Constraining the production mechanism of light (anti-)nuclei in small systems with ALICE at the LHC

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Outline

- Phenomenological models
  - The *statistical hadronisation* model
  - The *coalescence* model
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  ‣ The statistical hadronisation model
  ‣ The coalescence model

• The ALICE experiment
  ‣ Identification of nuclei
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  - The **statistical hadronisation** model
  - The **coalescence** model
- The **ALICE** experiment
  - **Identification** of nuclei
- **(Anti-)nuclei** production:
  - $p_T$ spectra in pp and p-Pb collisions
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• Phenomenological models
  ‣ The **statistical hadronisation** model
  ‣ The **coalescence** model

• The **ALICE** experiment
  ‣ **Identification** of nuclei

• (Anti-)nuclei production:
  ‣ $p_T$ **spectra** in pp and p-Pb collisions

• Testing the models
  ‣ Coalescence parameter $B_A$ vs multiplicity
  ‣ $d/p$ and $^3\text{He}/p$ vs multiplicity
Nuclear matter production

• Light (anti-)nuclei are abundantly produced at the LHC in pp, p-Pb and Pb-Pb collisions

• The production mechanisms of light (anti-)nuclei in high-energy physics are still not completely understood
  - light nuclei are characterised by a low binding energy ($E_B \sim 1$ MeV) with respect to the kinetic freeze-out temperature ($T_{fo} \sim 100$ MeV)

• Two classes of models are available:
  - the statistical hadronisation model
  - the coalescence model
The Statistical Hadronisation Model (SHM)

- It assumes hadron abundances from **statistical equilibrium** at the **chemical freeze-out**

- The chemical freeze-out temperature \( (T_{ch}) \) is a key parameter:
  \[
  dN/dy \propto \exp\left(-\frac{m}{T_{ch}}\right)
  \]

- Large reaction volume \( (VT^3 > 1) \) in Pb-Pb collisions
  - **grand canonical ensemble**

- Production yields \( dN/dy \) in central Pb-Pb collisions described over a wide range of \( dN/dy \) (**7 orders of magnitude**), including nuclei

- In **small systems** \( (VT^3 < 1) \) a local conservation of quantum numbers \( (S, Q \text{ and } B) \) is necessary
  - **canonical ensemble**
The coalescence model

- Nucleons that are close in the phase space at the freeze-out can form a nucleus via coalescence
- The key concept is the overlap between the nucleus wavefunction and the phase space of the nucleons
- The main parameter of the coalescence is the $B_A$, defined as:

$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left( E_p \frac{d^3N_p}{d^3p_p} \right)} A$$

where:
- $A$ is the mass number of the nucleus
- $p_p = p_A / A$

- $B_A$ is related to the probability to form a nucleus via coalescence

The ALICE experiment

- General purpose heavy-ion experiment
- 19 different sub-systems
- Excellent particle identification (PID)
- Most suited LHC experiment for studying the production of nuclei

Inner Tracking System
- Tracking and Vertex reconstruction
  - $\sigma_{DCA_{xy}} < 100 \, \mu m$ for $p_T > 0.5$ GeV/c in Pb-Pb
    - Separation of primary and secondary nuclei (coming from material knock-out)

V0
- Multiplicity/centrality determination
• Tracking
• PID via $dE/dx$ measurement
  ‣ $\sigma_{dE/dx} \sim 5.5\%$ (in pp collisions)
  ‣ $\sigma_{dE/dx} \sim 7\%$ (in Pb-Pb collisions)
• Raw yields extracted for each $p_T$ bin from the $n\sigma$ distributions
• $^3$He and $^4$He well separated
PID with the Time Of Flight

- **PID via $\beta$ measurement**
  - $\sigma_{\text{TOF-PID}} \sim 60$ ps in Pb-Pb collisions
  - $\sigma_{\text{TOF-PID}} \sim 70$ ps in pp collisions (lower precision on event collision time)

- Raw yields extracted for each $p_T$ bin from the TOF mass spectra distribution

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    (lower precision on event collision time)

• Raw yields extracted for each $p_T$ bin from the TOF mass spectra distribution
• **TRD** can be used as **trigger** for **nuclei**
  - Only events with a nucleus candidate are selected → **background reduced**
• With **TRD** trigger it is possible to measure:
  • \(^3\text{H}\) in \(pp\) collisions
  • (anti-)\(^4\text{He}\) in \(pp\) collisions (in the future)

**ALICE Performance**
- \(^3\text{H} \rightarrow ^3\text{He} + \pi^-\)
- \(\text{pp } \sqrt{s} = 13\ \text{TeV}\)
- \(L_{\text{int}}^{\text{TRD}} = 2.0\ \text{pb}^{-1}\)
- \(L_{\text{int}}^{\text{V0mult}} = 7.7\ \text{pb}^{-1}\)
- \(L_{\text{int}}^{\text{SPDmult}} = 0.9\ \text{pb}^{-1}\)
$^3$He spectra in p-Pb and pp

- $^3$He $p_T$ spectra measured in pp, p-Pb, and Pb-Pb collisions
  - A comparison between different systems can be performed

**pp, $\sqrt{s} = 13$ TeV**

**p-Pb, $\sqrt{s_{NN}} = 5$ TeV**
• $^3$H $p_T$ spectra measured in p-Pb collisions

• Comparison with $^3$He spectra is a cross-check for the isospin-invariance in the production mechanisms

• $^3$H $p_T$ spectra measured also in Pb-Pb collisions

  • see Esther's talk:

    “New results on light (anti-)(hyper-)nuclei production and hypertriton lifetime in Pb-Pb collisions at the LHC”

    - Collective dynamics II session
    - on 05.10.2019 at 15:40
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Deuteron in pp and p-Pb

ALICE Preliminary
deuterons, pp, $\sqrt{s} = 5$ TeV

\[
\left\langle \frac{dN_{\text{ch}}}{d\eta_{\text{lab}}} \right\rangle = 5.49
\]

\[
\left\langle \frac{dN_{\text{ch}}}{d\eta_{\text{lab}}} \right\rangle = 18.45
\]

Deuteron $p_T$ spectra have been measured in pp, p-Pb and Pb-Pb collisions

- Comparison with proton spectra → constrain to production mechanisms

arXiv:1906.03136 [nucl-ex]
• The **probability** to form a nucleus via coalescence can be quantified by the **coalescence parameter** $B_A$

• According to **simple coalescence** predictions, the $B_A$ is **flat in $p_T$**
  
  - Simple coalescence **does not describe** the behaviour observed in **Pb-Pb** collisions

• Moving from central to peripheral collisions (i.e. towards **lower multiplicities**), the rise in $p_T$ becomes milder

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**The coalescence parameter $B_A$**

![Graph showing $B_2$ vs. $p_T/A$ for different multiplicities and collision energies.](attachment:image.png)

**Pb-Pb, $\sqrt{s_{NN}} = 5$ TeV**

- $B_2$ values for different centrality classes are shown.
- The $B_2$ values decrease with increasing $p_T$ for each centrality class.

**ALICE Preliminary**

deuterons, $|y| < 0.5$
• In \textit{pp} collisions, the $B_2$ is flat in $p_T$, in agreement with the \textbf{simple coalescence} model.
The coalescence parameter $B_3$

- $B_3$ has also been measured in $pp$ and in $p$-$Pb$ collisions
- Comparison of the $B_3$ in different collision systems and at different multiplicities
  - Dependence of the coalescent production on the system size

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  ▸ Dependence of the coalescent production on the system size

\[ B_3 (\text{GeV}^4/c^6) \]

\[ p$-$Pb, \sqrt{s_{NN}} = 5 \text{ TeV} \]

ALICE

V0A Multiplicity Classes

- 0–10%
- 10–20% (x2)
- 20–40% (x4)
- 40–100% (x8)
- Minimum-bias (x16)

• $B_3$ evolves smoothly with multiplicity, regardless of the collision system:

- $B_3$ coalesc., $T^3$He = 2.48 fm
- SHM + blast-wave (ALICE πKp)
- fit to HBT radii
- GC GSI-Heid. ($T = 156$ MeV)
- constrained to ALICE $B_2$
- CSM ($T = 155$ MeV)

ALICE Preliminary
- Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, PRC 93 (2016) 2, 024917
- p-Pb $\sqrt{s_{NN}} = 5.02$ TeV, arXiv:1910.14401
- pp $\sqrt{s} = 7$ TeV ($p_x/A = 0.8$ GeV/c), PRC 97 (2018) 2, 024615
- pp $\sqrt{s} = 13$ TeV
- $p_x/A = 0.90$ GeV/c
• $B_3$ evolves **smoothly** with **multiplicity**, regardless of the collision system:
  ▶ production mechanism depending only on the system size
- $B_3$ evolves smoothly with multiplicity, regardless of the collision system:
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- Through the coalescence model it is possible to predict the $B_A$ as a function of the system volume, parameterised from the $dN/d\eta$
- $B_3$ evolves smoothly with multiplicity, regardless of the collision system:
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- Two regimes observed:
• $B_3$ evolves smoothly with multiplicity, regardless of the collision system:
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• Through the coalescence model it is possible to predict the $B_3$ as a function of the system volume, parameterised from the $dN/d\eta$

• Two regimes observed:
  1. flat: the system size is smaller than the nucleus size

Multiplicty dependence of $B_3$
**Multiplicity dependence of $B_3$**

- $B_3$ evolves **smoothly** with multiplicity, regardless of the collision system:
  - production mechanism depending only on the system size

- Through the coalescence model it is possible to predict the $B_A$ as a function of the **system volume**, parameterised from the $dN/d\eta$

- Two regimes observed:
  1. flat: the system size is smaller than the nucleus size
  2. decreasing: the system size is larger than the nucleus size
- Also $B_2$ shows a smooth evolution with multiplicity
- $B_2$ can be predicted as a function of the system volume, parameterised from $dN/d\eta$
- Two regimes observed:
  1. **flat**: the system size is smaller than the deuteron size
  2. **decreasing**: the system size is larger than the deuteron size
• d/p ratio evolves **smoothly** with multiplicity, regardless of the collision system:

  ▶ production mechanism depending only on the system size
• d/p ratio evolves smoothly with multiplicity, regardless of the collision system:
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• Two different regimes:
• d/p ratio evolves **smoothly** with multiplicity, regardless of the collision system:
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• Two different regimes:
  1. increasing:
     - Thermal model: **canonical suppression**
     - Coalescence: **small phase space**
• d/p ratio evolves **smoothly** with multiplicity, regardless of the collision system:
  
  ▶ production mechanism depending only on the system size

• Two different regimes:

  1. **increasing**:
     • Thermal model: **canonical suppression**
     • Coalescence: **small phase space**
  2. **flat**: at high multiplicity there is no dependence of the ratio on the multiplicity, in agreement with the predictions of the **thermal model** and coalescence
Also for $^3\text{He}/p$ we see a smooth evolution with the multiplicity, regardless of the collision system.

Two kinds of coalescence:

- **2-body** coalescence
- **3-body** coalescence

As for $d/p$, two different regimes:

1. **increasing:**
   - Thermal model: **canonical suppression**
   - Coalescence: **small phase space**

2. **flat:** in agreement with both models

\[ \text{ALICE Preliminary} \]

- $2 \cdot \frac{^3\text{He}}{(p + \bar{p})}$, Pb–Pb \[ \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} (|y_{\text{cms}}| < 0.5) \text{, PRC 93 (2016) 2, 024917} \]
- $2 \cdot \frac{^3\text{He}}{(p + \bar{p})}$, Pb–Pb \[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} (|y_{\text{cms}}| < 0.5) \]
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- $(^3\text{He} + ^3\text{He})/(p + \bar{p})$, p–Pb \[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} (|y_{\text{cms}}| < 0.5) \text{, arXiv:1910.14401} \]
- $(^3\text{H} + ^3\text{H})/(p + \bar{p})$, p–Pb \[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} (|y_{\text{cms}}| < 0.5) \text{, arXiv:1910.14401} \]
- $2 \cdot \frac{^3\text{He}}{(p + \bar{p})}$, pp \[ \sqrt{s} = 7 \text{ TeV} (|y_{\text{cms}}| < 0.5) \text{, PRC 97 (2018) 2, 024615} \]
- $(^3\text{He} + ^3\text{He})/(p + \bar{p})$, pp \[ \sqrt{s} = 13 \text{ TeV} (|y_{\text{cms}}| < 0.5) \]

\[ \text{CSM (Thermal-FIST), PLB 785 (2018) 171-174} \]
- $T = 155 \text{ MeV}$, $V_c = dV/dy$
- $T = 155 \text{ MeV}$, $V_c = 3 \ dV/dy$

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Quark Matter - Wuhan 2019

19
Conclusions

- ALICE has measured the production of light (anti-)nuclei in different collision systems and at different energies.

- The measurements of $B_A$, $d/p$ and $^3\text{He}/p$ as a function of multiplicity suggest a common production mechanism that depends only on the system size.

- The coalescence model can explain both the evolution of $B_A$, $d/p$ and $^3\text{He}/p$ with multiplicity.

- With a canonical approach for small systems, also the thermal model can describe the evolution of $d/p$ and $^3\text{He}/p$ with multiplicity.

- More data and more precise model calculations are needed to understand the production of light (anti-)nuclei in high-energy hadron collisions.
Conclusions

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Thanks for your attention!
Backup
The centrality of a Pb-Pb collision is described by the impact parameter $b$.

The estimation of the impact parameter is obtained from the track multiplicity, fitting the data with the predictions of the **Glauber model**.

\[ P_{\mu,k} \times \left[ f \frac{N_{\text{part}}}{N_{\text{coll}}} + (1-f)N_{\text{coll}} \right] \]

$P_{\mu,k}$: a parameter in the model

$N_{\text{part}}$: number of participants

$N_{\text{coll}}$: number of collisions

$f$: a fraction

$\mu$, $k$: model parameters

**The diagram shows the centrality distribution for Pb-Pb collisions at $s_{NN} = 5.02$ TeV.**

- **Data** points show the measured event yields.
- **NBD-Glauber fit** indicates the model prediction.
- The inset highlights the centrality ranges:
  - 80-90%
  - 70-80%
  - 60-70%
  - 50-60%
  - 40-50%
  - 30-40%
  - 20-30%
  - 10-20%
  - 7.5-10%
  - 5-7.5%
  - 2.5-5%
  - 0.2-5%

**ALICE, ALICE-PUBLIC-2015-008 (2015)**
• At the LHC energies the antiproton/proton ratio is compatible with the unity:
  
  ‣ the regime of nuclear transparency is reached: evanescent baryochemical potential ($\mu_B \sim 0$) in the central rapidity region

• Both thermal and coalescence models predict for a nucleus X with mass number $A$:
  \[ \frac{\overline{X}}{X} \approx \left( \frac{\overline{p}}{p} \right)^A \]

• The measurements of $\overline{d}/d$ and $^{3}\text{He}/^{3}\text{He}$ in Pb-Pb, p-Pb and pp collisions confirm the predictions:
  
  ‣ matter and anti-matter produced with the same abundances
The thermal model describes the production yields $dN/dy$ in Pb-Pb collisions over a wide range of $dN/dy$ (7 orders of magnitude).

- Also the yields of the nuclei are well reproduced
  - nuclei are thermally produced in the hadronisation, together with the other particle species
In Run2 the uncertainties on the particle yields have been reduced, thanks to a larger data sample and to the improvement in the analysis techniques.

Although describing qualitatively well the particle yields, there is less agreement between the thermal model prediction and the particle yields.
A rising in the multiplicity integrated $B_2$ as a function of $p_T$ can be obtained even if the $B_2$ of all the multiplicity classes is flat in $p_T$.

Indeed, a consistent change in the proton spectra with the multiplicity determines a mathematical bias in the computation of the multiplicity integrated $B_2$. 

- A rising in the multiplicity integrated $B_2$ as a function of $p_T$ can be obtained even if the $B_2$ of all the multiplicity classes is flat in $p_T$.
- Indeed, a consistent change in the proton spectra with the multiplicity determines a mathematical bias in the computation of the multiplicity integrated $B_2$. 

ALICE Preliminary

pp INEL, $\sqrt{s} = 7$ TeV

- $\bar{d}$, PRC 97 (2018) 024615
- Coalescence

$B_2$ (GeV$^2$/c$^2$)

$p_T/A$ (GeV/c)