PRODUCTION OF (ANTI-)HYPERNUCLEI WITH ALICE AT THE LHC

Stefano Piano on behalf of ALICE Collaboration
INFN sez. Trieste
MOTIVATION TO MEASURE (ANTI-)HYPERNUCLEI IN Pb-Pb COLLISIONS WITH ALICE AT THE LHC

ALICE aims to study the formation of Quark-Gluon Plasma, its properties and evolution:

- (anti-)(hyper)nuclei yields are sensitive to the freeze-out temperature due to their large mass (e.g. in the Thermal Model yield scales roughly $\propto e^{(-M/T_{\text{chem}})}$

- light (anti-)(hyper)nuclei, small binding energy and small $\Lambda$ separation energy, e.g. $B_{\Lambda}(^3\Lambda^3H) = 0.13 \pm 0.05$ MeV [H. Bando et al., Int. J. Mod. Phys. A 5 4021 (1990)]:
  - light (anti-)(hyper)nuclei should dissociate in a medium with high $T_{\text{chem}}$ (~156 MeV) and be suppressed
  - if light (anti-)(hyper)nuclei yields equal to thermal model prediction $\Rightarrow$ sign for adiabatic (isentropic) expansion in the hadronic phase

- $A=3$ (anti-)($^3$He, t, $^3\Lambda^3H$), a simple system of 9 valence quarks:
  - $^3\Lambda^3H / ^3\Lambda^3H / t$ (and anti) $\Rightarrow \Lambda$-nucleon correlation (local baryon-strangeness correlation)
  - t / $^3$He (and anti) $\Rightarrow$ local charge-baryon correlation
  - YN & YY interaction (strangeness sector of hadronic EOS, cosmology, physics of neutron stars)

Anti-nuclei in nature:

- matter–antimatter asymmetry [J.Adam et al. (ALICE Collaboration), Nature Phys. 11, no.10, 811 (2015)]
(ANTI-)(HYPER)NUCLEI PRODUCTION IN URHIC

Statistical Thermal model

- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out ($T_{chem}$) (hyper)nuclei are very sensitive to $T_{chem}$ because of their large mass ($M$)
- Exponential dependence of the yield $\propto e^{-\frac{M}{T_{chem}}}$

Coalescence

- If baryons at freeze-out are close enough in Phase Space an (anti-)(hyper)nucleus can be formed
- (Hyper)nuclei are formed by protons ($\Lambda$) and neutrons which have similar velocities after the freeze-out
(ANTI-)(HYPER)NUCLEI PRODUCTION AT LHC

Production yield estimate of (anti-)(hyper)nuclei in central heavy ion collisions at LHC energy based on thermal model:

<table>
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<tbody>
<tr>
<td>π</td>
<td>~800</td>
</tr>
<tr>
<td>p</td>
<td>~40</td>
</tr>
<tr>
<td>Λ</td>
<td>~30</td>
</tr>
<tr>
<td>d</td>
<td>~0.17</td>
</tr>
<tr>
<td>³He</td>
<td>~0.01</td>
</tr>
<tr>
<td>³ΛH</td>
<td>~0.003</td>
</tr>
</tbody>
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✓ Light nuclei (see Dönigus talk)
✓ Hypertriton
✓ Search for: Λn, ΛΛ dibaryons


A. Andronic, private communication

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Pb-Pb $s_{NN} = 2.76$ TeV
central collisions
thermal model, $T = 164$ MeV


A. Andronic, private communication
ALICE particle identification capabilities are unique. Almost all known techniques are exploited: $dE/dx$, time-of-flight, transition radiation, Cherenkov radiation, calorimetry and decay topology (V0, cascade).

**ITS:** precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material.
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**ITS+TPC+TRD**: excellent track reconstruction capabilities in a high track density environment

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**ITS+TPC+TRD**: excellent track reconstruction capabilities in a high track density environment.

**HMPID**: particle identification via Cherenkov radiation.

ALICE is ideally suited for the identification of light (anti-) (hyper)nuclei.
COLLISION GEOMETRY

- Nuclei are extended objects
- Geometry not directly measurable
- Centrality (percentage of the total cross section of the nuclear collision) connected to observables via Glauber model
- Data classified into centrality percentiles for which the average impact parameter, number of participants, and number of binary collisions can be determined

NUCLEI IDENTIFICATION

Nuclei identification via $dE/dx$ measurement in the TPC:

- $dE/dx$ resolution in central Pb-Pb collisions: ~7%
- Excellent separation of (anti-)nuclei from other particles over a wide momentum range
- About 10 anti-alpha candidates identified out of $23 \times 10^6$ events by combining TPC and TOF particle identification

Low momenta

Higher momenta

Excellent TOF performance:

- $\sigma_{\text{TOF}} \approx 85$ ps in Pb-Pb collisions allows identification of light nuclei over a wide momentum range
- Velocity measurement with the TOF detector is used to evaluate the $m^2$ distribution and to subtract background from the signal in each $p_T$-bin by fitting the $m^2$ distribution
(ANTI)HYPERTRITON IDENTIFICATION

Decay Channels

\[ \Lambda^3 H \rightarrow ^3 \text{He} + \pi^- \quad \bar{\Lambda}^3 H \rightarrow \bar{\text{He}} + \pi^+ \]  
\[ \Lambda^3 H \rightarrow ^3 \text{H} + \pi^0 \quad \bar{\Lambda}^3 H \rightarrow \bar{\text{H}} + \pi^0 \]  
\[ \Lambda^3 H \rightarrow d + p + \pi^- \quad \bar{\Lambda}^3 H \rightarrow \bar{d} + \bar{p} + \pi^+ \]  
\[ \Lambda^3 H \rightarrow d + n + \pi^0 \quad \bar{\Lambda}^3 H \rightarrow \bar{d} + \bar{n} + \pi^0 \]

\[ ^3 \Lambda H \text{ search via two-body decays into charged particles:} \]

- Two body decay: lower combinatorial background
- Charged particles: ALICE acceptance and reconstruction efficiency for charged particles higher than for neutrals

Signal Extraction:

- Identify \(^3\text{He}\) and \(\pi\)
- Evaluate \(^3\text{He,}\pi\) invariant mass
- Apply topological cuts in order to:
  - isolate secondary decay vertex and
  - reduce combinatorial background

\[ \text{APPLIED CUTS:} \]

- \(\cos(\text{Pointing Angle}) > 0.99\)
- \(\text{DCA } \pi \text{ to PV} > 0.4 \text{ cm}\)
- \(\text{DCA between tracks} < 0.7 \text{ cm}\)
- \(^3\text{He,}\pi\) \(p_{t}> 2 \text{ GeV}/c\)
- \(|y| \leq 1\)
- \(c\tau > 1 \text{ cm}\)

\[ \text{BR} = 0.25 (*) \]

\[ (*) \text{ Kamada et al., PRC57(1998)4} \]
THE EXPERIMENTAL CHALLENGE

The challenge: extract the $^3\Lambda$H signal from an overwhelming background

<table>
<thead>
<tr>
<th>At $\sqrt{s_{NN}}$ =</th>
<th>2.76 TeV</th>
<th>5.02 TeV</th>
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<tbody>
<tr>
<td>Centrality</td>
<td>$dN_{ch}/d\eta$ ($</td>
<td>\eta</td>
</tr>
<tr>
<td>0-5 %</td>
<td>1601 $\pm$ 60</td>
<td>1943 $\pm$ 54</td>
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(ANTI-)HYPERTRITON IDENTIFICATION

**Decay Channels**

\[ {}^3\Lambda\ H \rightarrow {}^3\text{He} + \pi^- \]
\[ {}^3\Lambda\ H \rightarrow {}^3\text{He} + \pi^+ \]
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**$^3\Lambda$** search via two-body decays into charged particles:
- Two body decay: lower combinatorial background
- Charged particles: ALICE acceptance and reconstruction efficiency for charged particles higher than for neutrals

**Signal Extraction:**
- Identify $^3\text{He}$ and $\pi$
- Evaluate ($^3\text{He},\pi$) invariant mass
- Apply topological cuts in order to:
  - isolate secondary decay vertex and
  - reduce combinatorial background
- Background estimation: $\pi$ track rotated 20 times

---

**Figure:**

- Data
- Background
- Combined Fit

**Invarient mass ($^3\text{He},\pi$) (GeV/c²):

$\mu = 2.991 \pm 0.001 \pm 0.003$ GeV/c²

$\sigma = (3.01 \pm 0.24) \times 10^{-3}$ GeV/c²

To be compared to literature value:

$\mu = 2.99131 \pm 0.00005$ GeV/c²

(ANTI-)HYPERTRITON IDENTIFICATION

Decay Channels

\[ \Lambda^3 H \rightarrow ^3\text{He} + \pi^- \quad \bar{\Lambda}^3 H \rightarrow \bar{^3}\text{He} + \pi^+ \]
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- Evaluate \((^3\text{He},\pi)\) invariant mass
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- Background estimation: \(\pi\) track rotated 20 times

\[\mu = 2.991 \pm 0.001 \pm 0.003\text{ GeV/c}^2\]
\[\sigma = (3.01 \pm 0.24) \times 10^{-3}\text{ GeV/c}^2\]

To be compared to literature value:
\[\mu = 2.99131 \pm 0.00005\text{ GeV/c}^2\]

\[\text{Invariant mass } (^3\text{He},\pi) (\text{GeV/c}^2)\]
New preliminary results at $\sqrt{s_{NN}} = 5.02$ TeV

Signal Extraction:
- Identify $^3\Lambda$He and $\pi$
- Evaluate ($^3\Lambda$He, $\pi$) invariant mass
- Apply topological cuts in order to:
  - isolate secondary decay vertex and
  - reduce combinatorial background
- Background estimation: $\pi$ track rotated 20 times

Decay Channels

\[
\begin{align*}
  \Lambda^3 \to & \ 3 \ ^3 \Lambda \to 3 \ ^3 \text{He} + \pi^- & \ ^3 \Lambda \to & \ 3 \ ^3 \text{He} + \pi^+ \\
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\end{align*}
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\Lambda^3 H &\rightarrow \bar{d} + \bar{p} + \pi^+ \\
\Lambda^3 H &\rightarrow \bar{d} + \bar{n} + \pi^0
\end{align*}
\]

\(\Lambda^3 H\) search via three-body decays into charged particles:

- Three body decay: higher combinatorial background but
- Higher B.R. \(~41\%\) (Kamada et al., PRC57(1998))
- Charged particles: ALICE acceptance and reconstruction efficiency for charged particles higher than for neutrals

Signal Extraction:

- Identify d, p and \(\pi\) and anti
- Evaluate \((d,p,\pi)\) invariant mass
- Apply topological cuts and background estimation

New preliminary results: three body decay at \(\sqrt{s_{NN}} = 2.76\) TeV
(ANTI-)HYPERTRITON YIELDS

\[ d^2N/d\Omega d\beta \times B.R. (\text{GeV/c})^{-1} \]

\[ \alpha \text{He} \rightarrow \text{He} + \pi^- \]
\[ \alpha \text{He} \rightarrow \text{He} + \pi^+ \]

\[ \begin{array}{c}
\begin{array}{c}
\text{ALICE 0-10%}
\end{array}
\end{array} \]
\[ \begin{array}{c}
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Pb-Pb \ \bar{s}_{NN} = 2.76 \text{ TeV}
\end{array}
\end{array} \]

\[ R = 0.95 \] (Cleymans et al, PRC84(2011) 054916)

STATISTICAL-THERMAL MODEL: \( R = \frac{\alpha}{R} \)

COALESCENCE MODEL: \( \bar{p}/p \sim \Lambda/\bar{\Lambda} \sim 1 \)

\[ dN/d\beta \times B.R. (\text{He} + \pi) \] yield extracted in three \( p_T \) bins for central (0-10%) events for \( \alpha \text{He} \) and \( \alpha \text{He} \) separately

\[ \begin{array}{c}
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\end{array} \]
Three different theoretical predictions drawn as a function of $\text{BR}(^3\Lambda H \to ^3\text{He}+\pi^-)$ after being multiplied by BR:

- **Hybrid UrQMD**: combines the hadronic transport approach with an initial hydrodynamical stage for the hot and dense medium ([J. Steinheimer et al., Phys. Lett. B 714, 85 (2012)]).


- **SHARE**: non-equilibrium thermal model with $T_{\text{chem}}=138.3$ MeV ([M. Petráň et al., Phys. Rev. C 88, 034907 (2013)]).

- Great sensitivity to theoretical models parameters
- Non-equilibrium statistical thermal model (Petran-Rafelsky SHARE) provides better global fitting ($\chi^2\sim1$) to lower mass hadrons but misses $^3\Lambda H$ and light nuclei
- Experimental data closest to equilibrium thermal model with $T_{\text{chem}} = 156$ MeV and to Hybrid UrQMD
HYPERTTRITON LIFETIME DETERMINATION

Direct decay time measurement is difficult (~ps), but the excellent determination of primary and decay vertex allows measurement of lifetime via:

$$N(t) = N(0) e^{-\frac{t}{\tau}}$$

where $t = L/(\beta \gamma c)$ and $\beta \gamma c = p/m$ with $m$ the hypertriton mass, $p$ the total momentum and $L$ the decay length

$$ct = \left(5.4^{+1.6}_{-1.2}(\text{stat.}) \pm 1.00(\text{syst.})\right)\text{cm}$$

$$\tau = \left(181^{+54}_{-39}(\text{stat.}) \pm 33(\text{syst.})\right)\text{ps}$$

(Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV)

Re-evaluation of world average including ALICE result:

\[ \tau = (215^{+18}_{-15}) \text{ ps} \]

ALICE value compatible with the computed average
HYPERTRITON LIFETIME DETERMINATION


ALICE

Pb-Pb \( \sqrt{s_{NN}} = 2.76 \) TeV

\( c\tau = (5.4 \pm 1.6^{+1.2}_{-1.0}) \) cm

\( \tau = (181^{+54}_{-39}) \) ps

New preliminary results at \( \sqrt{s_{NN}} = 5.02 \) TeV

ALICE Preliminary

Pb-Pb \( \sqrt{s_{NN}} = 5.02 \) TeV

0-90%, \(|y| < 0.8\)

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

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

\( dN/d(c\tau) \) (cm\(^{-1}\))
HYPERTRITON LIFETIME DETERMINATION

Two methods for estimation:
- $ct$ spectra fit (exponential fit to the differential yield in different $ct$ bins)
- $ct$ unbinned fit as crosscheck method

New preliminary results at $\sqrt{s_{NN}} = 5.02$ TeV

$\tau = 223^{+41}_{-33} \, \text{(stat.)} \pm 20 \, \text{(syst.) \, ps}$

$\langle ct \rangle = 7.10^{+1.00}_{-1.07} \, \text{(stat.)} \pm 0.50 \, \text{(syst.) \, cm}$

$\tau = 237^{+33}_{-36} \, \text{(stat.)} \pm 17 \, \text{(syst.) \, ps}$
Previous heavy-ion experiment results show a trend well below the free $\Lambda$ lifetime.

ALICE preliminary result from Pb-Pb at 5.02 TeV is closer to the free $\Lambda$ lifetime.
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ALICE preliminary result from Pb-Pb at 5.02 TeV is closer to the free $\Lambda$ lifetime

STAR result from Au-Au collision is about 50% shorter than the free $\Lambda$ lifetime

The puzzle of the $^3\Lambda$H lifetime is still open

$\tau = \left(142^{+24}_{-21} (\text{stat.}) \pm 31 (\text{syst.})\right) \text{ps}$

Previous heavy-ion experiment results show a trend well below the free $\Lambda$ lifetime

ALICE preliminary result from Pb-Pb at 5.02 TeV is closer to the free $\Lambda$ lifetime

More precision, reducing the statistical uncertainties can be reached:
- Another Pb-Pb data sample will be collected in 2018 at the LHC:
  - the expected statistics for $^3\Lambda$H is $\sim$2x
  - lifetime in the 3-body decay channel
HYPERTRITON LIFETIME UNCERTAINTIES

\[
c\tau = \left( 5.4^{+1.6}_{-1.2} \text{(stat.)} \pm 1.00 \text{(syst.)} \right) \text{cm}
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<tr>
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<tbody>
<tr>
<td>Syst:</td>
<td>18%</td>
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<tr>
<td>Signal Extraction</td>
<td>9%</td>
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<td>Tracking Efficiency</td>
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At the end of Pb-Pb during RUN2 (Nov. 2018) the expected statistics for \(^3\Lambda H\) is >2x

During the Long Shutdown 2 (2019-2020):
- **New Inner Tracking System (ITS):**
  - improved pointing precision
  - less material -> thinnest tracker at the LHC
- **Upgrade of Time Projection Chamber (TPC):**
  - new GEM technology for readout chambers
  - continuous readout
  - faster readout electronics
- **High Level Trigger (HLT):**
  - new architecture
  - on line tracking & data compression
  - 50kHz PbPb event rate

At the end of RUN3 (2023) (*) the expected Integrated Luminosity: \(\sim 10 \text{nb}^{-1}\)

the expected statistics for \(^3\Lambda H\) is \(\sim 200x\)


At the end of RUN3: Statistical uncertainty will be negligible

With the LS2 ALICE upgrades: Signal extraction and tracking efficiency uncertainties will be strongly reduced

ASTRA: Advances and open problems in low-energy nuclear and hadronic STRAngeless physics | 27-10-2017 | Stefano Piano 28
CONCLUSIONS

☑ Excellent ALICE performance allows for detection of light (anti-)nuclei and (anti-)hypernuclei

☑ Blast-Wave fits can be used to extrapolate the yields to the unmeasured $p_T$ region of light hypernuclei in Pb-Pb.

☑ Hypertriton yield is in agreement with the current best thermal fit from equilibrium thermal model ($T_{\text{chem}} = 156 \pm 2$ MeV)

☑ The excellent determination of primary and decay vertices allows for the measurement of lifetime via exponential fit of the proper decay time distribution

☑ Re-evaluation of the hypertrion lifetime world average

☑ ALICE preliminary result from Pb-Pb at 5.02 TeV is close to the the free $\Lambda$ lifetime

☑ Future LHC runs, RUN2 and RUN3, and ALICE upgrades will allow for precise study of (anti)hypertriton production yield and lifetime
(ANTI-)HYPERTRITON YIELDS RATIOS

Hypermatter / Matter Ratio

Anti-hypermatter / Anti-matter Ratio

STATISTICAL-THERMAL MODEL: $R = \frac{\frac{3}{A}H}{\frac{3}{A}Λ}$

$R = 0.95$ (Cleymans et al, PRC84(2011) 054916)
HYPERTRTITON LIFETIME UNCERTAINTIES

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c\tau = \left( 5.4^{+1.6}_{-1.2} \text{(stat.)} \pm 1.00 \text{(syst.)} \right) \text{cm}
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(anti)hypertriton absorption is not negligible:
- (anti)hypertriton is barely bound: stronger absorption in matter than \( t \) or \( ^3\text{He} \)
- distribution of the material well known from the distribution of reconstructed photon conversions
- more precise evaluation of absorption cross section of \( ^3\Lambda\text{H} \) and \( ^3\text{He} \) is needed