Recent results for the (anti-)(hyper-)nuclei production and search for exotica by ALICE at the LHC

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Outline

- Introduction, ALICE detector, PID

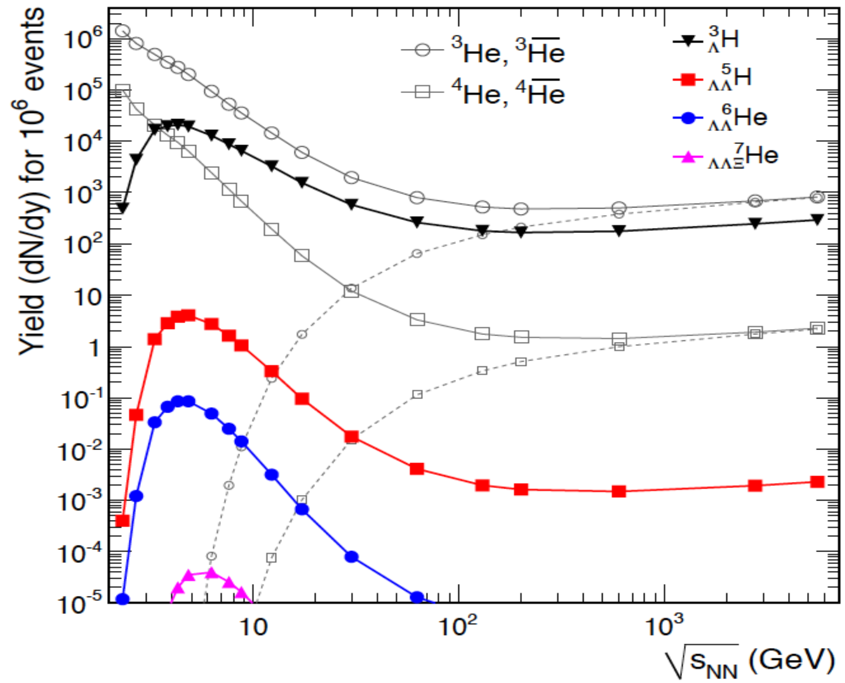
- Recent results:

  d, ^{3}He, $^{3}_{\Lambda}H$, Λn, H^{0}-dibaryon

- Conclusions

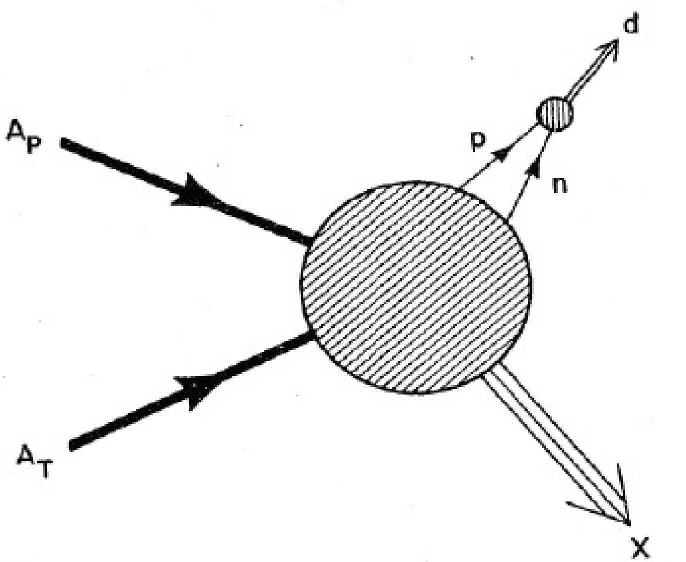
Introduction

Thermal model



- The key parameter at the LHC energies is the T_{chem}
- Nuclei abundance strongly depends on the value of T_{chem}
  - large mass
  - exponential dependence of the yield ~ $\exp(-m/T_{chem})$

A.Andronic, P.Braun-Munzinger, J.Stachel and H.Stoecker, Phys.Lett. B607, 203 (2011), 1010.2995



Schematic for the production of a deuteron in the final state of a relativistic collision between two heavy nuclei.

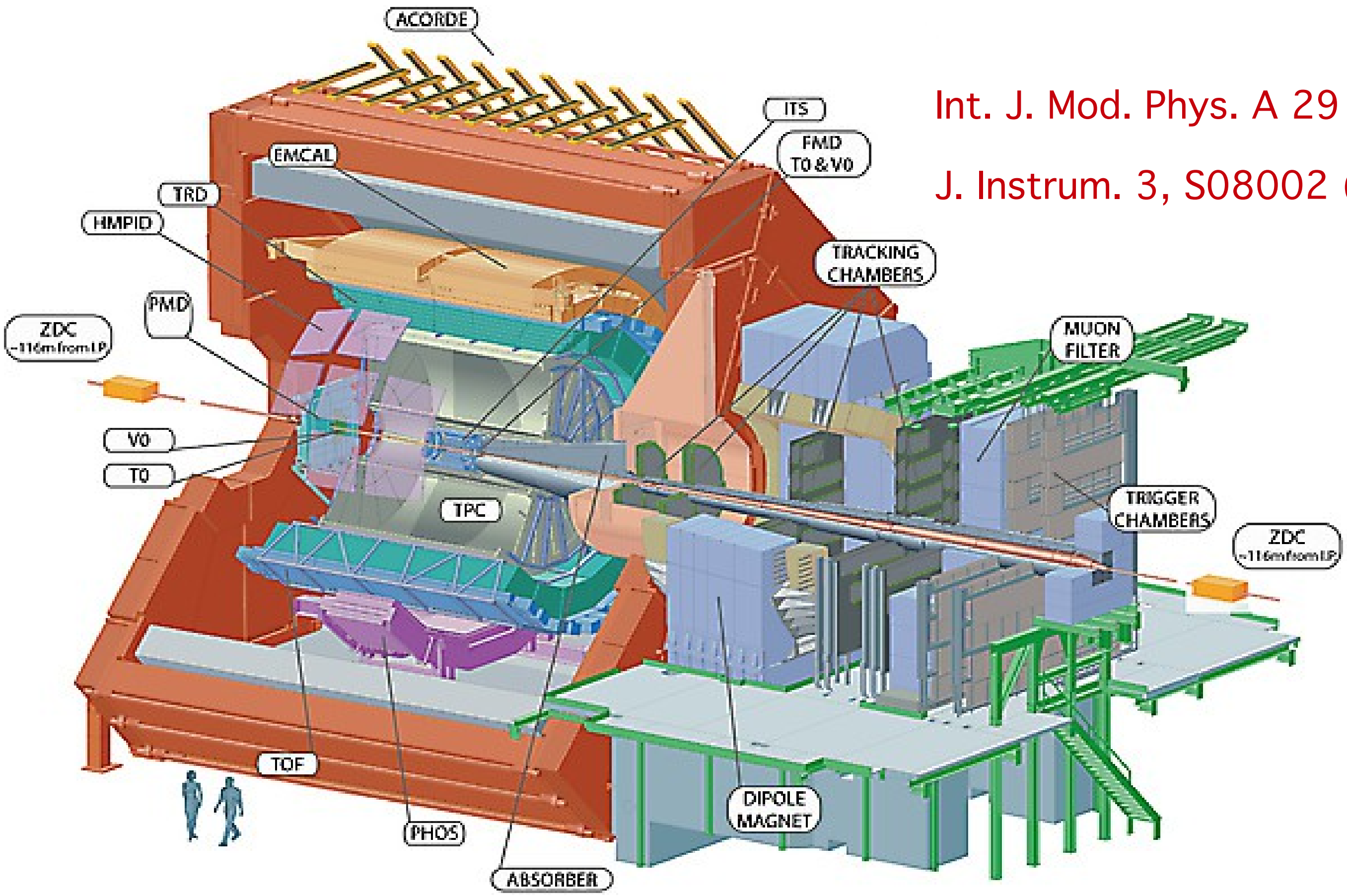
Coalescence model

- Nuclei are formed by protons and neutrons which are near in space and have similar velocities (after kinetic freeze-out)
- Nuclei produced at chemical freeze-out
  - Can break apart
  - Created again by final-state coalescence

J.I. Kapusta, Phys.Rev. C21, 1301 (1980)

ALICE detector

ALICE is ideally suited for the identification of light (anti-)nuclei and (anti-)(hyper-)nuclei thanks to its excellent particle identification capabilities:



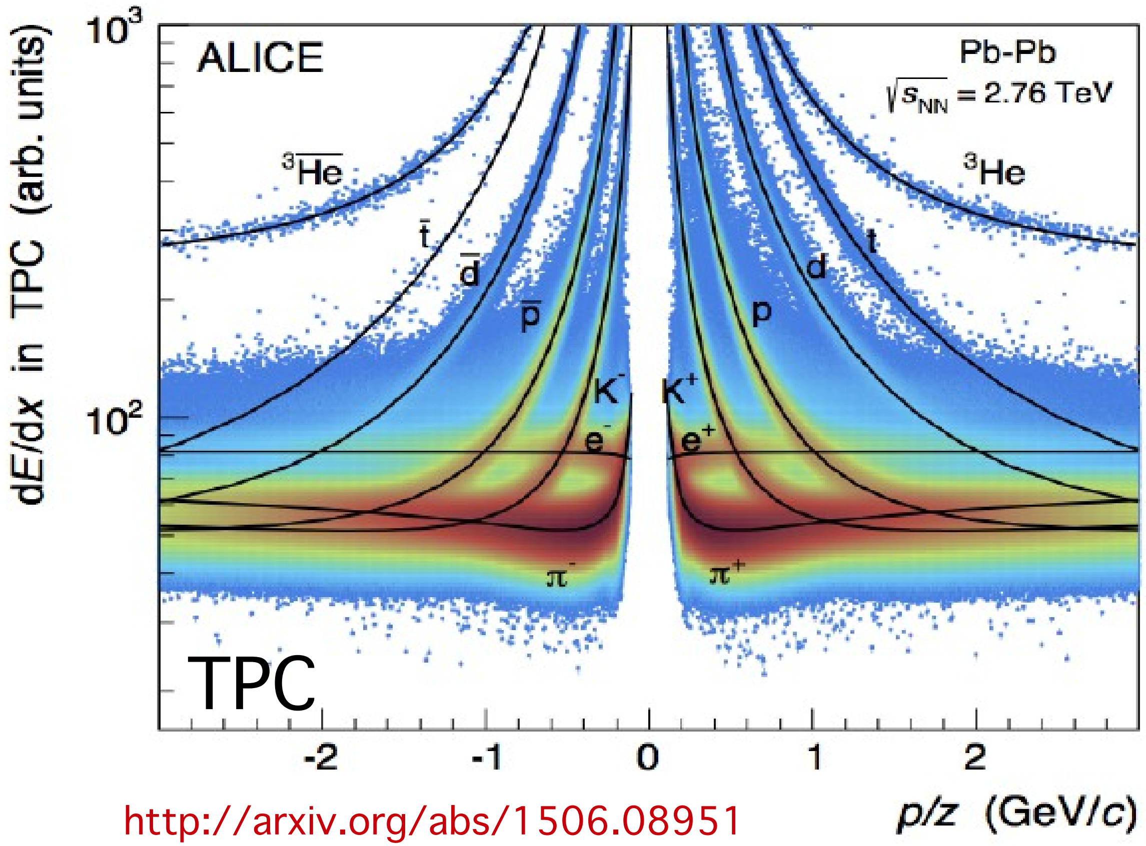
Int. J. Mod. Phys. A 29 (2014) 1430044

J. Instrum. 3, S08002 (2008)

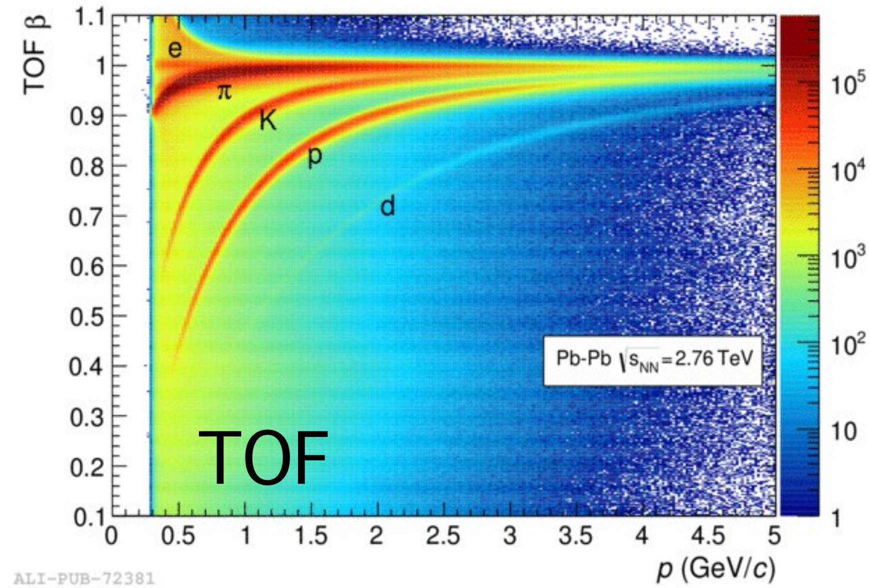
ALICE subdetectors (central barrel):

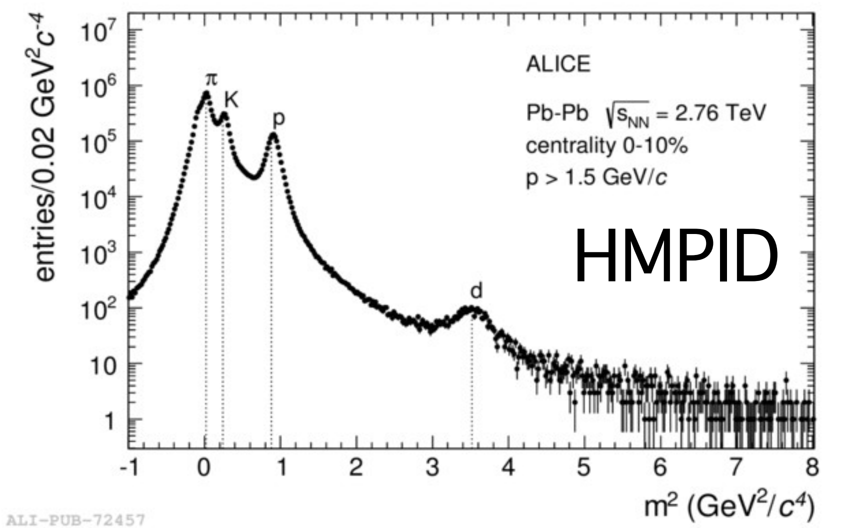
- ✓ **ITS** tracking + vertexing + PID (dE/dx)
- ✓ **TPC** tracking + vertexing + PID (dE/dx)
- ✓ **TOF** PID (time-of-flight)
- ✓ **HMPID** PID (ring imaging Cherenkov)

Particle Identification (nuclei)



http://arxiv.org/abs/1506.08951





Results

- Production of light nuclei and anti-nuclei in pp and Pb-Pb collisions at the LHC energies
  Link arXiv: http://arxiv.org/abs/1506.08951

- Hypertriton and anti-Hypertriton production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  Link arXiv: http://arxiv.org/abs/1506.08453

- Search for weakly decaying $\overline{\Lambda n}$ and $\Lambda\Lambda$ exotic bound states in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  Link arXiv: http://arxiv.org/abs/1506.07499

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  ..+ p-Pb results

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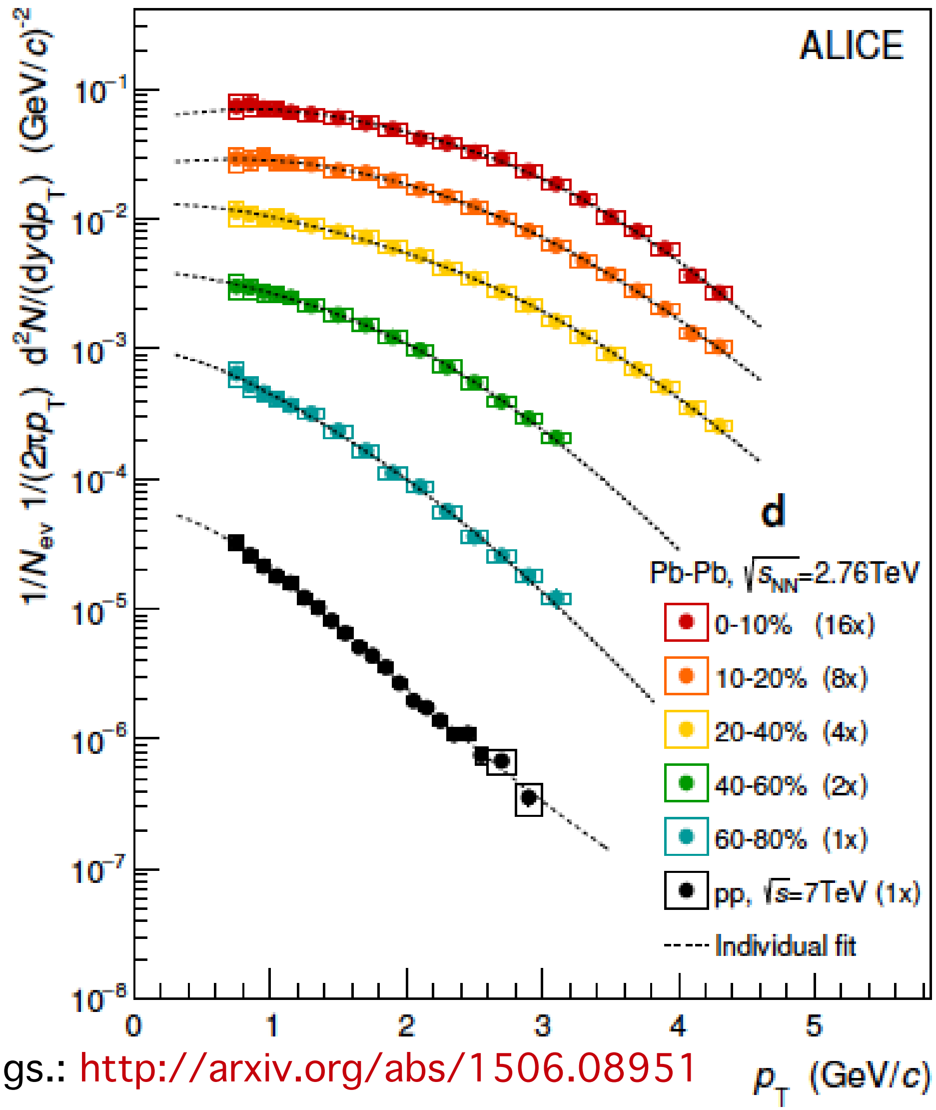
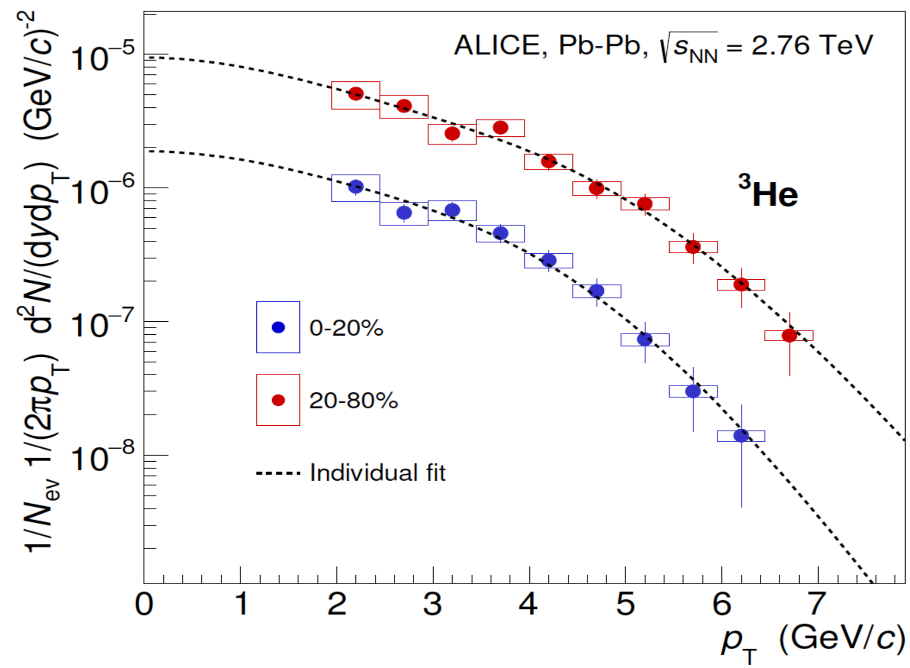
Deuterons and ^{3}He



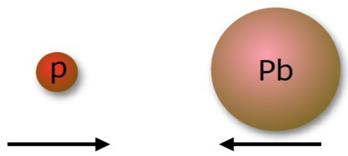
Figs.: http://arxiv.org/abs/1506.08951



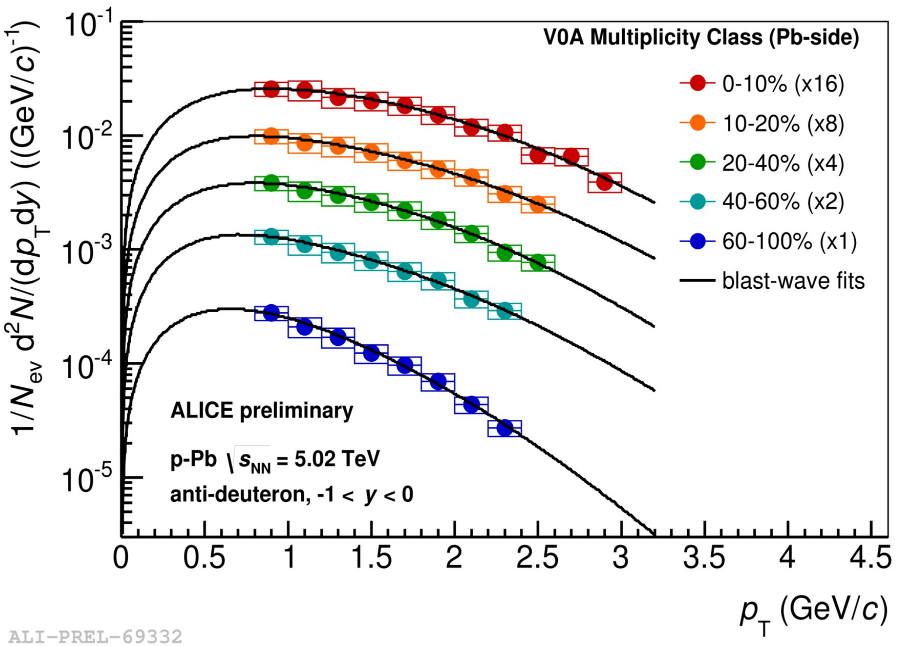
- Pb-Pb spectra are fitted with the blast-wave function (simplified hydro model [1]) → these fits are used for the extrapolation of the yield to the unmeasured region at low and high p_T
- A hardening of the spectrum with increasing centrality is observed → expected in a hydrodynamic description of the fireball as a radially expanding source
  - Similar behavior observed for protons

[1] E. Schnedermann et al., Phys. Rev. C48, 2462 (1993)

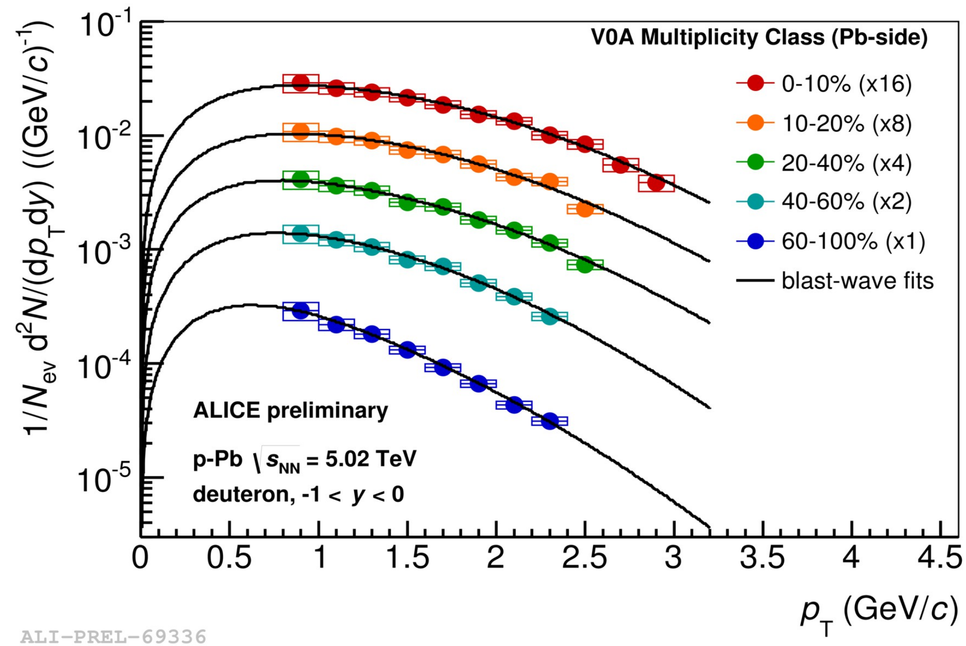
Deuterons in p-Pb



anti-deuteron

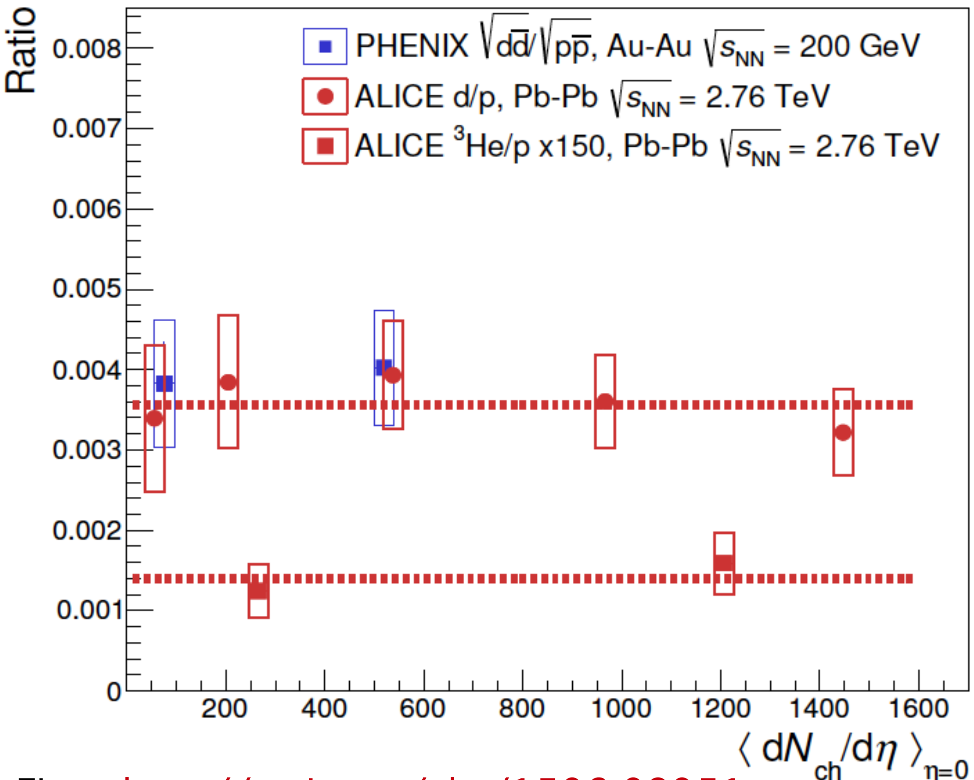


deuteron

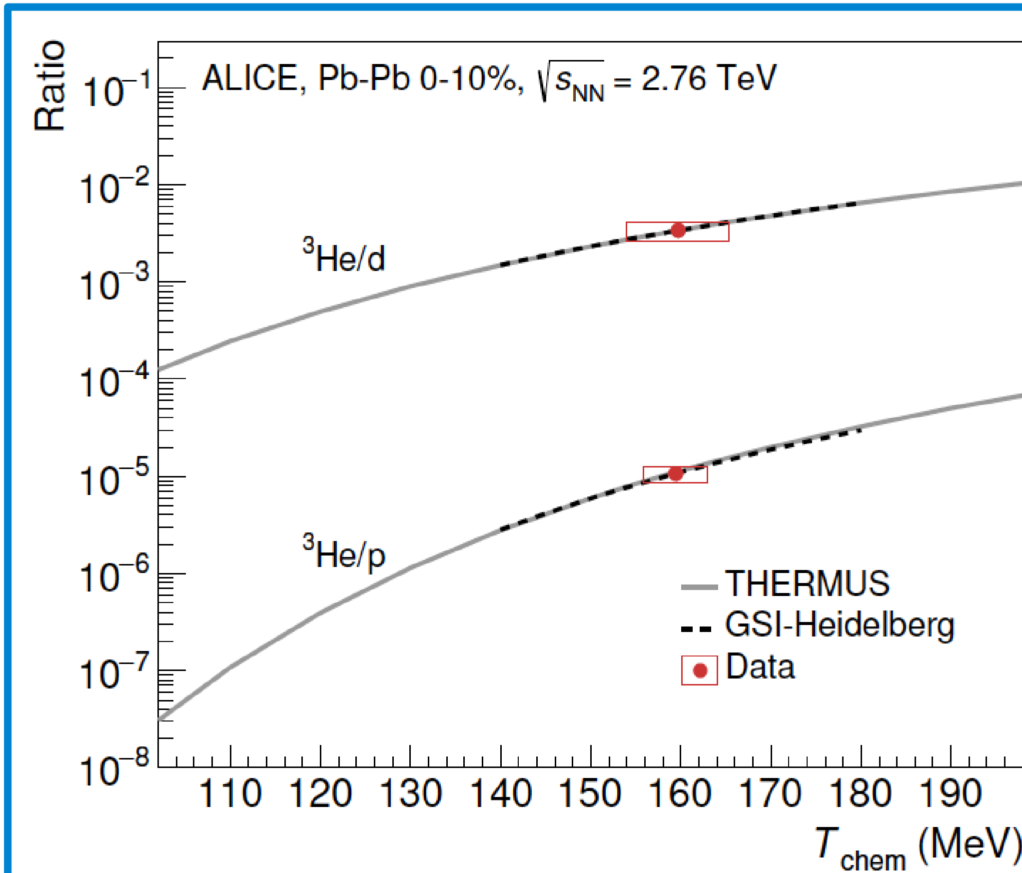


- Spectra are fitted with the blast-wave function
- Spectra become harder with increasing multiplicity

d/p - ^{3}He/p - ^{3}He/d



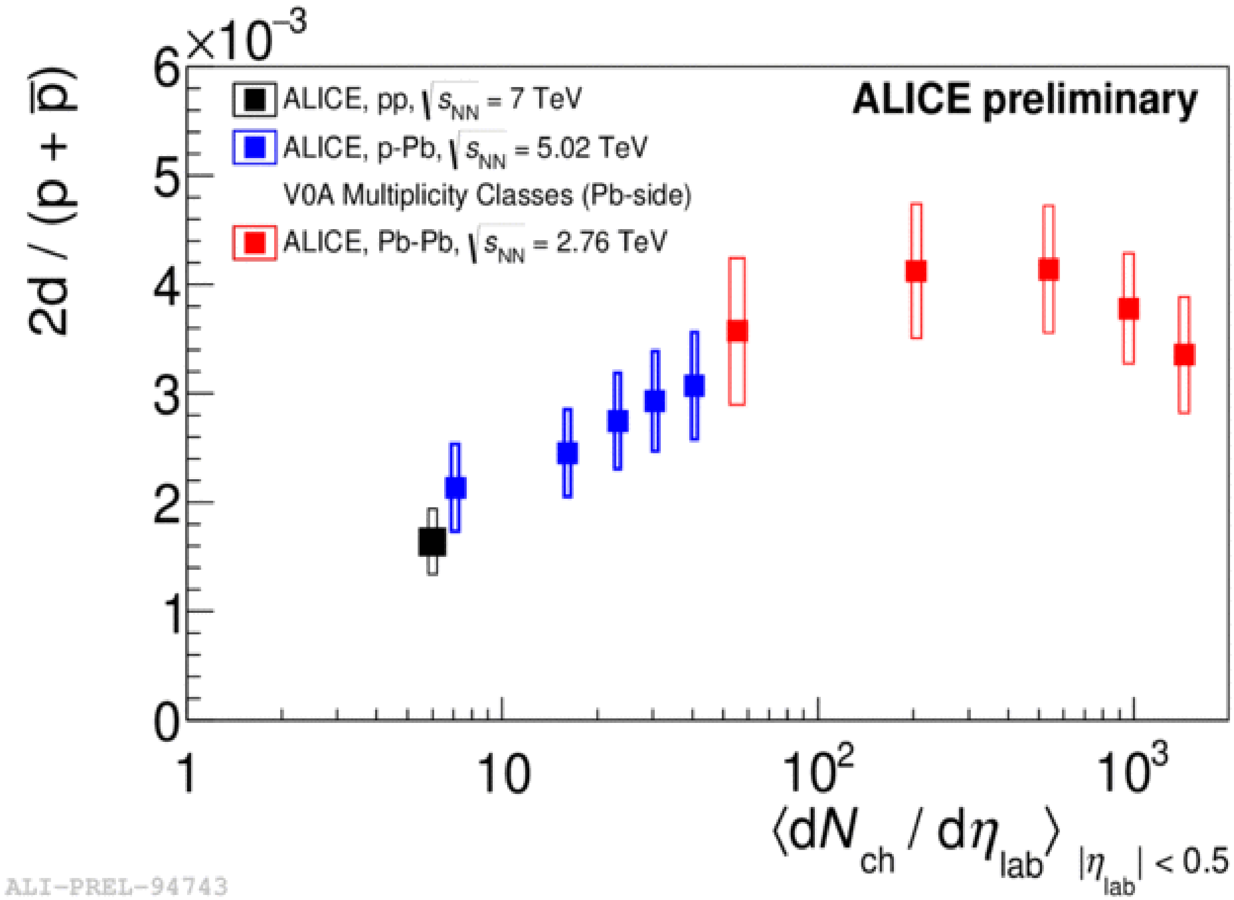
Figs.: http://arxiv.org/abs/1506.08951



- d/p and ^{3}He/p in agreement with expectations from thermal-statistical models
- No dependence of these ratios on the event multiplicity observed at RHIC and LHC energies

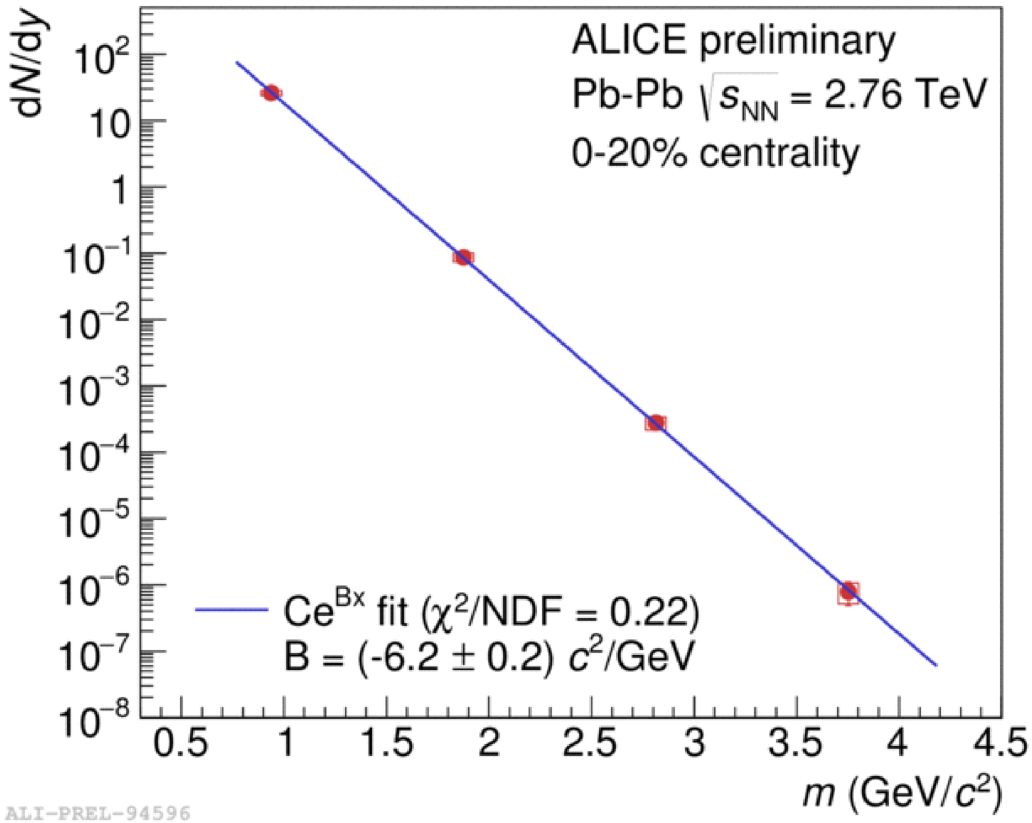
- Comparison with thermal models: THERMUS and GSI-Heidelberg model
  - dependence with $\exp(-\Delta m / T_{\mathrm{chem}})$
  - agreement with a chemical freeze-out temperature in the range [150, 165] MeV

Deuteron-to-proton ratio



- An increasing trend with multiplicity in p-Pb data is observed
- Ratio in pp collisions is a factor 2.2 lower than in Pb-Pb collisions

Nuclei in Pb-Pb



- Thermal model prediction → $\frac{dN}{dy} \propto \exp(-\frac{m}{T_{chem}})$
- Exponential decrease with the mass of the particle, 300x penalty factor for each additional nucleon
  - Decrease already observed at lower energies

Coalescence parameter B_2

- **Coalescence model** In this picture the nuclei are formed in the last stage of the collision (after kinetic freeze-out) by protons and neutrons which are close in position and momentum space
- The formation probability of nuclei can be quantified through the coalescence parameter B_A

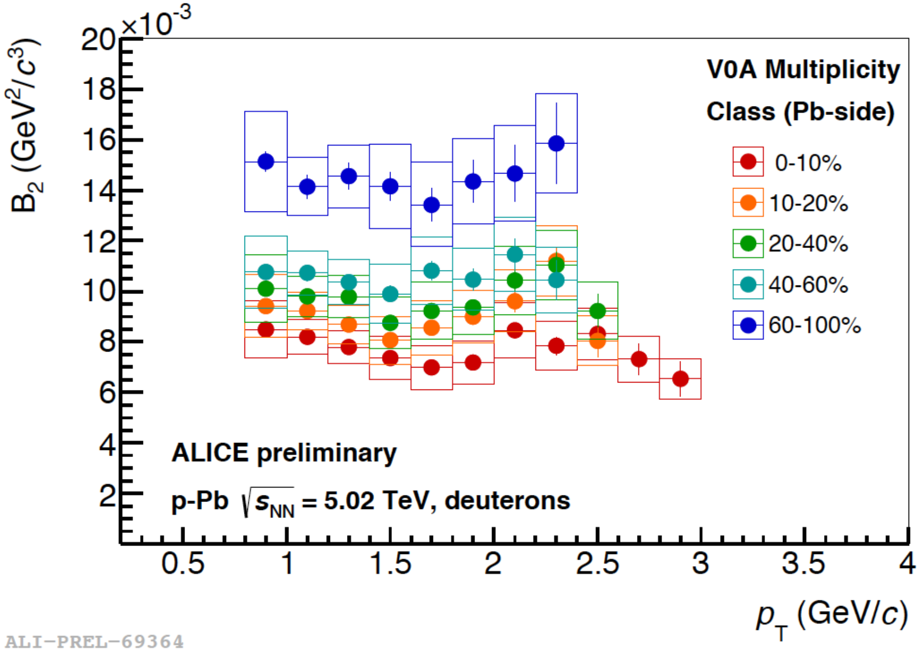
$$B_A = \frac{E_A \frac{d^3N_A}{dp_A^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^A}$$

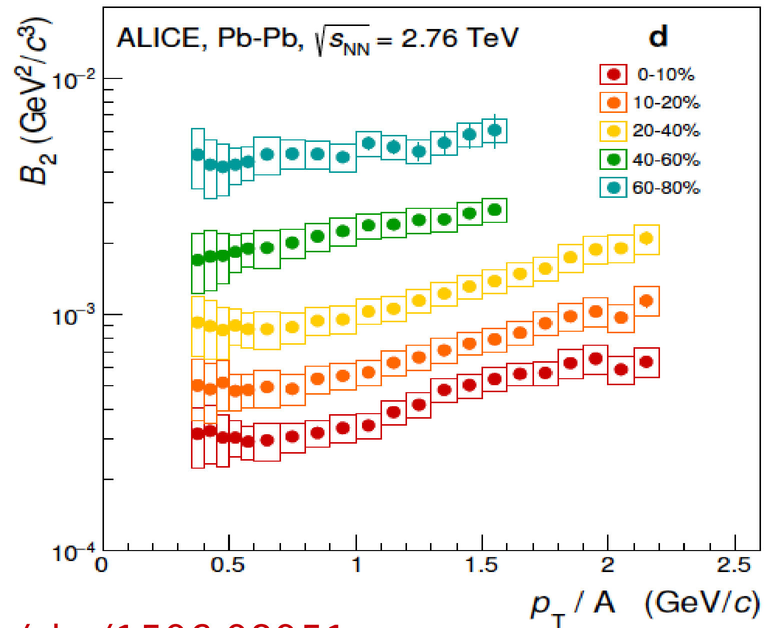
→ deuterons

$$B_2 = \frac{E_d \frac{d^3N_d}{dp_d^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^2}$$

- To first order, B_2 is expected to depend only on the maximum difference in the momentum of the two constituents ("pure nuclear physics")
  - B_2 should be flat vs. p_T and should not depend on multiplicity/centrality
  - The d/p ratio should strongly increase with multiplicity/centrality

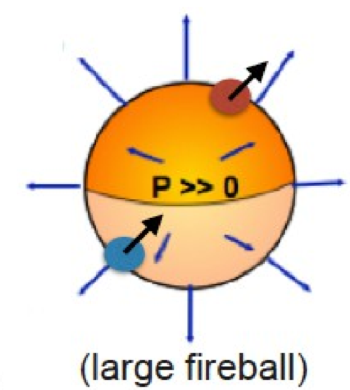
Coalescence parameter B_2





Figs.: http://arxiv.org/abs/1506.08951

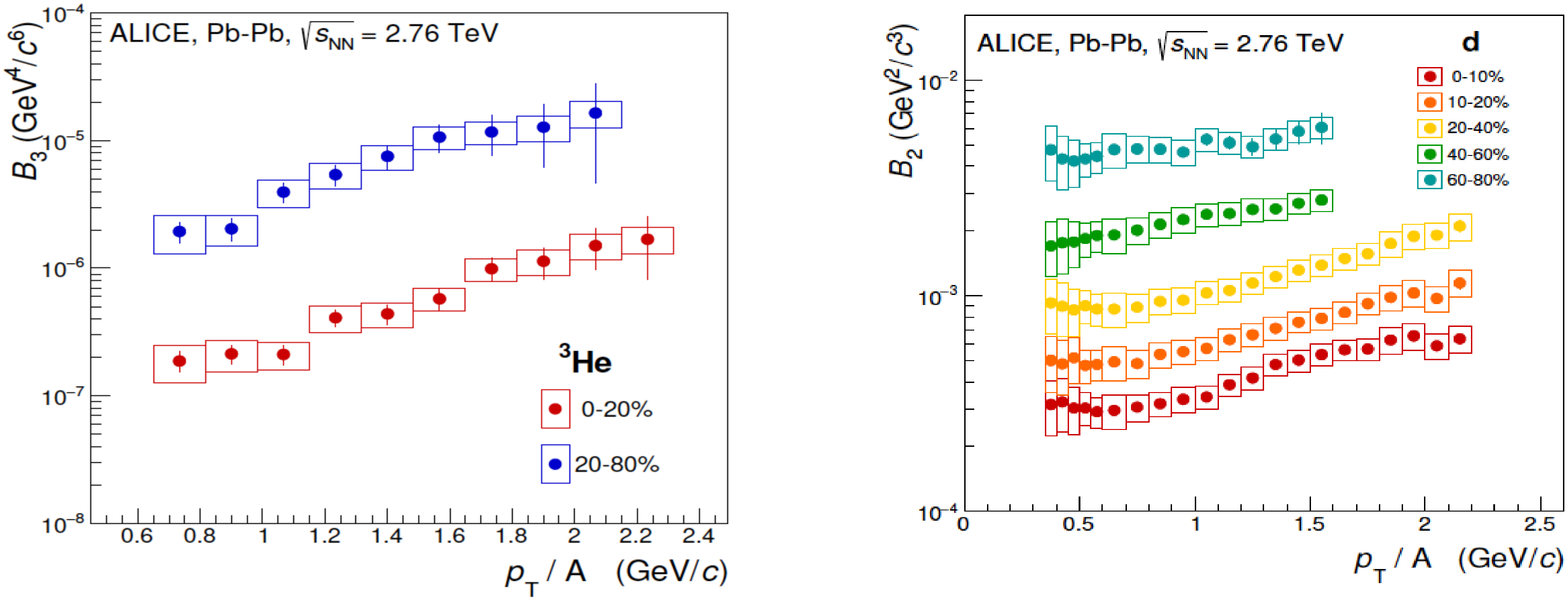
- B_2 is flat vs. transverse momentum in p-Pb and peripheral Pb-Pb
- p-Pb:
  - d/p shows increasing trend in p-Pb
  - B_2 is slightly decreasing with multiplicity
- Pb-Pb:
  - B_2 is strongly decreasing with centrality in Pb-Pb collisions
    → increasing of the source volume
  - d/p shows no significant dependence with centrality



$B_2 \sim 1/V_{eff}$

B_2 scales like the HBT radii

Coalescence parameter B_2



Figs.: http://arxiv.org/abs/1506.08951

- Pb-Pb:
  - B_2 is strongly decreasing with centrality in Pb-Pb collisions
    → increasing of the source volume
  - d/p shows no significant dependence with centrality

  - B_2 tends to increase with transverse momentum in central collisions → position-momentum correlations caused by a radially expanding source

Results

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Hypertriton and anti-Hypertriton production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
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Search for weakly decaying Λn and $\Lambda\Lambda$ exotic bound states in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
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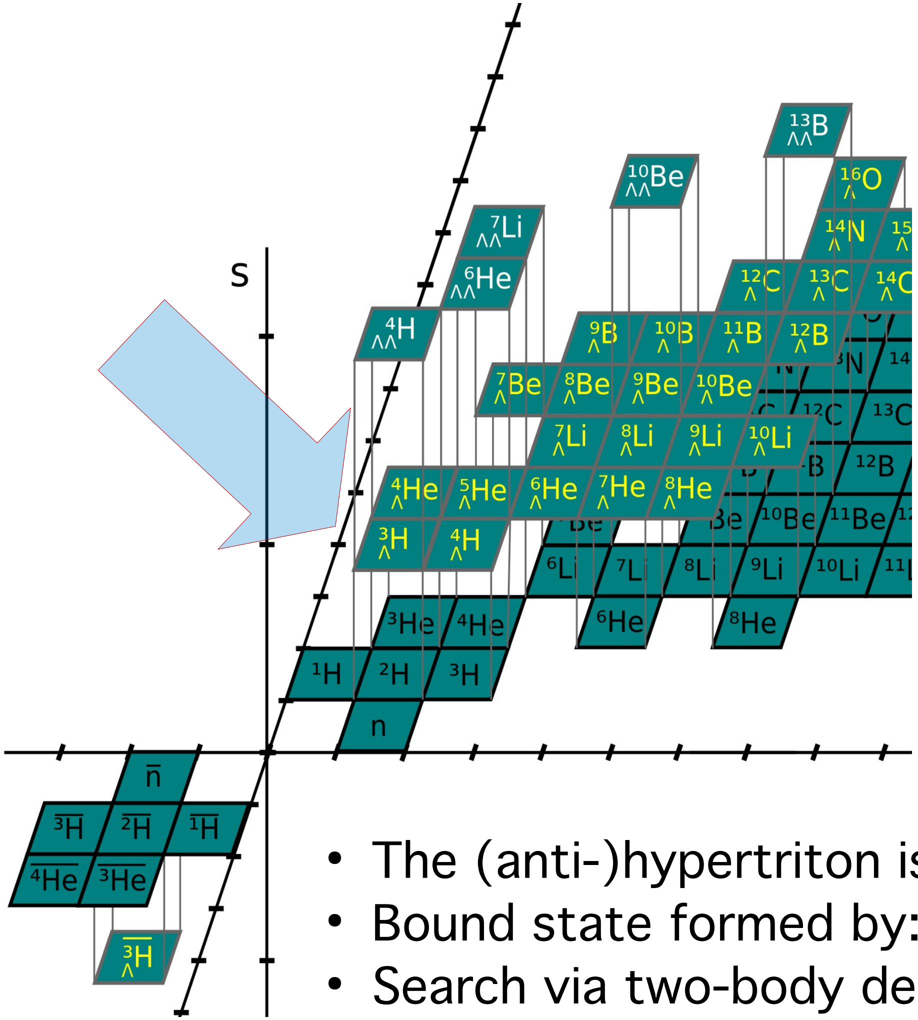
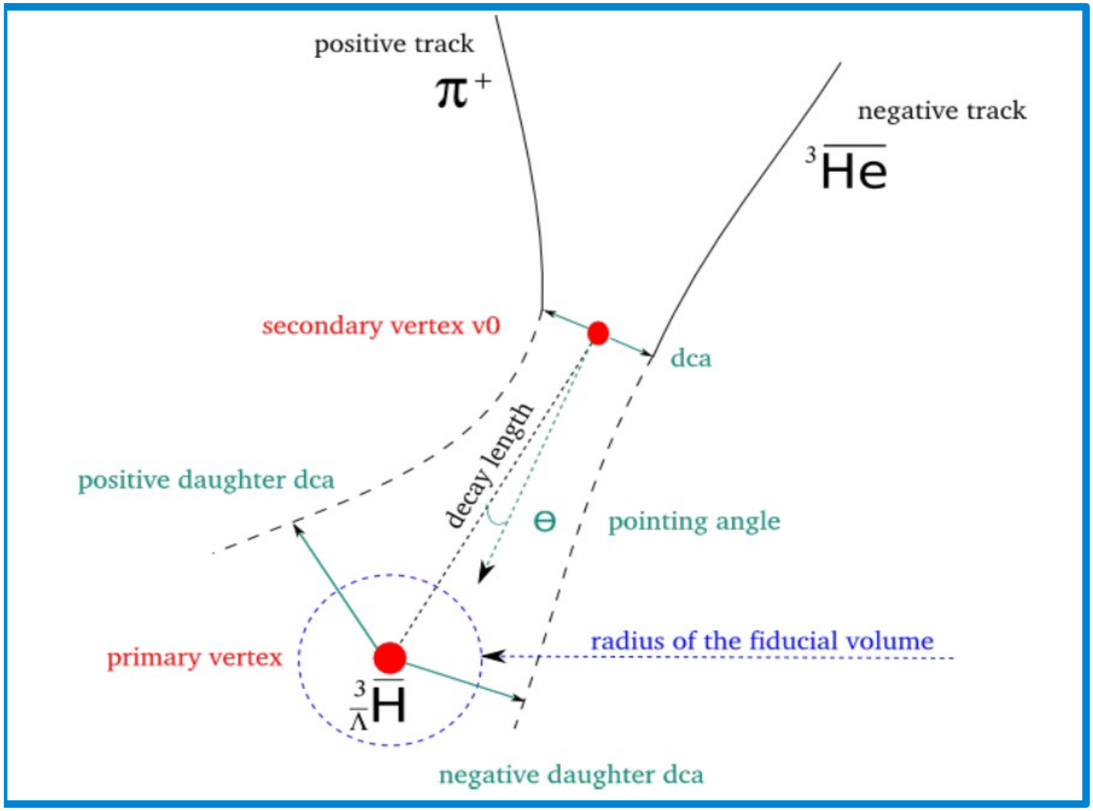
Hypertriton



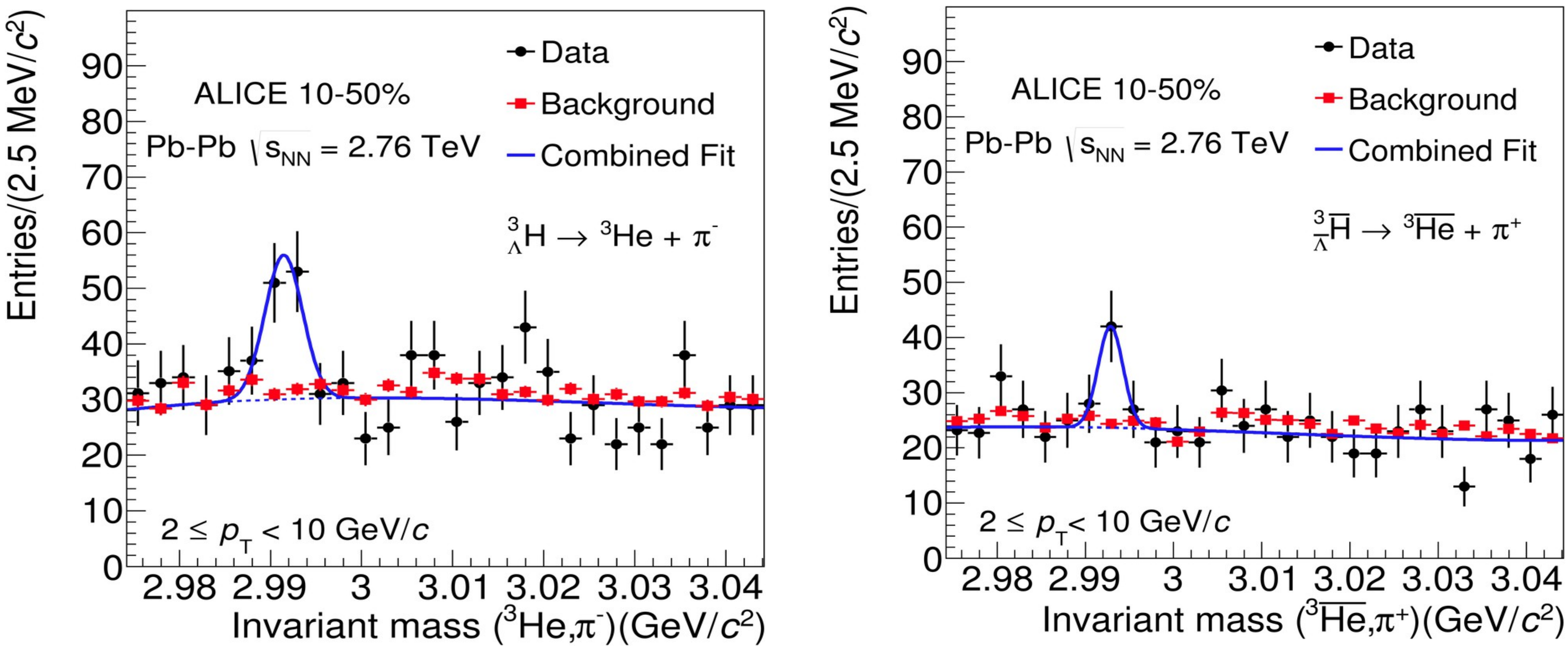


- The (anti-)hypertriton is the lightest observed hypernucleus
- Bound state formed by: p, n, Λ (anti-p, anti-n, anti-Λ)
- Search via two-body decays into charged particles

$$^{3}_{\bar{\Lambda}}\overline{\mathrm{H}} \rightarrow {}^{3}\overline{\mathrm{He}} + \pi^{+} \qquad\qquad ^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$$

- Signal extraction: identify ^{3}He and pion → invariant mass

Hypertriton



- Search via two-body decays into charged particles
- Signal extraction: identify ^{3}He and pion → invariant mass

- Invariant mass distributions: 10-50% centrality, $2 < p_T < 10$ GeV/c
  - Gauss + third degree polynomial

Figs.:http://arxiv.org/abs/1506.08453

Hypertriton vs p_T

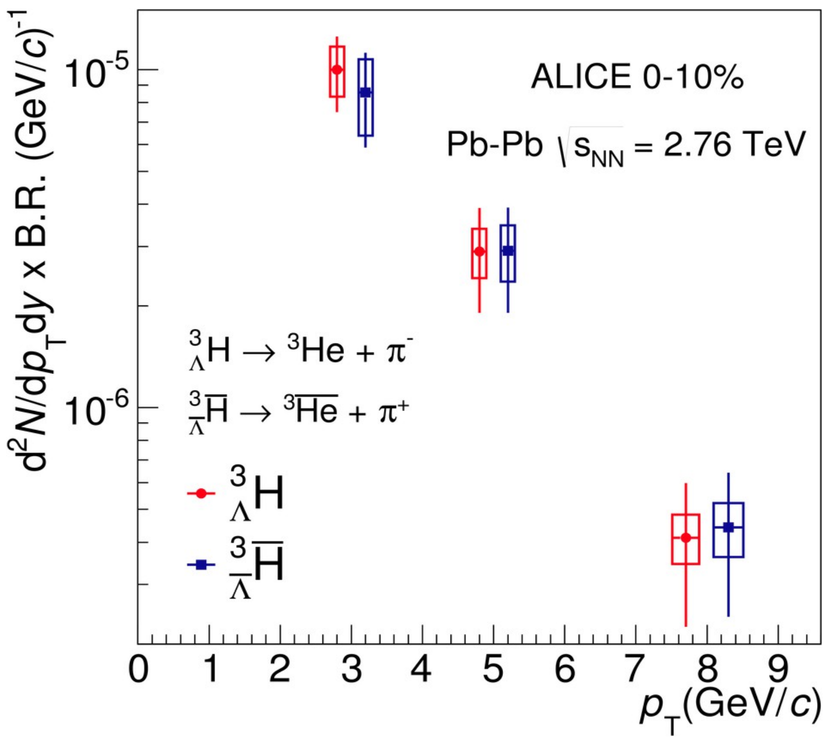


Fig.:http://arxiv.org/abs/1506.08453

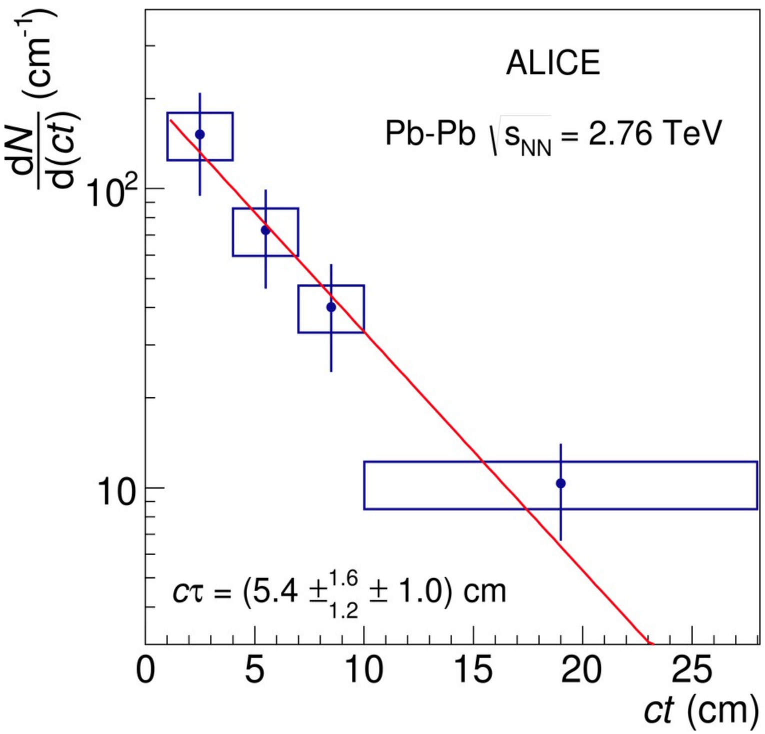
- In 0-10% centrality class, three transverse momentum intervals:
  - $2 \leq p_T < 4$ GeV/c , $4 \leq p_T < 6$ GeV/c , $6 \leq p_T < 10$ GeV/c

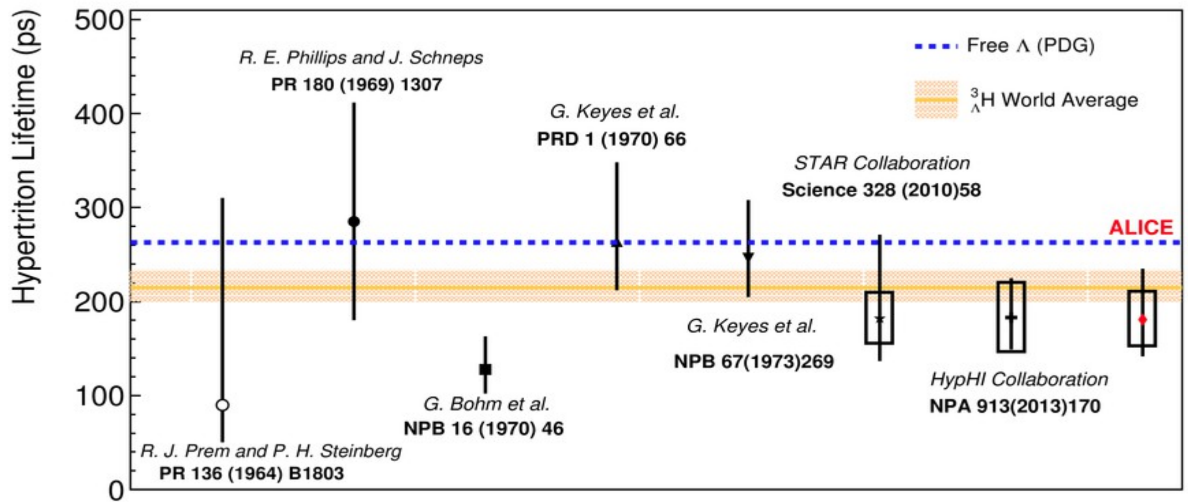
- m(Hypertriton) = 2.991 ± 0.001 (stat.) ± 0.003 (syst.) GeV/c^2

- Inclusion of d, ^{3}He and ${}^3_\Lambda$H in the thermal fit (+ lighter particles), does not change the T_{chem} (156 ± 2 MeV)

TALK: B.Guerzoni

Hypertriton lifetime





Figs.:http://arxiv.org/abs/1506.08453

- Measurement of lifetime: anti-hyp. + hyper. sample in 4 intervals
- Exponential fit is performed: $c\tau = (5.4^{+1.6}_{-1.2}(\text{stat.}) \pm 1.0(\text{syst.}))$ cm
- From ALICE data: $\tau = (181^{+54}_{-39}(\text{stat.}) \pm 33(\text{syst.}))$ ps
- World average: $\tau = (215^{+18}_{-16}$ ps$)$
- ALICE result compatible with the computed average

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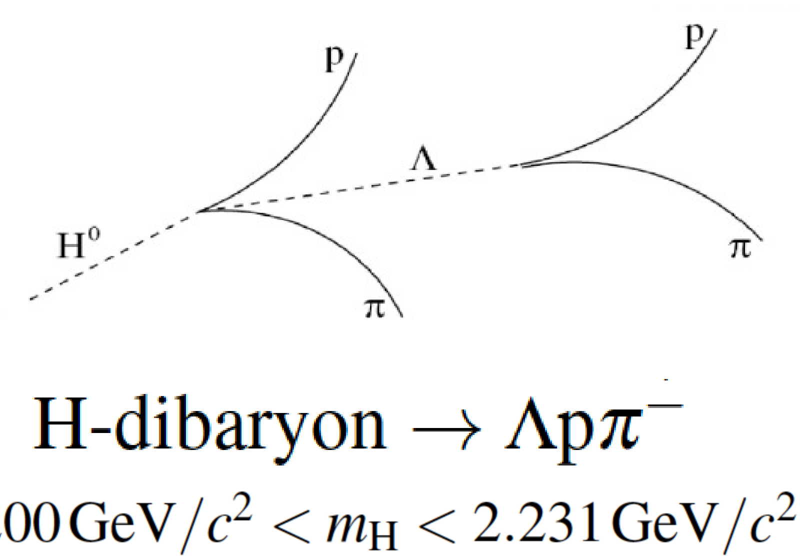
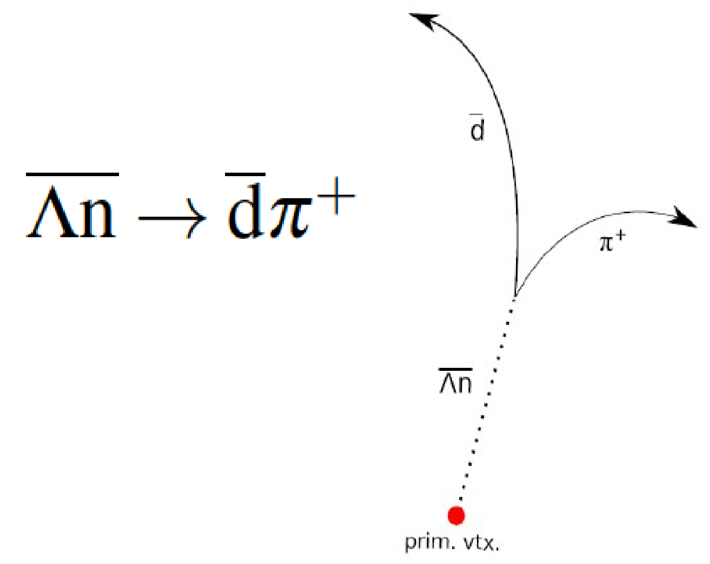
Search for weakly decaying dibaryon states





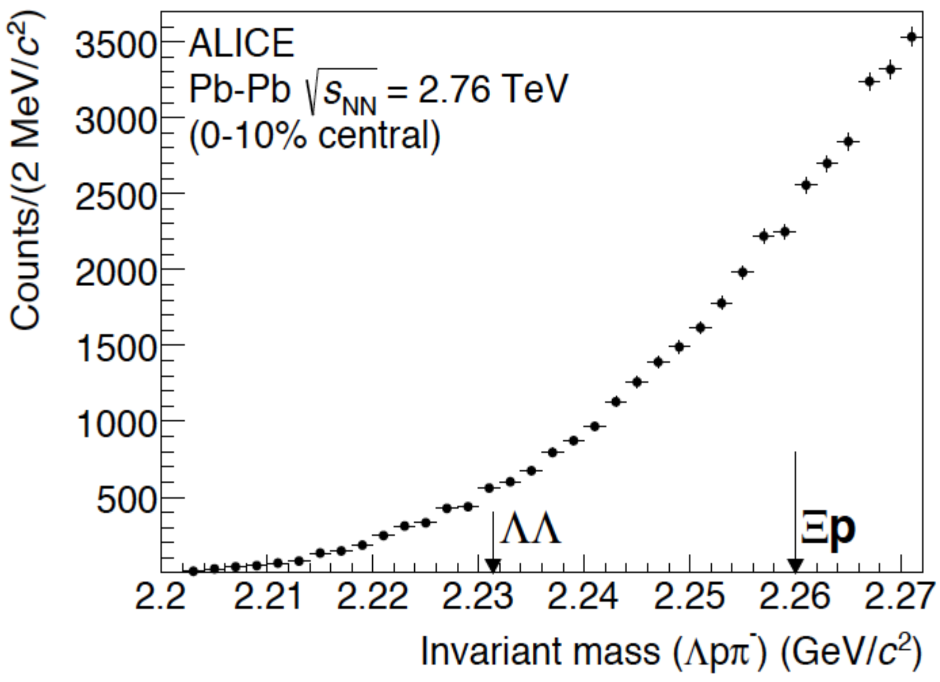
- Search for two hypothetical strange dibaryon states: H-dibaryon and anti-(Λn) bound state (Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, 0-10%: rapidity density well predicted by thermal and coalescence models)

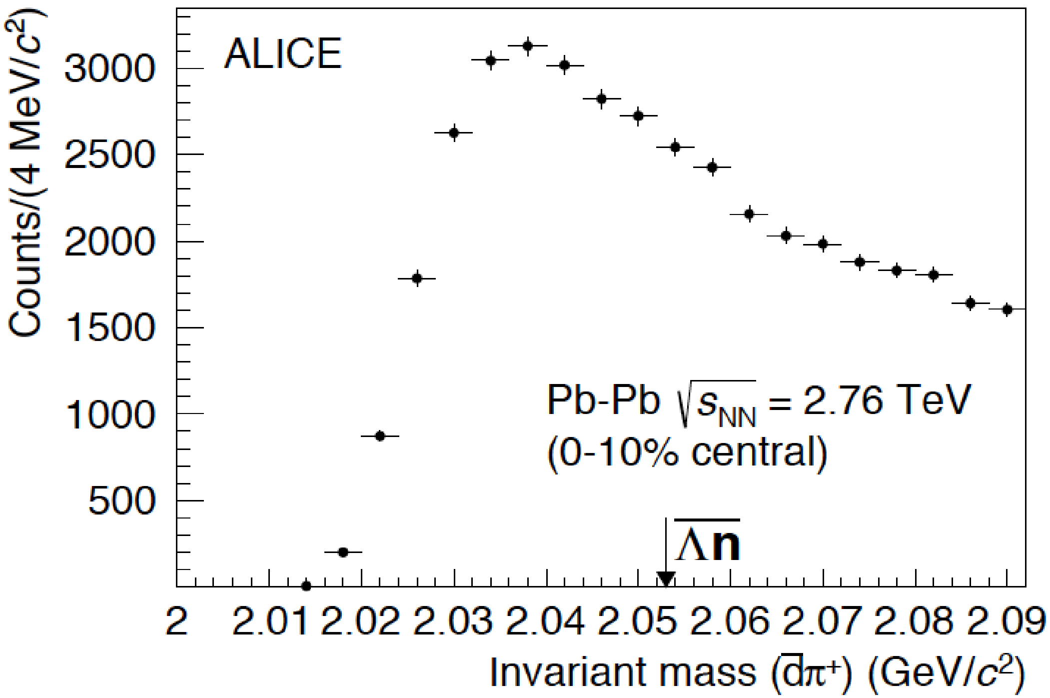
- H^0-dibaryon:
  - Hypothetical bound state of *uuddss* (ΛΛ)
  - First predicted by Jaffe in a bag model approach R.L. Jaffe, PRL 38, 195 (1977)

- Bound state of anti-(Λn) ?

Inoue et al., PRL 106, 162001 (2011)
Beane et al., PRL 106, 162002 (2011)

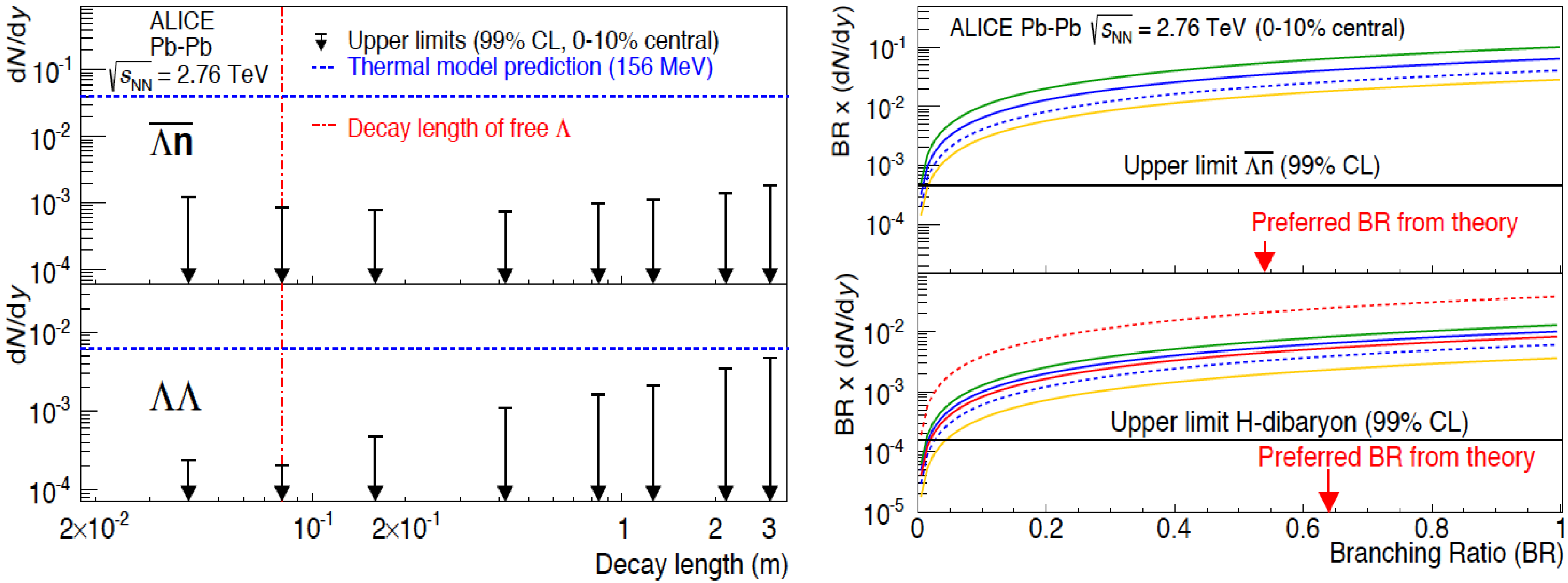
Search for weakly decaying dibaryon states





- Shape of the invariant mass distributions caused by the kinematic range of identified daughter tracks
- anti-(Λn): dominating source of secondary anti-deuterons from three-body decays of the anti-hypertriton
- No signal in the invariant mass distributions observed
- Upper limits are estimated

Search for weakly decaying dibaryon states



- Limits obtained on the dN/dy are more than one order of magnitude below the expectations of particle production models
- Yields for a very loosely bound hypertriton (E_B < 150 keV) agree well with the prediction of the thermal model
  → Λn (if it exists) is predicted by this model and with a dN/dy ~ factor 300 higher that the measured hypertriton yield.
- Similar considerations for the H-dibaryon

Thermal model provides a baseline for exotica searches

Conclusions

- ALICE at the LHC offers unique experimental possibilities for the study of light (hyper-)nuclei

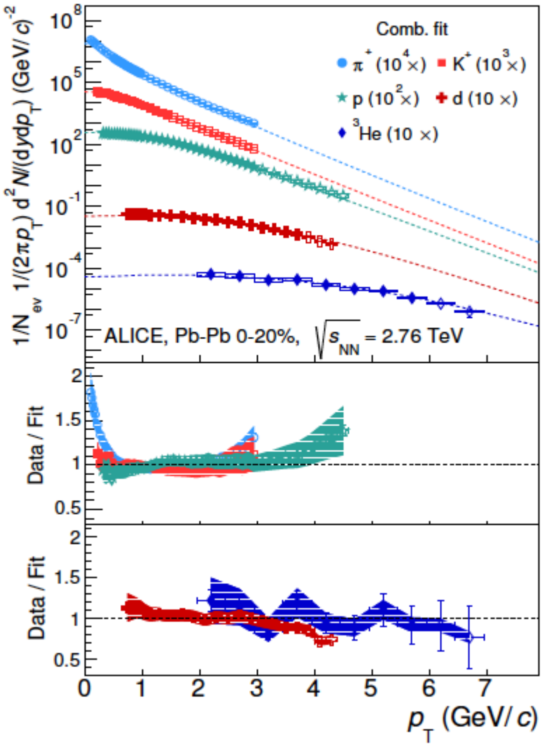
- Coalescence and thermal (statistical) models describe different aspects of the data:
  - production rates (light nuclei and hypertriton) in Pb-Pb collisions are in agreement with thermal model expectation

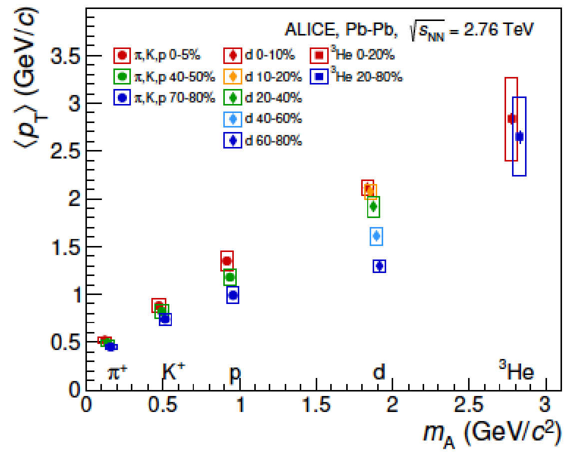
- d/p ratio in pp collisions is a factor 2.2 lower than in Pb-Pb. The p-Pb results connect the pp and Pb-Pb results

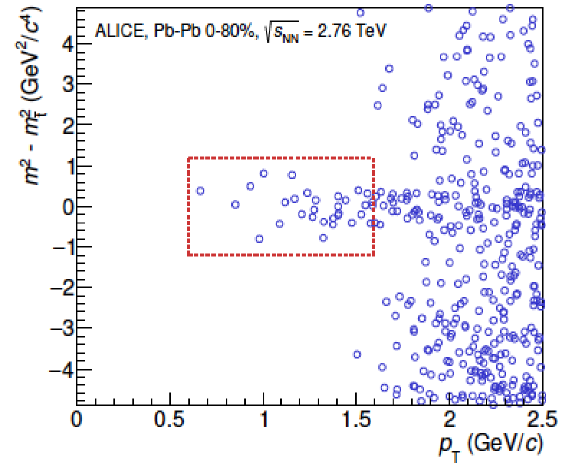
- The measured lifetime of the hypertriton is consistent with previous measurements

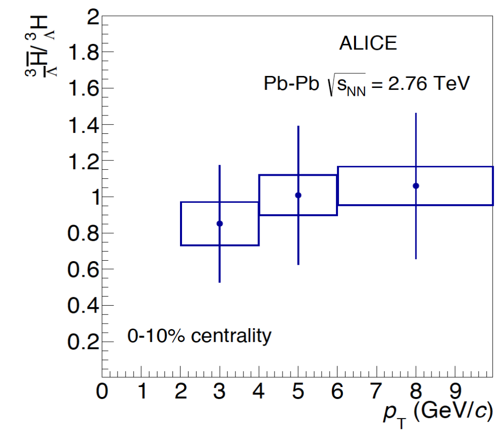
- Existence of Λn and H^0-dibaryon is doubtful
  - Upper limits have been estimated

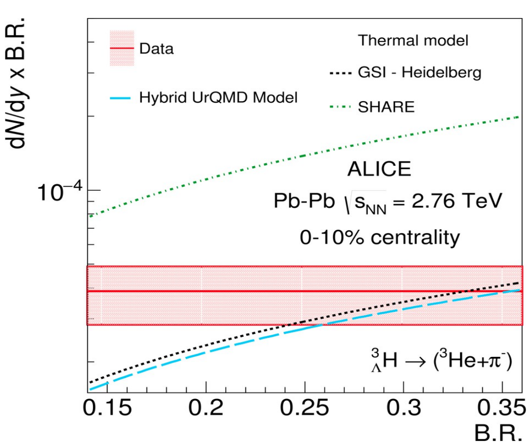
More…

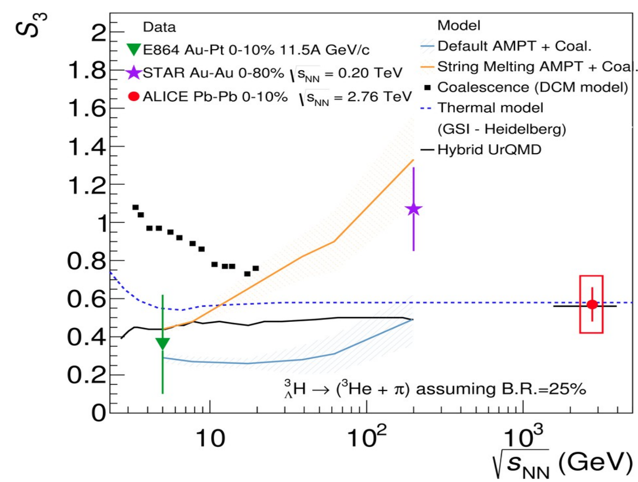


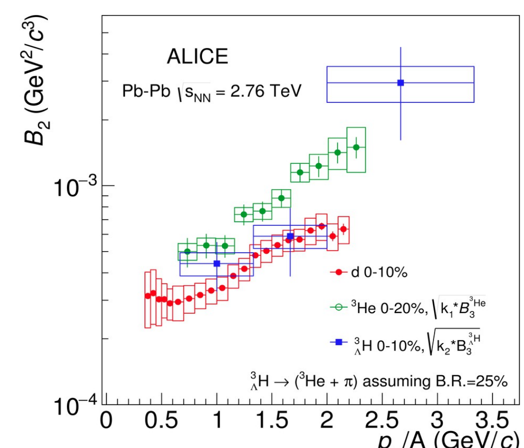












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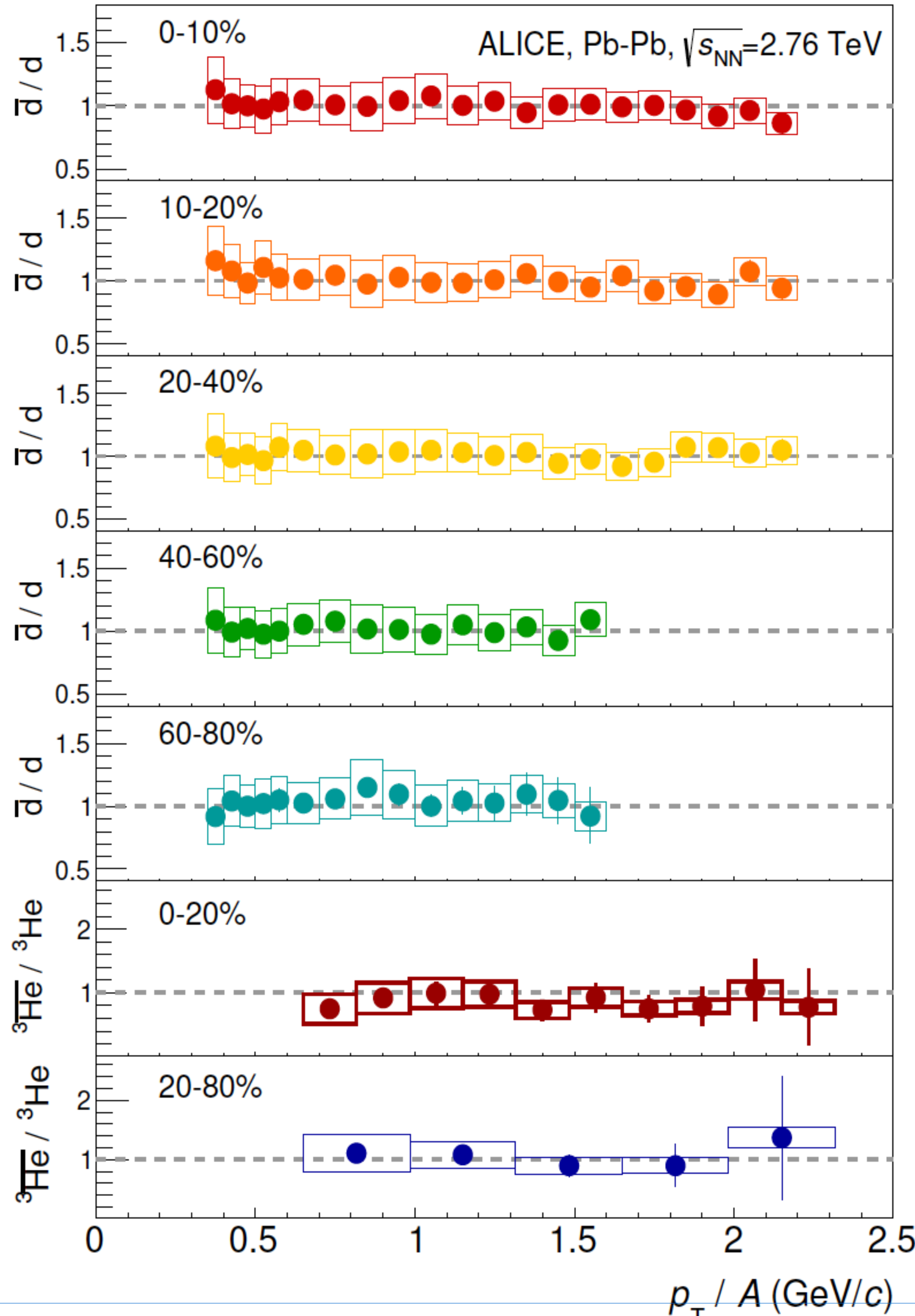
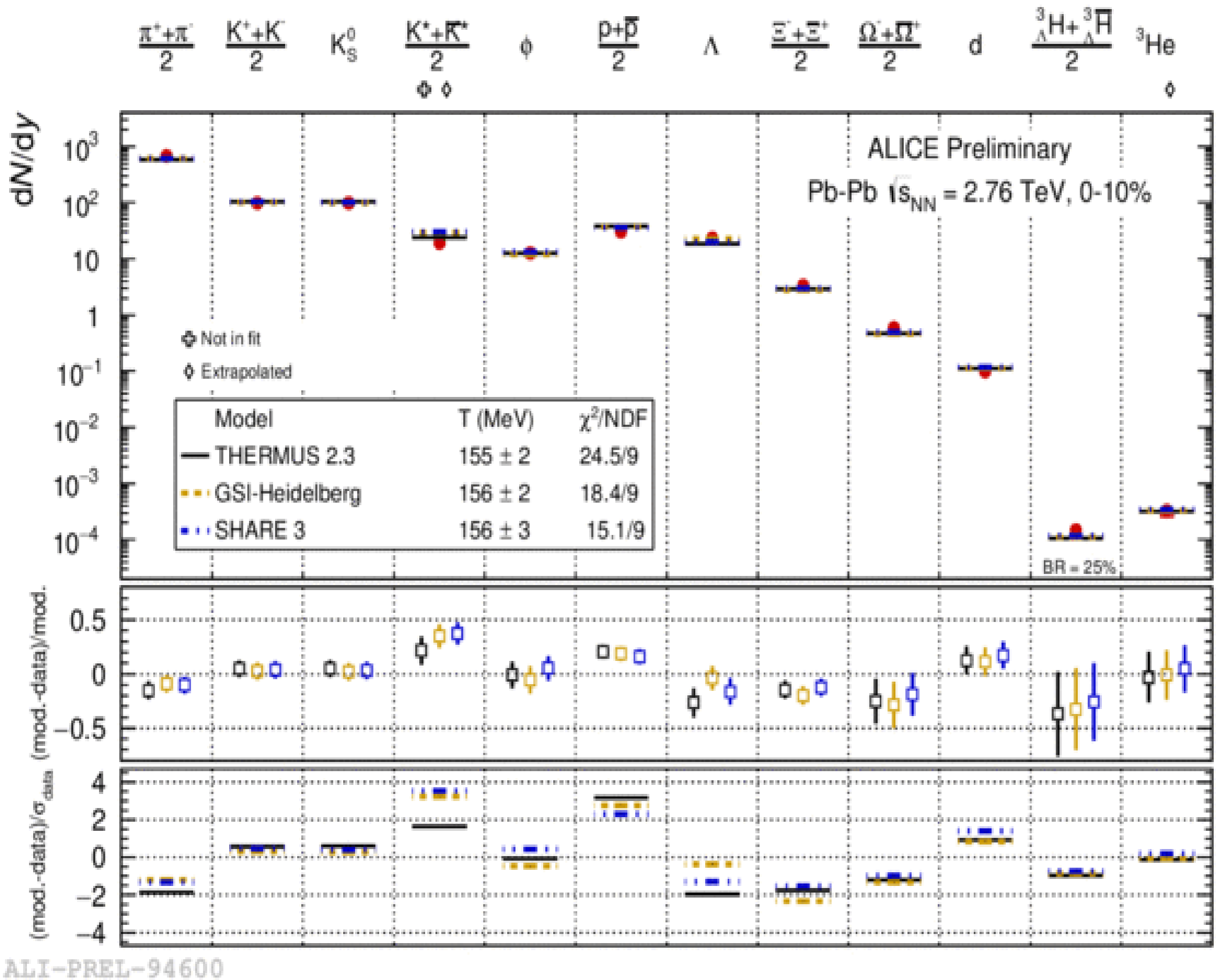
Back-up

Ratio

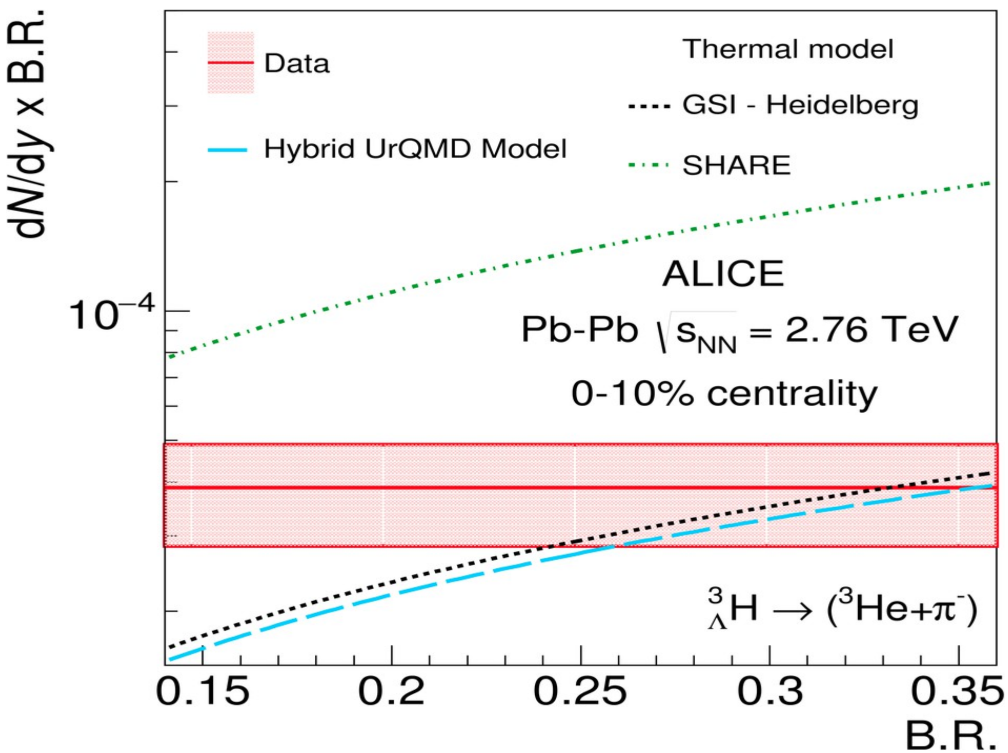


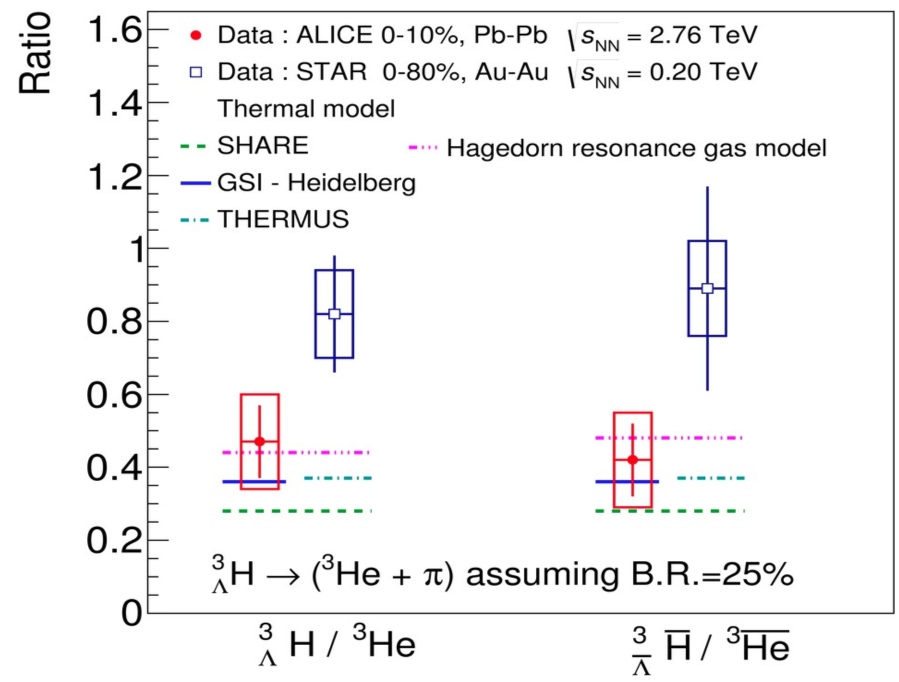
ALICE
0-10%
ALICE, Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV
10-20%
20-40%
40-60%
60-80%
0-20%
20-80%
$\bar{d}$ / d
$^3\overline{He}$ / ^{3}He
0.5
1
1.5
2
2.5
p_T / A (GeV/c)



Model	T (MeV)	χ^2/NDF
THERMUS 2.3	155 ± 2	24.5/9
GSI-Heidelberg	156 ± 2	18.4/9
SHARE 3	156 ± 3	15.1/9

Hypertriton



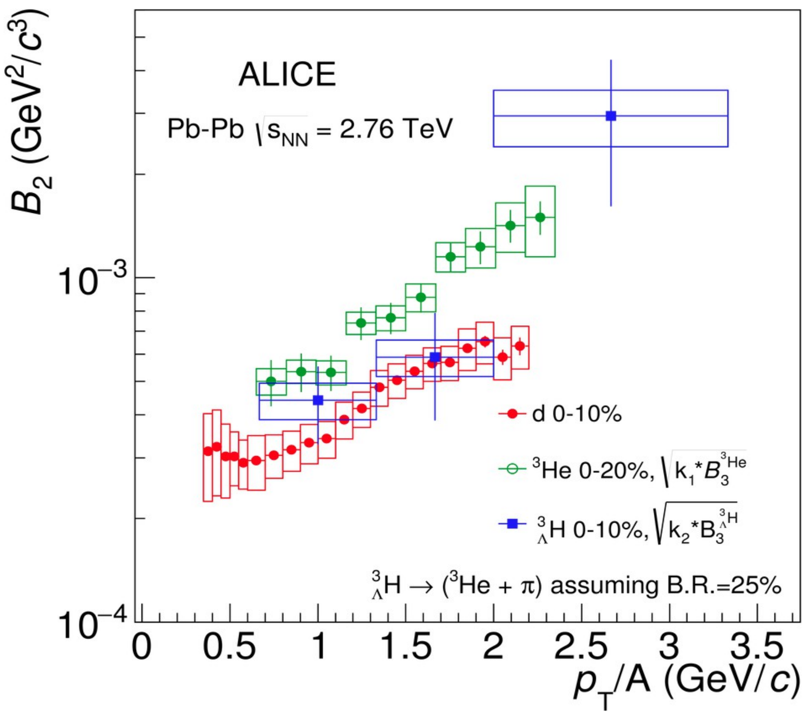


Figs.: http://arxiv.org/abs/1506.08453

- Comparison with different theoretical model calculations
  - 2 versions of the stat. hadronization model: GSI (T_{ch} = 156 MeV) and SHARE (non-equilibrium thermal model, T_{ch} = 138.3 MeV)
  - Hybrid UrQMD Model (hadronic transport approach + initial hydrodynamical stage)

- Ratio: STAR results are higher than ALICE, but compatible within uncert.

Hypertriton

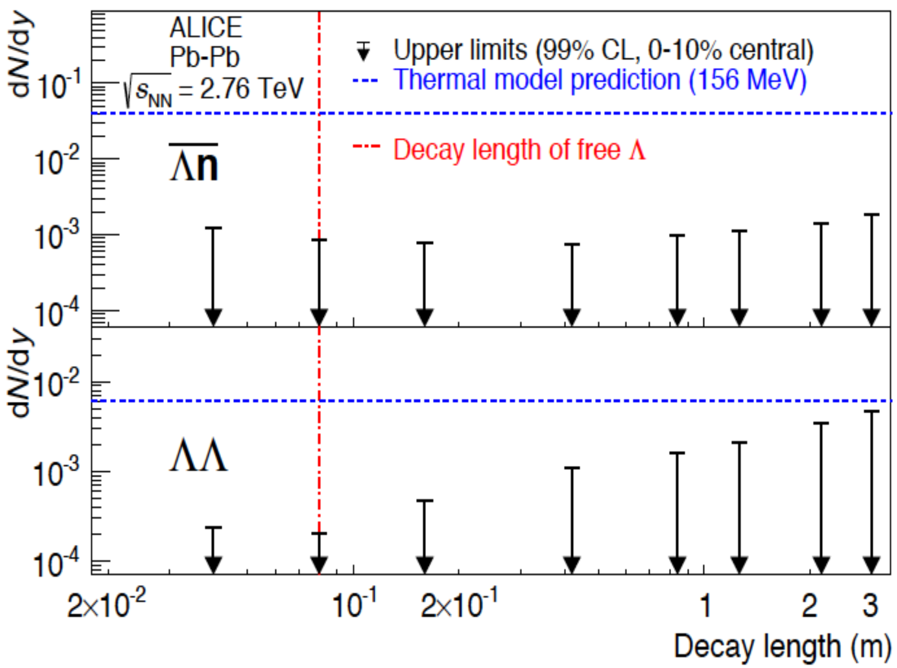


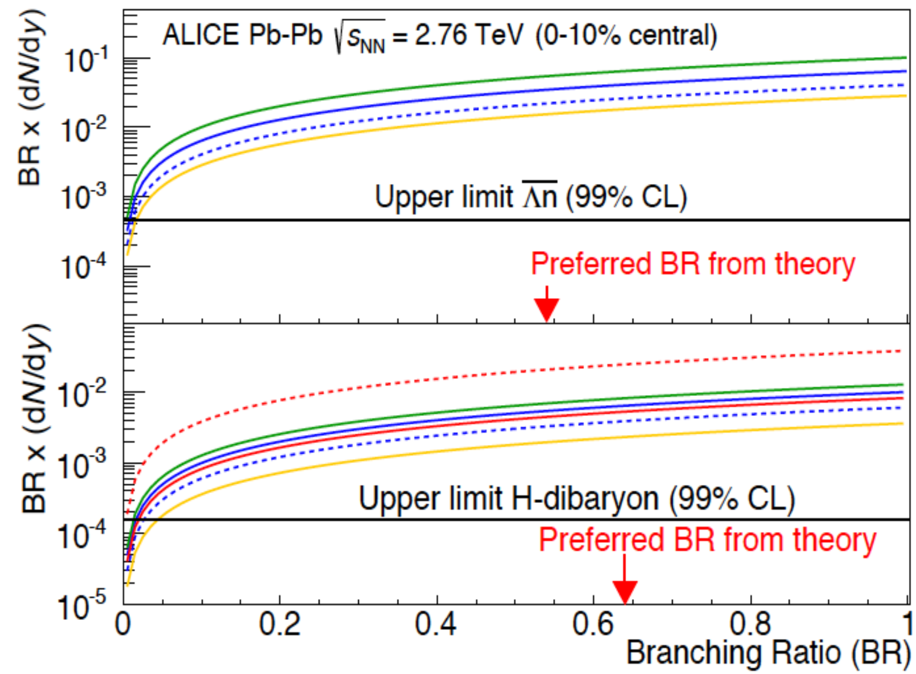
- The hypertriton coalescence parameter is not flat as a function of transverse momentum, contrary to the prediction of the simple coalescence model (no characteristics of the emitting source)

- Same behaviour for deuteron and ^{3}He;

Fig.:http://arxiv.org/abs/1506.08453

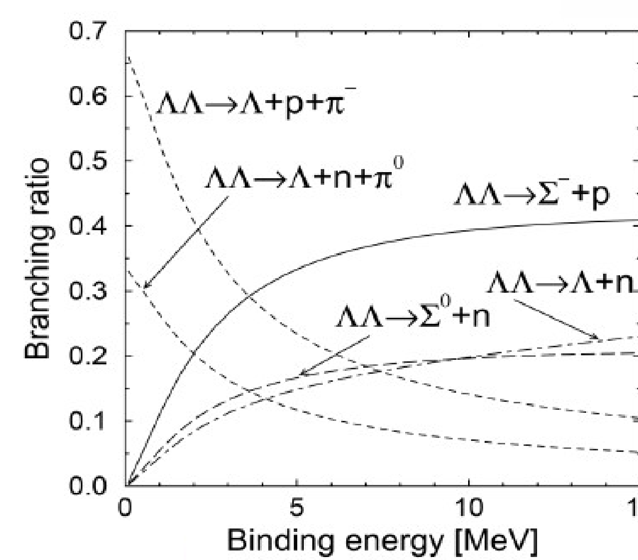
Search for weakly decaying dibaryon states





- Upper limits are estimated
  - B.R. at 1MeV d 54% (bound state)
  - B.R. at 1MeV d 64% (H-dibaryon)

- Comparison with model predictions (blue lines):
  - Thermal model predicition (T_{ch} = 165 MeV):
    - dN/dy = 4.06 x 10^{-2} (bound state)
    - dN/dy = 6.03 x 10^{-3} (H-dibaryon)



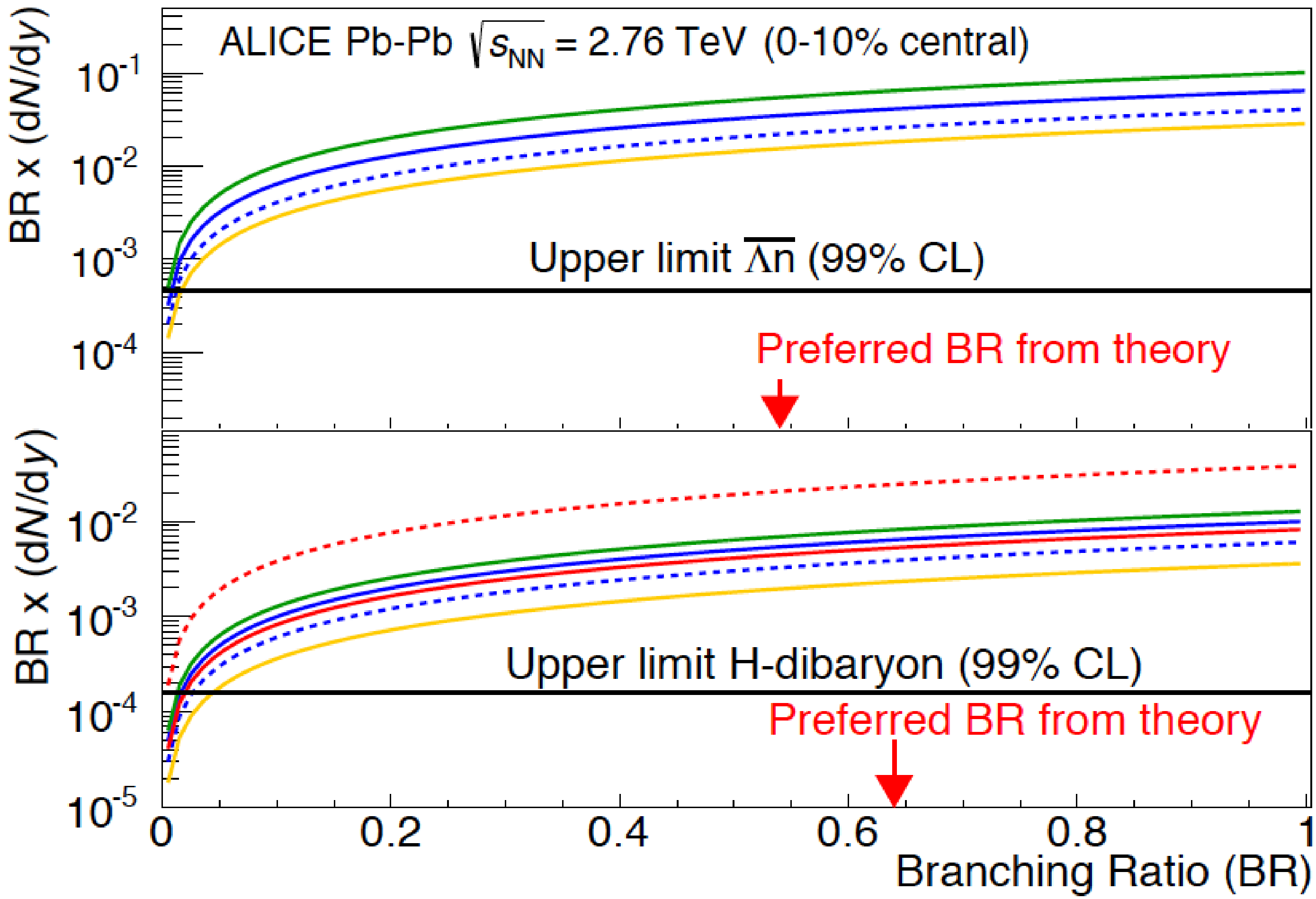


Fig. 5: Experimentally determined upper limit, under the assumption of the lifetime of a free Λ. In the upper panel shown for the $\overline{\Lambda}$n bound state and for the H-dibaryon in the lower panel. It includes 30% systematic uncertainty for each particle and 6% correction for absorption with an uncertainty of 7% for the $\overline{\Lambda}$n bound state. The theory lines are drawn for different theoretical branching ratios (BR) in blue for the equilibrium thermal model from [16] for two temperatures (164 MeV the full line and 156 MeV the dashed line), in green the non-equilibrium thermal model from [30] and in yellow the predictions from a hybrid UrQMD calculation [50]. The H-dibaryon is also compared with predictions from coalescence models, where the full red line visualises the prediction assuming quark coalescence and the dashed red line corresponds to hadron coalescence [31].

$$B_2 = \frac{3\pi^{3/2}\langle C_{\mathrm{d}}\rangle}{2m_{\mathrm{T}}R_{\perp}^2(m_{\mathrm{T}})R_{\parallel}(m_{\mathrm{T}})}$$