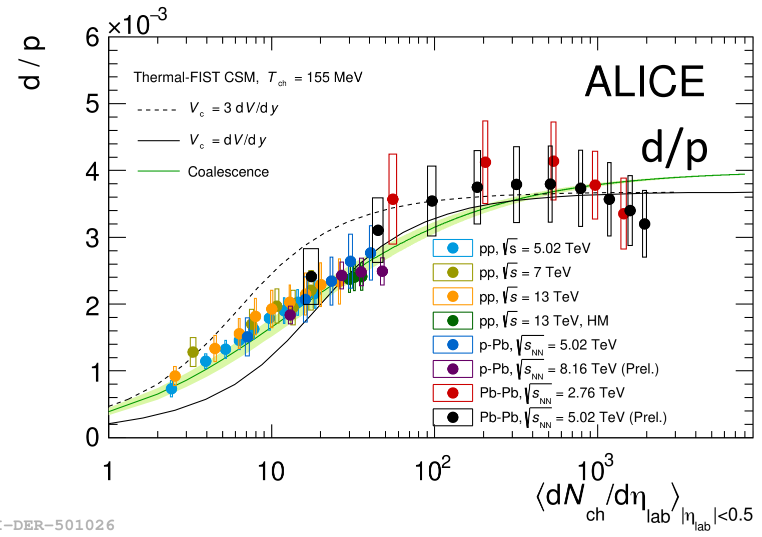


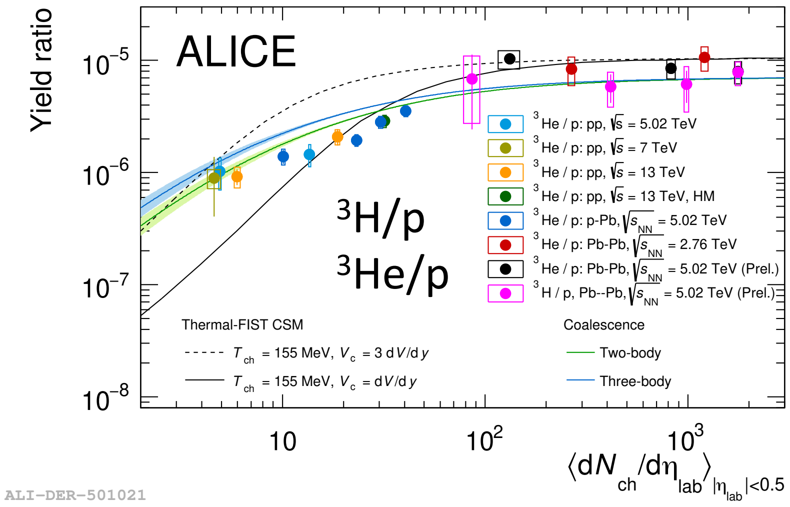
F. Bellini, A. Kalweit, Acta Phys. Pol. B, 50(6):991

Light nuclei production in small systems

Light nuclei production in small systems

Comprehensive ALICE data on d, ^{3}H and ^{3}He production in different collision systems exist:





- Suppression at small system sizes observed
- Compatible with coalescence calculations
- SHM with canonical suppression can explain data as well

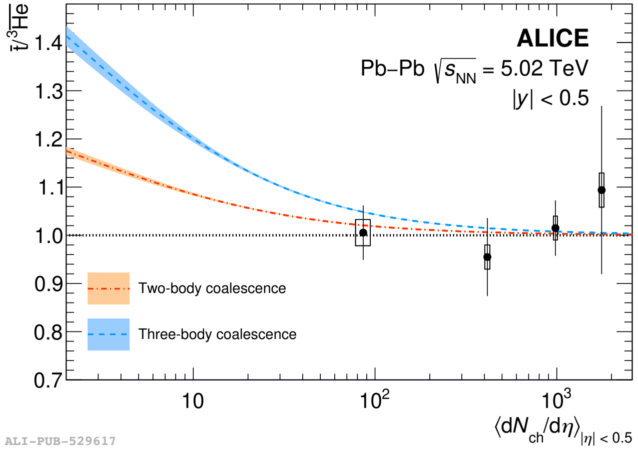
$^3H/^3He$ ratio

Coalescence predicts $^3H/^3He$ > 1 in small systems due to different nuclear radii:

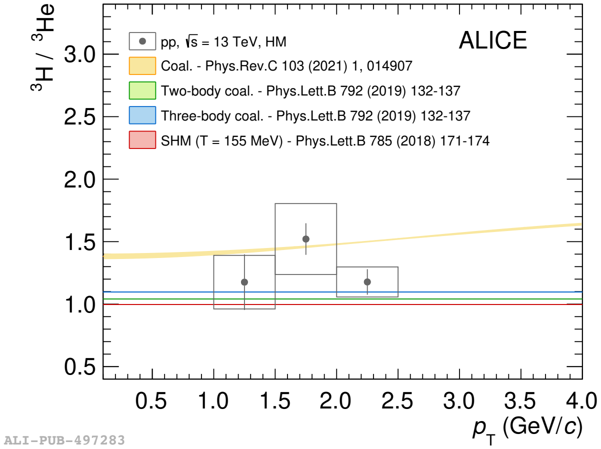
$$r_{\,^3H}/r_{\,^3He} \approx 0.9$$

while $^3H/^3He$ = 1 in SHM

ALICE, arXiv:2211.14015



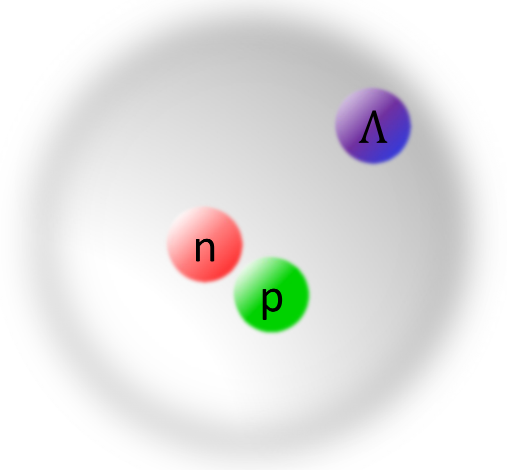
ALICE, JHEP 01 (2022) 106



- present data not yet conclusive

Hypertriton

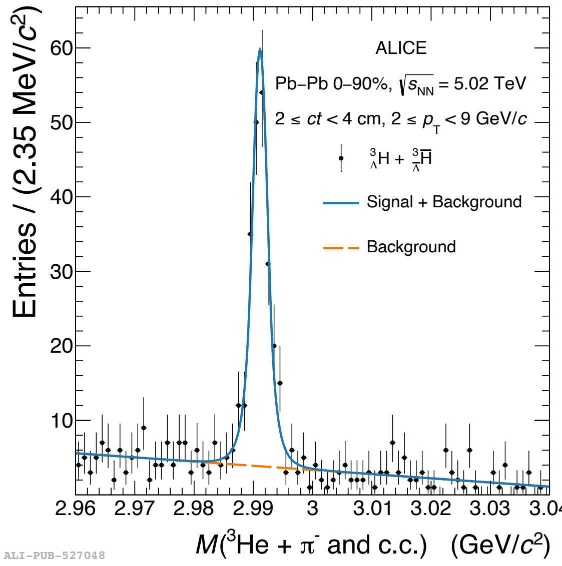
- Λ, p, n bound state
- Lightest known hypernucleus

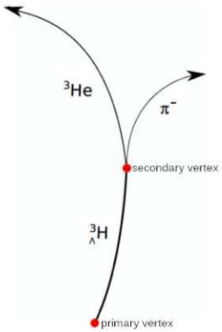


Hypertriton

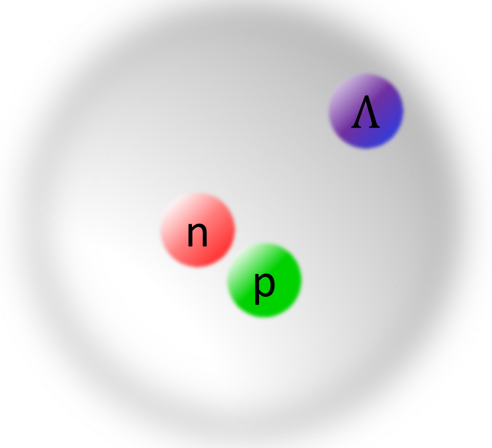
- Λ, p, n bound state
- Lightest known hypernucleus

ALICE, arXiv:2209.07360v2



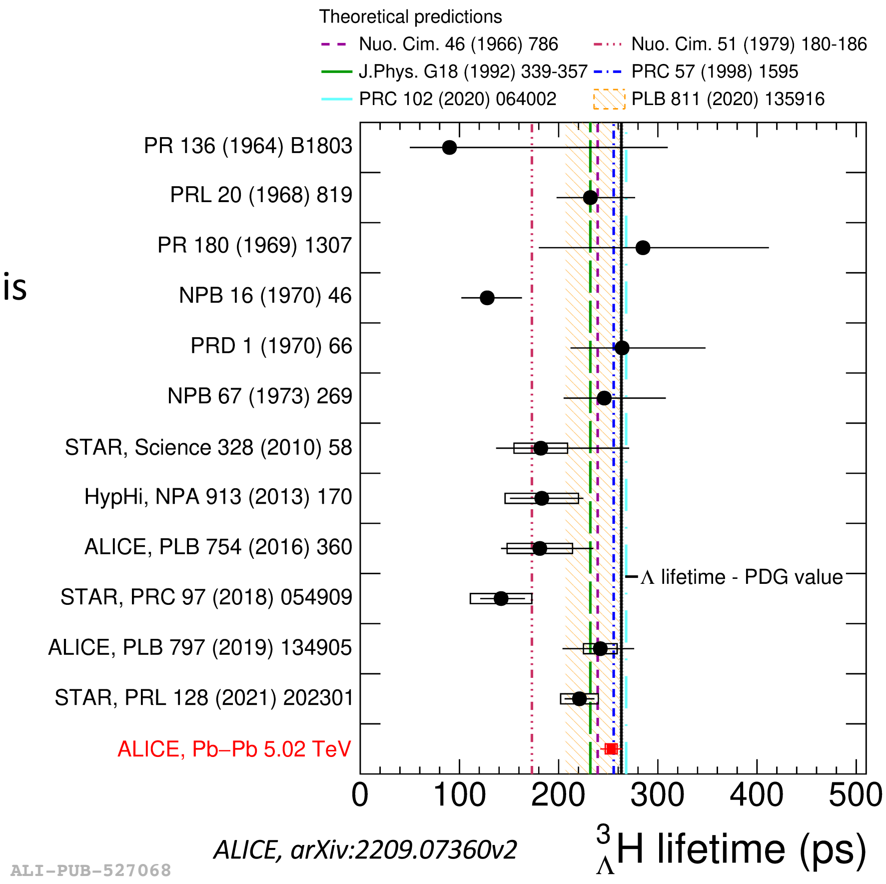


$$^{3}_{\Lambda}H \rightarrow\ ^{3}He + \pi^{-}$$



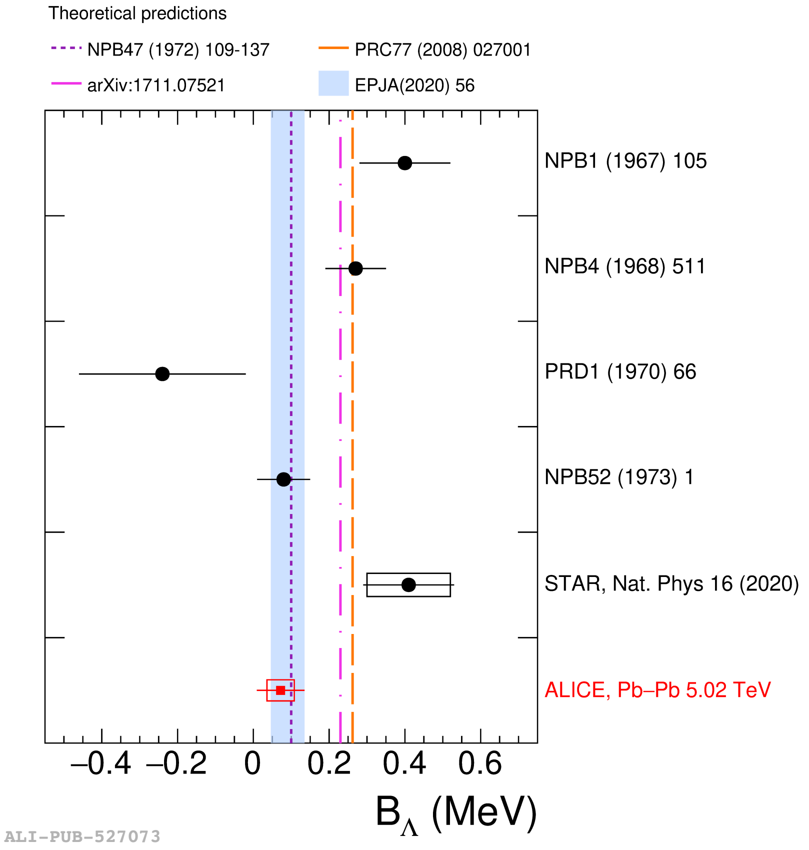
Hypertriton lifetime

- Hypertriton lifetime measured by ALICE is compatible with the free-Λ lifetime
- $\tau = 253 \pm 11\,(\text{stat.}) \pm 6\,(\text{syst.})$ ps
- No more lifetime puzzle



Hypertriton binding energy

- High-resolution mass spectroscopy allows measurement of the Λ binding energy
- $B_\Lambda = 72 \pm 63\ (\text{stat.}) \pm 36\ (\text{syst.})\ \text{keV}$
- In agreement with estimates based on $p\Lambda$ correlation data

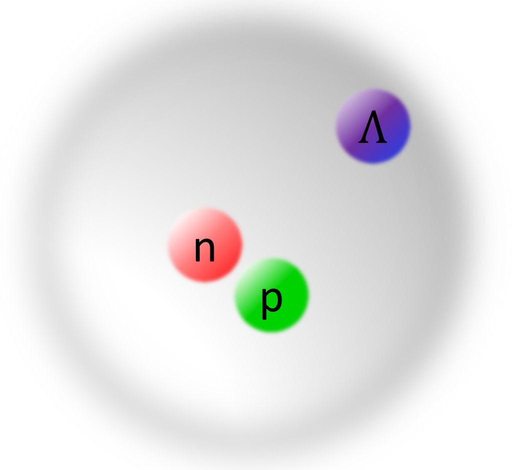


ALICE, arXiv:2209.07360v2

Hypertriton

- Λ, p, n bound state
- Lightest known hypernucleus
- Loosely bound
- Large radius ≈10 fm:

$$r_{{}^{3}_{\Lambda}H}/r_{{}^{3}He} \approx 3 - 5$$



Hypertriton coalescence

- Λ, p, n bound state
- Lightest known hypernucleus
- Loosely bound

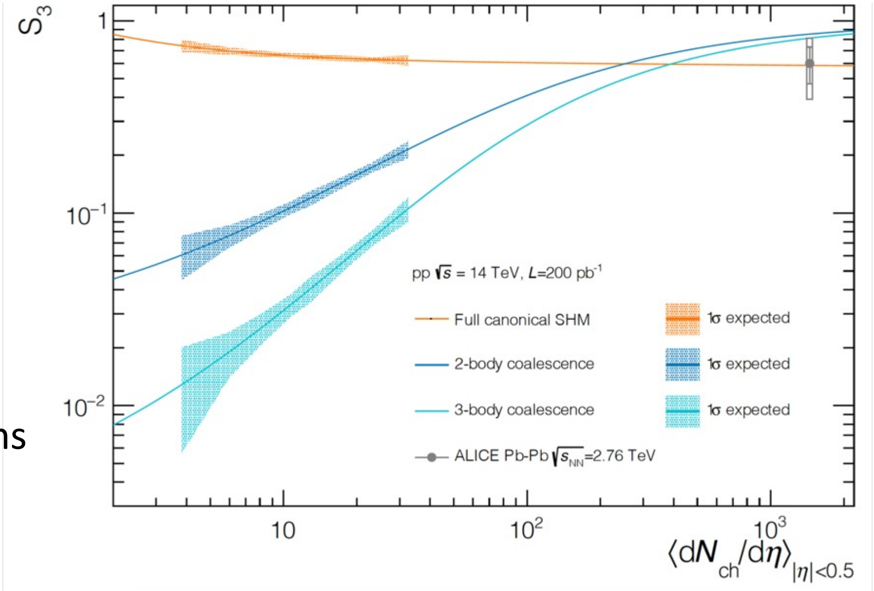
- Large radius ≈10 fm:

$$r_{{}^{3}_{\Lambda}H}/r_{{}^{3}He} \approx 3-5$$

- Large discriminating power between SHM and coalescence expected in small systems e.g. in

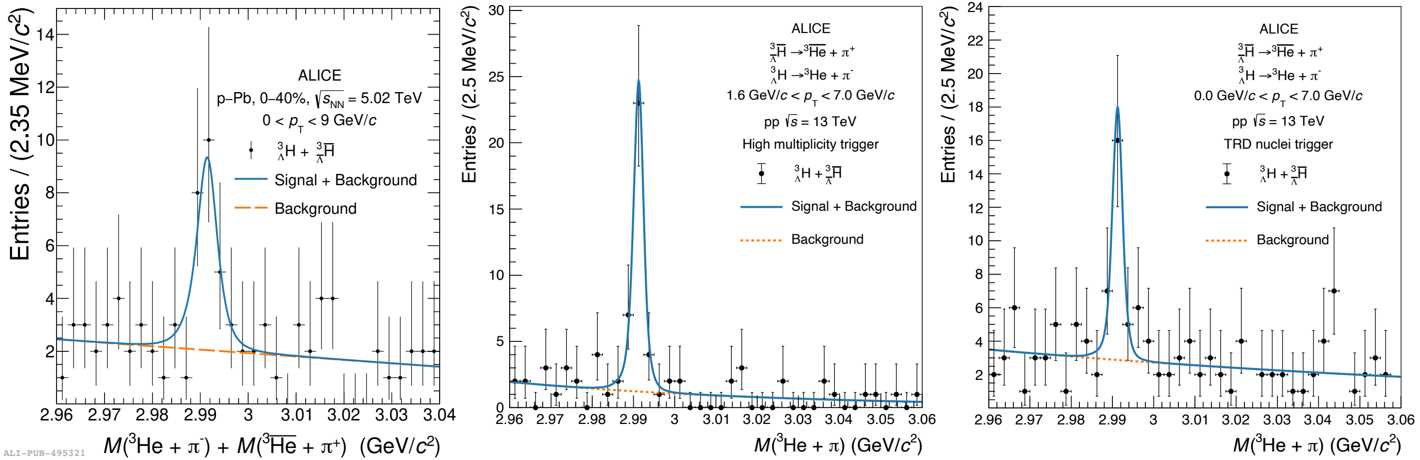
$$S_3 = \frac{{}^{3}_{\Lambda}H/\,{}^{3}He}{\Lambda/p}$$

CM: K.-J. Sun, C.M. Ko, B. Dönigus, PLB792 (2019) 132
SHM: V. Vovchenko, B. Dönigus, and H. Stoecker, PLB785 (2018) 171

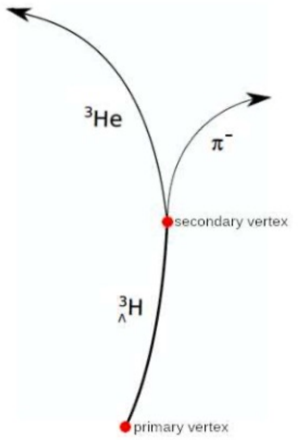


Hypertritons in pp and p-Pb

- First data available on hypertriton production in p-Pb and pp collisions from ALICE:



ALICE, PRL 128 (2022) 252003

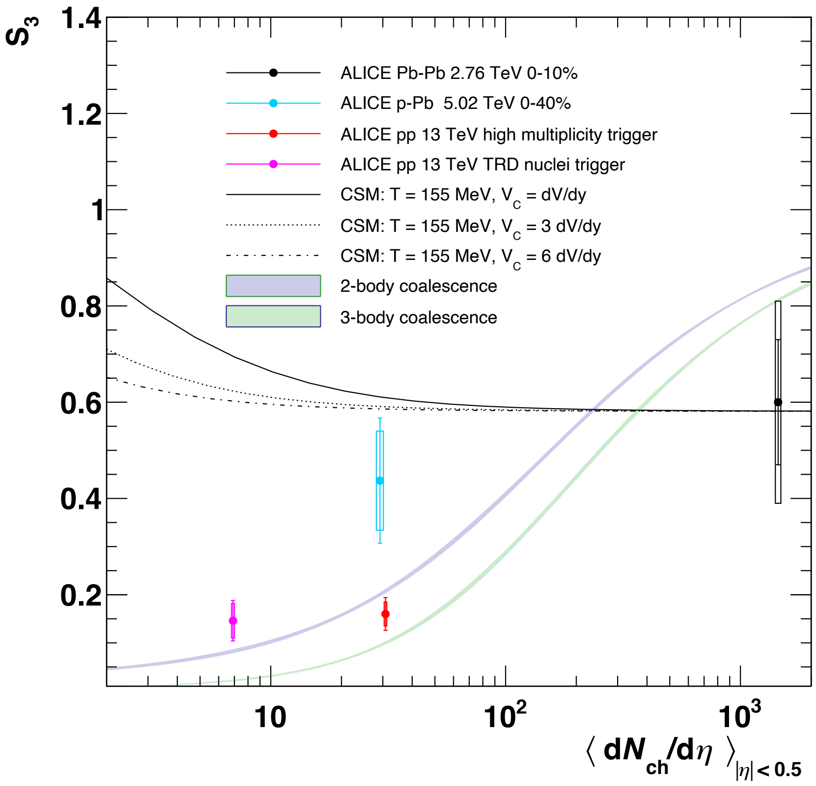


$$ {}^3_\Lambda H \rightarrow {}^3He + \pi^- $$
$$ B.R. = 0.25 $$

Hypertritons in pp and p-Pb

- First S_3 measurements in p-Pb and pp are compatible with coalescence models and disfavor SHM predictions

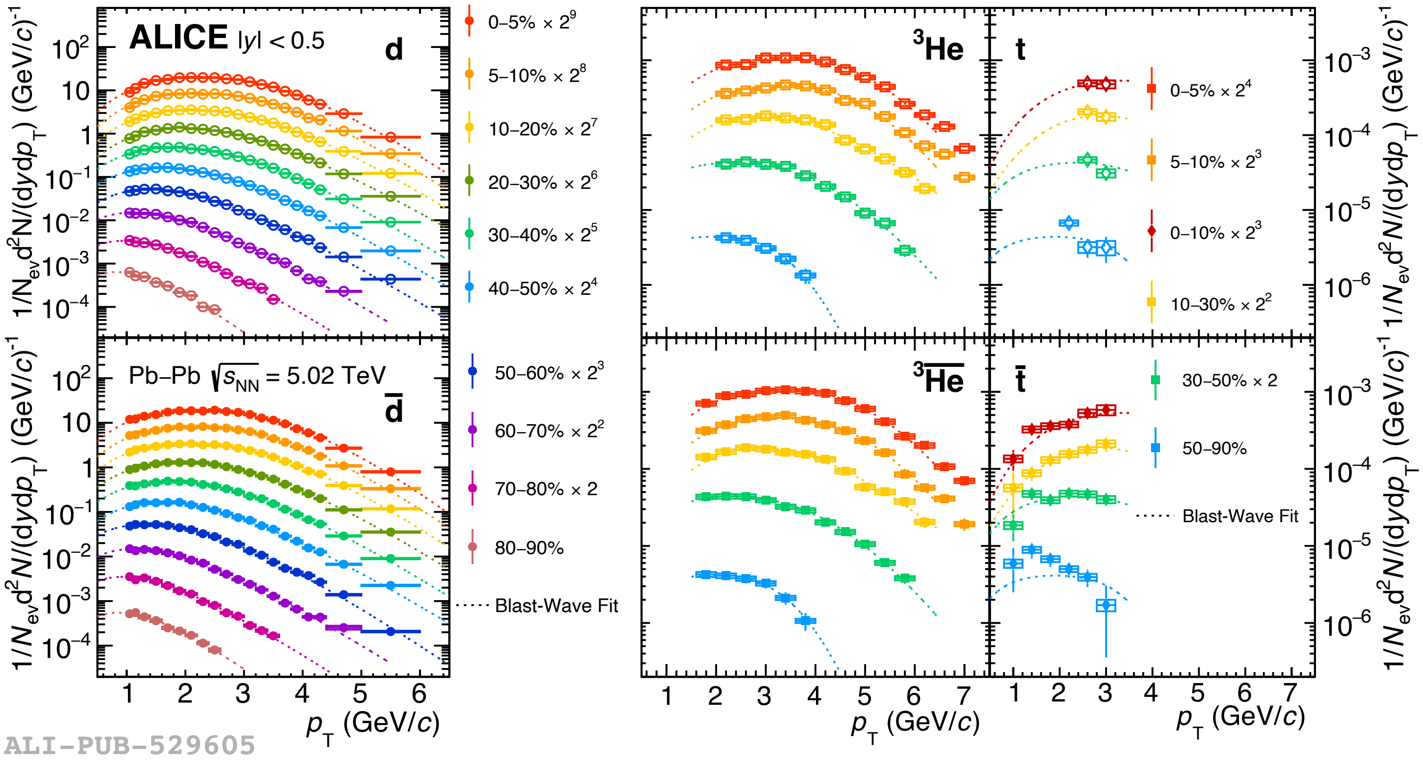
CM: K.-J. Sun, C.M. Ko, B. Dönigus, PLB792 (2019) 132
SHM: V. Vovchenko, B. Dönigus, and H. Stoecker, PLB785 (2018) 171



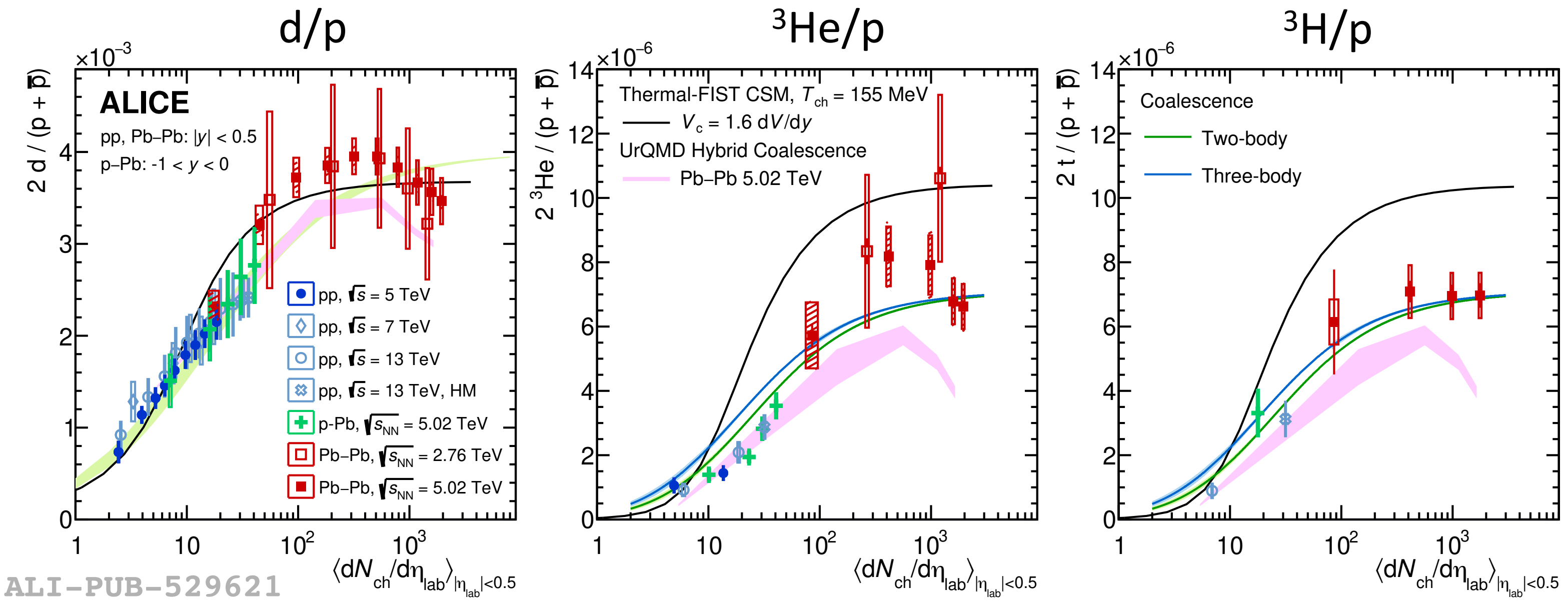
Light nuclei production in large systems

Light nuclei in large systems: Pb-Pb

$A = 2$ *ALICE, arXiv:2211.14015* $A = 3$



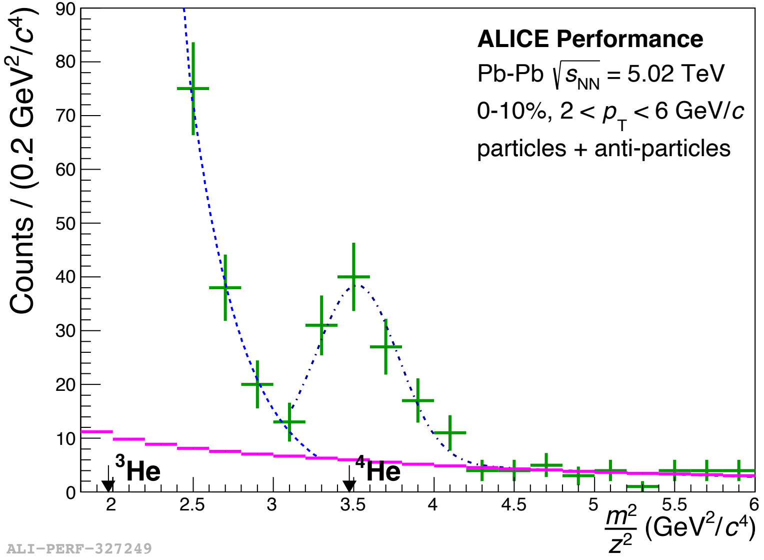
Light nuclei in Pb-Pb: ratios

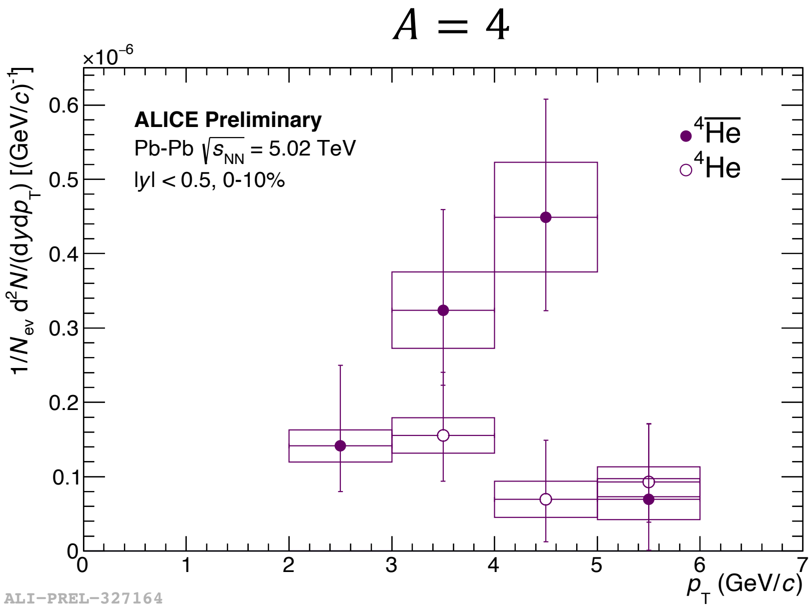


ALICE, arXiv:2211.14015

- Both coalescence and canonical SHM describe the system size dependence qualitatively
- Possible indication of absorption in central collisions

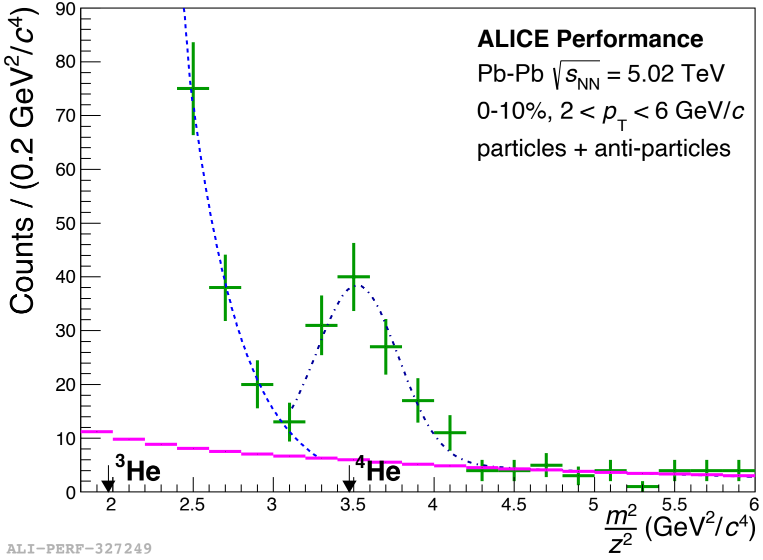
Light nuclei in Pb-Pb – ^{4}He

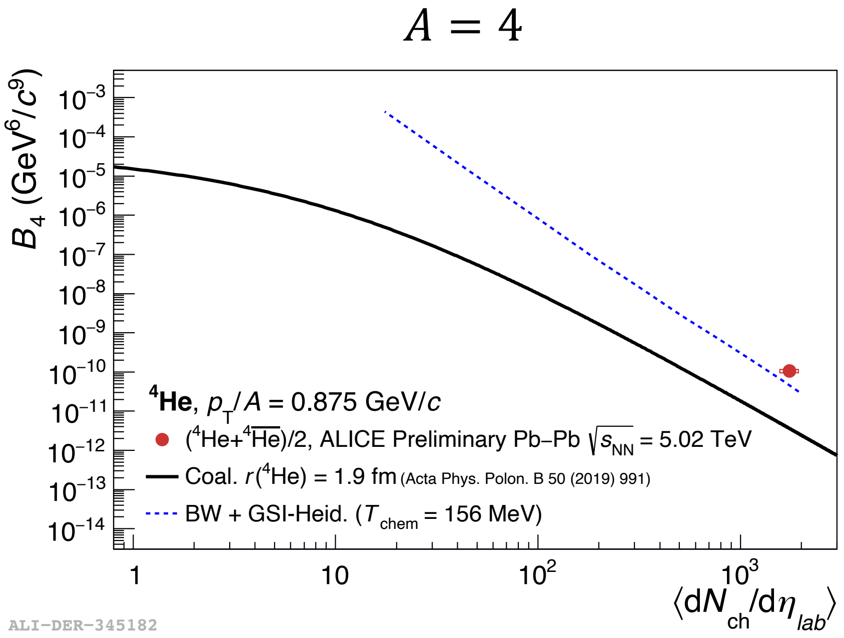




- First measurement of (anti-)^{4}He momentum spectra

Light nuclei in Pb-Pb – ^{4}He





- First measurement of (anti-)^{4}He momentum spectra
- (anti-)^{4}He production favors SHM

Nuclei freeze-out

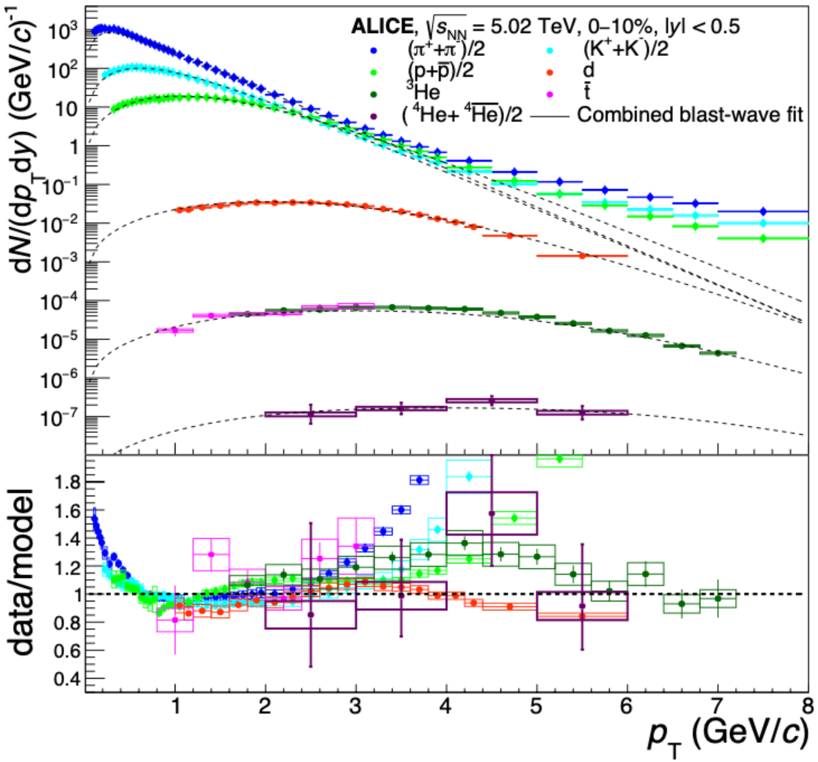
- Momentum spectra of measured hadron species (π, K, p) are compatible with a common radial flow field

$$\langle \beta \rangle \approx 0.65$$

and kinetic freeze-out temperature

$$T_{kin} \approx 115 \text{ MeV}$$

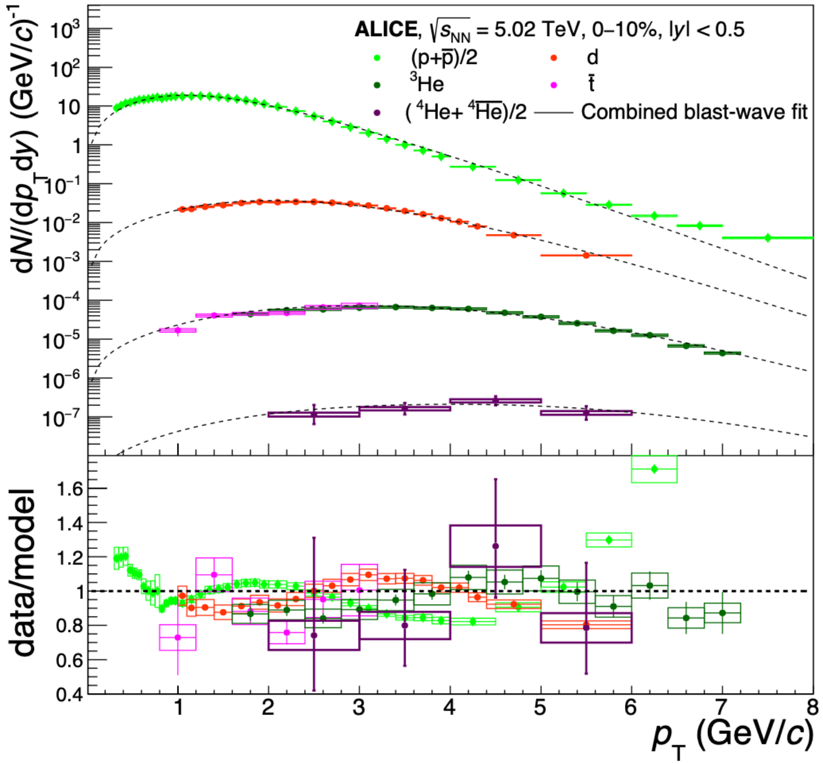
- Light nuclei (d, ^{3}He, ^{3}H, ^{4}He) are consistent with this picture



Nuclei freeze-out

- Exclusive fit of only p, d, ^{3}He, ^{3}H, ^{4}He points also to a common flow velocity

$$\langle \beta \rangle \approx 0.65$$



Nuclei freeze-out

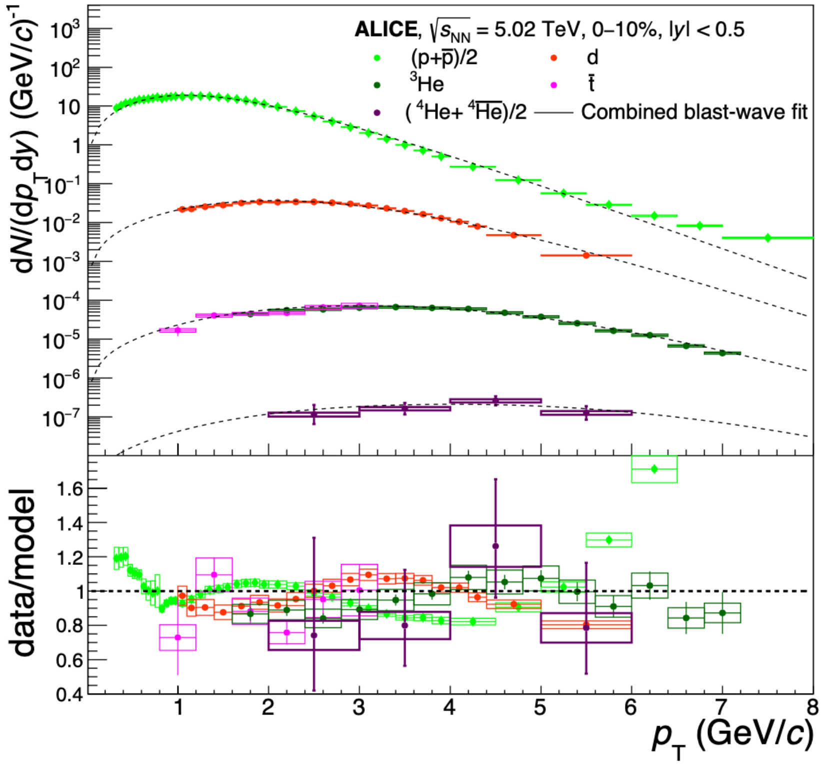
- Exclusive fit of only p, d, ^{3}He, ^{3}H, ^{4}He points also to a common flow velocity

$$\langle \beta \rangle \approx 0.65$$

but significantly larger kinetic freeze-out temperature

$$T_{kin} \approx 145 \text{ MeV}$$

i.e. $T_{kin} \lesssim T_{ch} \approx T_c$



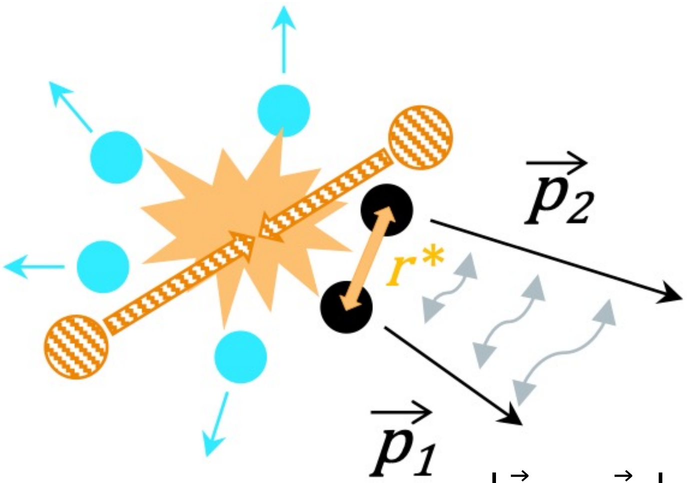
Femtoscopy as a tool to study nuclei formation

Femtoscopy

Employ final-state correlations to unravel two- (or multi-) particle dynamics

Experimental correlation function:

$$C(k^*) = A\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$



Koonin-Pratt formalism connects characteristics of the emission source with two-particle dynamics:

$$C(k^*) = \int S(r^*)|\Psi(k^*,r^*)|^2 d^3r^*$$

$$k^* = \frac{|\vec{p}_1 - \vec{p}_2|}{2}$$

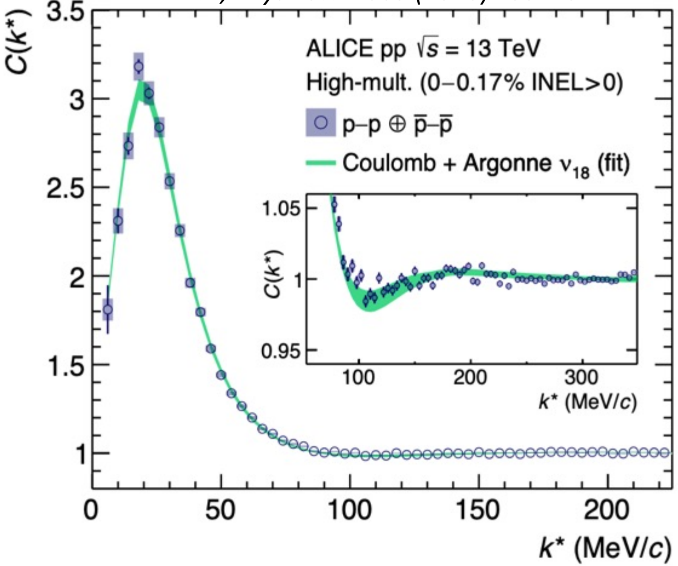
$S(r^*)$: source function

$\Psi(k^*,r^*)$: quantum statistics, final-state interactions (strong, EM)

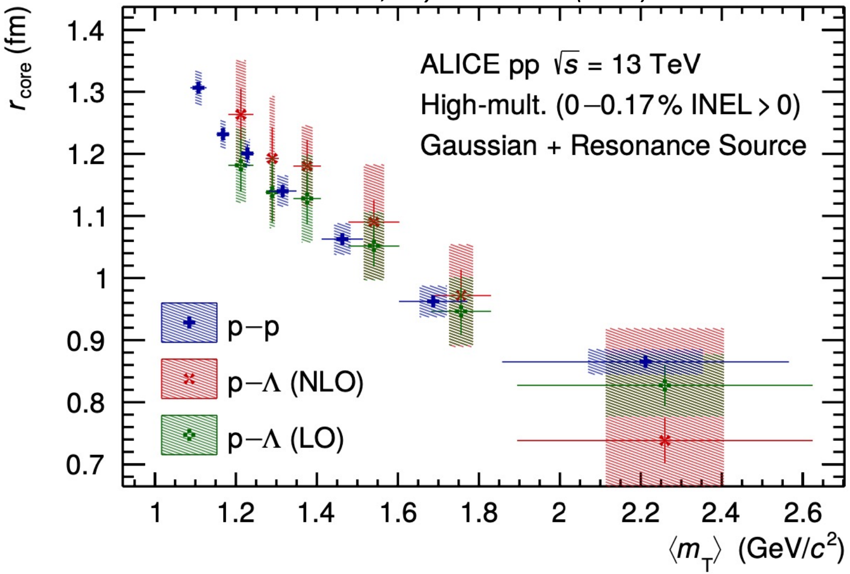
Femtoscopy 1: Source size

If $\Psi(k^*, r^*)$ is well known, study of $C(k^*)$ allows characterization of the particle source $S(k^*)$:

ALICE, Phys.Lett.B 805 (2020) 135419



ALICE, Phys.Lett.B 811 (2020) 135849

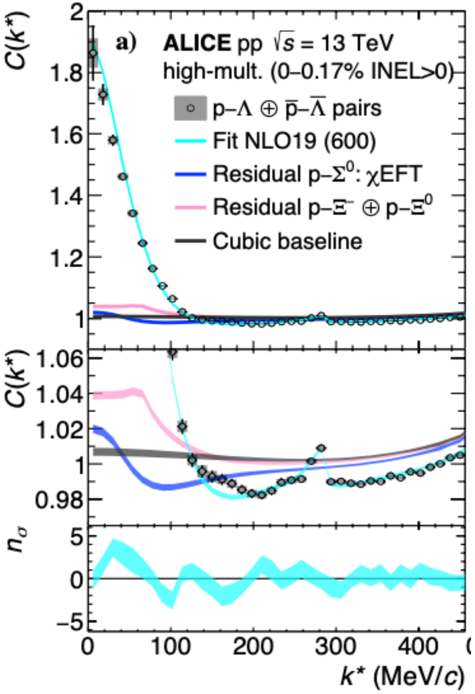


- Excellent description of the **p-p** correlation function using known interaction and quantum statistics
- Common baryon source in pp collisions observed

Femtoscopy 2: Interactions

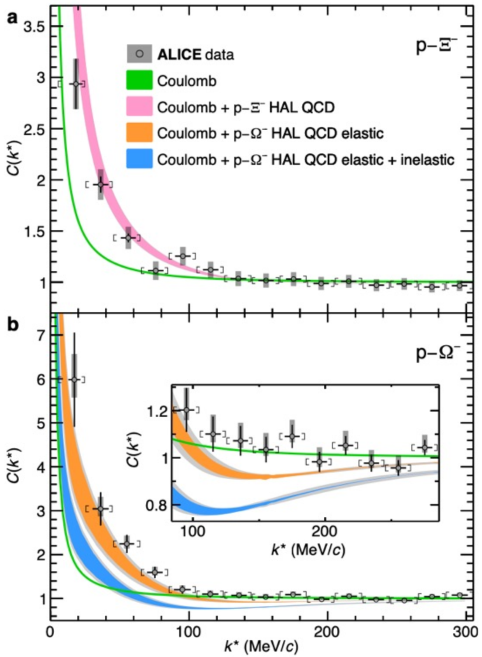
If $S(k^*)$ is well known, study of $C(k^*)$ allows characterization of the particle dynamics in $\Psi(k^*, r^*)$:

ALICE, PLB 833 (2022) 137272



- Cusp structure in **p-Λ** correlation function at 289 MeV/c is evidence for $N\Sigma \leftrightarrow N\Lambda$ coupling
- Analysis of **p-Λ** correlations constrains Λ separation energy in $^{3}_{\Lambda}$H, confirmed by recent measurements
- High-precision study of **p-Ξ** correlations constrains Ξ in-medium properties relevant for hyperon puzzle in neutron stars

ALICE, Nature 588 (2020) 232



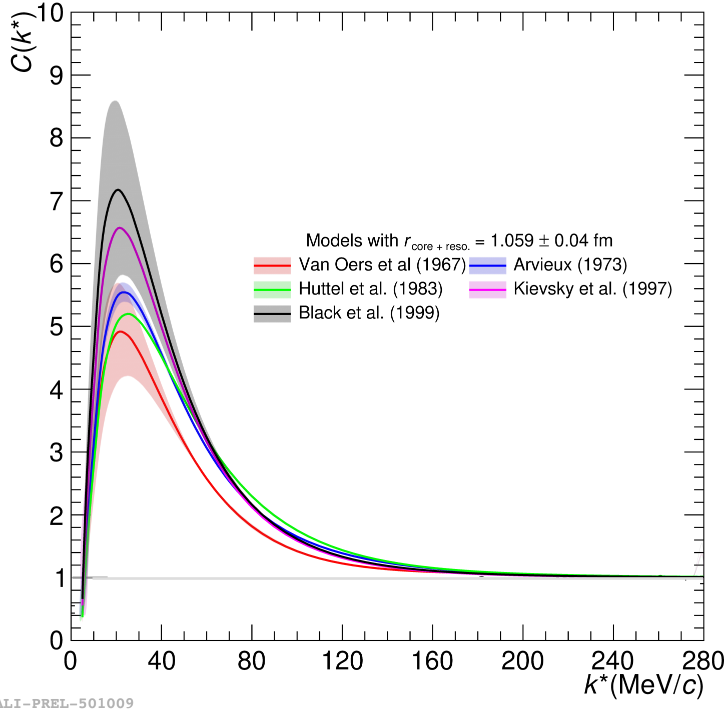
Femtoscopy of the Third Kind

In the case of **p-d**, both $S(k^*)$ and $\psi(k^*, r^*)$ are well constrained:

Measured p-d scattering parameters allow prediction of p-d correlation functions

- Coulomb + strong interaction from Lednicky-Lyuboshits approach
- $r_{core+reso.} = 1.06 \pm 0.04$ fm
- Scattering parameters from experiments ($S = 3/2$ and $S = 1/2$)

	Quartet $^4S_{3/2}$	Doublet $^2S_{1/2}$
Van Oers et al. (1967)	$11.4^{+1.8}_{-1.2}$	$1.2^{+0.2}_{-0.2}$
Arvieux et al. (1973)	$11.88^{+0.4}_{-0.1}$	$2.73^{+0.1}_{-0.1}$
Huttel et al. (1983)	11.1	4.0
Kievsky et al. (1997)	13.8	0.024
Black et al. (1999)	$14.7^{+2.3}_{-2.3}$	$-0.13^{+0.04}_{-0.04}$

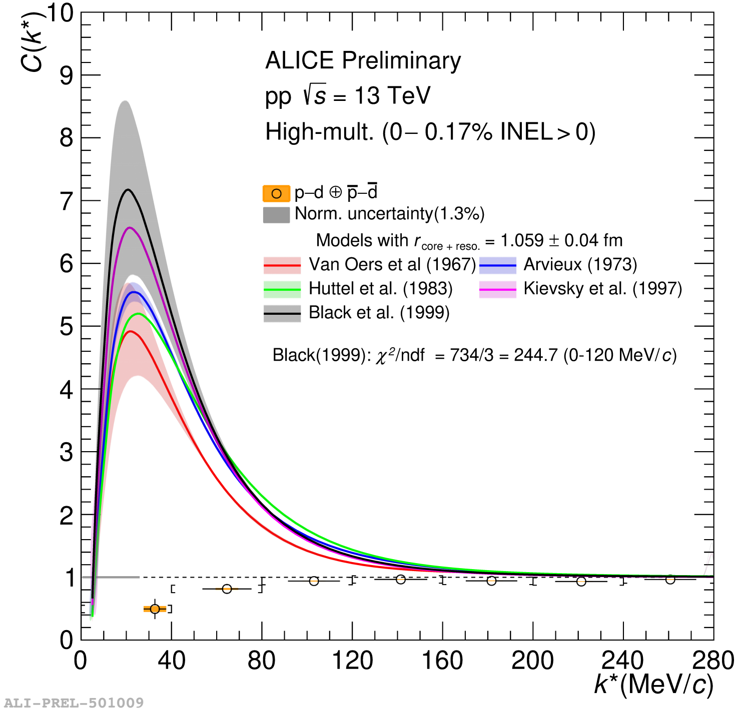


Femtoscopy of the Third Kind

Preliminary p-d correlation data in significant disagreement with predictions based on scattering data and known source characteristics

- First occurence in ALICE femto analyses
- First time nuclei are involved: possible effects from formation time, coalescence, and three-body interactions

→ *see presentation by B. Singh on Friday*



Summary

- Study of light nuclei production in small collision systems at the LHC reveals patterns suggestive of coalescence mechanism
- Observed object-size dependence may enable tomographic studies of composite and exotic objects
- Dominant production mechanism in central collisions not yet fully resolved
- Study of femtoscopic correlations can shed light on underlying two- and three-body dynamics
- Precision will improve by factor 10-100 with new ALICE data in Run 3 and 4