Results from (anti-)(hyper-)Nuclei Production and Searches for Exotic Bound States with ALICE at the LHC

Natasha Sharma,
University of Tennessee, Knoxville, USA.
for the ALICE Collaboration

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Motivation: (Anti-)nuclei production

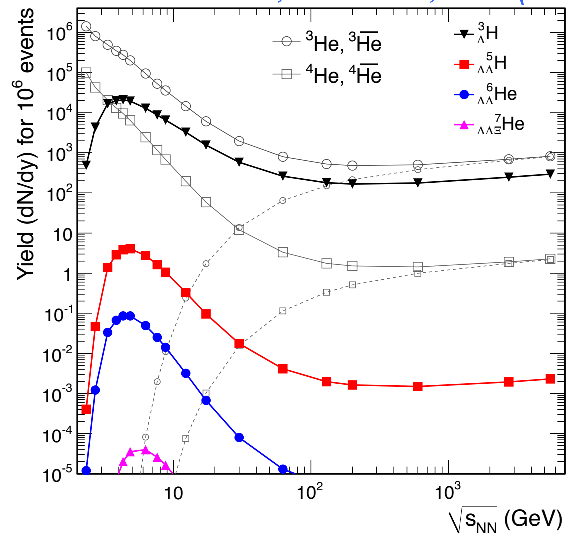
Thermal models

- At chemical freeze-out: Particle yields get fixed
- Abundance is determined by thermodynamic equilibrium

$$\frac{dN}{dy} \propto \exp\left(\frac{-m}{T_{chem}}\right)$$

- For nuclei (large m) strong dependence on T_{chem}

A. Andronic et al., PLB 697, 203 (2011)



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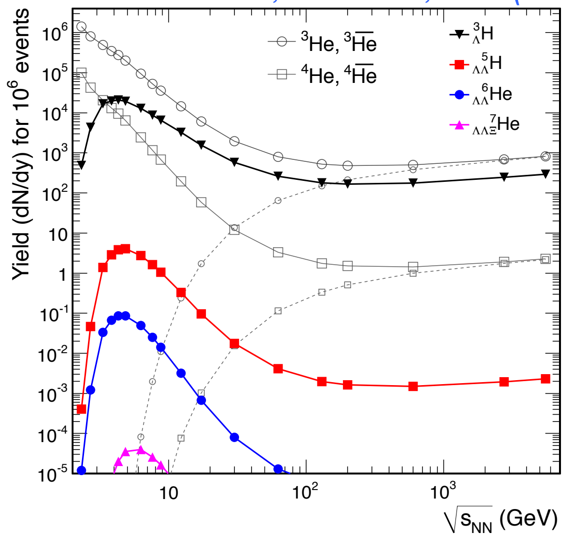
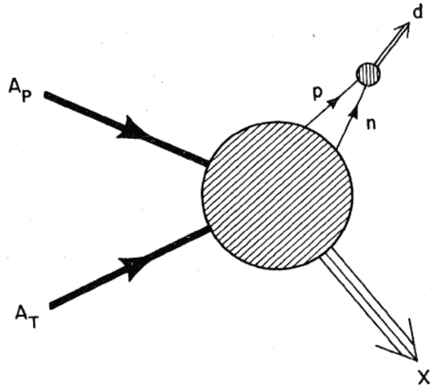


Test model predictions: thermal and coalescence



J. I. Kapusta, PRC 21, 1301 (1980)

Coalescence models

(Anti-)(hyper)nuclei formation requires that (anti-)nucleons and/or (anti-)hyperons are close in phase space.

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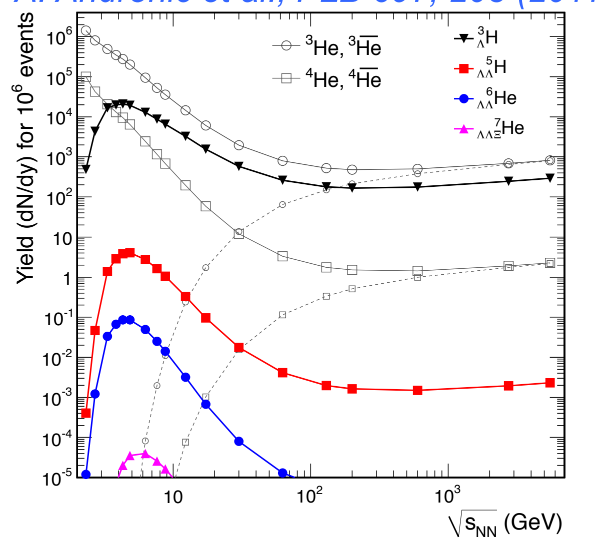

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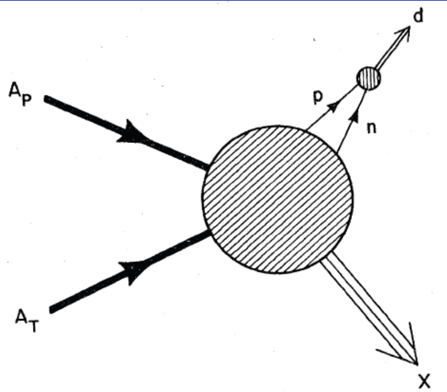

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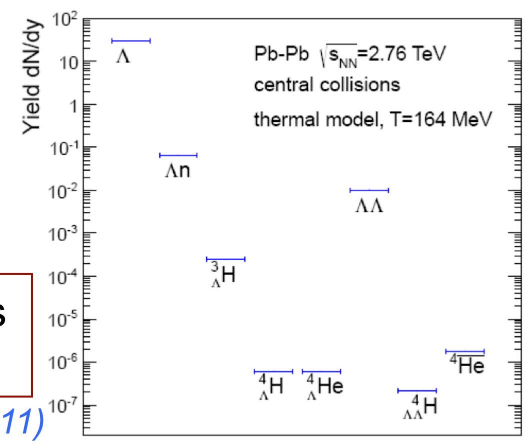
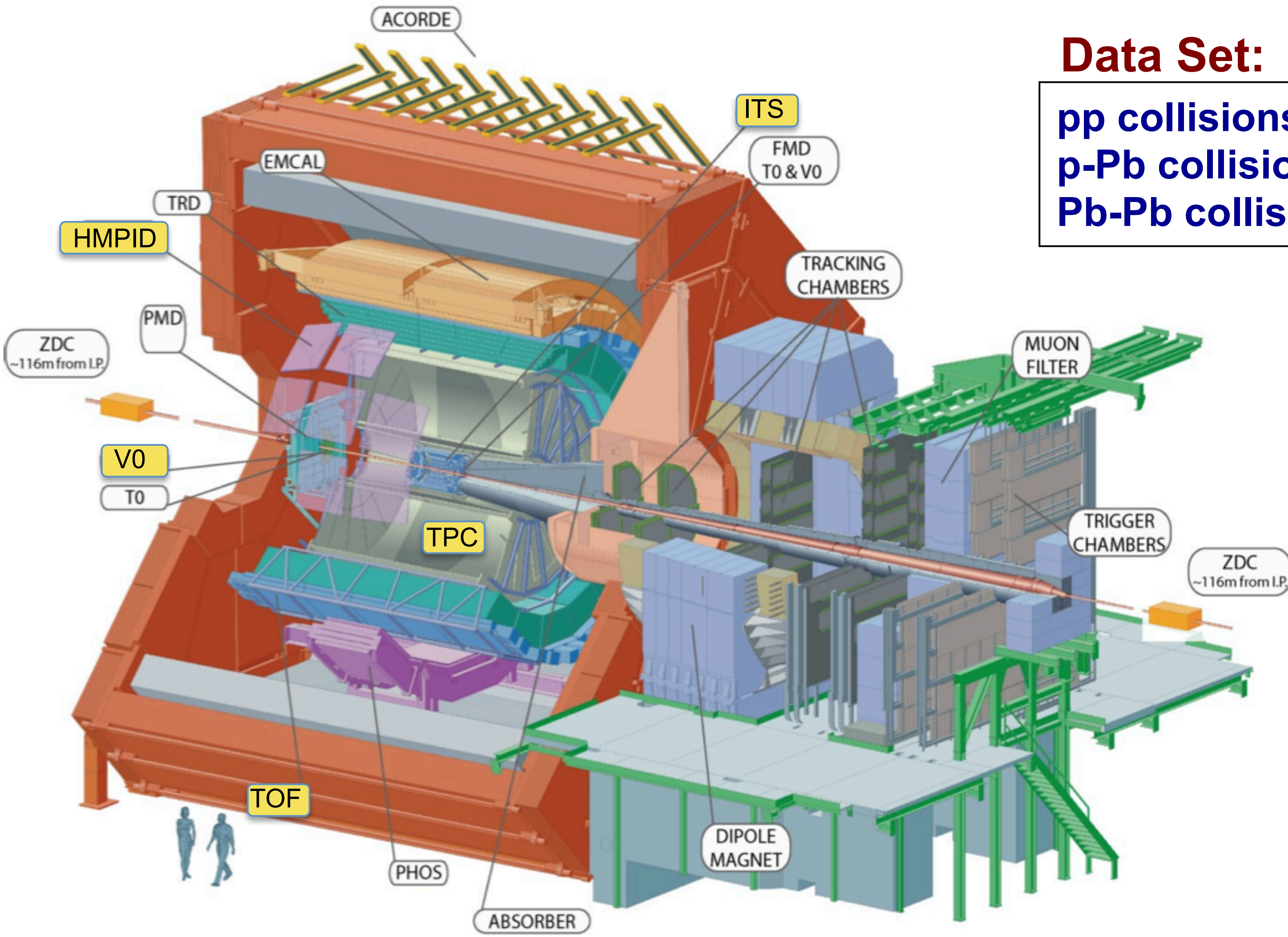


Exotic searches

- Explore QCD prediction for exotic bound states of baryons
- Search for rarely produced anti- and hyper-matter

A. Andronic et al., PLB 697, 203 (2011)

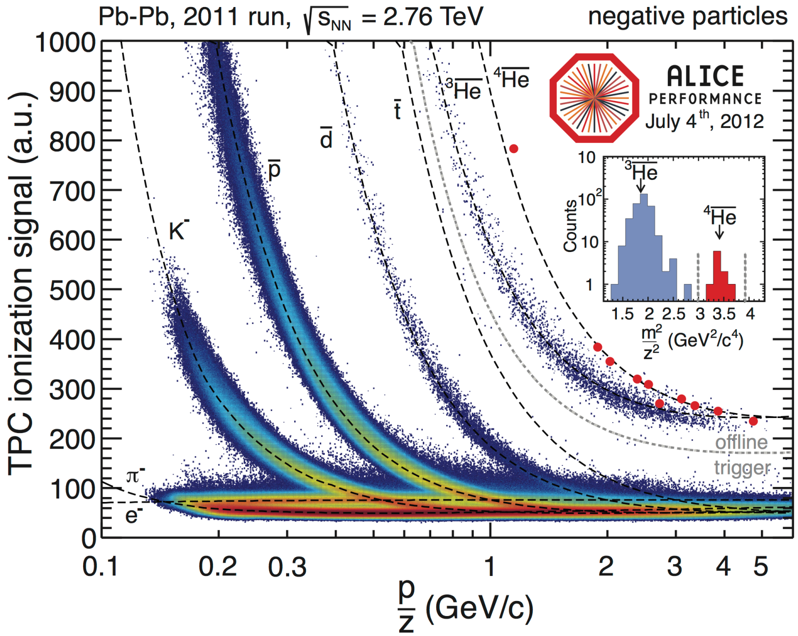
A Large Ion Collider Experiment (ALICE)



Data Set:

pp collisions at 7 TeV
p-Pb collisions at 5.02 TeV
Pb-Pb collisions at 2.76 TeV

Nuclei identification: Time Projection Chamber



ALI-PERF-36713

Light nuclei and anti-nuclei are identified using dE/dx measurement in the TPC.
Deuterons below $p_T \leq 1.4$ GeV/c, and ^{3}He between $1.5 < p_T < 7$ GeV/c.

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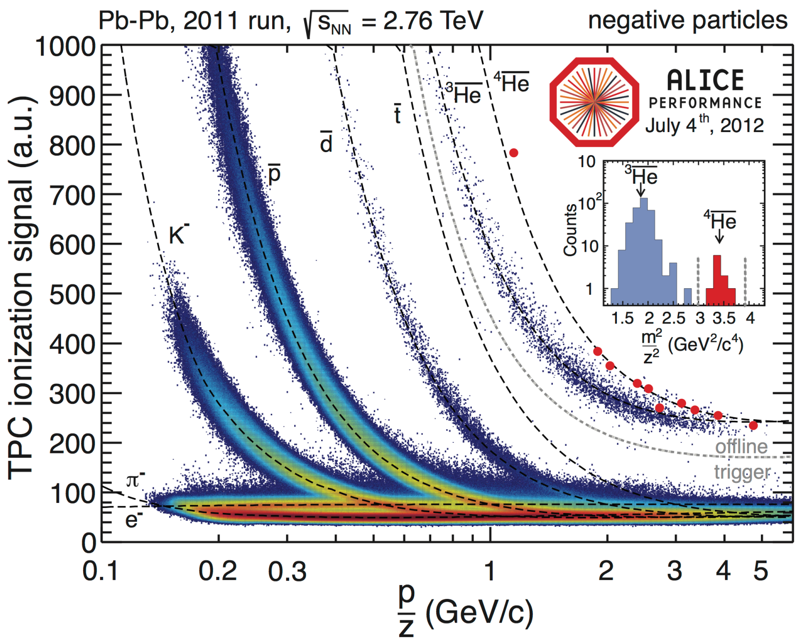

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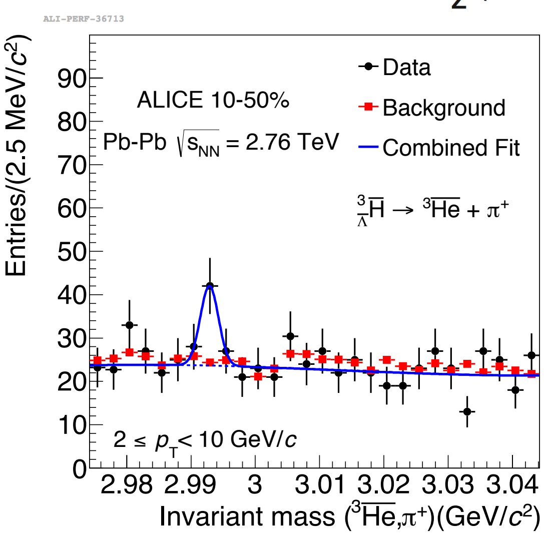
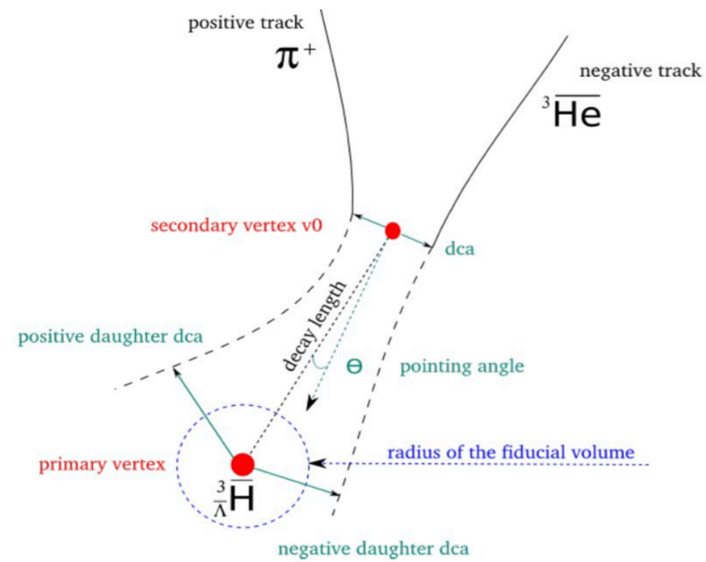
$^3_\Lambda$H ($^3_\Lambda\overline{\text{H}}$) signal

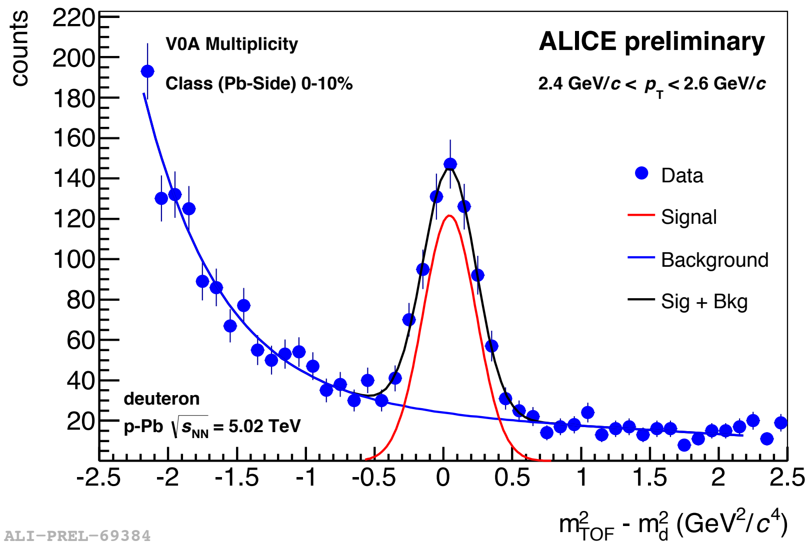


Hypertriton (M = 2.991 GeV/c^2) signal extracted using invariant mass of ^{3}He + π^-.
Applied topological cuts in order to:

- identify secondary decay vertex and
- reduce combinatorial background.



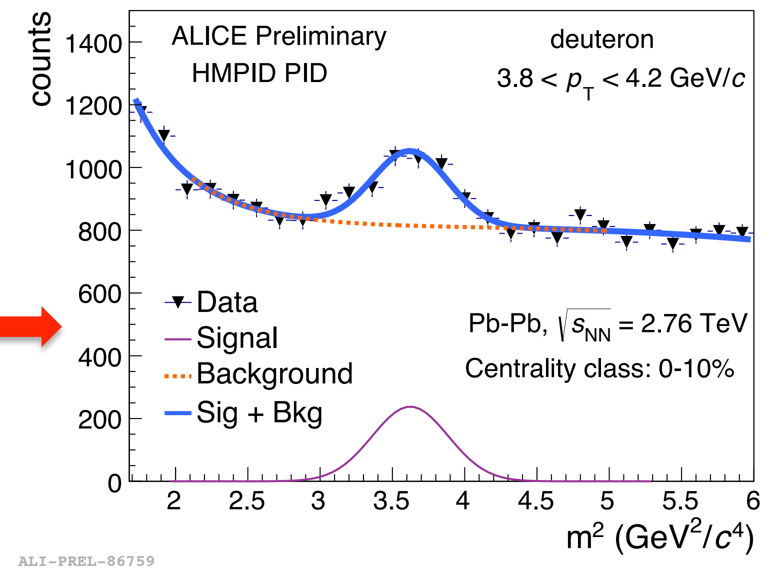
Nuclei identification: Time-Of-Flight and HMPID



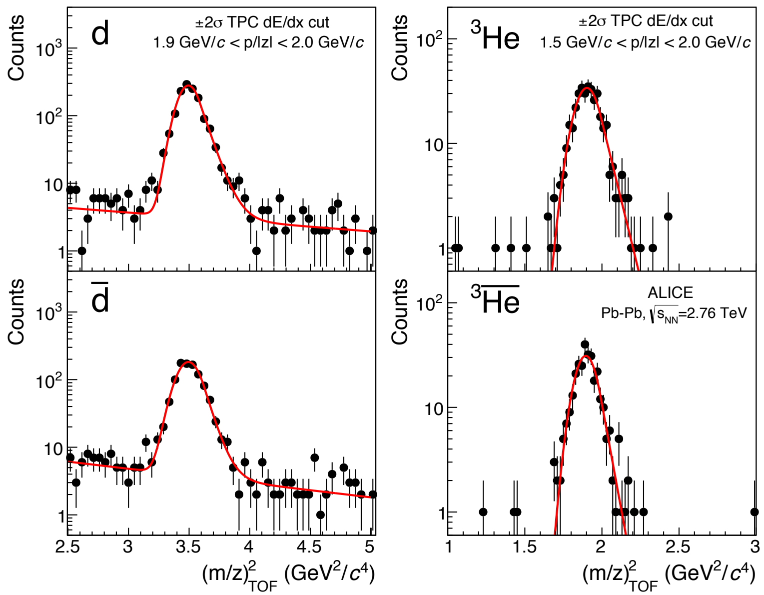
Deuterons above 1.4 GeV/c are identified using velocity measurement with the TOF detector and extracting the yield from the Δm^2 distribution.

$$m^2_{TOF} = \frac{p^2}{c^2}\left(\frac{c^2 t^2_{TOF}}{l^2_{track}} - 1\right)$$

- High p_T deuterons are identified based on Cherenkov radiation (HMPID)
- The m^2 distribution is obtained using relation → $m^2 = p^2 (n^2\cos^2\theta_{Cherenkov} - 1)$



Mass difference nuclei/anti-nuclei

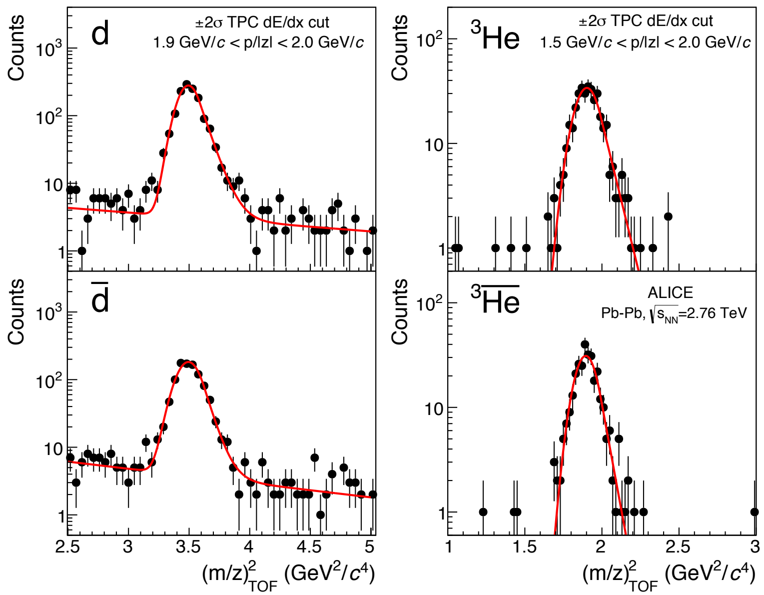


The precise measurement of (anti-)nuclei mass difference allows probing any difference in the interaction between nucleons and anti-nucleons.

Performed test of the CPT invariance of residual QCD "nuclear force" by looking at the mass difference between nuclei and anti-nuclei.

Mass difference nuclei/anti-nuclei

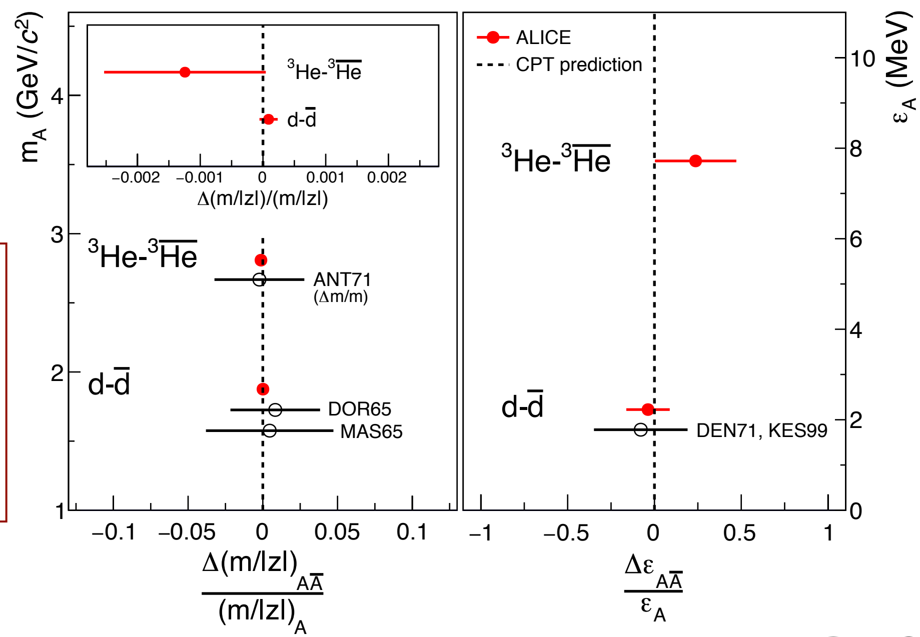
ALICE Coll: **Nature Phys. doi:10.1038/nphys3432**



The precise measurement of (anti-)nuclei mass difference allows probing any difference in the interaction between nucleons and anti-nucleons.

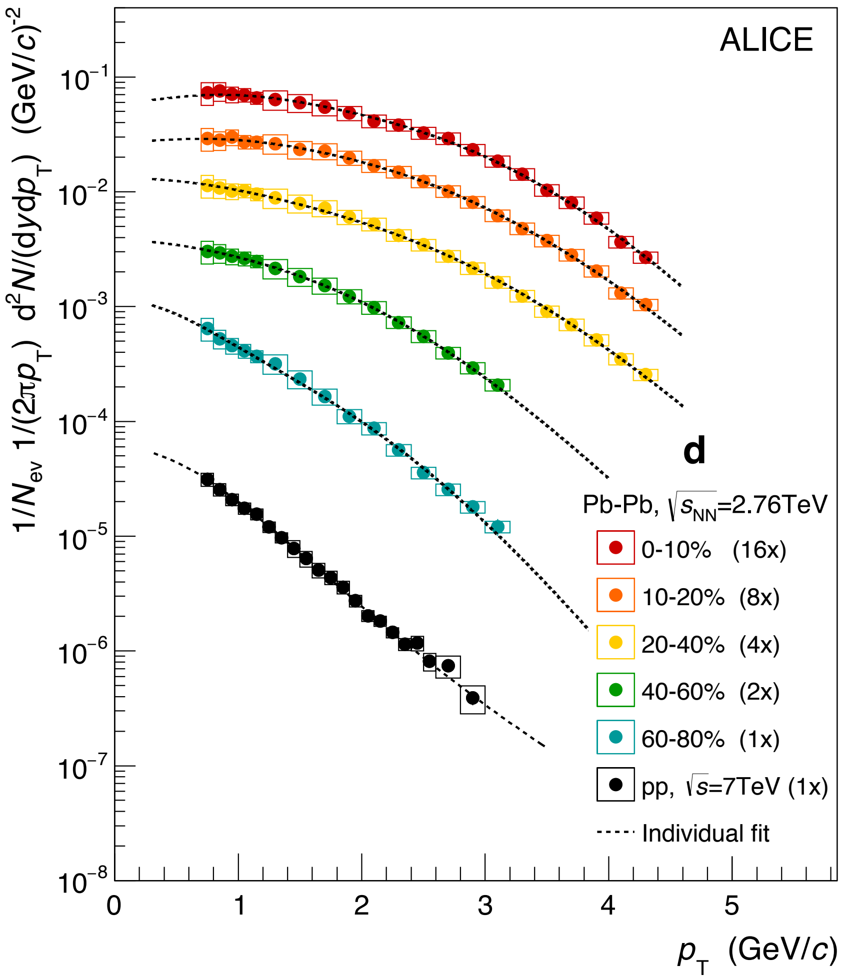
Performed test of the CPT invariance of residual QCD "nuclear force" by looking at the mass difference between nuclei and anti-nuclei.

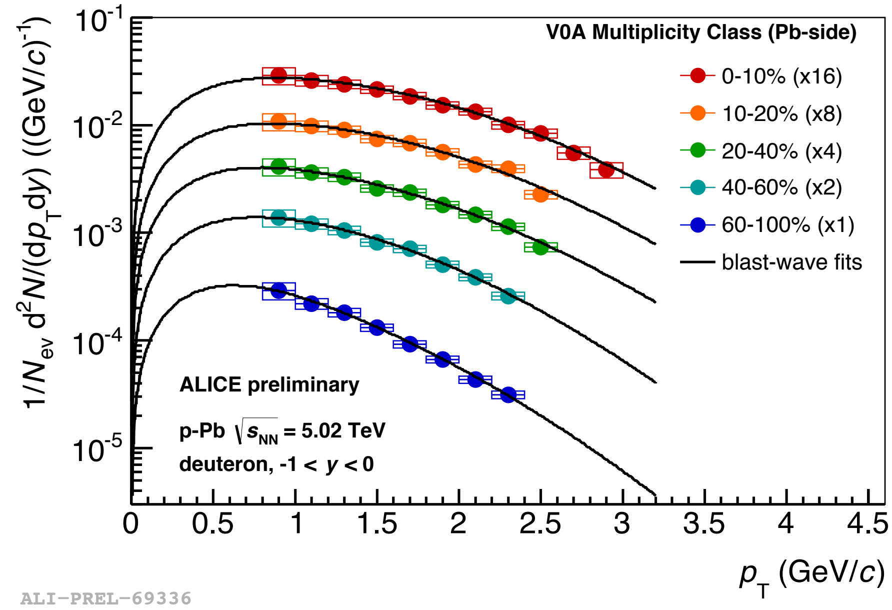
- ✓ Mass and binding energies of nuclei and anti-nuclei are compatible within uncertainties.
- ✓ Measurement **confirms the CPT invariance** for light nuclei.



Deuteron production at LHC

ALICE Coll.: arXiv:1506.08951 [nucl-ex]



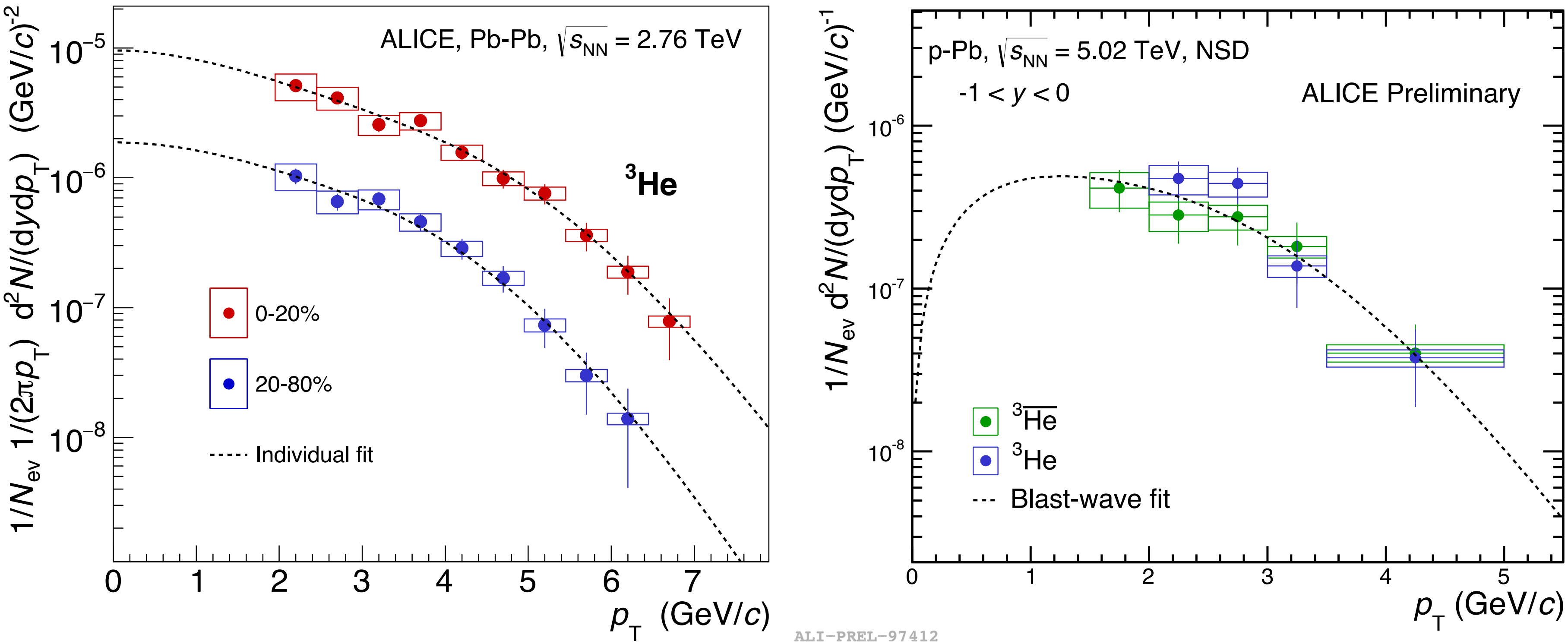


- ✓ The Blast-Wave function (*) fits the data well in p-Pb and Pb-Pb.
- ✓ pp spectrum well described by the Levy-Tsallis fit.
- ✓ Fit used for extrapolation of yield to unmeasured low and high p_T region.
- ✓ Spectra become harder with increasing multiplicity for p-Pb and Pb-Pb.

(*) E. Schnedermann et al., PRC 48, 2462 (1993).

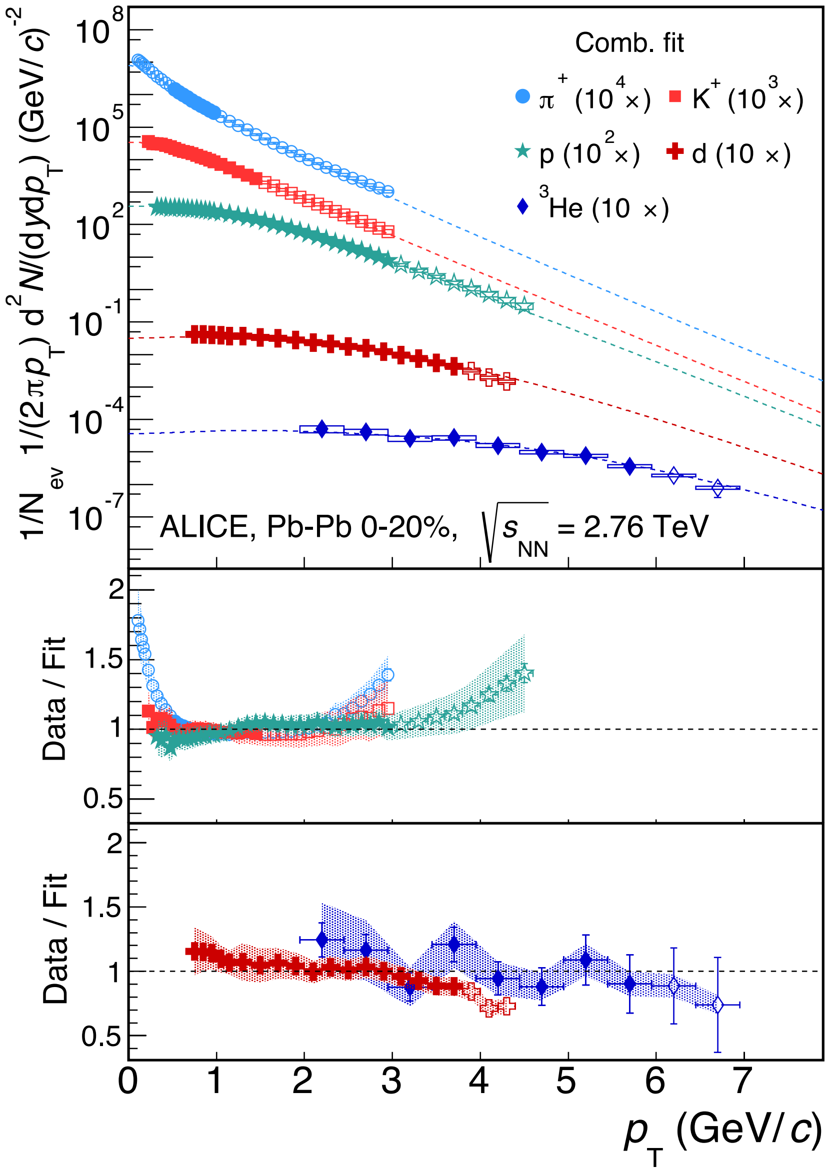
^{3}He production in Pb-Pb and p-Pb

ALICE Coll.: arXiv:1506.08951 [nucl-ex]



- ✓ Dashed curve represents individual Blast-Wave fits.
- ✓ Spectrum obtained for 2 centrality classes in Pb-Pb and for NSD collisions in p-Pb.

Combined Blast-Wave fit



ALICE Coll.: arXiv:1506.08951 [nucl-ex]

- ✓ π, K, p, d, and ^{3}He are fitted simultaneously for central Pb-Pb collisions with the Blast-Wave model in the limited p_T range.
- ✓ All particle spectra are described well with the BW fit.
- ✓ Common fit parameters are:
  - $\langle\beta\rangle = 0.63 \pm 0.01$,
  - $T_{kin} = 113 \pm 12$ MeV, and
  - $n = 0.72 \pm 0.03$.
- ✓ Fit parameters are comparable to those from the combined BW fit to only π, K, and p.

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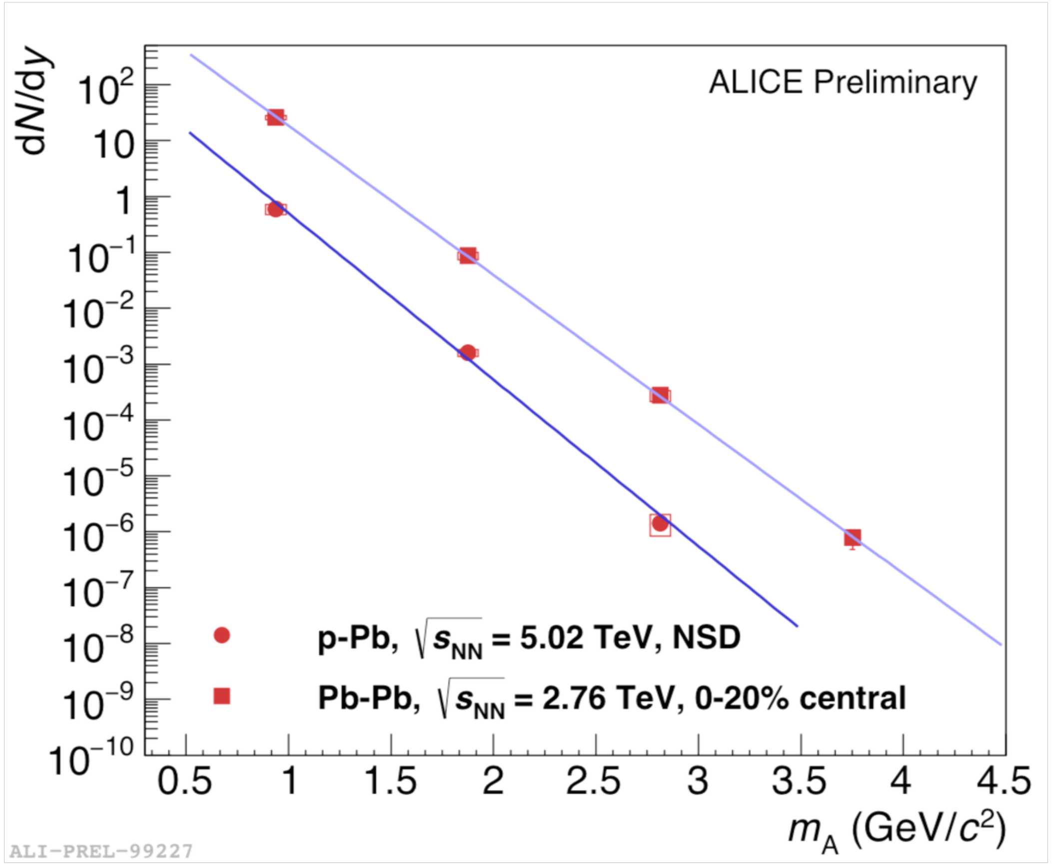
Mass dependence of yield

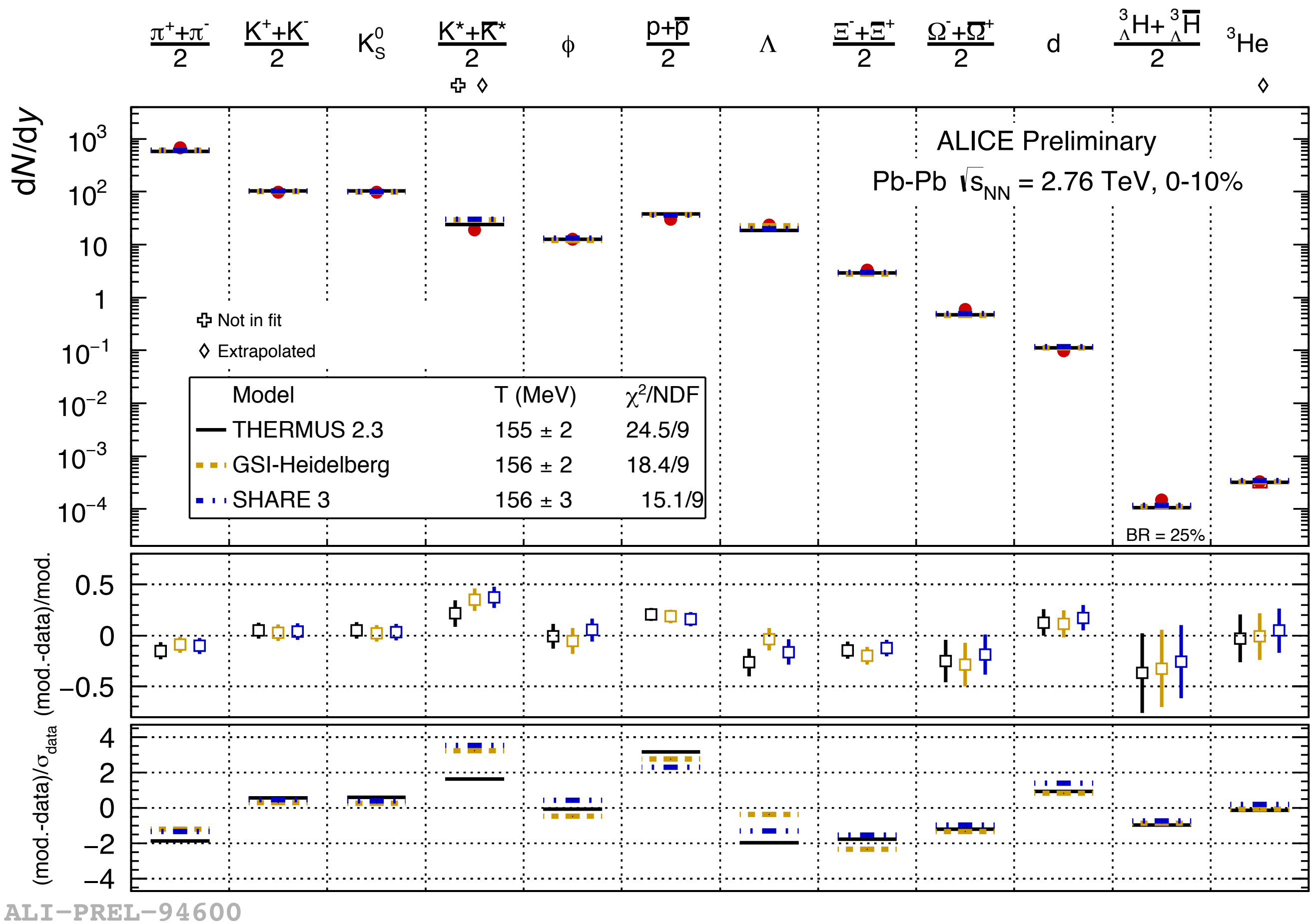


Thermal model predicts

$$\frac{dN}{dy} \propto \exp\left(\frac{-m}{T_{chem}}\right)$$

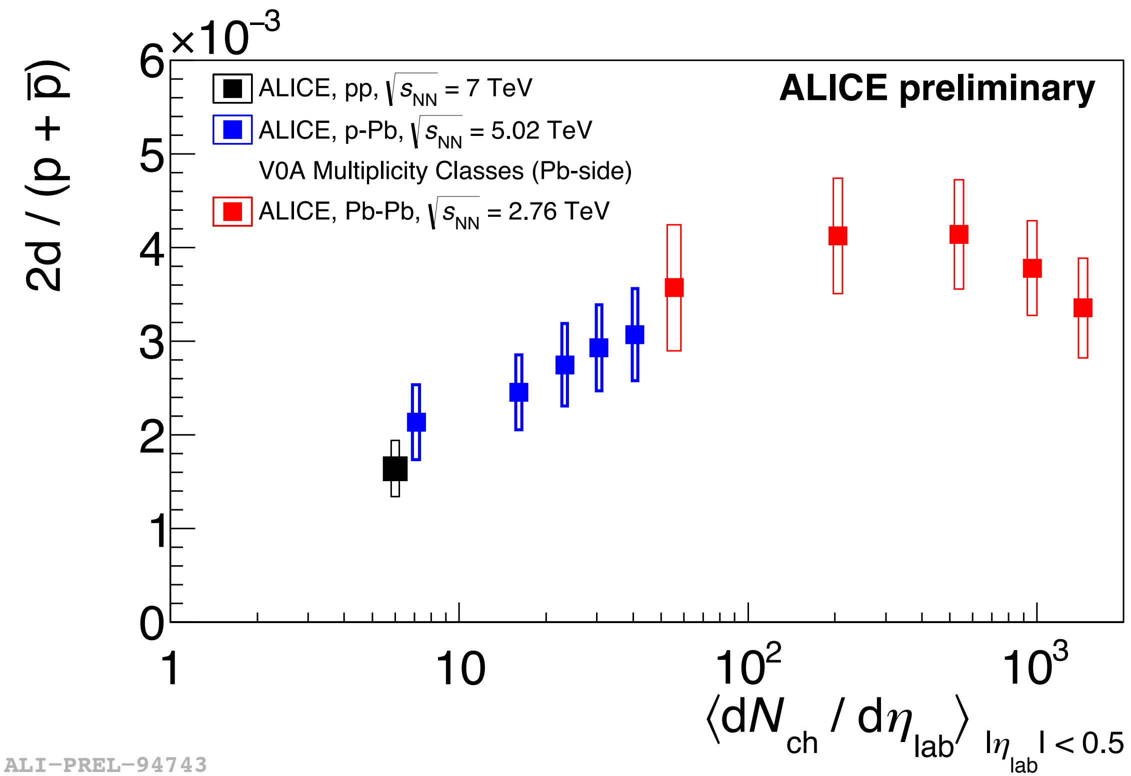
- ✓ Nuclei yields follow an exponential decrease with mass
- ✓ Each added nucleon reduces yield by a factor called 'Penalty factor'
  - ➢ Central Pb-Pb ~ 300
  - ➢ NSD p-Pb ~ 600

Models fit to yields (Pb-Pb)



- Different models describe particle yields including light (hyper-)nuclei well with T_{chem} of about 156 MeV.
- Including nuclei in the fit causes no significant change in T_{chem}.

Deuteron to proton ratio



- ✓ Pb-Pb: p/π remains constant with multiplicity.
- ✓ d/p ratio remains almost constant.

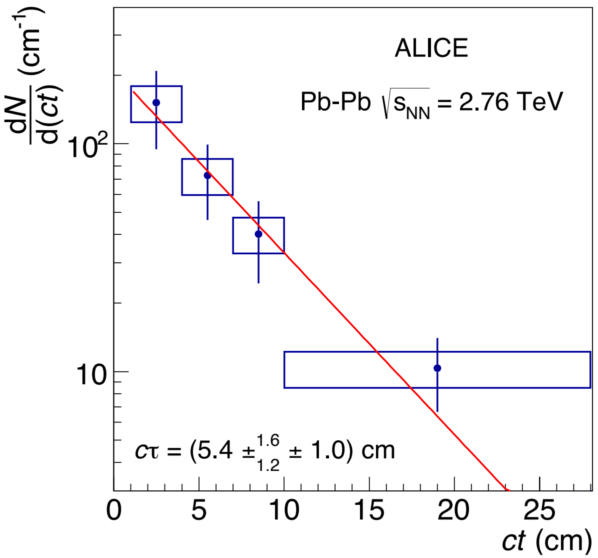
→ Consistent with thermal and coalescence model expectations.

- ✓ p-Pb: p/π almost constant with multiplicity.
- ✓ d/p ratio increases with multiplicity.

→ Deviation from thermal model expectation.

Ratio in pp collisions is a factor 2.2 lower than in Pb-Pb collisions.

Hypertriton lifetime

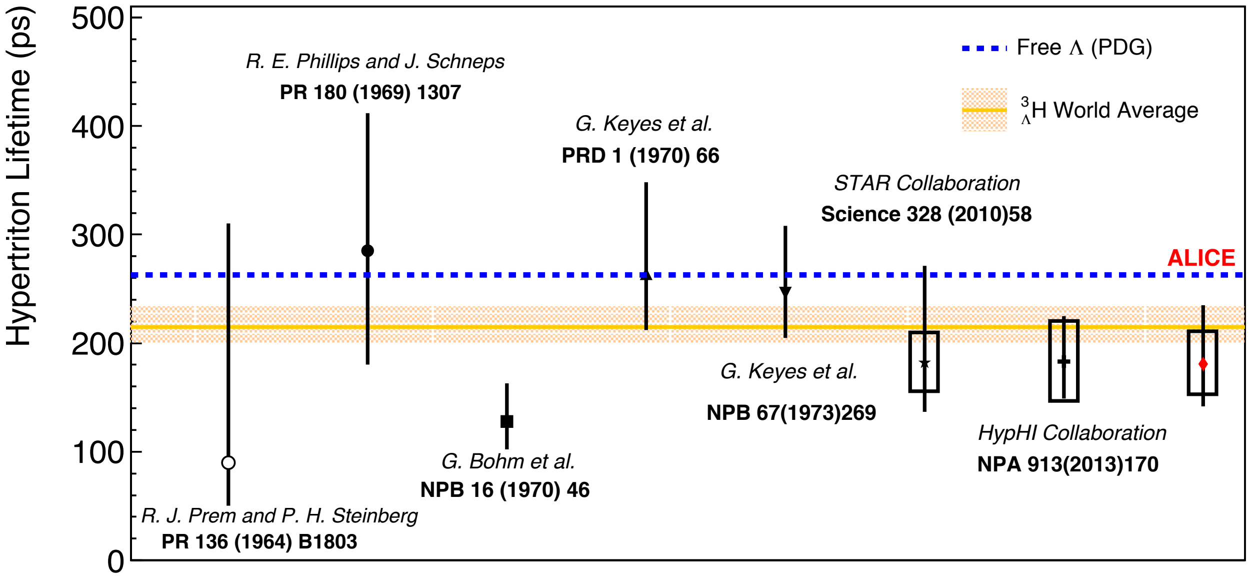


ALICE Coll.: arXiv:1506.08453 [nucl-ex]

$c\ \tau\ = mL/p$

$c\ \tau = (5.5 \pm 1.4 \pm 0.68)$ cm
$\tau\ = 185 \pm 48 \pm 29$ ps

Hypertriton lifetime measurement is in agreement with previous measurements.



Searches for exotica

Thermal models predict the abundances of nuclei correctly and therefore can be used as prediction for weakly decaying exotic bound states like ΛΛ and Λn-bar.

ΛΛ (H-dibaryon)

- Predicted by Jaffe in bag model calculations
  R. L. Jaffe, PRL 38, 195 (1977).
- Decay channel: $\Lambda\Lambda \rightarrow \Lambda + p + \pi^-$
- Thermal model prediction at T_{chem} = 156 MeV is dN/dy = 6.03 x 10^{-3}.

Λn-bar

- Decay channel: $\overline{\Lambda n} \rightarrow \overline{d} + \pi^+$
- Thermal model prediction at T_{chem} = 156 MeV is dN/dy = 4.06 x 10^{-2}.

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- Decay channel: $\overline{\Lambda n} \rightarrow \bar{d} + \pi^+$
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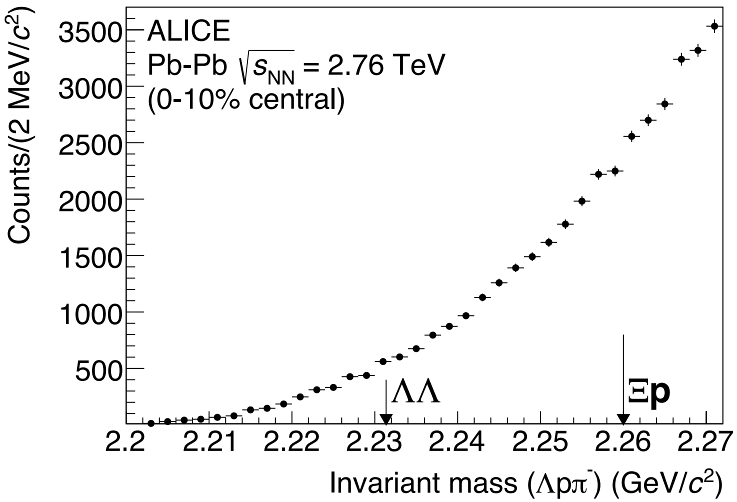
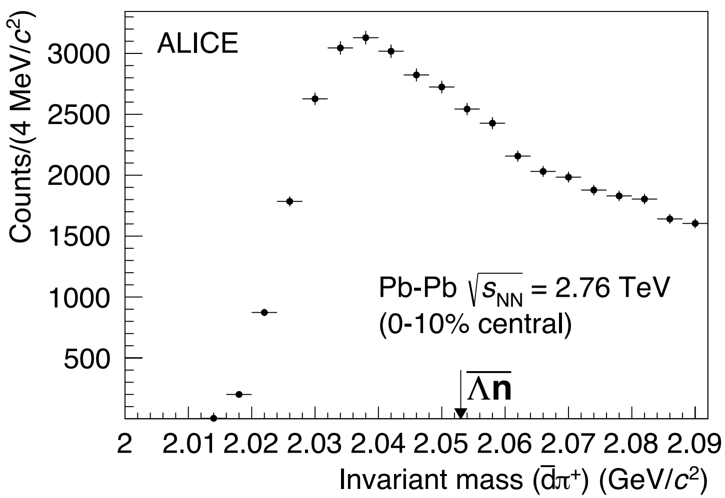
ALICE Coll.: arXiv:1506.07499 [nucl-ex]

- ✓ Both ΛΛ and Λn-bar are expected to be seen with the statistics available in ALICE.
- ✓ No signal visible in the invariant mass spectra.
- ✓ From the non observation, upper limit set on dN/dy for ΛΛ and Λn-bar bound states.





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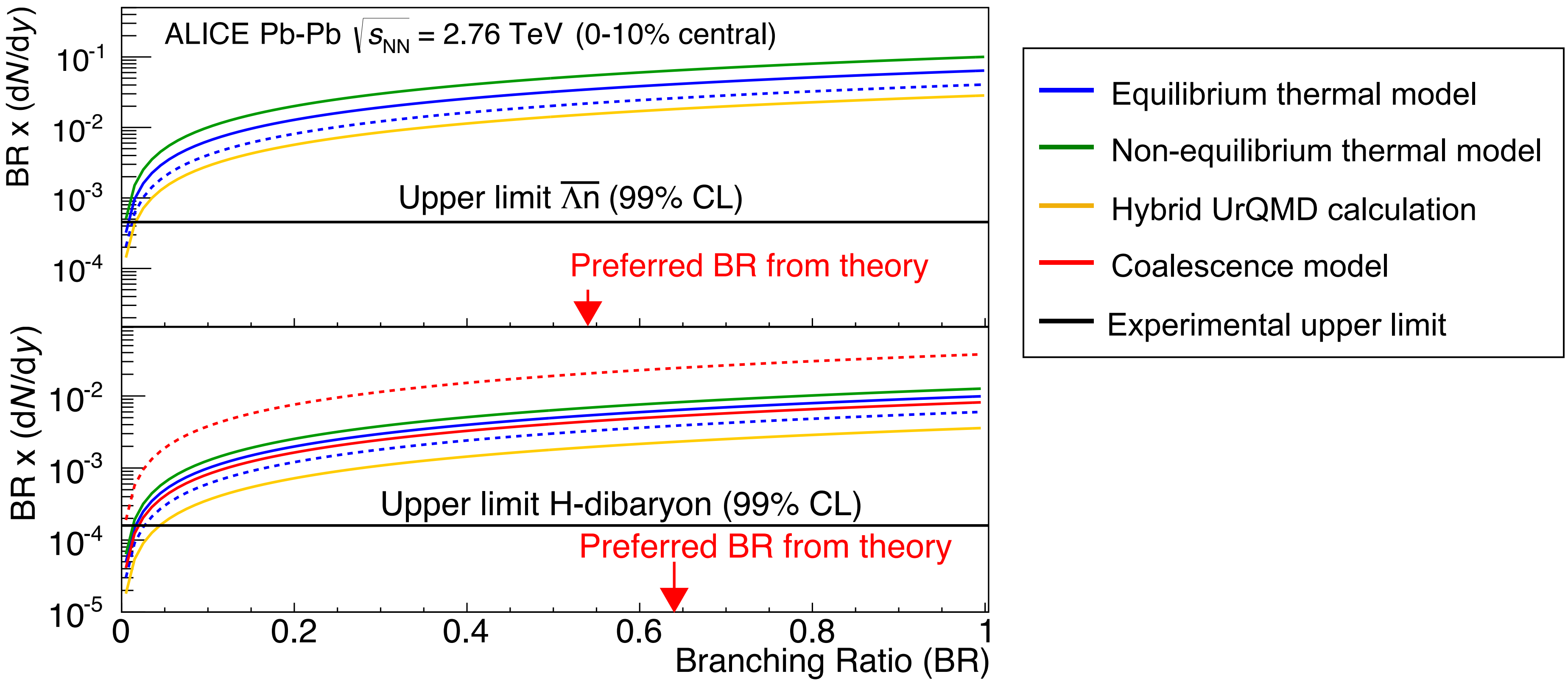
Exotic searches: Upper limit

ALICE Coll.: arXiv:1506.07499 [nucl-ex]

Experimentally determined upper limit for ΛΛ and Λn-bar bound states compared with the models calculation as a function of BR.



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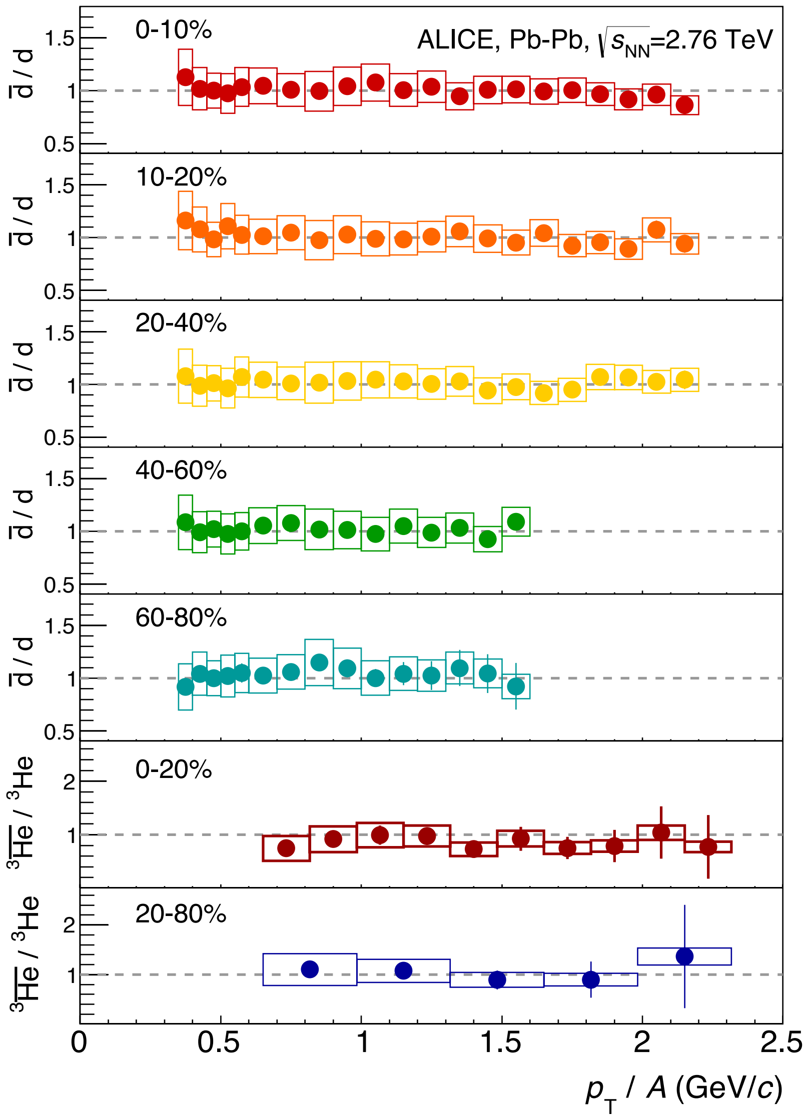
Summary and conclusions

- ✓ Nuclei production (up to A=4) has been measured by the ALICE experiment.
- ✓ Obtained deuteron and ^{3}He spectra in p-Pb and Pb-Pb; d spectrum in pp collisions. Hardening of deuteron spectra with multiplicity is observed for both p-Pb and Pb-Pb.
- ✓ π, K, p, d, and ^{3}He spectra in central Pb-Pb collisions are well described by a single set of common freeze-out parameters in the Blast-wave model.
- ✓ The nuclei yields follow an exponential decrease with mass. The penalty factor is ~300 in Pb-Pb collisions and is ~600 in p-Pb. The decrease in Pb-Pb reflects thermal behavior described by T_{chem}.
- ✓ Both coalescence and thermal models describe different aspects of the data.
  - ➢ Thermal model describes particles and light nuclei yields (including hypertritons) well at $T_{chem} \approx 156$ MeV in Pb-Pb.
  - ➢ d/p ratio rises with multiplicity in p-Pb but remains constant for Pb-Pb.
- ✓ The data from ALICE do not support the existence ΛΛ and Λn-bar.

Thank you

Back up

Anti-matter to matter ratio

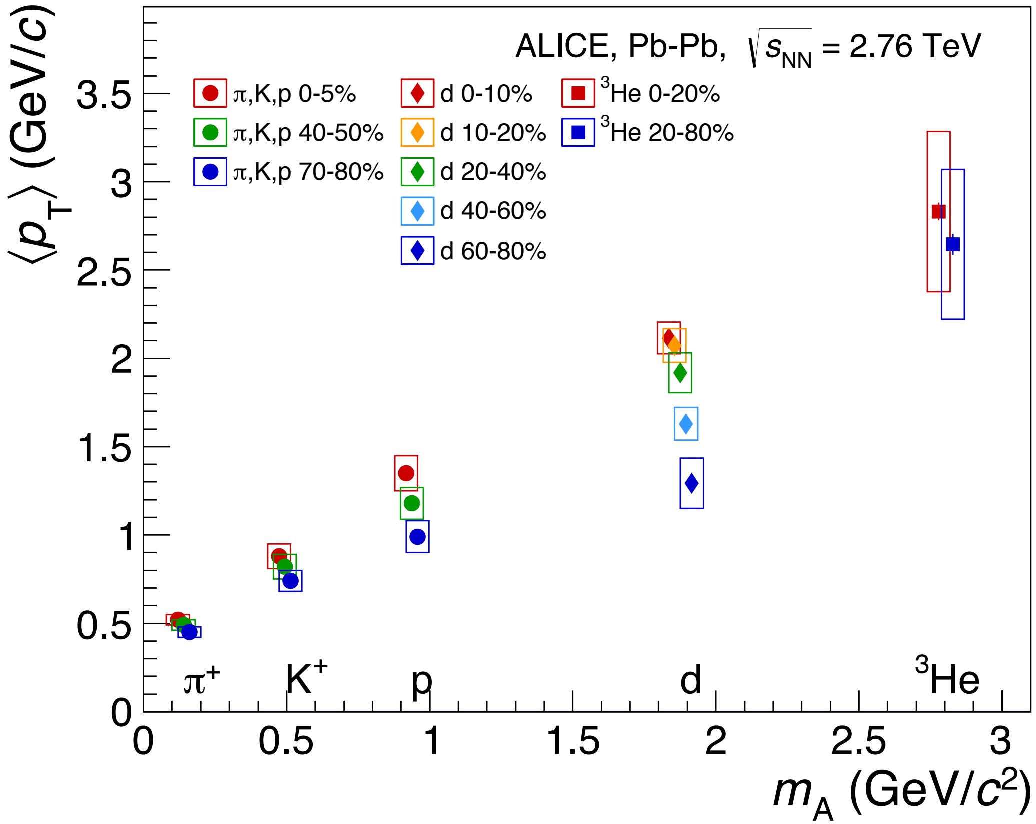


ALICE Coll.: [arXiv:1506.08951](https://arxiv.org/abs/1506.08951) [nucl-ex]

- Anti-nuclei / nuclei ratios are consistent with unity (similar to other light particle species).
- Ratios exhibit constant behavior as a function of p_T and centrality.
- Are in agreement with the coalescence and thermal model expectations.

<p_T> vs mass (in Pb-Pb)

ALICE Coll.: arXiv:1506.08951 [nucl-ex]



✓ <pT> increases with increasing particle mass.