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Measurements of the hypertriton production and properties with ALICE

Politecnico di Torino

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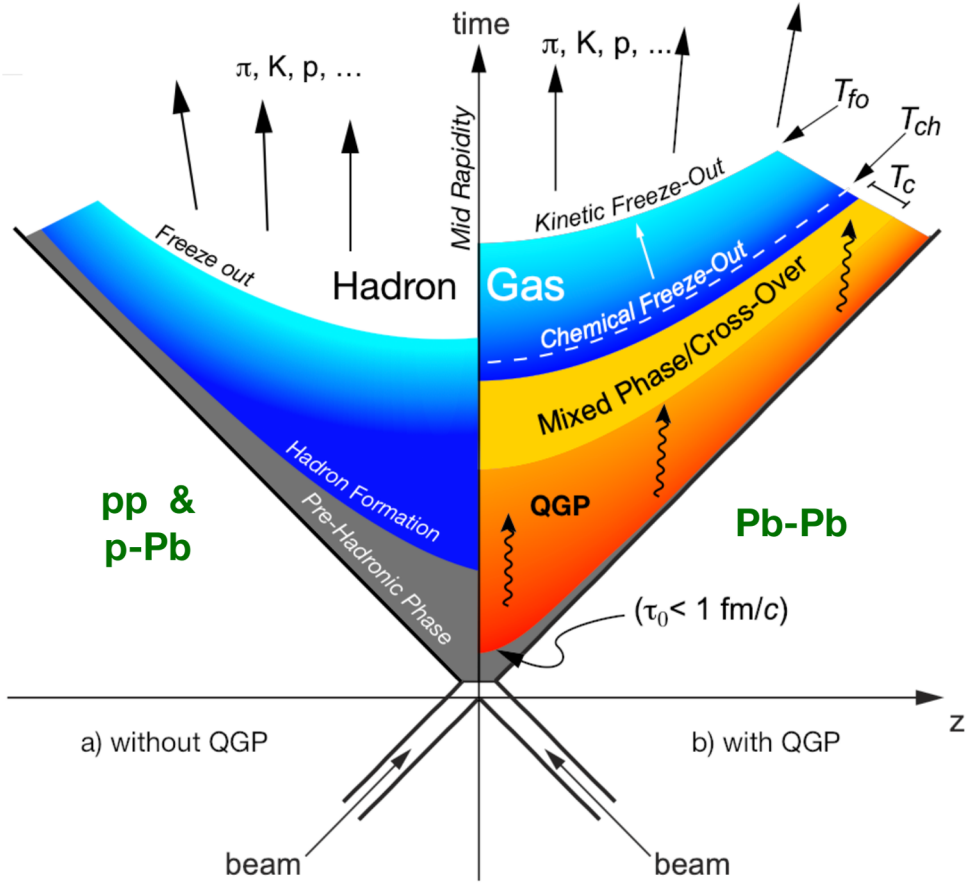
and Politecnico di Torino

(Hyper)nuclei at the LHC



- (Hyper)nuclei at the LHC observed in all the collision systems
  - pp, p–Pb, Pb–Pb
  - Pb–Pb: complex dynamics and quark-gluon-plasma (QGP) formation
- Nuclei and hypernuclei produced in the latest stages of the collision evolution
  - Chemical and kinetic freeze-outs
- B_Λ ≅100 keV, T_{ch} = 156.5 ± 1.5 MeV[1], T_{fo} =90 MeV[2]
  - formation mechanism of these objects at the LHC energies still debated
- Production mechanism usually described with two classes of phenomenological models:
  - statistical hadronization (SHM)
  - coalescence

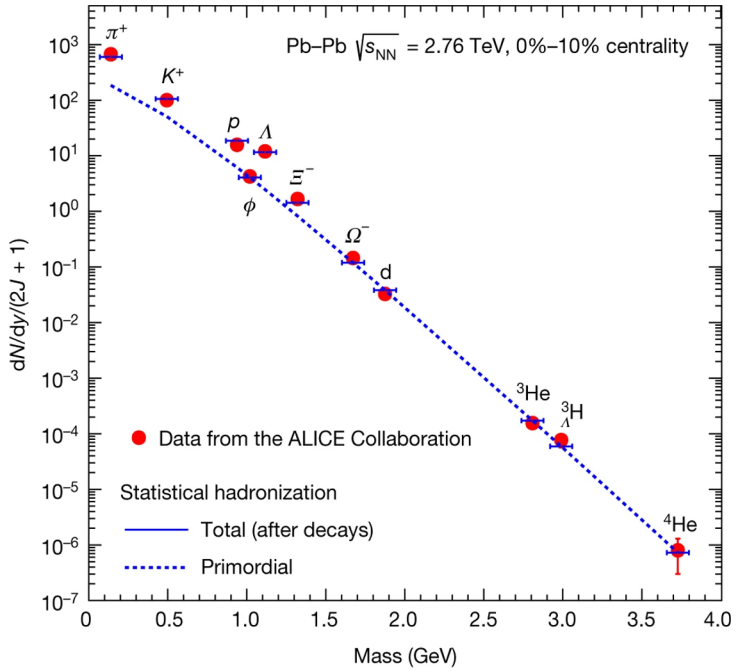
[1] A. Andronic et al., Nature 561, (2018) 3210
[2] For the most central collisions: Phys. Lett. B728, 25–38 (2014)

Modeling the (hyper)nuclei production

Thermal Models (SHMs)

- Hadrons emitted from the interaction region in statistical equilibrium when the system reaches the chemical freeze-out temperature
- Abundance of a species
  - ∝ Exp(-m/T_{chem})
- Mainly used for Pb–Pb, it can be used in smaller systems (pp and p–Pb) by using the canonical ensemble

A. Andronic et al., Nature 561, (2018) 3210
Vovchenko et al., Phys. Lett. B 785, (2018) 171



Modeling the (hyper)nuclei production

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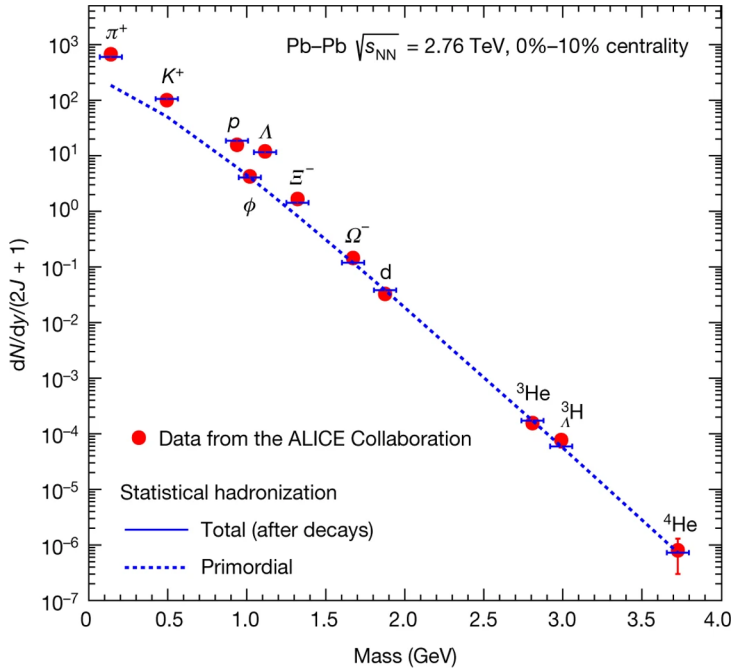

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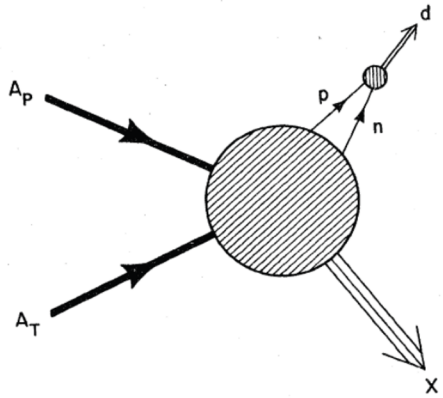
Coalescence

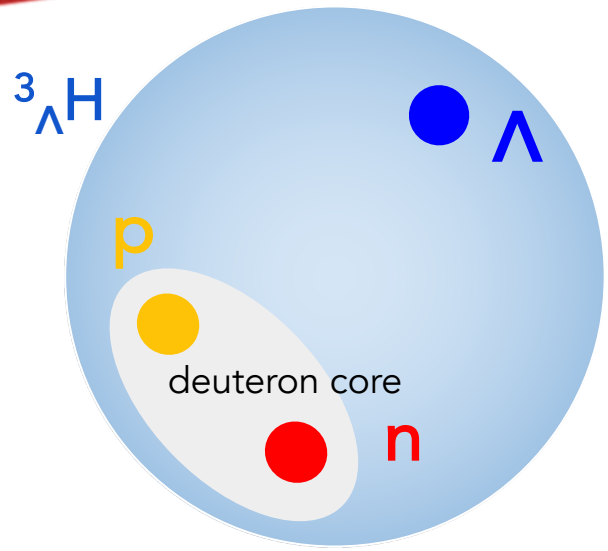


Baryons close in phase space can form a nucleus

- Interplay between the configuration of the phase space of the nucleons and the wave function of the nucleus

J. I. Kapusta, Phys.Rev. C21, 1301 (1980)
Sun. et al., Phys. Lett. B, 792, 132–137, (2019)

The hypertriton in a nustshell



- Lightest known hypernucleus
  - Bound state of a neutron, a proton and a **Λ**
  - Discovered in early 50s by M.Danysz and J.Pniewski
    - Balloon-flown experiments [1, 2]

Mass: ~ 2.991 GeV/c^2
Spin: 1/2
Lifetime: ~ 250 ps

Mesonic charged decay channels:
^{3}He + π (B.R. ≅ 0.25)
d + p + π (B.R. ≅ 0.40)

[1] M. Danysz et al., Philos. Mag. 44, (1953)
[2] Bonetti et al., Il Nuovo Cimento 11.2, (1954)

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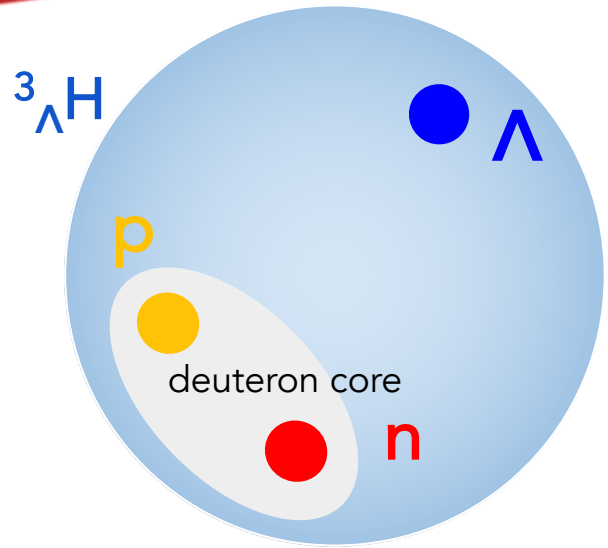

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- **Λ** - separation energy B_Λ = m(d) + m(**Λ**) - m($^3_\Lambda$H)
  - Reflects the extension of the $^3_\Lambda$H wave function
- Emulsion experiments[3] : $^3_\Lambda$H is a loosely bound nucleus
  - B_Λ = 130 ± 50 keV

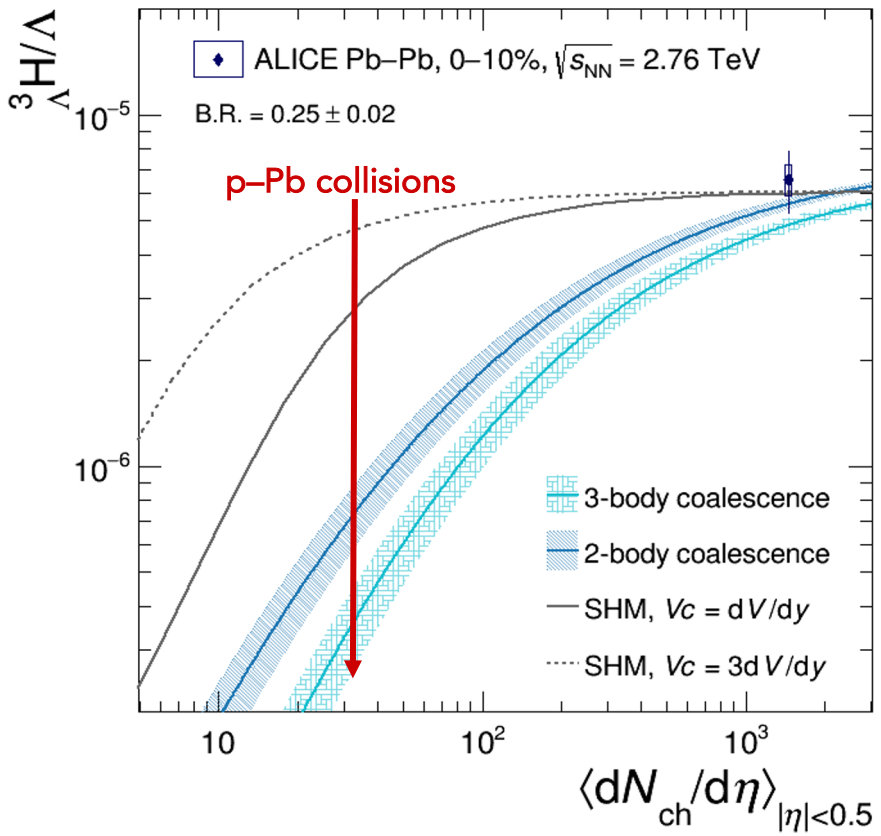
Recent pionless Effective Field Theory (EFT) calculations[4] show large separation (~11 fm) between the **Λ** and the "deuteron core" for B_Λ = 130 keV and give lifetime predictions as a function of B_Λ

[1] M. Danysz et al., Philos. Mag. 44, (1953)
[2] Bonetti et al., Il Nuovo Cimento 11.2, (1954)
[3] M.Juric et al., Nucl. Phys. B, 52, 1-30, (1973)
[4] F. Hildenbrand et al., Phys. Rev., 100 (2019)

The hypertriton in ALICE

- Recent results in heavy-ion collisions suggest that $^{3}_{\Lambda}$H could be more compact than expected [1, 2]
  - precise measurements required to shed light on the $^{3}_{\Lambda}$H structure
- $^{3}_{\Lambda}$H / Λ
  - large separation between SHM[3] and coalescence[4] predictions at low charged-particle multiplicity density
  - coalescence is sensitive to the interplay between the size of the collision system and the spatial extension of the nucleus wave function
- $^{3}_{\Lambda}$H production in p–Pb collisons: a key to understand the nuclear production mechanism at the LHC

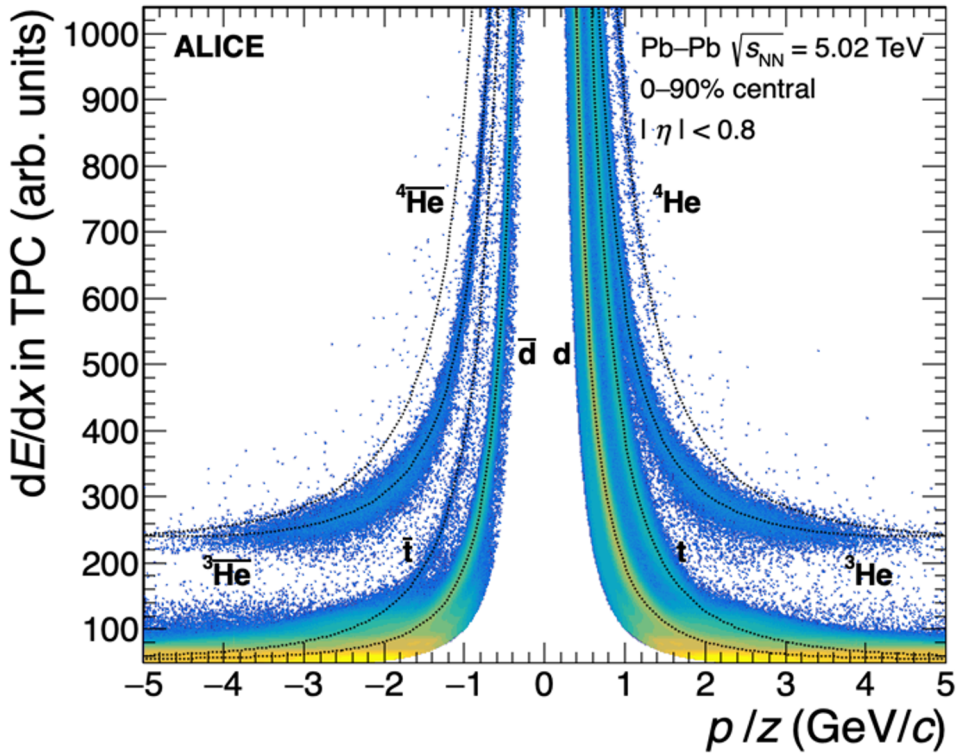
The ALICE Coll., Phys. Lett. B 754, 360–372, (2016)



1 STAR, Phys. Rev. C 97, 5, 054909 (2018)
2 STAR, Nature Physics 16, 409–412 (2020
3 *Vovchenko, et al.*, Phys. Lett., B 785, 171-174, (2018)
4 *Sun. et al.*, Phys. Lett. B 792, 132–137, (2019)

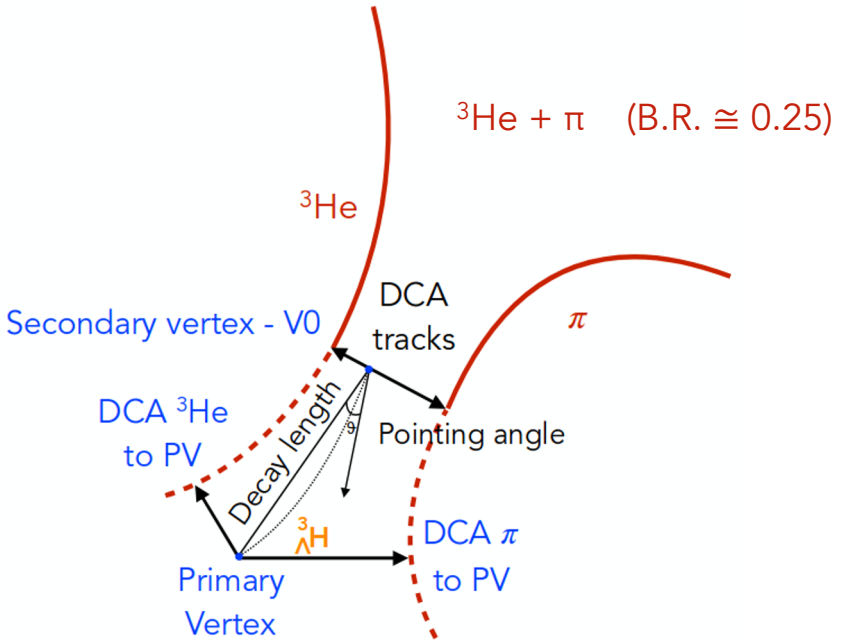
$^{3}_{\Lambda}$H reconstruction

- Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by ALICE in 2018
- Huge combinatorial background topological and kinematical cuts plus Machine Learning approach

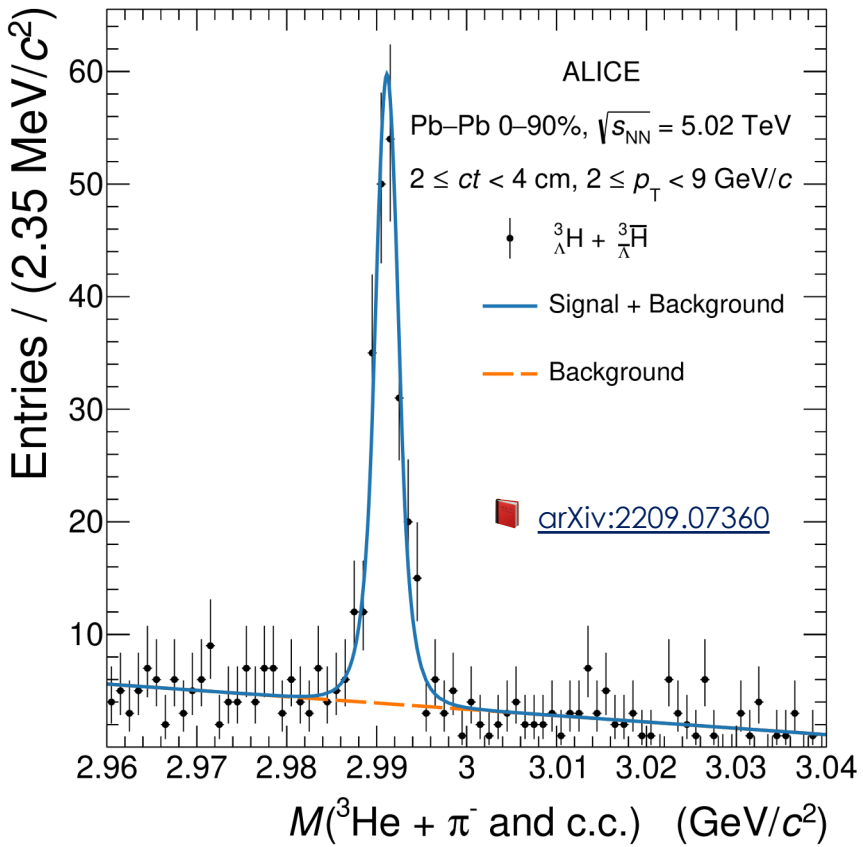


Decay daughters identified through their specific energy loss in the TPC

Secondary vertex reconstruction: loose pre-selections applied to the decay topology



${}^{3}_{\Lambda}$H signal extraction and lifetime



- Signal extracted with a fit to the invariant mass spectrum of the selected candidates
- High significance in 9 *ct* bins from 1 to 35 cm
- Integral of the signal function (N^{raw}) for the lifetime, mass peak position (μ) for the B_Λ

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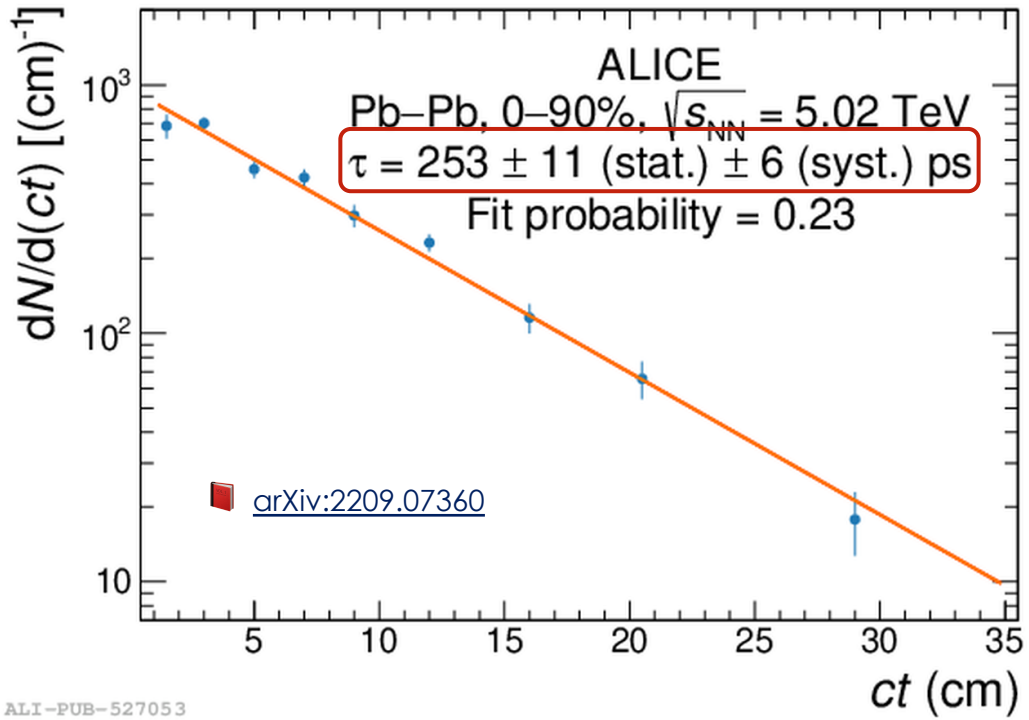
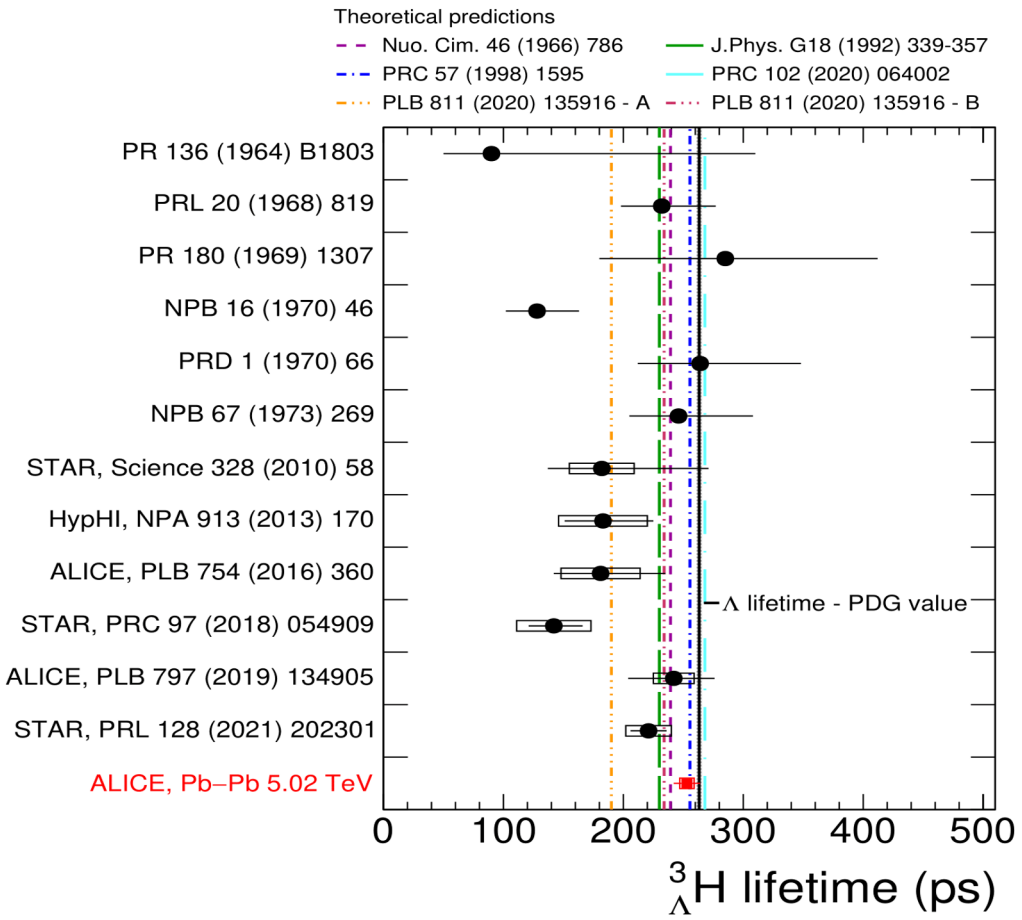


- Signal extracted with a fit to the invariant mass spectrum of the selected candidates
- High significance in 9 *ct* bins from 1 to 35 cm
- Integral of the signal function (N^{raw}) for the lifetime, mass peak position (μ) for the B_{Λ}
- Corrected *ct* spectrum fitted with an exponential function
- Lifetime value from the fit
  - Statistical uncertainty ~ 4%
  - Value compatible within 1**σ** with free **Λ** lifetime measured with unprecedented precision by ALICE[1]

[1] https://arxiv.org/abs/2303.00606

$^{3}_{\Lambda}$H lifetime measurements vs theory



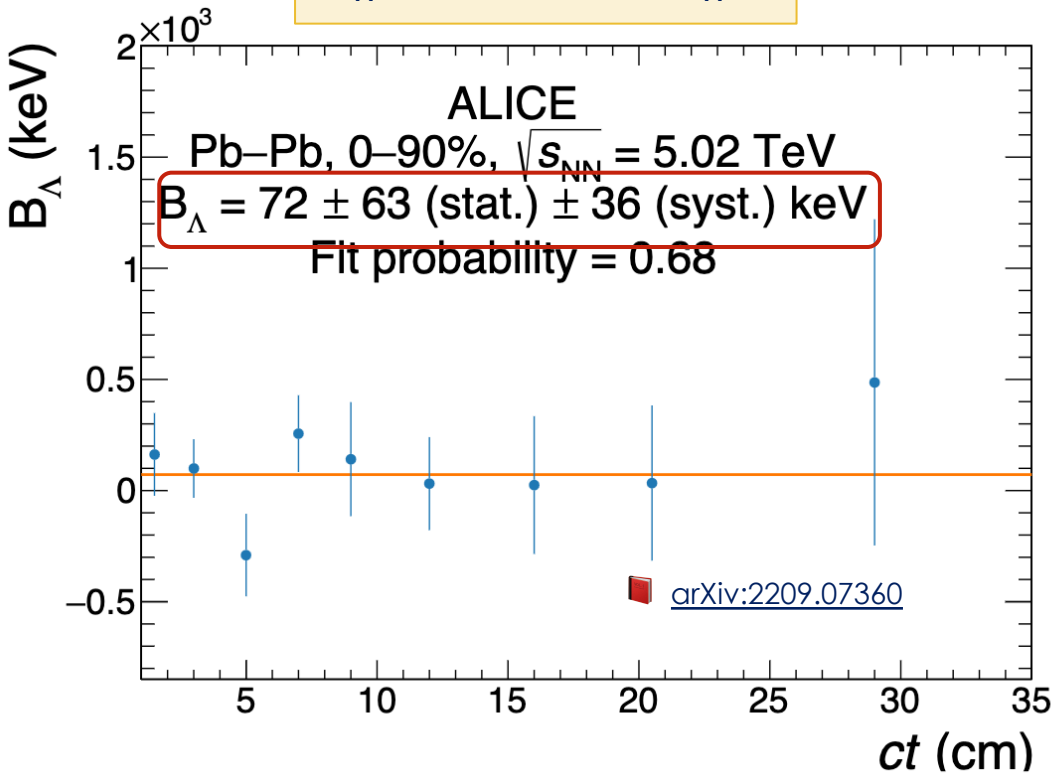
arXiv:2209.07360

- Most precise measurement to date
- Compatible with latest ALICE and STAR measurements
- Strong hint that hypertriton is weakly bound

Compatible with all the theoretical predictions assuming $^{3}_{\Lambda}$H as weakly bound

$^{3}_{\Lambda}$H binding energy

B_Λ = m(d) + m(Λ) - m($^{3}_{\Lambda}$H)



- Extremely precise mass measurement
  - 0.0016% stat.
- Low B_Λ, in agreement with early emulsion experiments

$^3_\Lambda$H binding energy

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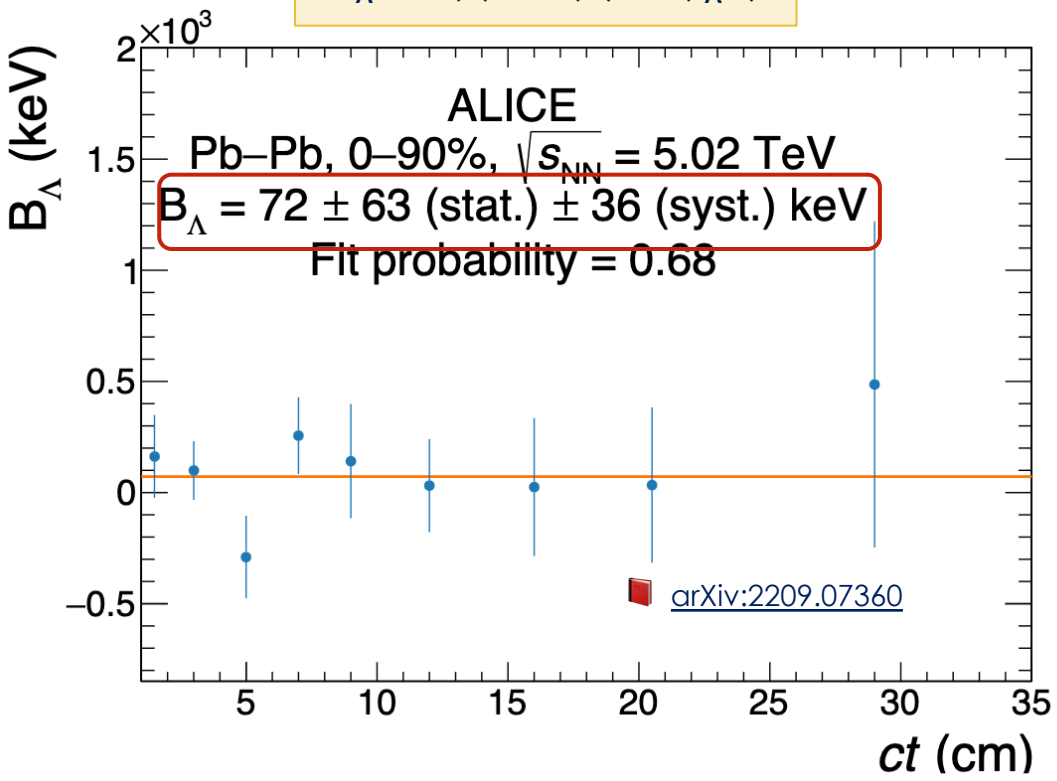
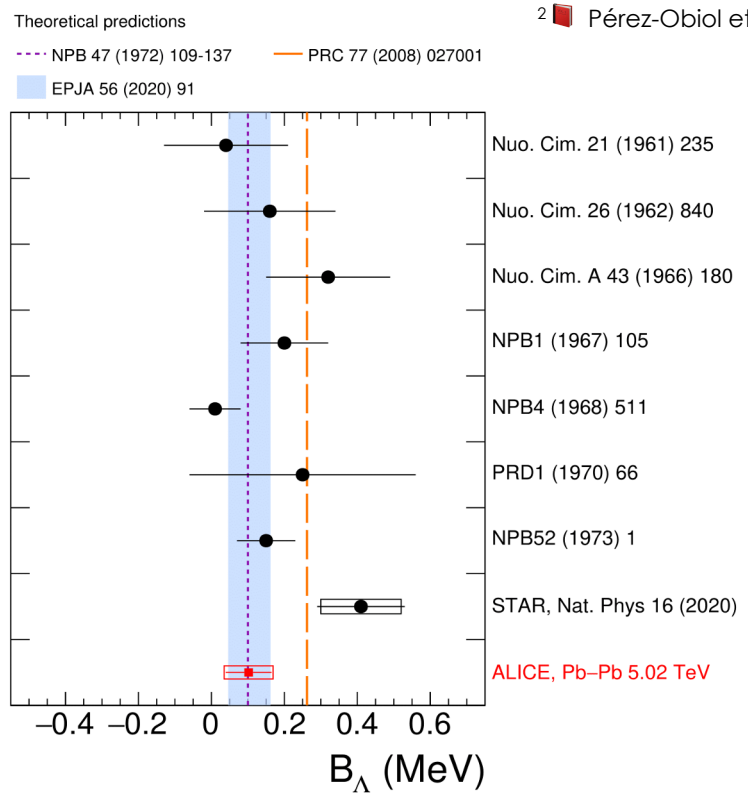


- B_Λ compatible with zero
- agreement within 1**σ** with Dalitz and χEFT-based predictions
- fully consistent with the lifetime measurement according to recent theoretical calculations[1,2]

[1] Hildenbrand et al., PRC 102 (2020) 6
[2] Pérez-Obiol et al., PLB (2020) 811



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  - 0.0016% stat.
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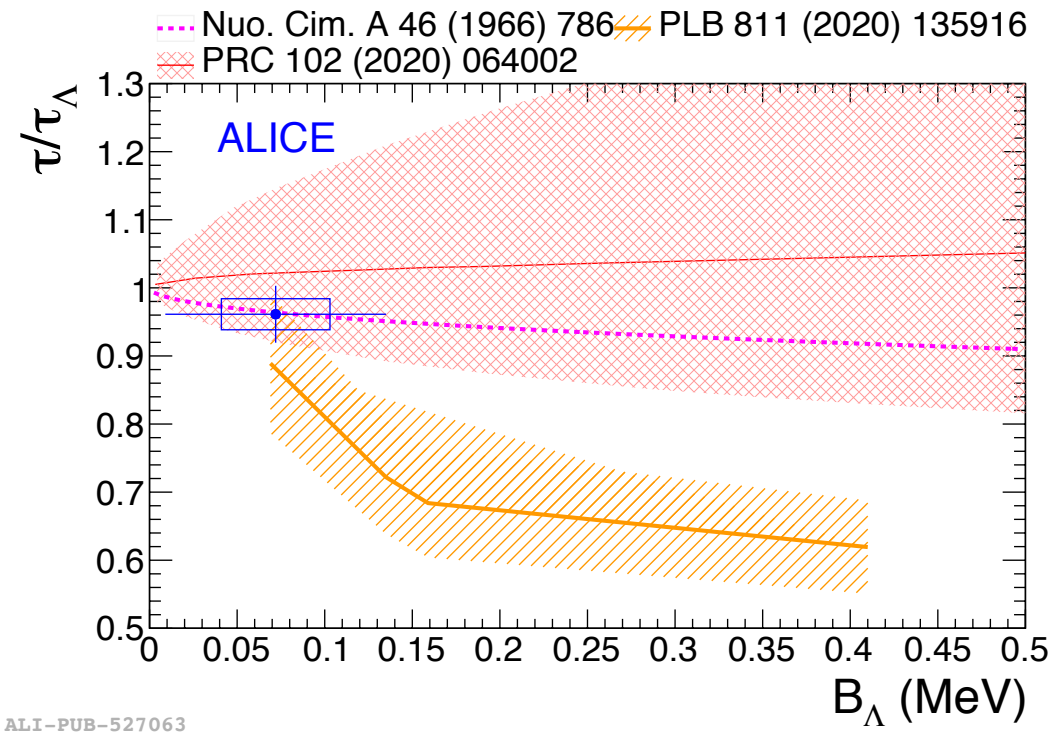
$^{3}_{\Lambda}$H properties in Pb-Pb



ALI-PUB-527063

arXiv:2209.07360

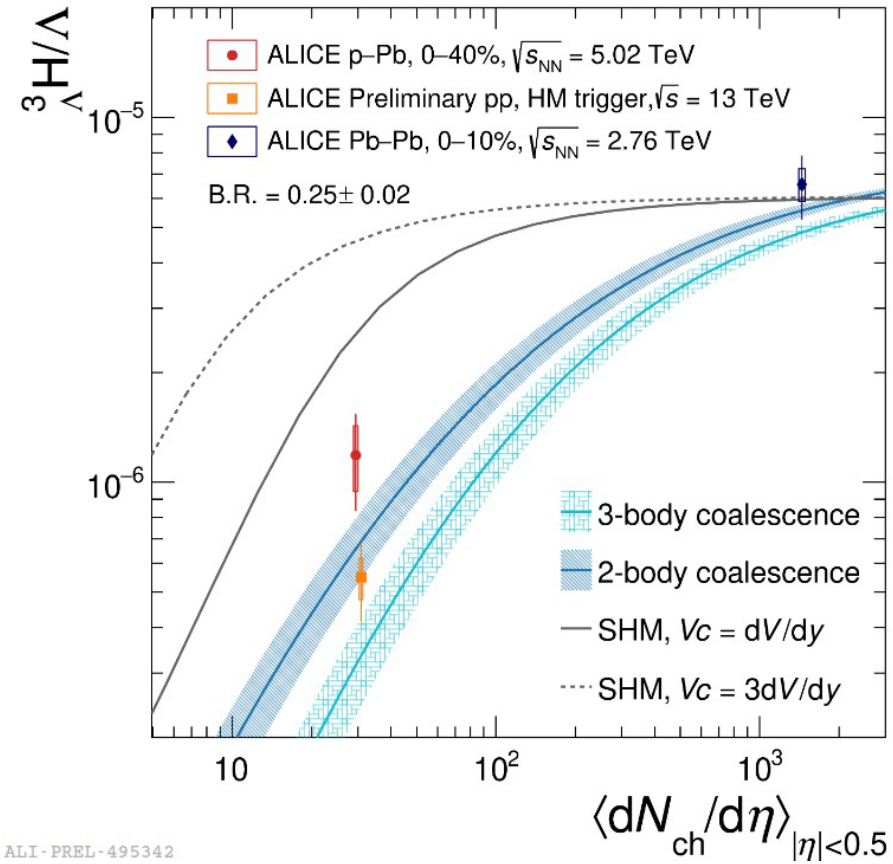
- Most precise measurements of **τ** and B_{Λ} of the $^{3}_{\Lambda}$H
  - **τ** = 253 ± 11 (stat.) ± 6 (syst.) ps
  - B_{Λ} = 72 ± 63 (stat.) ± 36 (syst.) keV

- Weakly-bound nature of the $^{3}_{\Lambda}$H finally confirmed
  - $^{3}_{\Lambda}$H could be approximated as a shallow d-**Λ** state with a wide d-**Λ** radius of ~ 10 fm

- How does this reflect on its production?

$^{3}_{\Lambda}$H in small collision systems

pp at 13 TeV and p–Pb at 5.02 TeV collisions collected by ALICE during Run 2



- good agreement with 2-body coalescence
- tension with SHM at low charged-particle multiplicity density
  - V_C = 3 dV/dy excluded: deviation > 6**σ**
  - First significant constraint to SHM possible configurations

- Coalescence quantitatively describes the $^{3}_{\Lambda}$H suppression in small systems
  - the nuclear size matters at low charged-particle multiplicity

p-Pb: Phys. Rev. Lett. 128, (2022) 252003
Pb-Pb: Phys. Lett. B 754, 360–372, (2016)

Summary

- $^{3}_{\Lambda}$H in large systems:
  - precise measurements of lifetime and B_{Λ} in Pb–Pb collisions
    - weakly bound nature of $^{3}_{\Lambda}$H confirmed

- $^{3}_{\Lambda}$H in small systems
  - first measurement of the $^{3}_{\Lambda}$H production in p–Pb collisions
  - $^{3}_{\Lambda}$H / Λ favours coalescence predictions
  - radial extension of the hypertriton is an important input for coalescence models

Stay tuned for the LHC Run 3!