Measurement of the hypertriton properties and production with ALICE

Francesco Mazzaschi$^1,2$

on behalf of the ALICE Collaboration

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Università degli Studi di Torino $^1$, INFN Torino $^2$
Hypertriton \((^3\Lambda H)^\)

- Lightest known hypernucleus
  - bound state of a neutron, a proton and a \(\Lambda\)
  - discovered in early 50s by Polish physicists
    - M. Danysz and J. Pniewski \(^1\)

- \(^3\Lambda H\) approximated as a bound state of a deuteron and a \(\Lambda\) with an expected radius of \(\sim 10\) fm \(^2\)
  - two-body halo nucleus

- Unique probe for understanding the \(\Lambda\)-nucleus interaction
  - strong implications for astro-nuclear physics
  - hyperons expected to be produced in the inner core of neutron stars \(^3\)

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3. Tolos L. et al., Progress in Particle and Nuclear Physics, 112 (2020)
3\textsubscript{Λ}H in ALICE

3\textsubscript{Λ}H in large systems (Pb-Pb collisions): lifetime and $B_{\Lambda}$

- 3\textsubscript{Λ}H lifetime and $B_{\Lambda}$ reflect its structure
  - Most of the theoretical models assume $B_{\Lambda} \approx 130$ keV and predict lifetime close to the free $\Lambda$ one
  - Latest models based on EFT give lifetime predictions as a function of the $B_{\Lambda}$
- Recent results suggest that 3\textsubscript{Λ}H could be more compact than expected\textsuperscript{1,2}
  - Precise measurements required to shed light on the 3\textsubscript{Λ}H structure

\begin{center}
\begin{tabular}{ccc}
$\Lambda_{uv}$ & $B_{\Lambda}$ (keV) & $\tau$ (ps) \\
800 & 69 & 234±27 \\
900 & 135 & 190±22 \\
1000 & 159 & 180±21 \\
- & 410 & 163±18 \\
\end{tabular}
\end{center}

\textsuperscript{1} STAR, Phys. Rev. C 97, 5, 054909 (2018)
\textsuperscript{2} STAR, Nature Physics 16, 409–412 (2020)
$^3\Lambda\bar{H}$ production in small systems (pp and p-Pb collisions)

- Loosely bound nature of $^3\Lambda\bar{H}$ has strong implications for its production mechanism:
  - thermal (SHM)\(^1\) and coalescence\(^2\) predictions well separated at low charged-particle multiplicity density
  - Coalescence relies on the radius of the particle while SHM don’t

- $^3\Lambda\bar{H}$ production in pp and p-Pb is a key to understand the nuclear production mechanism in hot and dense matter

Hypertriton in large systems

Precision measurements of lifetime and $B_\Lambda$ in Pb-Pb collisions
The ALICE detector

- We can identify the hypertriton daughter particles ($^3\text{He}$ and $\pi^-$) exploiting the excellent particle identification (PID) capabilities of the ALICE apparatus.
The ALICE detector

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Inner Tracking System
- Track reconstruction
- Reconstruction of primary and decay vertices
- PID of low momentum particles
The ALICE detector

- We can identify the hypertriton daughter particles ($^3$He and $\pi^-$) exploiting the excellent particle identification (PID) capabilities of the ALICE apparatus.

**Time Projection Chamber**
- Tracking
- PID via specific energy loss
The ALICE detector

- We can identify the hypertriton daughter particles (\(^3\text{He}\) and \(\pi^-\)) exploiting the excellent particle identification (PID) capabilities of the ALICE apparatus.

**Time Of Flight detector**
- Particle identification with time-of-flight
We can identify the hypertriton daughter particles ($^3\text{He}$ and $\pi^-$) exploiting the excellent particle identification (PID) capabilities of the ALICE apparatus.
$^3\Lambda^\Lambda$ in large systems

- Analysed data sample:
  - Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV collected by ALICE in 2018

- $^3\Lambda^\Lambda$ candidate: $^3\text{He} + \pi^-$ pairs (and related charge conjugated states)

- Secondary vertex reconstruction
  - matching of $^3\text{He} + \pi^-$ tracks coming from a common vertex

- Huge combinatorial background
H selection: machine learning approach

Boosted Decision Trees Classifier (BDT) trained on a dedicated sample

- BDT output (independent trainings for each bin):
  - **Score** related to the probability of the candidate to be signal or background
H selection: machine learning approach

- Selection applied on the BDT score
  - maximisation of the expected significance (assuming thermal production)

Boosted Decision Trees Classifier (BDT) trained on a dedicated sample
Signal extraction

- Signal extracted with a fit to the invariant mass spectrum of the selected candidates
- High significance over a wide range
  - 9 ct bins from 1 to 35 cm
• Corrected ct spectrum fitted with an exponential function
• Lifetime value from the fit
  ○ Statistical uncertainty ~ 6%
  ○ Systematic uncertainty ~ 7%
• Most precise measurement of the lifetime ever done so far
Most precise measurement

Compatible with latest STAR measurement

Models predicting a lifetime close to the free $\Lambda$ one are favoured
  
  strong hint that hypertriton is weakly bound, but $B_{\Lambda}$ is still needed to solve the puzzle

\[
\begin{align*}
\geq 2020 \text{ models: assuming } B_{\Lambda} &= 70 \text{ keV} \\
< 2020 \text{ models: assuming } B_{\Lambda} &= 130 \text{ keV}
\end{align*}
\]
- Same signal extraction technique and ct bins used for the lifetime: precise mass measurement needed to obtain $B_\Lambda$
- Extremely precise measurement
  - 0.0016% stat.
- Systematic uncertainty of ~100 keV (0.003%)
• From the mass measurement to $B_\Lambda$
  ○ $B_\Lambda = M_\Lambda + M_d - M_{^3\Lambda H}^3$
• Weakly bound nature of $^3\Lambda H$ is confirmed by the latest ALICE measurement
  ○ $B_\Lambda$ compatible with zero
  ○ in agreement within $1\sigma$ with Dalitz and $\chi$EFT based predictions
  ○ fully consistent with the lifetime measurement according to recent theoretical calculations $^1,^2$

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1 Hildenbrand F. et al., Physical Review C, vol. 102, no. 6, Dec. 2020
Hypertriton in small systems
First measurements of $^3_\Lambda$H production in pp and p-Pb collisions
3\(^\Lambda\) H selection in pp and p-Pb collisions

- Data samples:
  - pp at \(\sqrt{s} = 13\) TeV and p-Pb at \(\sqrt{s_{NN}} = 5.02\) TeV collisions collected during Run 2

- 3\(^\Lambda\) H selection in pp: trigger on high multiplicity events using V0 detectors + topological cuts on triggered events

- 3\(^\Lambda\) H selection in p-Pb: 40% most central collisions + BDT Classifier

- Significance > 4\(\sigma\) both in pp and p-Pb
$^3\Lambda$H / $\Lambda$ in pp and p-Pb collisions

- $^3\Lambda$H / $\Lambda$ in small systems:
  - large separation between production models
  - measurements in good agreement with 2-body coalescence
  - tension with SHM at low charged-particle multiplicity density
    - configuration with $V_C = 3dV/dy$ is excluded at level of more than 6$\sigma$

References:
$S_3$ in pp and p-Pb collisions

- $S_3$: strangeness population factor
  $$\left(\frac{^3\Lambda \text{H}}{^3\text{He}}\right) / (\Lambda / p)$$

- $S_3$ in small systems:
  - same conclusions as for $^3\Lambda \text{H} / \Lambda$ but with a lower sensitivity
  - Run 3 will be crucial to finally distinguish between SHM \(^1\) and coalescence \(^2\) and explore the multiplicity dependence of $S_3$!


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Summary and perspectives

- $^3\Lambda^1\text{H}$ in large systems:
  - precise measurements of lifetime and $B^\Lambda$ in Pb-Pb collisions
    - weakly bound nature of $^3\Lambda^1\text{H}$ confirmed

- $^3\Lambda^1\text{H}$ in small systems:
  - first measurement of $^3\Lambda^1\text{H}$ production in pp and p-Pb collisions
  - concrete possibility to distinguish with high significance between the two nucleosynthesis mechanisms
    - it will be possible in Run 3!

Thanks for your attention!
Precision measurement of the $\Lambda$ lifetime

- Precision measurement of the $\Lambda$ lifetime in ALICE
  - factor 3 more precise than the current world average taken from the PDG
  - important reference for hypertriton
  - confirms the excellent capabilities of the ALICE detector for lifetime measurements
Expected $S_3$ performance for Run 3

ALICE Run 3 pp program public note