Results on (anti-)(hyper-)nuclei production and searches for exotic bound states with ALICE at the LHC

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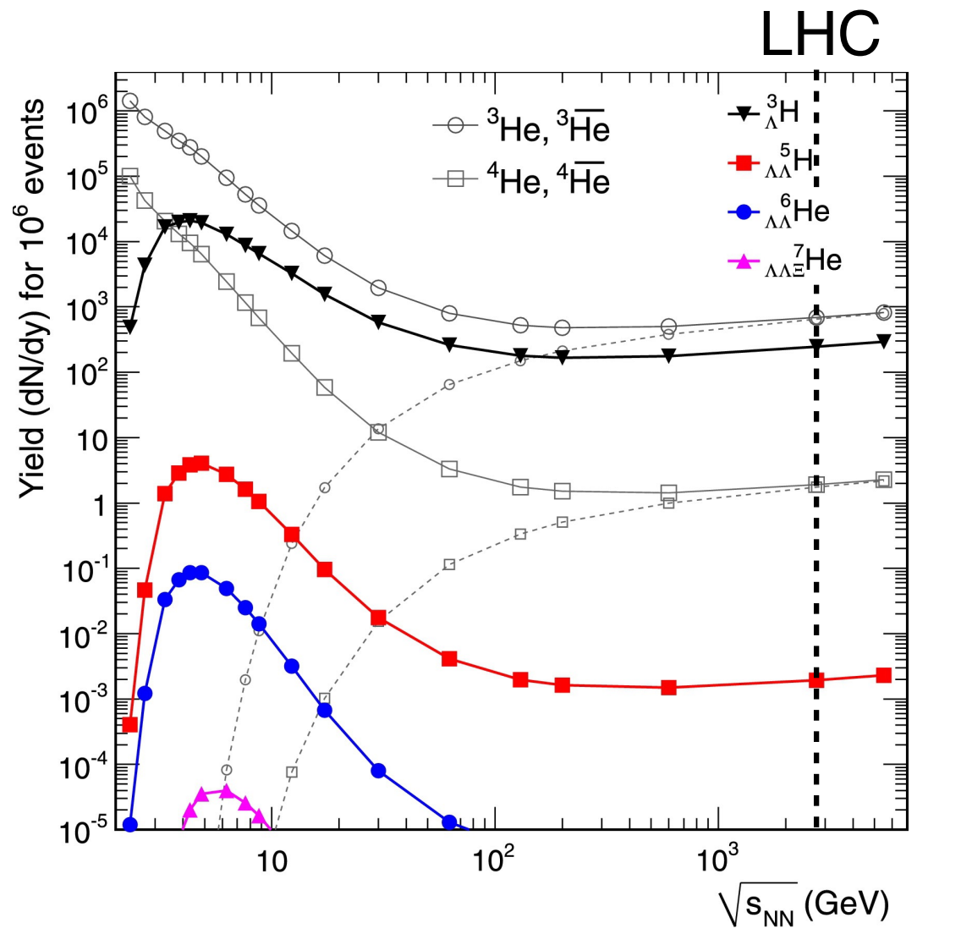
1. Introduction

- ☑ LHC energies lead to large production probabilities for (anti-)(hyper-)nuclei and exotic states
- ☑ At these energies large and equal amounts of particles and anti-particles are produced in the mid-rapidity region
- ☑ Production mechanism:

THERMAL Model [1]

- Hadrons emitted from the interaction region at the *chemical freeze-out* temperature (T_{chem})
- Abundance of species $\propto \exp(-m/T_{chem})$
- (Hyper-)nuclei large m ⟶ strong dependence on T_{chem}



COALESCENCE Model [2]

- (Anti-)baryons close in the phase space at the *kinetic freeze-out* can form a (anti-)(hyper-)nucleus
- Formation probability can be quantified through the *coalescence parameter* B_A
- In a naive approach B_A is expected to be independent of p_T and centrality

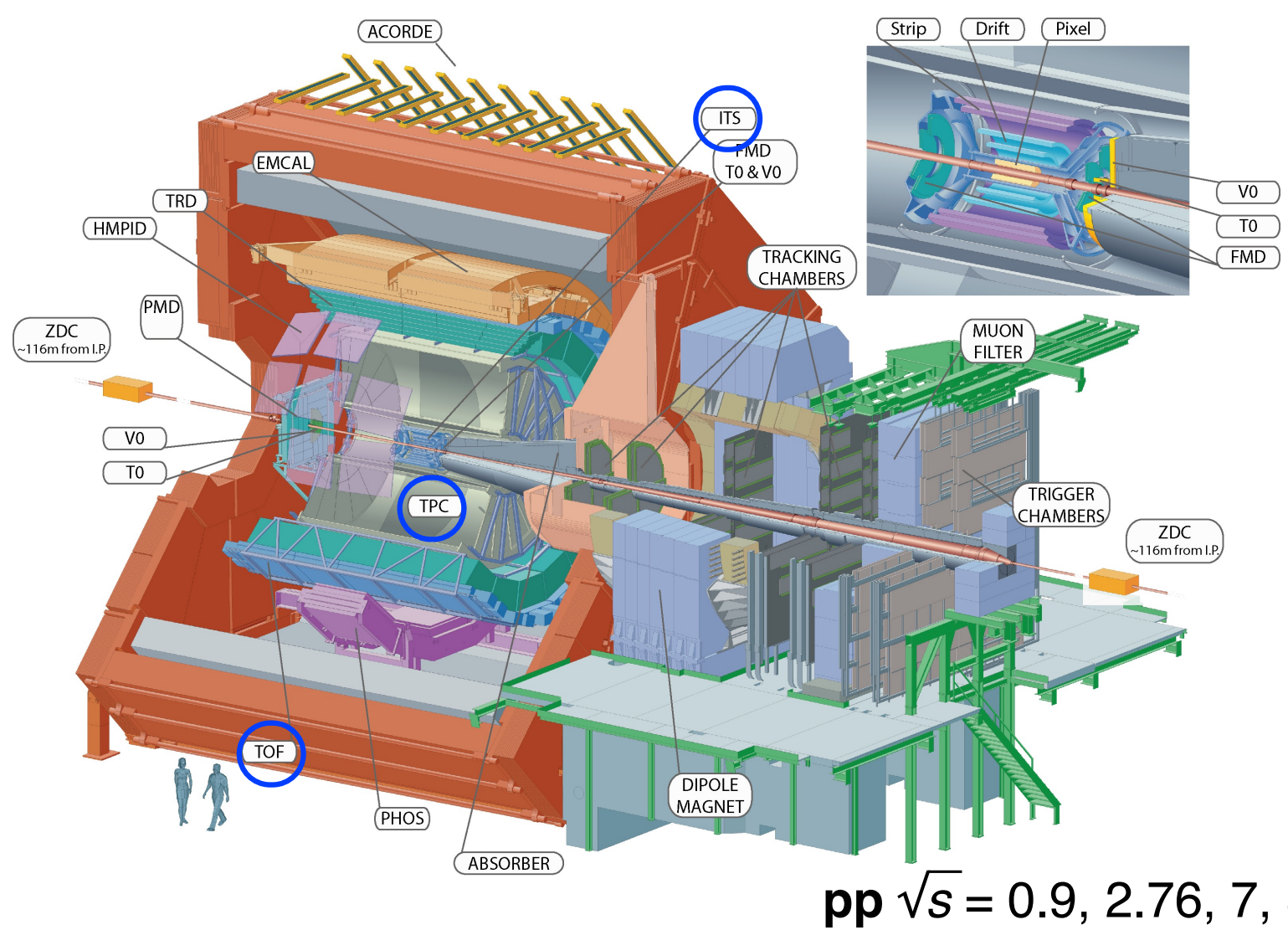
$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A} \quad [3]$$

*A = N_{proton} + $N_{neutron}$

References
[1] A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stocker. *Phys. Lett. B* 697, 203 (2011)
[2] S. T. Butler, C. A. Pearson. *Phys. Rev.* 129, 836 (1963)
[3] J. Gosset, et al. *Phys. Rev. C* 16, 629 (1977)

2. ALICE

- ☑ Excellent **particle identification** and **high performance tracking and vertexing** allow one to measure the production of (anti-)(hyper-)nuclei and exotic states

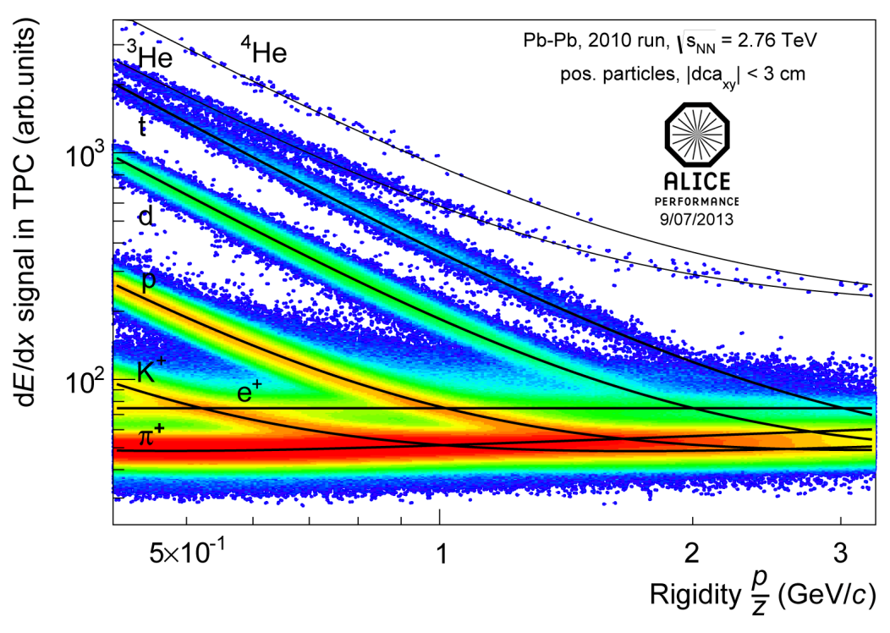


pp $\sqrt{s}$ = 0.9, 2.76, 7, 8, 13 TeV
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

Inner Tracking System

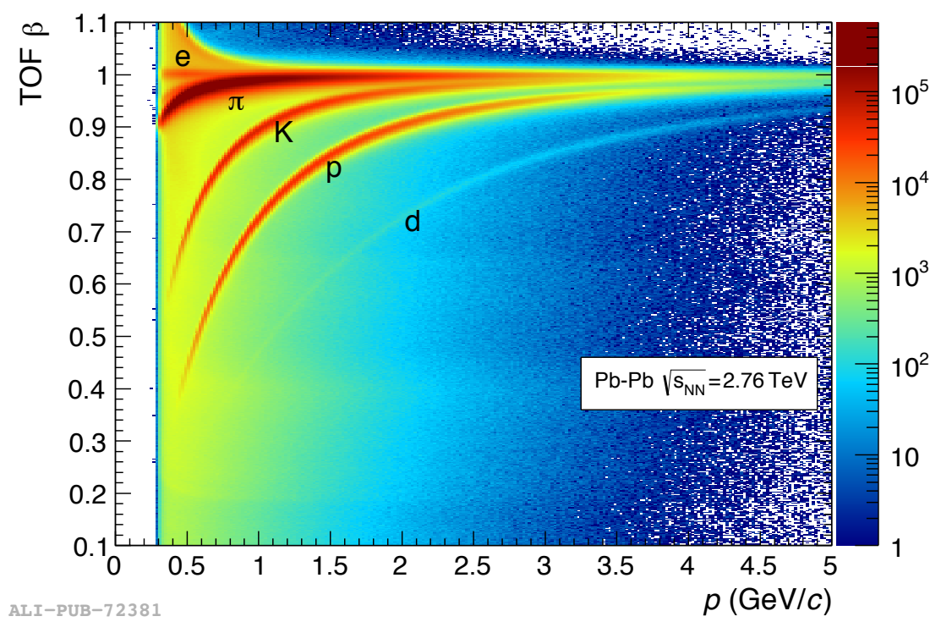
- $\sigma_{DCA_{xy}}$ < 100 µm for p_T > 0.5 GeV/*c* (in Pb-Pb collisions)
- separation of primary and secondary nuclei produced in material knock-out via DCA_{xy} measurement

Time Projection Chamber



- Specific energy loss d*E*/d*x* ($\sigma_{TPC} \simeq$ 7% in central Pb-Pb)
- Clear nuclei separation at low p/z

Time-Of-Flight [4]

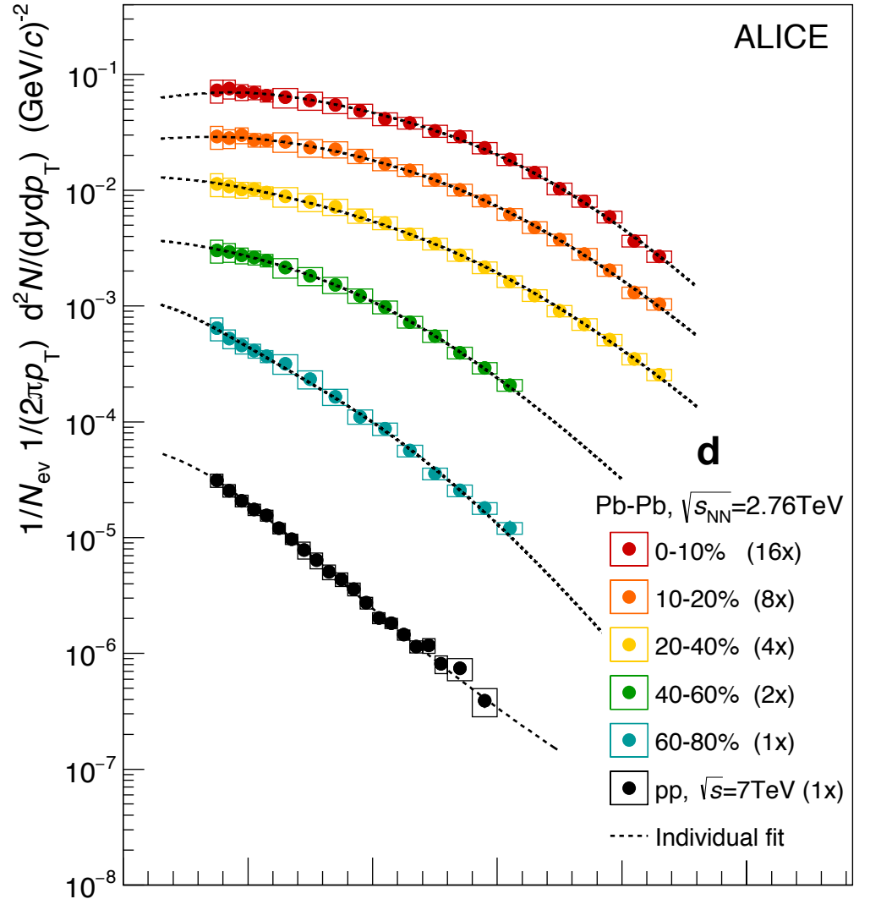


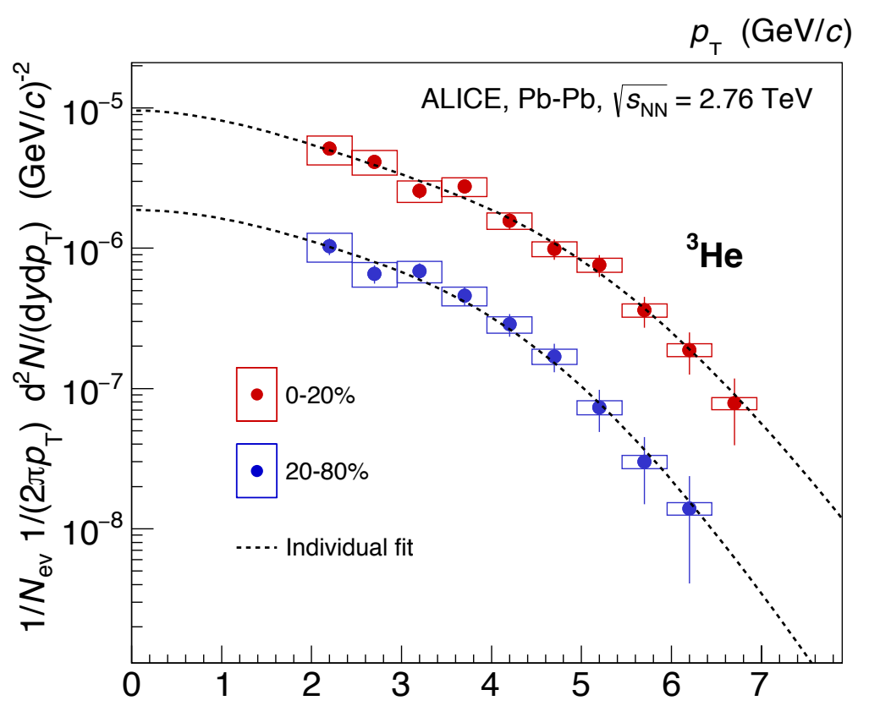
- $\sigma_{TOF} \simeq$ 85 ps in central Pb-Pb
- deuteron identification up to 4.5 GeV/*c* in Pb-Pb collisions

References
[4] ALICE Collaboration. *Int. J. Mod. Phys. A* 29 (2014) 1430044

3. Nuclei

arXiv 1506.08951 - accepted by *Phys. Rev. C*



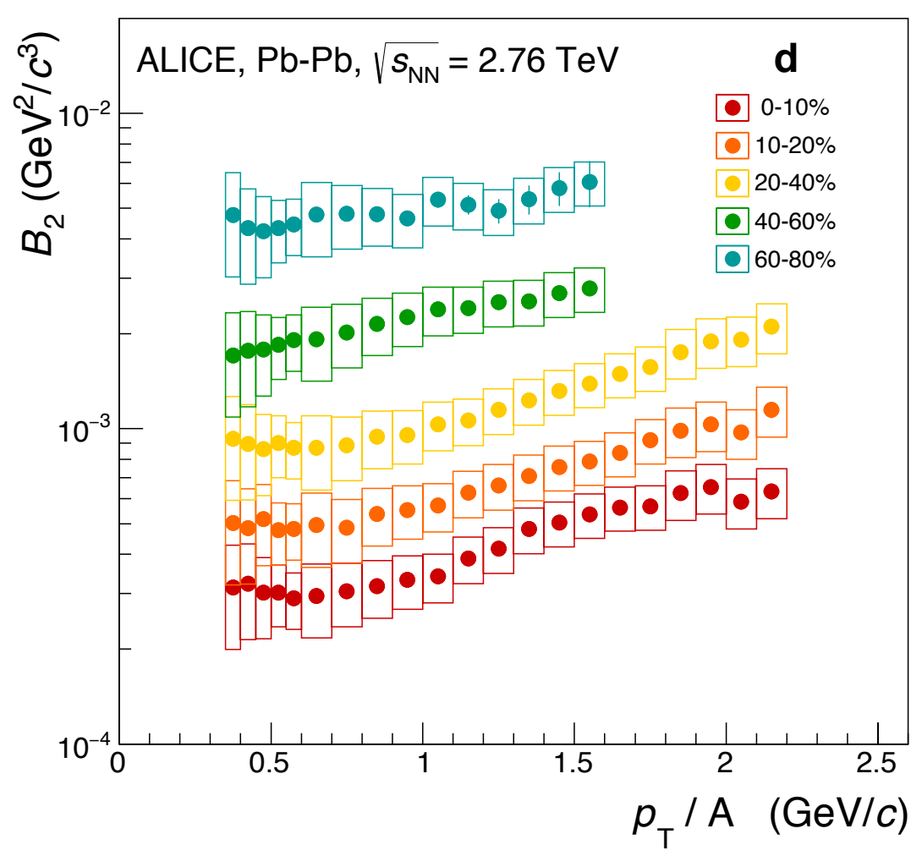


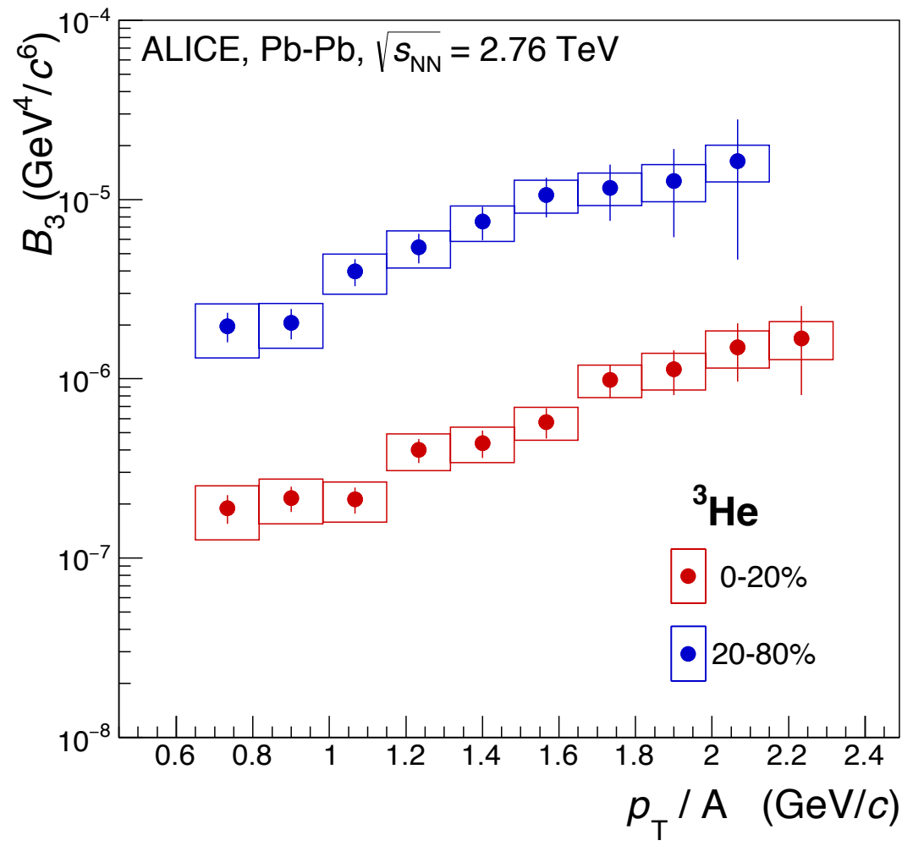
☑ p_T spectra

- d in pp: Levy-Tsallis [5] fit to obtain the p_T integrated yield dN/dy
- d and ^{3}He Pb-Pb spectra become harder as the centrality increases
- Blast-Wave [6] fit to obtain *transverse expansion velocity* and *kinetic freeze-out* temperature

☑ Coalescence parameter B_2 and B_3

- Decrease with increasing centrality: $B_{2,3} \propto V_{eff}^{-1}$ where $V_{eff} = R_\perp^2 R_\parallel$ is source volume
- p_T dependence for central collisions in contrast with the simple model [3]
- explained by space-momentum correlations caused by radial flow [7]





☑ Light (anti-)nuclei mass difference

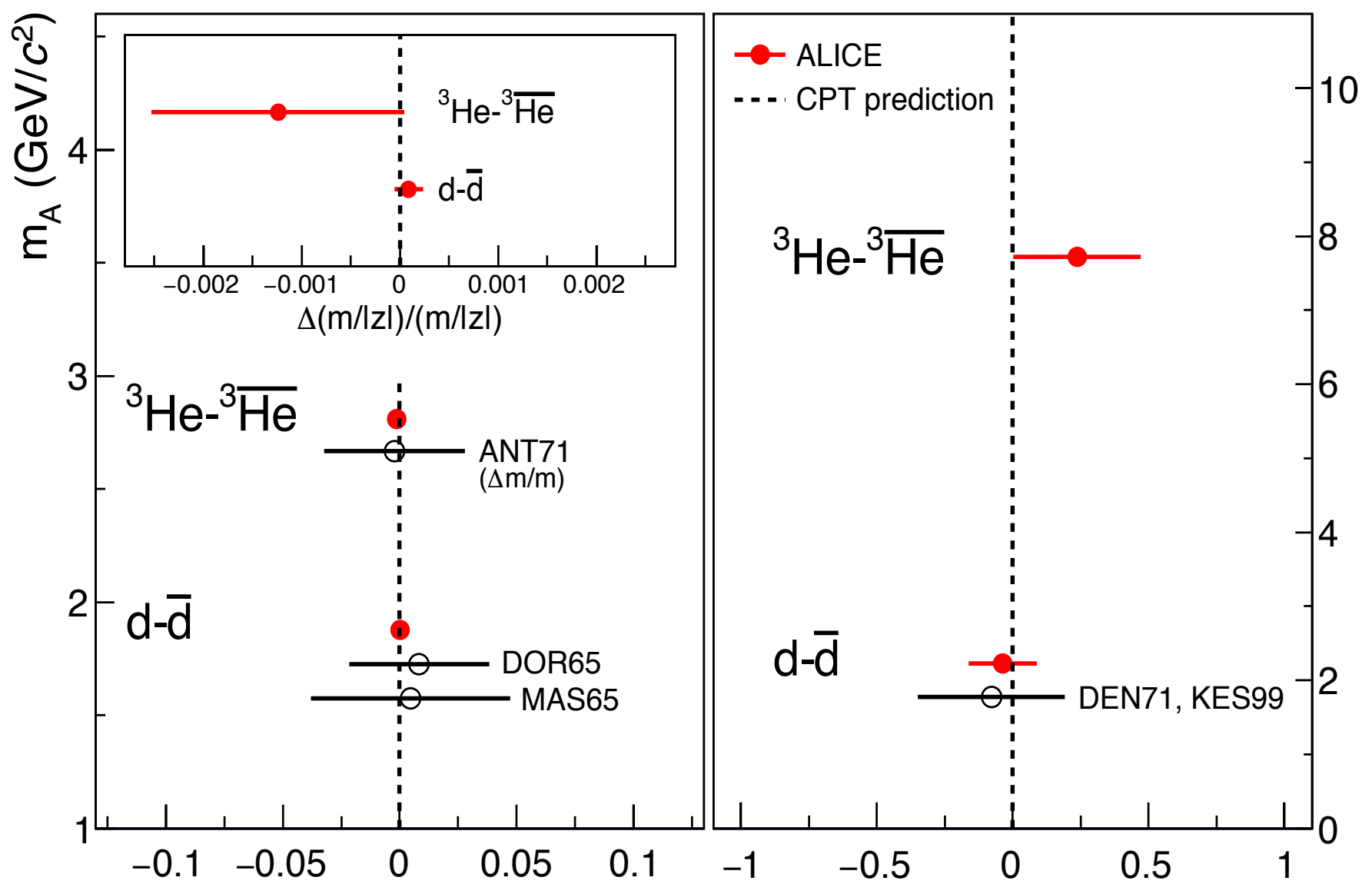
- Probe difference in nucleon anti-nucleon interaction encoded in (anti-)nuclei masses
- Mass-over-charge ratio measured with the TOF
- ε_A is the binding energy of nucleus A

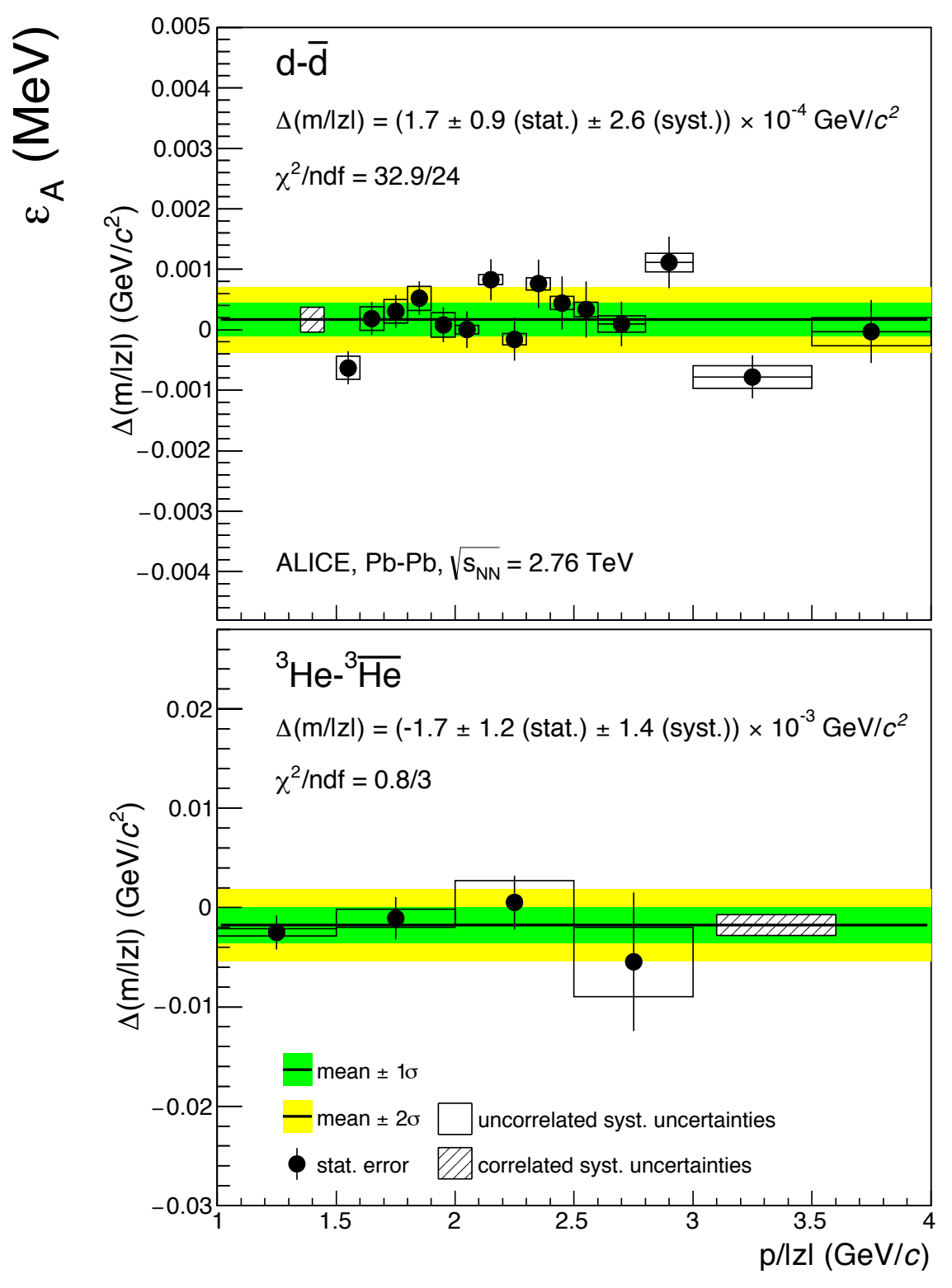
$\varepsilon_A = Zm_p + (A-Z)m_n - m_A$

$$\frac{\Delta(m/|z|)_{d\bar{d}}}{(m/|z|)_d} = (0.9 \pm 0.5(stat.) \pm 1.4(syst.)) \times 10^{-4}$$

$$\frac{\Delta(m/|z|)_{^3He^3\overline{He}}}{(m/|z|)_{^3He}} = (-1.2 \pm 0.9(stat.) \pm 1.0(syst.)) \times 10^{-3}$$

Nature Physics 11, 811-814 (2015)





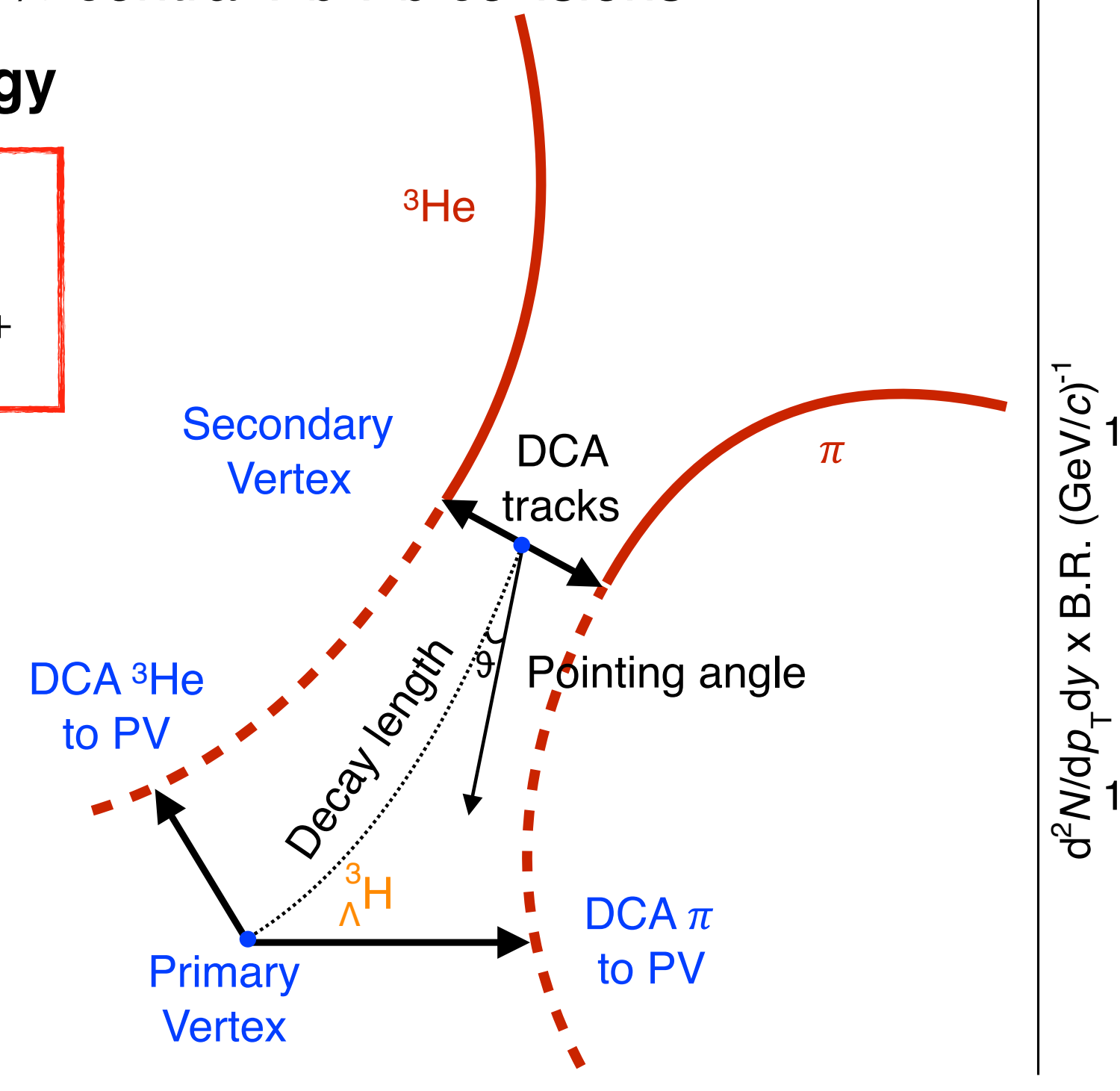
References
[5] C. Tsallis. *Journal of Statistical Physics* 52, 479 (1988)
[6] E. Schnedermann, J. Sollfrank, U. Heinz. *Phys. Rev. C* 48, 2462 (1993)
[7] R. Scheibl, U. Heinz. *Phys. Rev. C* 59, 1585-1602 (1999)

4. Hypertriton

- ☑ (Anti-)$^3_\Lambda$H lightest known hypernucleus: bound state of **p**, **n** and **Λ**
- ☑ Identification via charged mesonic 2-body decay channel up to 10 GeV/*c* in 0-10% central Pb-Pb collisions
- ☑ **2-body decay topology**

$$^3_\Lambda\text{H} \longrightarrow {}^3\text{He} + \pi^-$$
$$^3_{\bar\Lambda}\overline{\text{H}} \longrightarrow {}^3\overline{\text{He}} + \pi^+$$

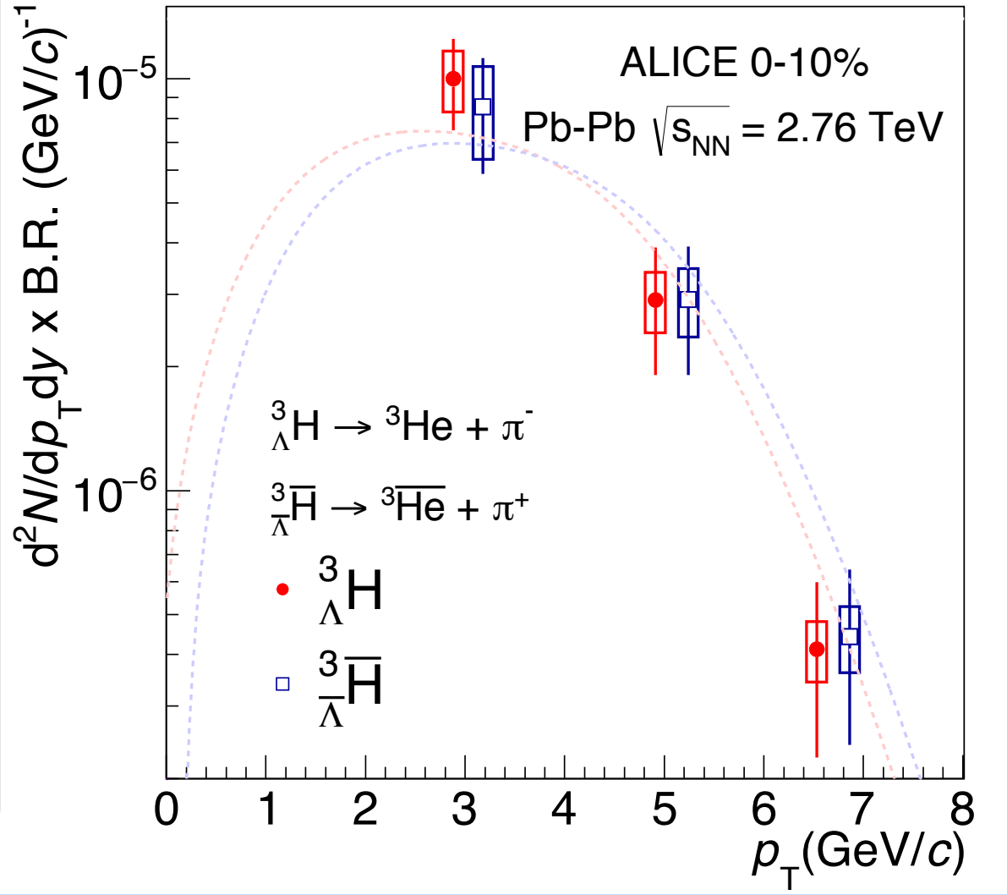
- B.R. [8] (2-body) ≅ 25%
- Mass = 2.992 GeV/c^2
- Λ binding energy B_Λ = 0.13 ± 0.05 MeV/c^2
- Λ-free lifetime ~ 263 ps

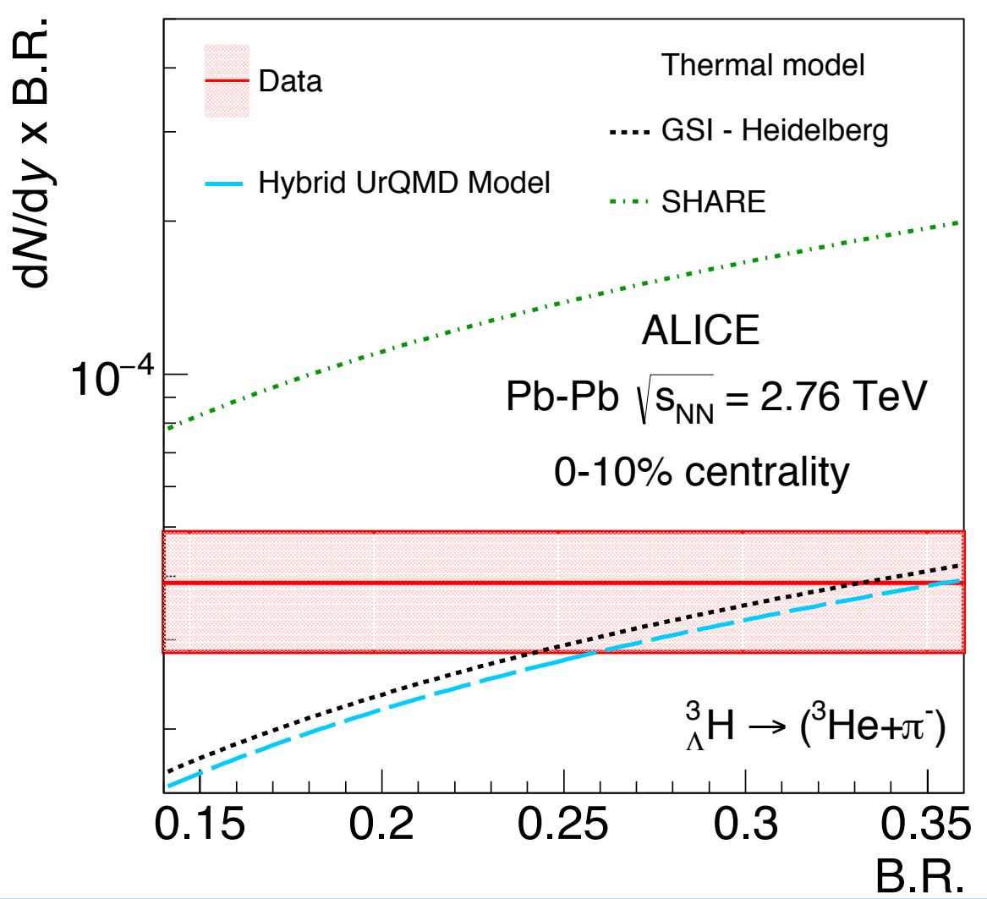


☑ Production yield

- p_T spectra for the 0-10% central collisions
- Blast-Wave fit to extract the particle yields integrated over full p_T
- d*N*/dy x B.R. compared with thermal models over B.R. range
- Model assuming thermal equilibrium and T_{chem} = 156 MeV (GSI-Heidelberg) and UrQMD model (hadron transportation and initial hydrodynamical stage) are favoured

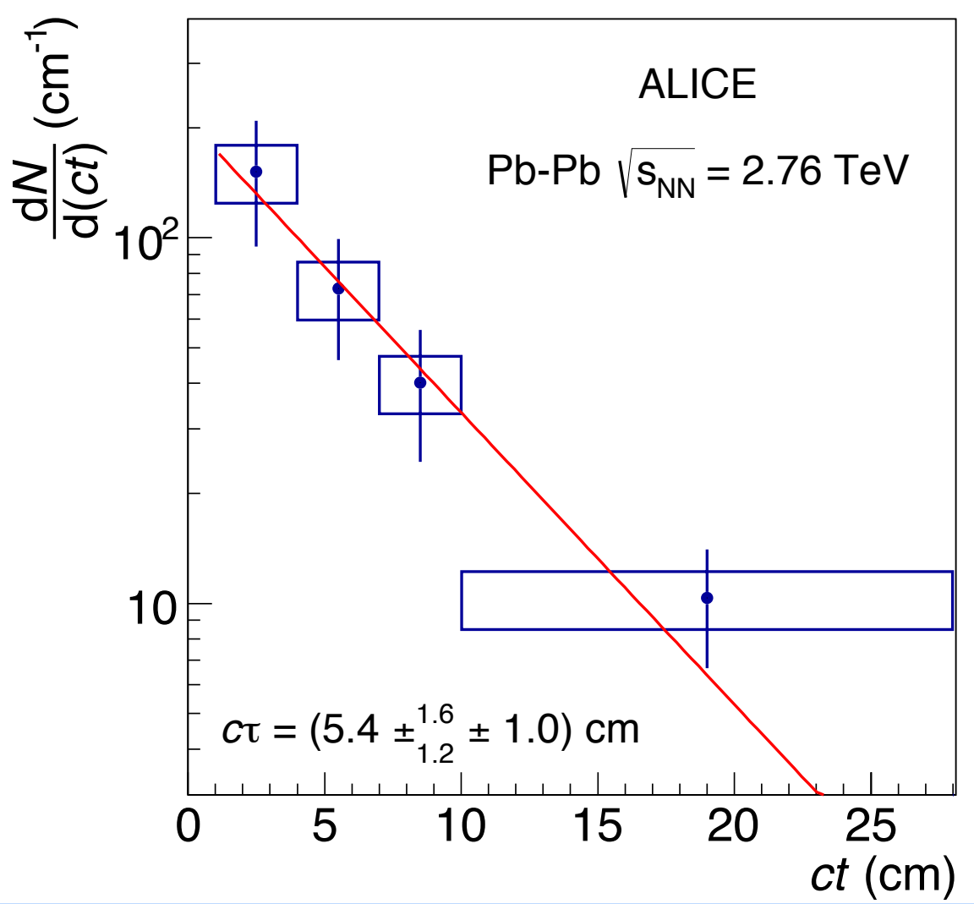
Phys. Lett. B 754, 360-372 (2016)





☑ Lifetime determination

- Hypertriton lifetime is expected to be slightly below than Λ lifetime
- $^3_\Lambda$H and $^3_{\bar\Lambda}\overline{\text{H}}$ in 0-10% and 10-50% centrality used for lifetime determination
- Exponential fit to d*N*/d(*ct*) distribution to obtain the proper decay length *cτ*
- Comparison with published experimental lifetime estimates



➡ World Average [9]

$$\tau = \left(216^{+19}_{-18}\right) ps$$

➡ ALICE result

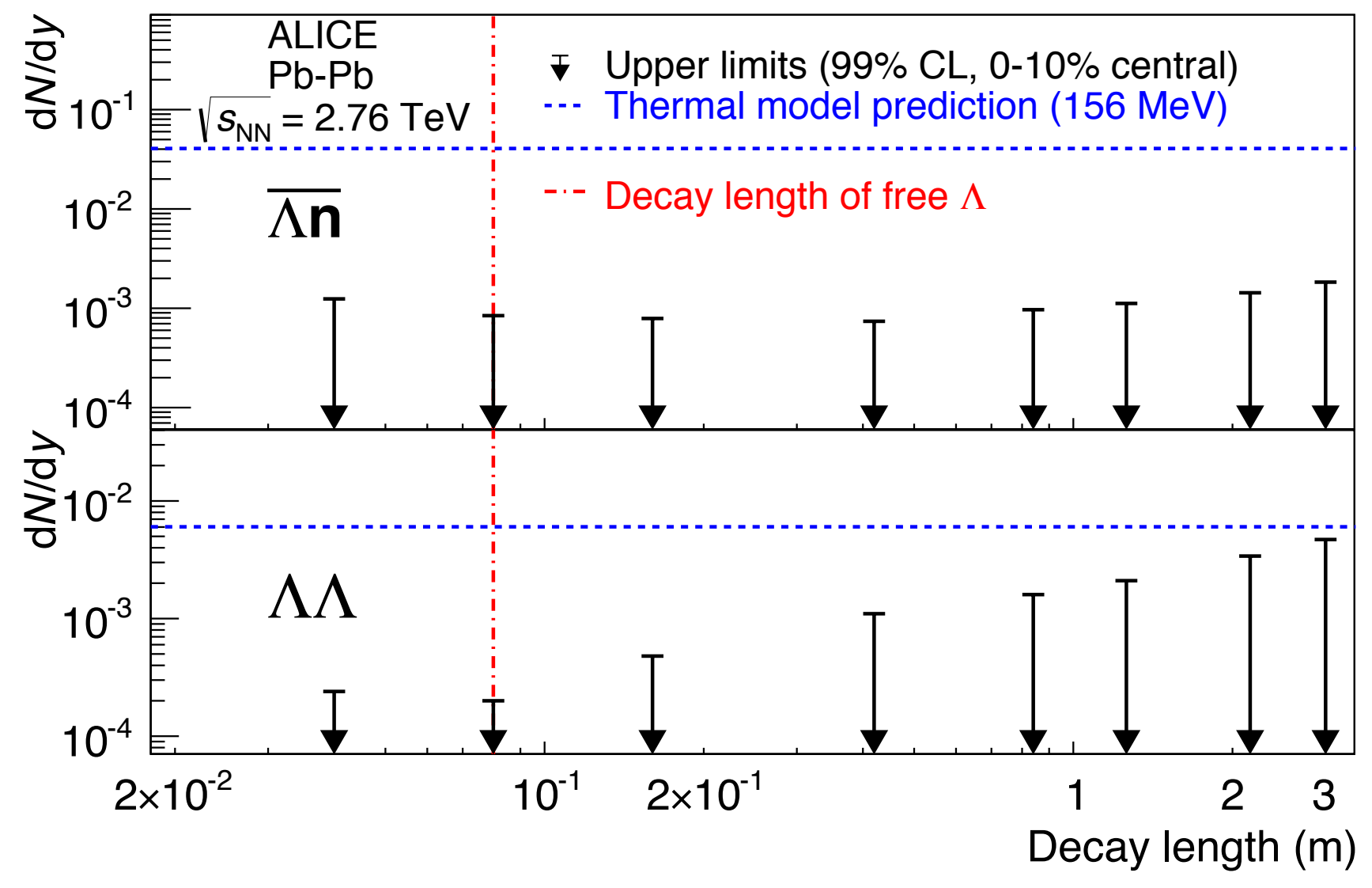
$$\tau = \left(181^{+54}_{-39}(stat.) + 33(syst.)\right) ps$$

References
[8] H. Kamada et al. *Phys. Rev. C* 57, 1595-1603 (1998)
[9] C. Rappold et al. *Phys. Lett. B* 728, 543-548 (2014)

5. Exotica

- ☑ **H-dibaryon** and **Λn** bound state discovery would be important as it would provide crucial information on the *Λ-nucleon* and *Λ-Λ* interaction
- ☑ H-dibaryon is a hypothetical bound state of *uuddss* (ΛΛ), first predicted by R.L. Jaffe [10] using a bag model approach
- ☑ Assumption of weakly-bound H-dibaryon
  - m_H < ΛΛ threshold (2.231 GeV/c^2)
  - H ⟶ Λpπ^- measurable channel
- ☑ Search for Λn bound state in the decay channel
  - $\overline{\Lambda n} \longrightarrow \bar{d}\pi^+$
- ☑ Prediction from thermal model (T_{chem} = 156 MeV)
  - d*N*/d*y* = 6.03 x 10^{-3} for H-dibaryon
  - d*N*/d*y* = 4.06 x 10^{-2} for $\overline{\Lambda n}$
- ☑ ALICE upper limits are a factor 20 below these model predictions for the Λ-free lifetime

Phys. Lett. B 752, 267-277 (2016)



References
[10] R.L. Jaffe. *Phys. Rev. Lett.* 38, 195 (1977); Erratum ibid 38, 617 (1977)

6. Conclusion and perspective

- ☑ (Hyper-)Nuclei production in heavy-ions collisions described by equilibrium thermal model (T_{chem} = 156 MeV) and coalescence model
- ☑ ALICE tested the CPT symmetry in the nuclei sector with an excellent precision
- ☑ H-dibaryon and Λn search in Pb-Pb lead to upper limits which are at least one order of magnitude lower than thermal model predictions
- ☑ ALICE measured the $^3_\Lambda$H lifetime in the charged mesonic 2-body decay channel and started the analysis in the 3-body decay channel ($^3_\Lambda$H ⟶ dpπ^-). Run2 will be crucial to improve the resolution on this measurements
- ☑ LHC Run2 will allow us to enhance the measurements in the nuclei sector thus improving the constraints on the theoretical models (e.g. coalescence)
- ☑ Very good improvement in (anti-)(hyper-)matter studies thanks to the ALICE Upgrade Program in LS2