Shedding light on the hypertriton lifetime with ALICE at the LHC
Hypernuclei in heavy-ion collisions

- Thermal Model
- Coalescence Model
Hypernuclei in heavy-ion collisions

**Thermal Model**

- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out \( (T_{\text{chem}}) \)
- Hypernuclei are very sensitive to \( T_{\text{chem}} \) because of their large mass \( (M) \)
- Exponential dependence of the yield \( e^{-M/T_{\text{chem}}} \)
- Depends only on \( T, V \) and \( \mu_B \), which is basically zero at the LHC

**Coalescence Model**
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**Coalescence Model**

- If baryons at freeze-out are close enough in Phase Space an (anti-)hypernucleus can be formed
- Hypernuclei are formed by protons ($\Lambda$) and neutrons which have similar velocities after the freeze-out

SQM 2019, Bari
Hypernuclei in heavy-ion collisions

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Stefania Bufalino

SQM 2019, Bari
• Hadrons emitted from the interaction region in statistical equilibrium once the chemical freeze-out temperature is reached
• Estimation for central heavy-ion collisions at LHC energies
Hypertriton: lightest known hypernucleus bound state of p, n and Λ

- Mass\(^{(2)}\) = 2.992 GeV/c\(^2\)
- Λ-Lifetime\(^{(3)}\) \(~\)263 ps

Decay Channel:
1. Mesonic
2. Non Mesonic

Mesonic decay

<table>
<thead>
<tr>
<th>Charged</th>
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<td>(^3\Lambda H \rightarrow ^3\text{He}+\pi^-)</td>
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- Study of the production in the charged decay channel
  - 2 body (B.R.\(^{(1)}\) \(\approx\) 25%)
  - 3 body (B.R.\(^{(1)}\) \(\approx\) 41%)


\(^{(3)}\) M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

**Hypertriton measurement: methodology**

**Hypertriton**: lightest known hypernucleus bound state of \( p, n \) and \( \Lambda \)

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**Signal extraction:**

- Identify daughters (\( ^3\text{He}, \pi \)) or (\( d, p, \pi \))
- Apply topological cuts in order to:
  - Identify secondary decay vertex
  - Reduce combinatorial background
- Evaluate invariant mass

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- 2 body (B.R.\(^{(1)}\) \( \approx 25\% \))
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Hypertiriton measurement with ALICE

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$\sqrt{s_{\text{NN}}} = 5.02$ $\text{ TeV}$

Pb–Pb, 0–80%

$|y| < 0.9$
Hypertriton: lightest known hypernucleus bound state of $p$, $n$ and $\Lambda$

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**ALICE Performance**

$Pb-Pb \sqrt{s_{NN}} = 2.76$ TeV (2011)
0-10%, $|y| < 0.5$

$^3\Lambda \rightarrow d + p + \pi^+$

Hypertriton production

Measurement performed in semi-central collisions (10-40%) for the first time at 5.02 TeV. The measurement at 2.76 TeV was performed in 3 $p_T$ bins and 2 centrality classes (0-10% and 10-50%). Blast-Wave$^4$ distribution used to extrapolate the yield in the unmeasured $p_T$ region.

Hypertriton production vs models

\[ \text{dN/dy} \times \text{B.R.} \text{ vs B.R.} \]

- Hyper-triton decay B.R. is not precisely known, only constrained by the ratio between all charged channels containing a pion.
- The study of the 3-body decay channel can help in improving our knowledge of B.R.

✓ **Hybrid UrQMD**: combines the hadronic transport approach with an initial hydrodynamical stage for the hot and dense medium


✓ **GSI-Heidelberg**: equilibrium statistical thermal model with \[ T_{\text{chem}} = 156 \text{ MeV} \]

A. Andronic et al. *Phys. Lett. B* 697,

- **SHARE**: non-equilibrium thermal model with

M. Pétran et al. *Phys. Rev. C* 88 (3)

agreement with **equilibrium thermal model GSI-Heidelberg** and with **Hybrid UrQMD** in the B.R. range between 0.24 and 0.35
Hypernuclei lifetime: exp vs theory

Small $E_{B\Lambda}$ (~130 keV) $\rightarrow$ lifetime is slightly below the free $\Lambda$ lifetime (263.2 ± 2 ps [5])

Hypothesis: $\Lambda$ would spend most of its time far from the deuteron core due to the very small value of $E_{B\Lambda}$


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- one-pion exchange (OPE) model approach with the addition of 2π/σ and 2π/ρ exchange terms to the OPE exchange potential

- plus correction from
- Better description of NN interaction and 2 Nucleon Non Mesonic Weak Decay taken into account

- one-pion exchange (OPE) model approach with the addition of many exchange terms to the OPE exchange potential

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heavy = weighted average of lifetime for hypernuclei with 180<A<238
Hypertriton lifetime: experimental results

- Emulsion technique: $203^{+40}_{-31}$ ps
- He Bubble Chamber: $195^{+15}_{-13}$ ps
- Digital readout: $185^{+28}_{-23}$ ps without [21]
- Digital readout: $163^{+18}_{-16}$ ps with [21]

World averages and uncertainties grouping the measurements on the basis of the experimental technique

ALICE: ref [23]
STAR: ref [20,21]
For all the references in the plot: see slide17
Hypertriton: the *lifetime* puzzle

Data compilation after LHC Run 1

Re-evaluation of world average including ALICE result:

\[
t = (215^{+18}_{-16}) \, \text{ps}
\]

ALICE value compatible with the computed average
Hypertriton lifetime with Pb-Pb at 5 TeV

\[ \tau = 237^{+33}_{-36} \text{(stat.)} \pm 17 \text{(syst.) ps) } \]

**\( \tau \) spectra (default)**

- Exponential fit to the differential yield in different \( \tau t \) bins
Hypertriton lifetime with Pb-Pb at 5 TeV

\( \tau = 237^{+33}_{-36} \text{(stat.)} \pm 17 \text{(syst.)} \) ps

\( \frac{dN}{d(\text{c}t)} \) (cm\(^{-1}\))

\( c t = 7.10^{+1.00}_{-1.07} \) (stat.) \( \pm 0.50 \) (syst.) (cm)

\( \tau = 237^{+33}_{-36} \) (stat.) \( \pm 17 \) (syst.) (ps)

\( \frac{\text{Events}}{1.25 \text{ MeV/} \text{c}^2} = 8.42 \sigma \) Significance (3\( \sigma \)) = 8.42

**ct spectra (default)**

- Exponential fit to the differential yield in different ct bins
Hypertriton lifetime with Pb-Pb at 5 TeV

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- Exponential fit to the differential yield in different ct bins

**Unbinned fit**

- Crosscheck method

- Fit to the invariant mass distribution \( \rightarrow \sigma \)
  used to define the signal range \([+3\sigma,-3\sigma]\)
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**Unbinned fit**

- Fit to the ct distribution in the signal range with function:
  - *signal*: single exponential
  - *background*: double exponential

\[
\tau = 223^{+41}_{-33} \text{(stat.)} \pm 20 \text{(syst.) ps}
\]
Hypertriton lifetime with Pb-Pb at 5 TeV

- Exponential fit to the differential yield in different $ct$ bins
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$ct$ spectra (default)

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  - background: double exponential

\[ \tau = 223^{+41}_{-33} \text{(stat.)} \pm 20 \text{(syst.) ps) } \]
Previous heavy-ion experiment results show a trend below the free $\Lambda$ lifetime. Result from Pb-Pb at 5.02 TeV: improved precision and value compatible with that of free $\Lambda$. 

New result at 5.02 TeV not included in the world average.
• Production and lifetime measurements of the (anti-)hypertriton performed in more centrality classes w.r.t. the results at 2.76 TeV and with improved precision thanks to Run 2 data

• Integrated yields are well described by thermal models

• Recent ALICE hypertriton lifetime measurement shows an improved precision and a value closer to the $\Lambda$ lifetime with respect to the previous heavy-ion results

  • Lifetime determination via 3-body decay channel will be important
  • New analysis approaches based on Machine Learning are ongoing (poster by P. Fecchio)
  • New theoretical calculations for the lifetime are needed as well as more precise measurements of the $B_\Lambda$
Measurements with higher significance of anti-hypernuclei will be possible in central Pb–Pb collisions in Runs 3 and 4 also for $A > 3$.
BACKUP
Hyper-triton lifetime: experimental results

Upgrade strategy

- Measurement of (anti-)hyper-triton yields and lifetime is an interesting topic and nice inputs come from the heavy-ion experiment.
- New measurement from HI experiments gives a shorter lifetime than the expected free Lambda lifetime recently confirmed by ALICE at a new energy (5.02 TeV).
- What about Run 3 & Run 4 of LHC? More statistics delivered (50 kHz Pb-Pb collision rate).

<table>
<thead>
<tr>
<th>State</th>
<th>dN/dy</th>
<th>B.R.</th>
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<td>(^3\Lambda H)</td>
<td>(1 \times 10^{-4})</td>
<td>25%</td>
<td>11%</td>
<td>44000</td>
</tr>
<tr>
<td>(^4\Lambda H)</td>
<td>(2 \times 10^{-7})</td>
<td>50%</td>
<td>7%</td>
<td>110</td>
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<td>32%</td>
<td>8%</td>
<td>130</td>
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**Introduction: ALICE**

- General purpose heavy ion experiment
- Excellent particle identification (PID) capabilities and low material budget
- Most suited detector at the LHC to study the (anti-)(hyper-)nuclei produced in the collisions
Particle identification in ALICE

Detectors used for (anti-)(hyper-)nuclei analysis:

- **ITS**
  - Separation of primary and secondary nuclei from knock-out
  - $p_T > 0.5 \text{ GeV/c} \rightarrow \sigma_{\text{DCA}_{xy}} < 100 \mu\text{m}$

- **TPC**
  - $dE/dx$ in gas (Ar-CO$_2$)
  - $\sigma_{dE/dx} \sim 5.5\%$

- **TOF**
  - Time-of-flight measurement
  - $\sigma_{\text{TOF}} \sim 80 \text{ ps (Pb-Pb), 120 ps (pp)}$

- **V0**
  - Two arrays of 64 scintillators
  - Determination of the centrality of a collision