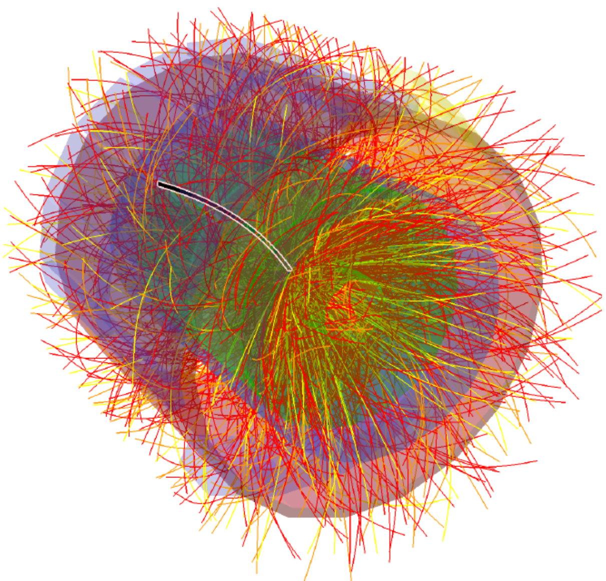
Results on (anti-)(hyper-)nuclei production and searches for exotic bound states with ALICE at the LHC

SQM Berkeley 2016



ALICE

06/30/2016
SQM2016 Berkeley

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IKF Institut für Kernphysik Frankfurt

Content

- Introduction
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- (Anti-)hypertriton
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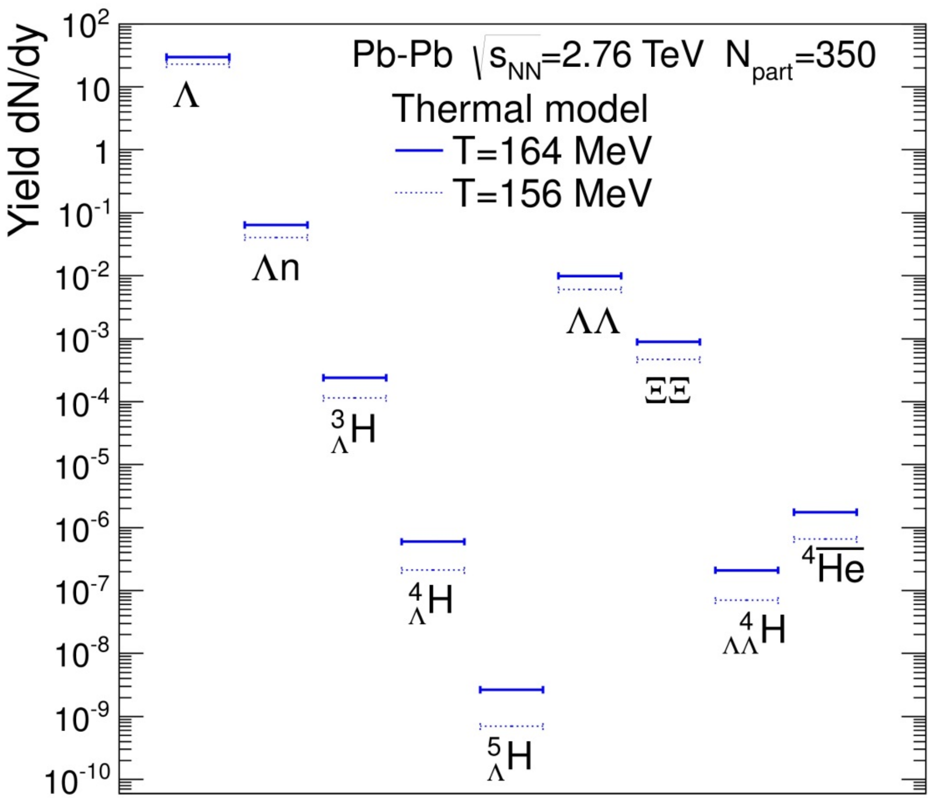
Motivation

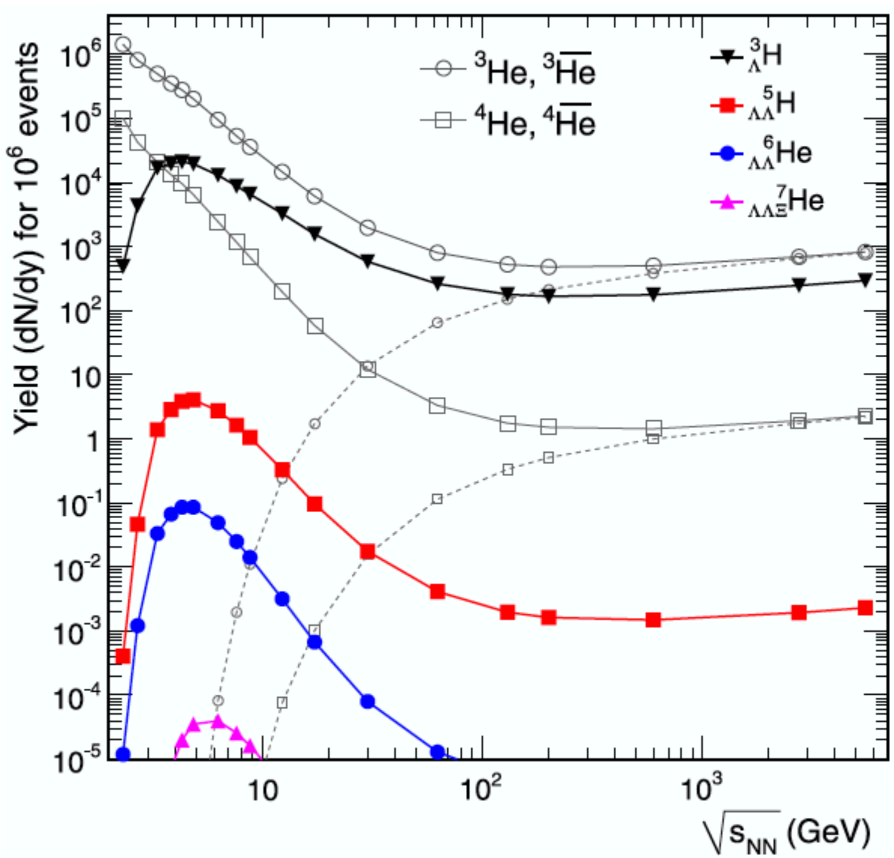


A. Andronic et al., PLB 697, 203 (2011) and references therein for the model, figure from A. Andronic, private communication

- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states
- Search for rarely produced anti- and hyper-matter
- Test model predictions, e.g. thermal and coalescence

→ Understand production mechanisms

Thermal model

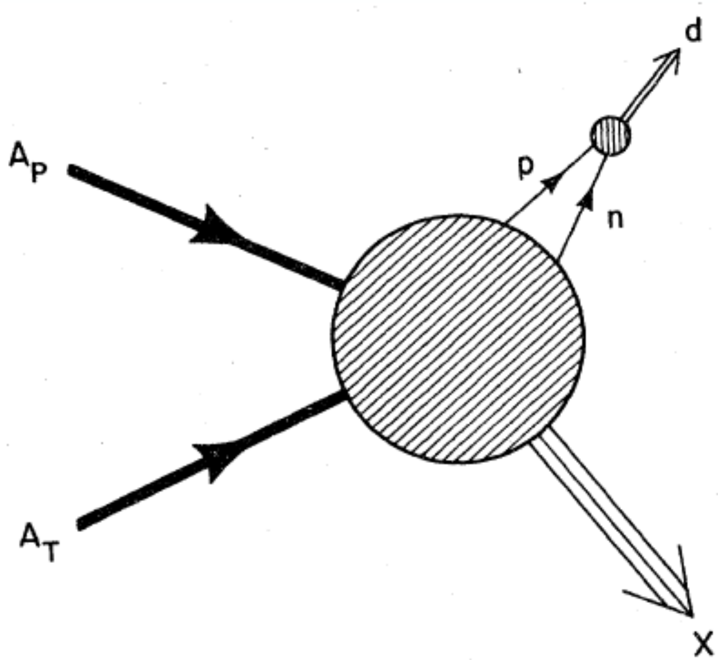


A. Andronic et al., PLB 697, 203 (2011)

- Key parameter at LHC energies:
  - chemical freeze-out temperature T_{ch}
- Strong sensitivity of abundance of nuclei to choice of T_{ch} due to:
  1. large mass *m*
  2. exponential dependence of the yield ~ exp($-m/T_{ch}$)

→ Binding energies small compared to T_{ch}

Coalescence



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

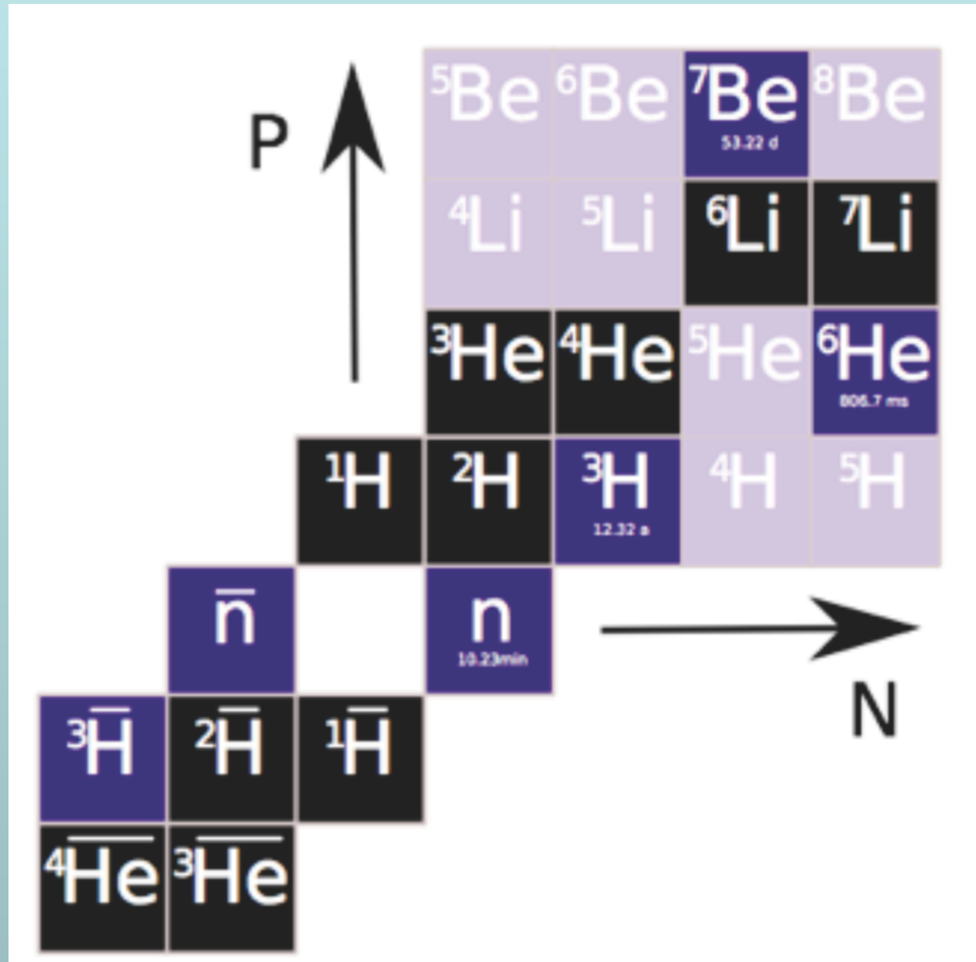
- Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

- Produced nuclei

➜ can break apart

➜ created again by final-state coalescence

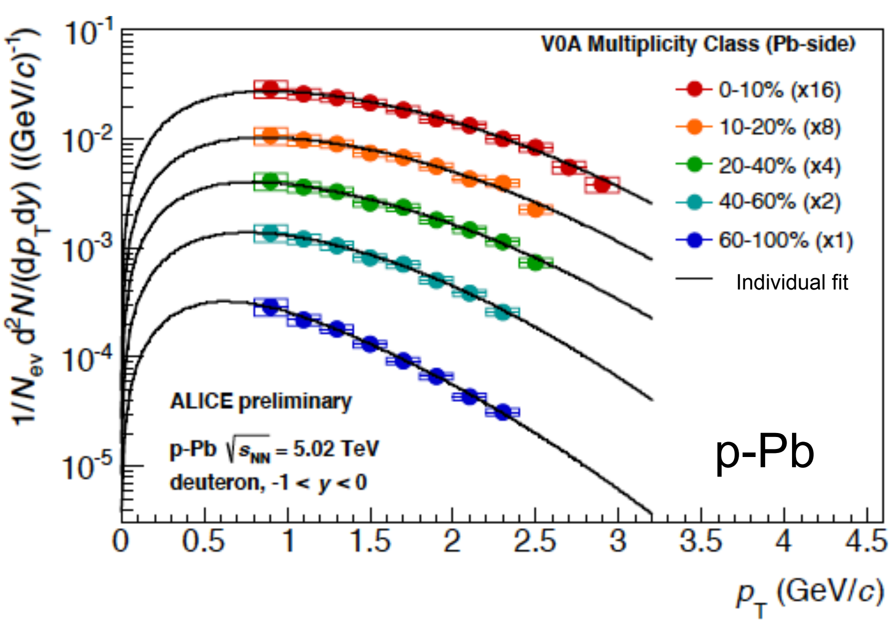
(Anti-)Nuclei

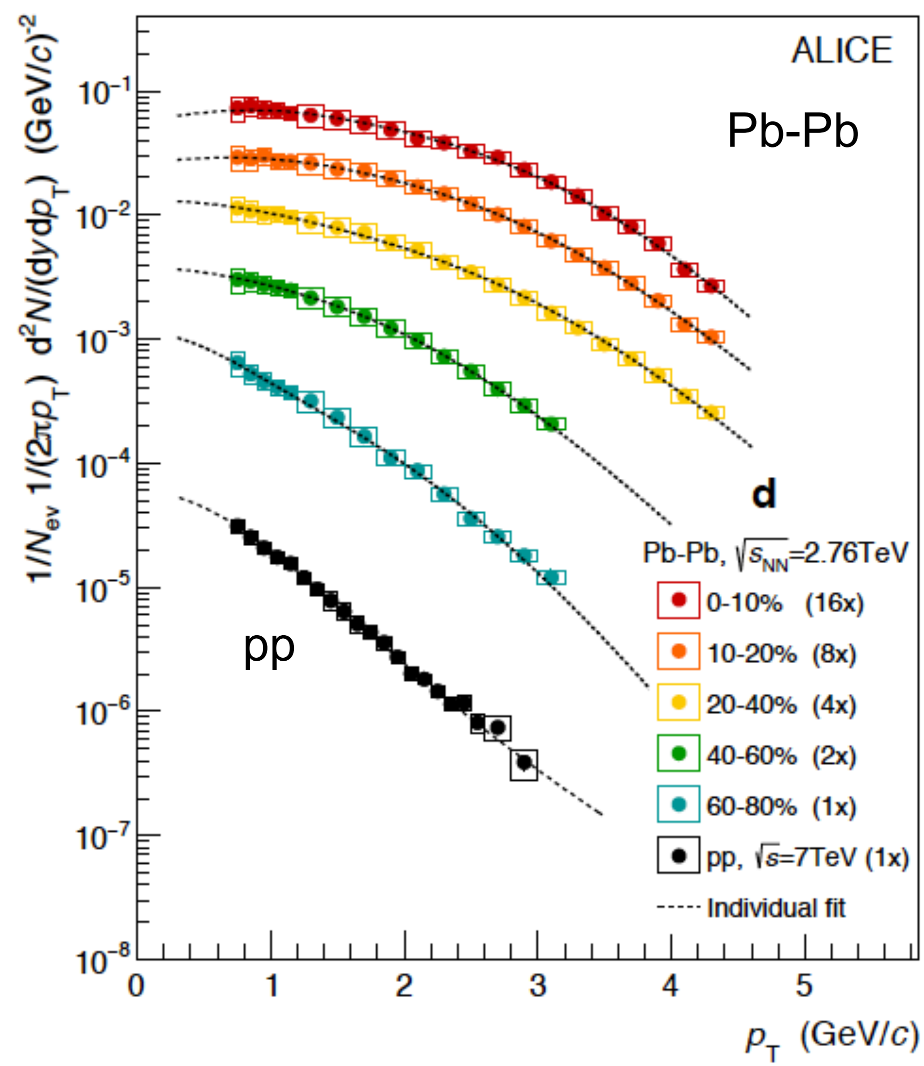

P
^{5}Be
^{6}Be
^{7}Be
53.22 d
^{8}Be
^{4}Li
^{5}Li
^{6}Li
^{7}Li
^{3}He
^{4}He
^{5}He
^{6}He
806.7 ms
^{1}H
^{2}H
^{3}H
12.32 a
^{4}H
^{5}H
$\bar{n}$
n
10.23min
N
$^{3}\bar{H}$
$^{2}\bar{H}$
$^{1}\bar{H}$
$^{4}\overline{He}$
$^{3}\overline{He}$

Deuterons

ALICE Collaboration: PRC 93, 024917 (2016)

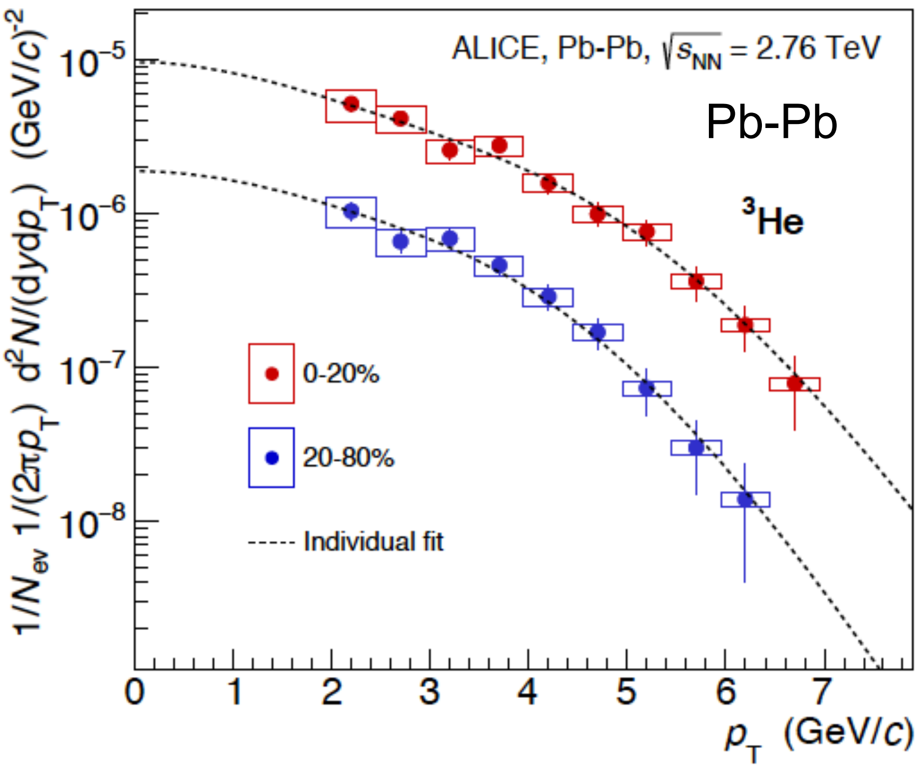
- Spectra become harder with increasing multiplicity in p-Pb and Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
- pp spectrum shows no sign of radial flow

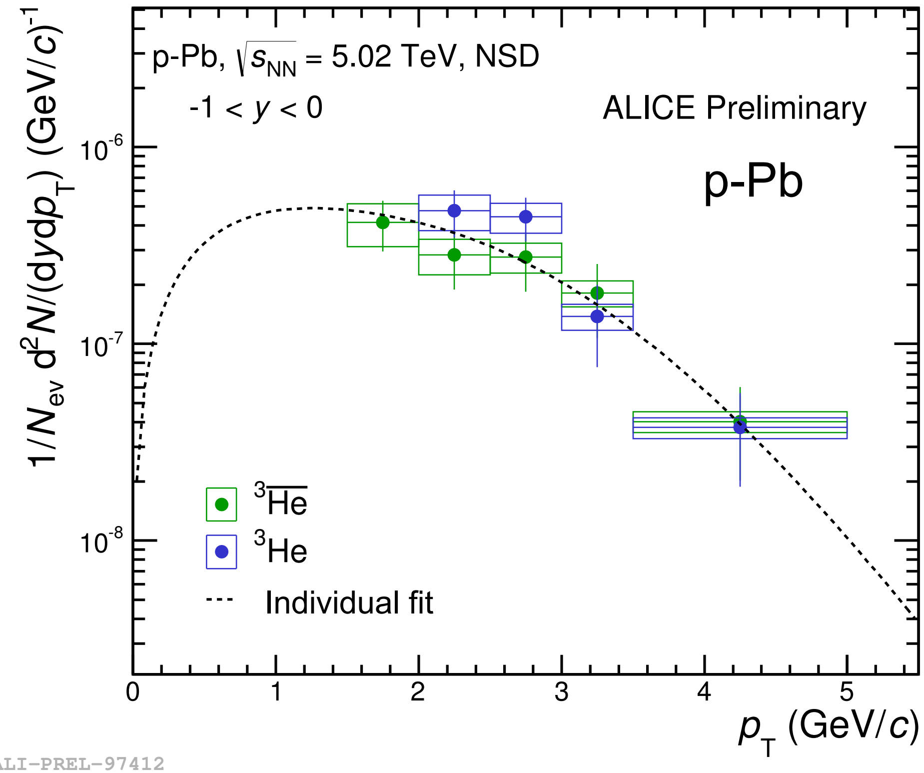




^{3}He

ALICE Collaboration: PRC 93, 024917 (2016)

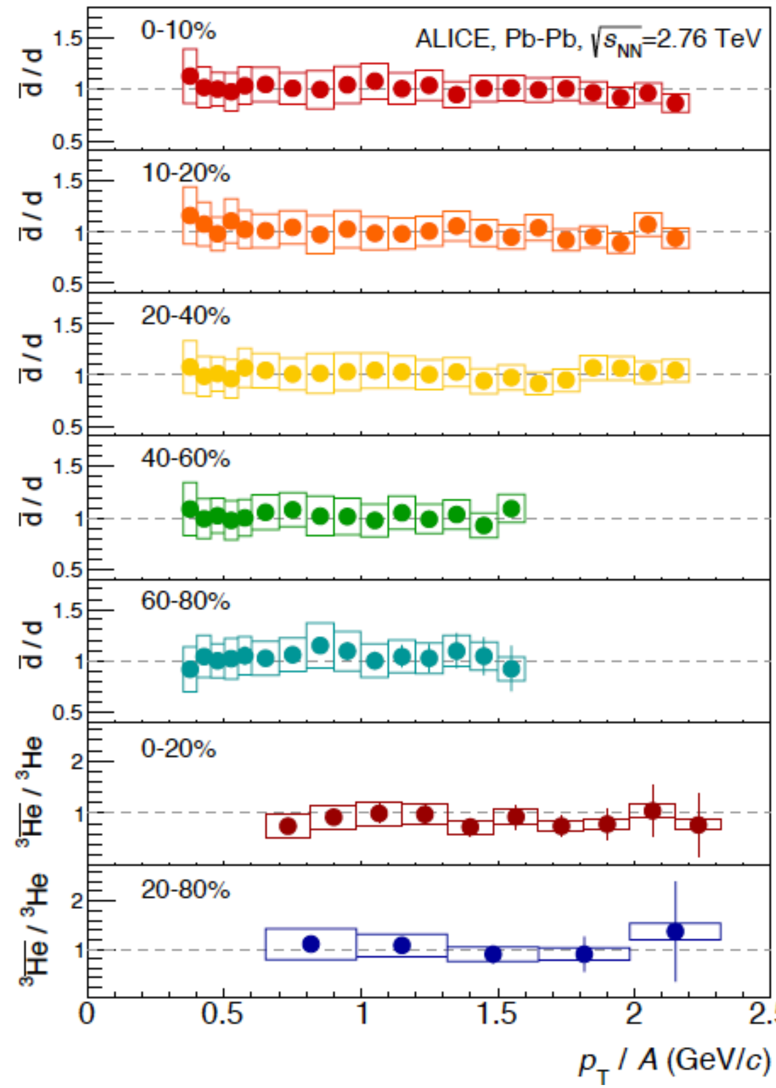




- Dashed curve represents individual Blast-Wave fits
- Spectrum obtained in 2 centrality classes in Pb-Pb and for NSD collisions in p-Pb

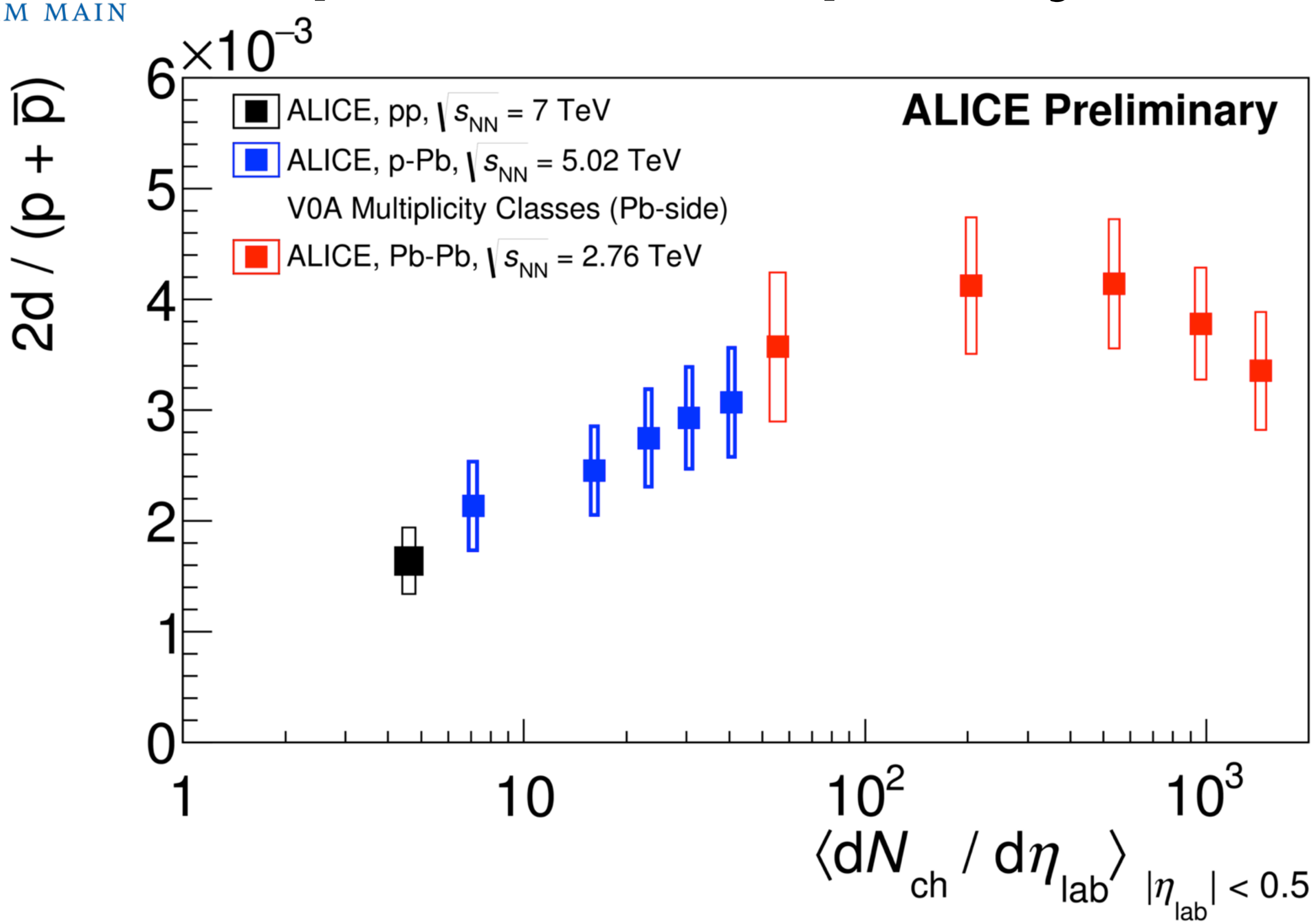
LHC: factory for anti-matter and matter

- 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
- Ratios are in agreement with the coalescence and thermal model expectations



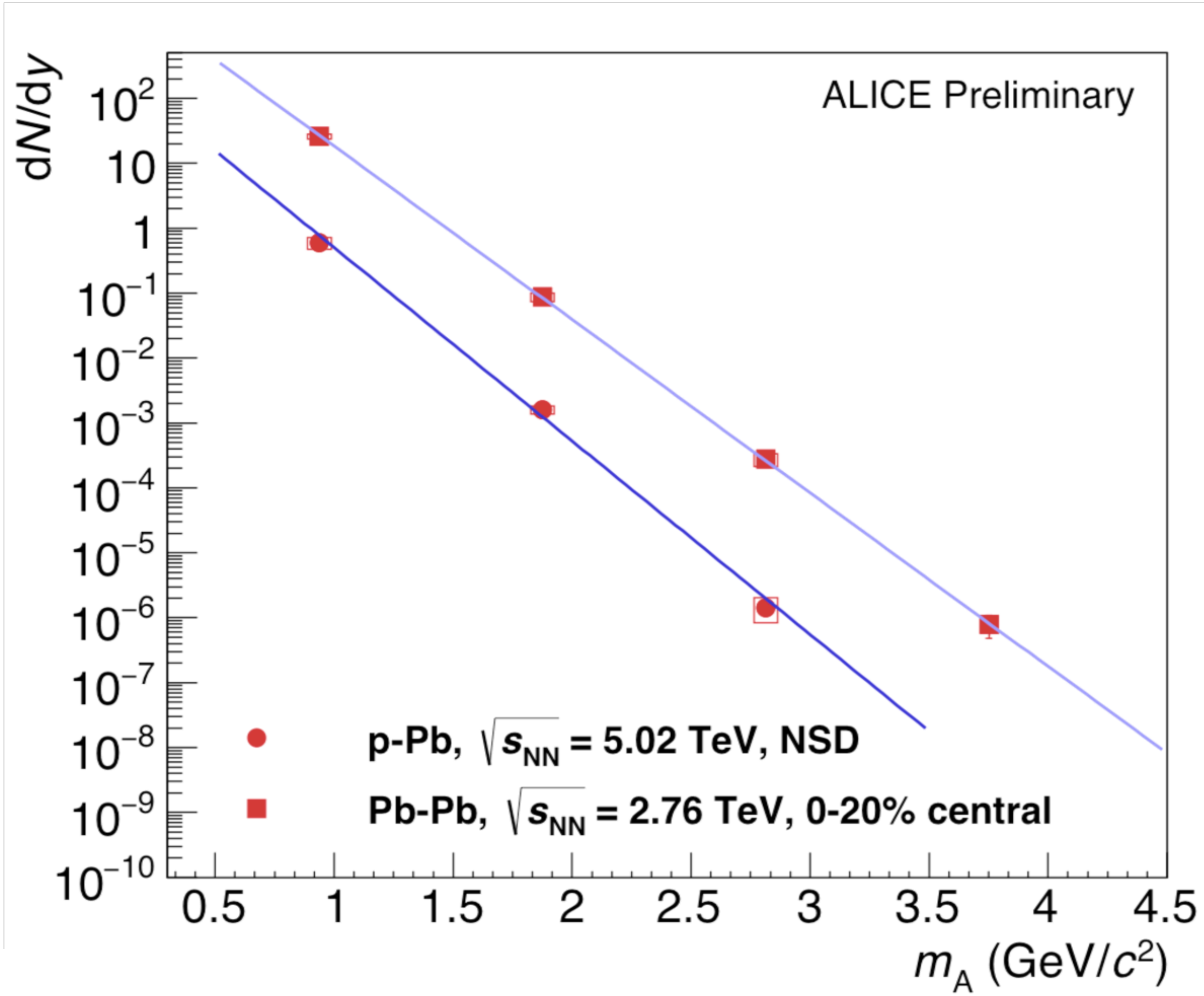
ALICE Collaboration: PRC 93, 024917 (2016)

d/p vs. multiplicity



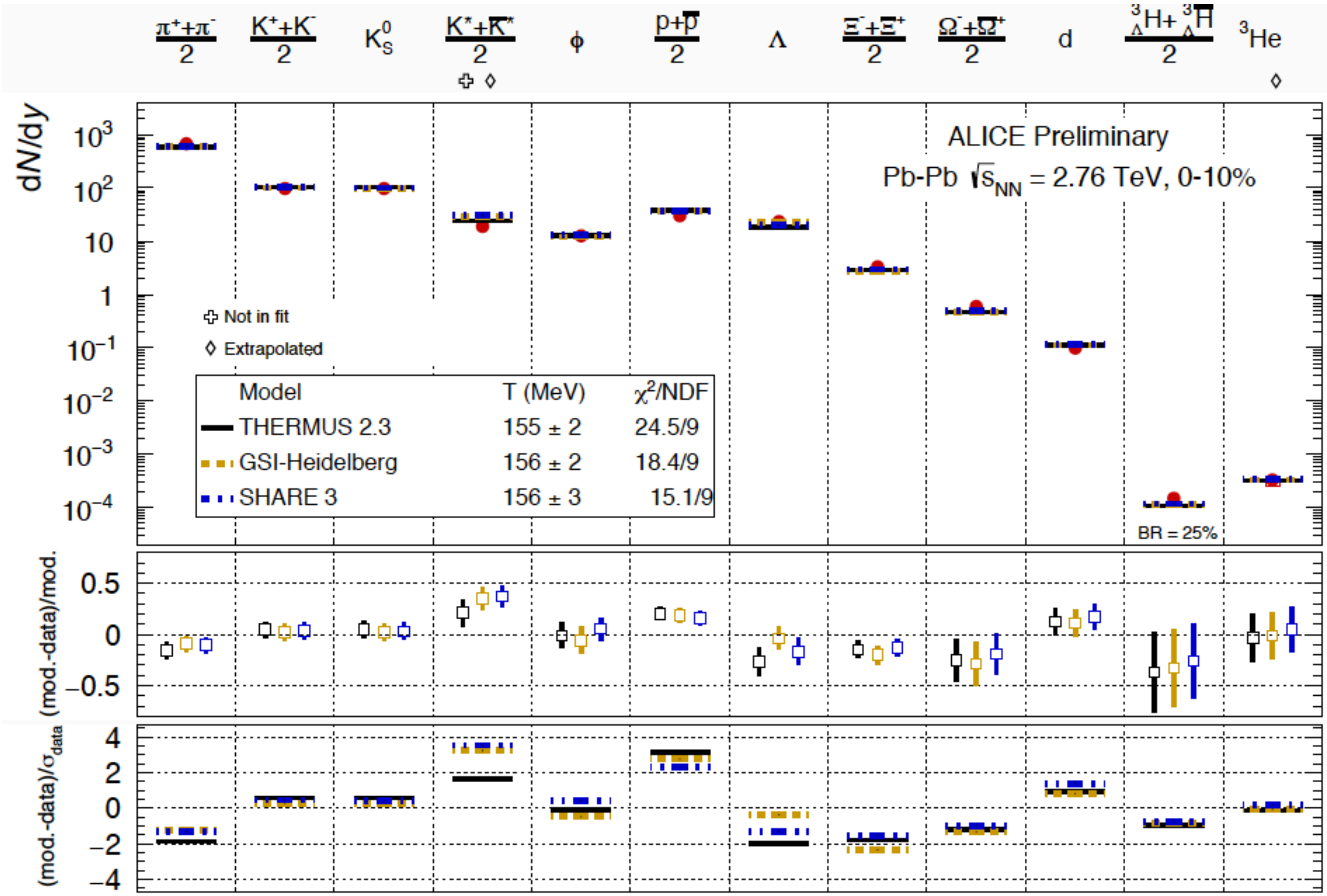
d/p ratio increases when going from pp to p-Pb, until it reaches the grand canonical thermal model value
(d/p=3×10^{-3} at 156 MeV)

Mass dependence



- Nuclei production yields follow an exponential decrease with mass as predicted by the thermal model
- In Pb-Pb the penalty factor for adding one baryon is ~300 and for p-Pb ~600

Thermal model fits

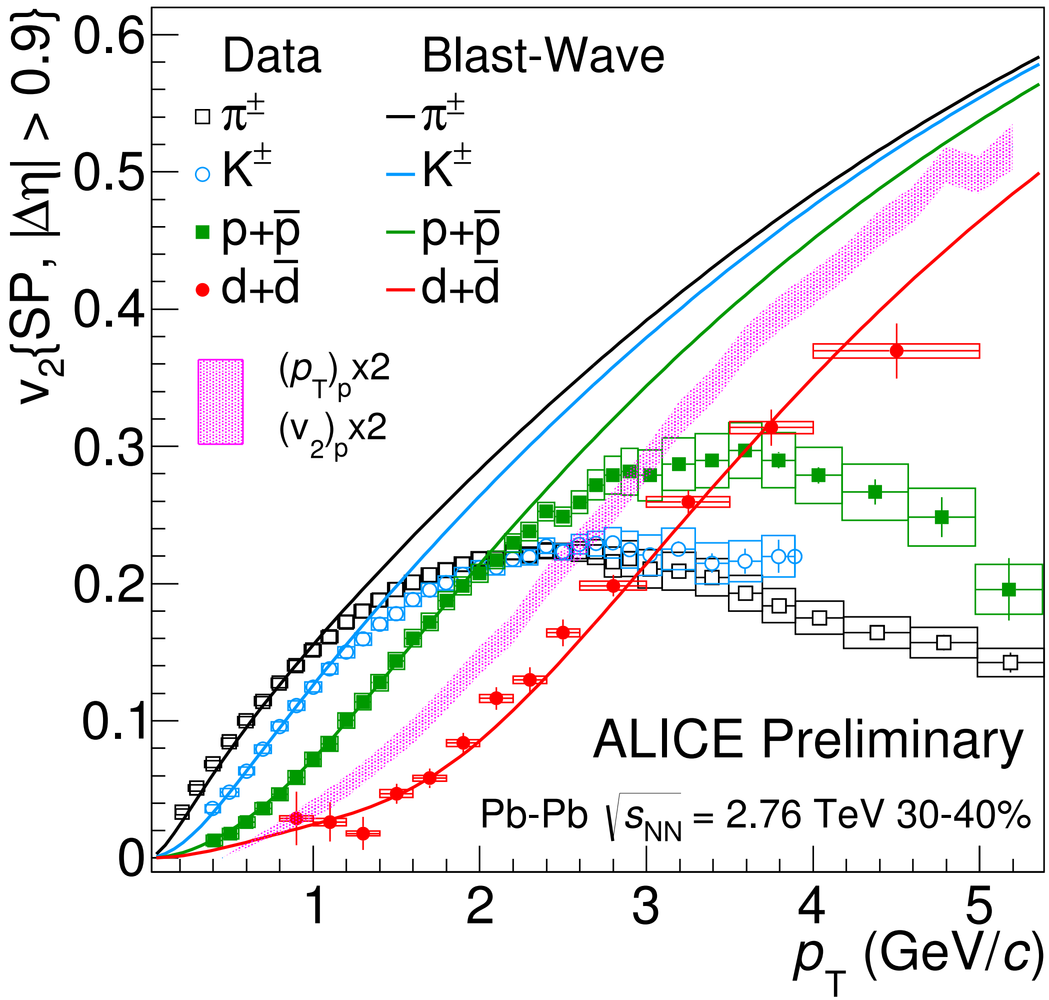


THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

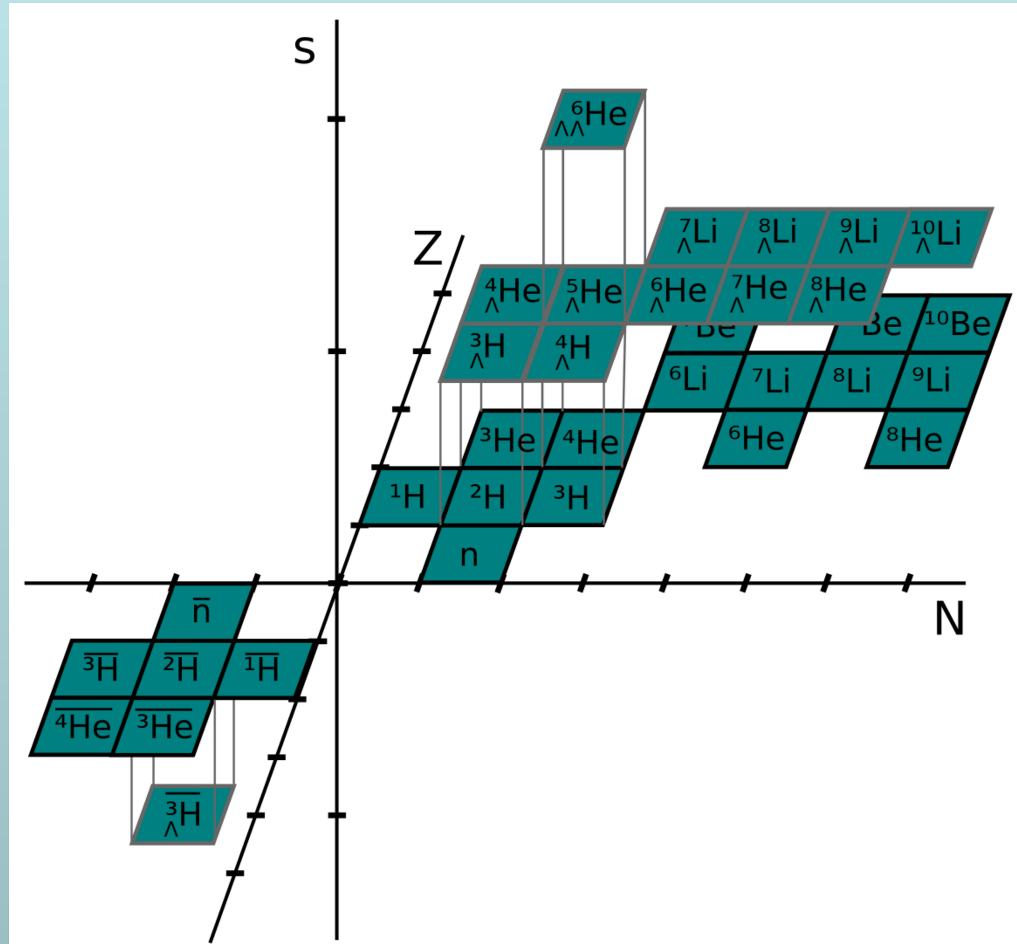
- Different models describe particle yields including light (hyper-)nuclei well with T_{ch} of about 156 MeV
- Including nuclei in the fit causes no significant change in T_{ch}

Deuteron flow

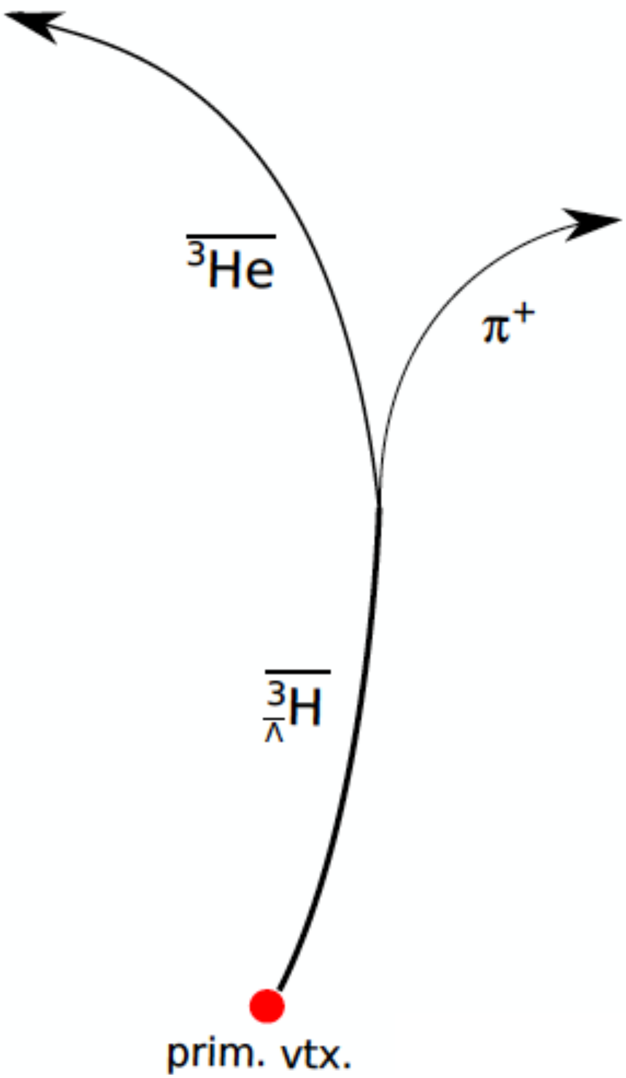
- Deuterons show a significant v_2
- Also the v_2 of deuterons follows the mass ordering expected from hydrodynamics
- A naive coalescence prediction is not able to reproduce the deuteron v_2
- A Blast-Wave prediction is able to describe the v_2 reasonably well



Hypernuclei



Hypertriton identification



Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)

→ rms radius: 10.3 fm

Decay modes:

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

$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \pi^{0}$$

$$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$$

$$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^{0}$$

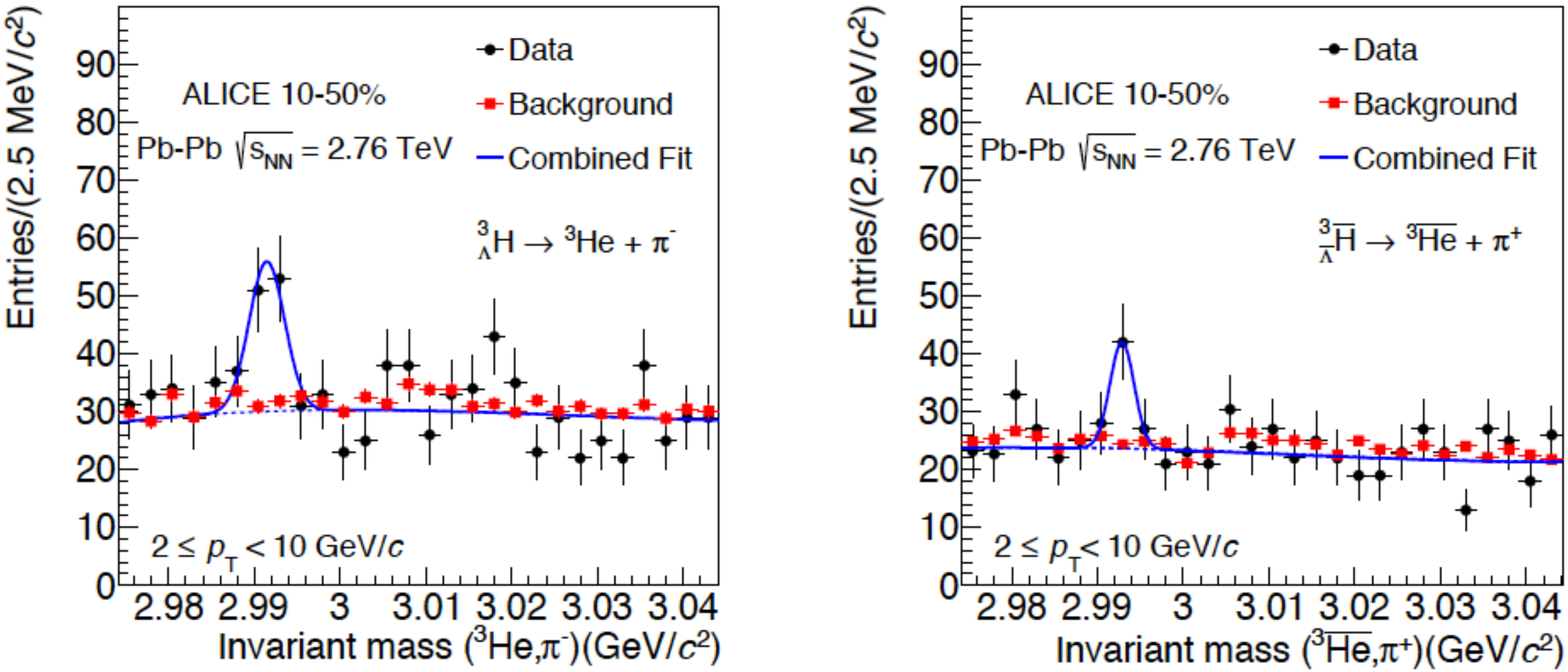
\+ anti-particles

→ Anti-hypertriton was first observed by the STAR Collaboration:

Science 328,58 (2010)

Hypertriton signal

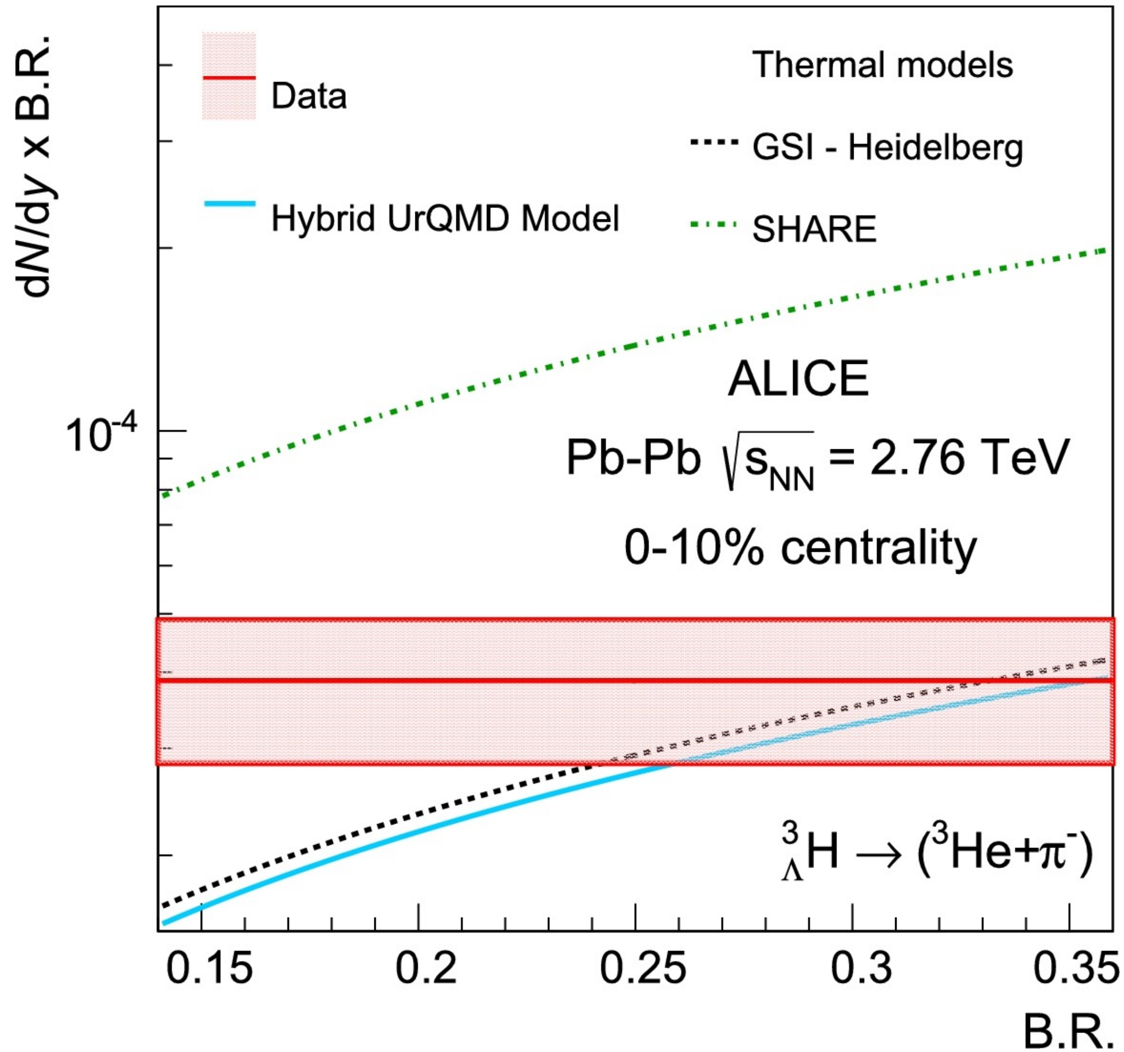
ALICE Collaboration: PLB 754, 360 (2016)



- Peaks are clearly visible for particle and anti-particle
  → Extracted yields in 3 p_T bins and 2 centrality classes

Hypertriton yield vs. B.R.

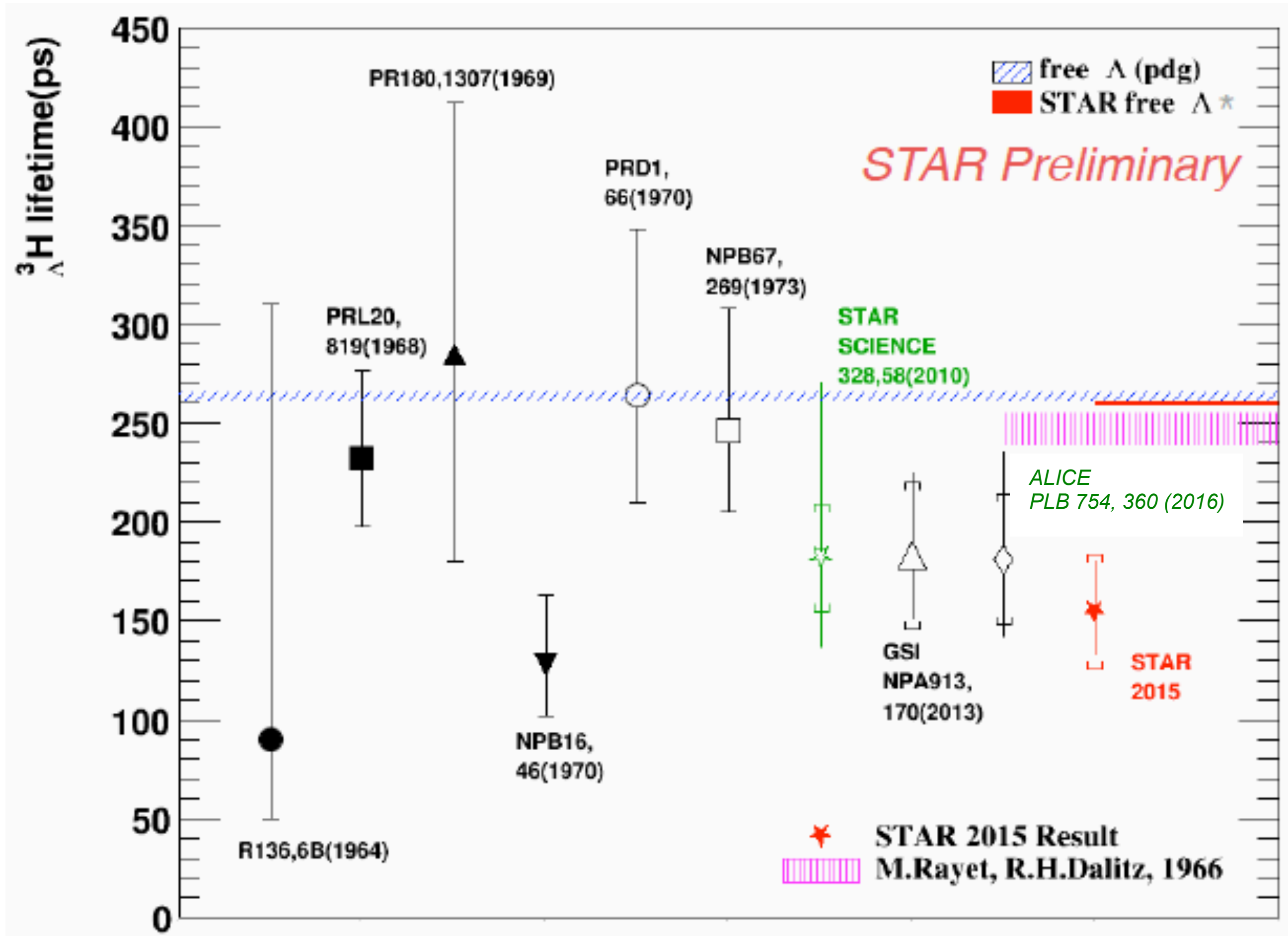
ALICE Collaboration: PLB 754, 360 (2016)



- The hypertriton branching ratio is not well known, only constrained by the ratio between all charged channels containing a pion
- Theory which prefers a value of around 25% gives a lifetime of the hypertriton close to the one of the free Λ

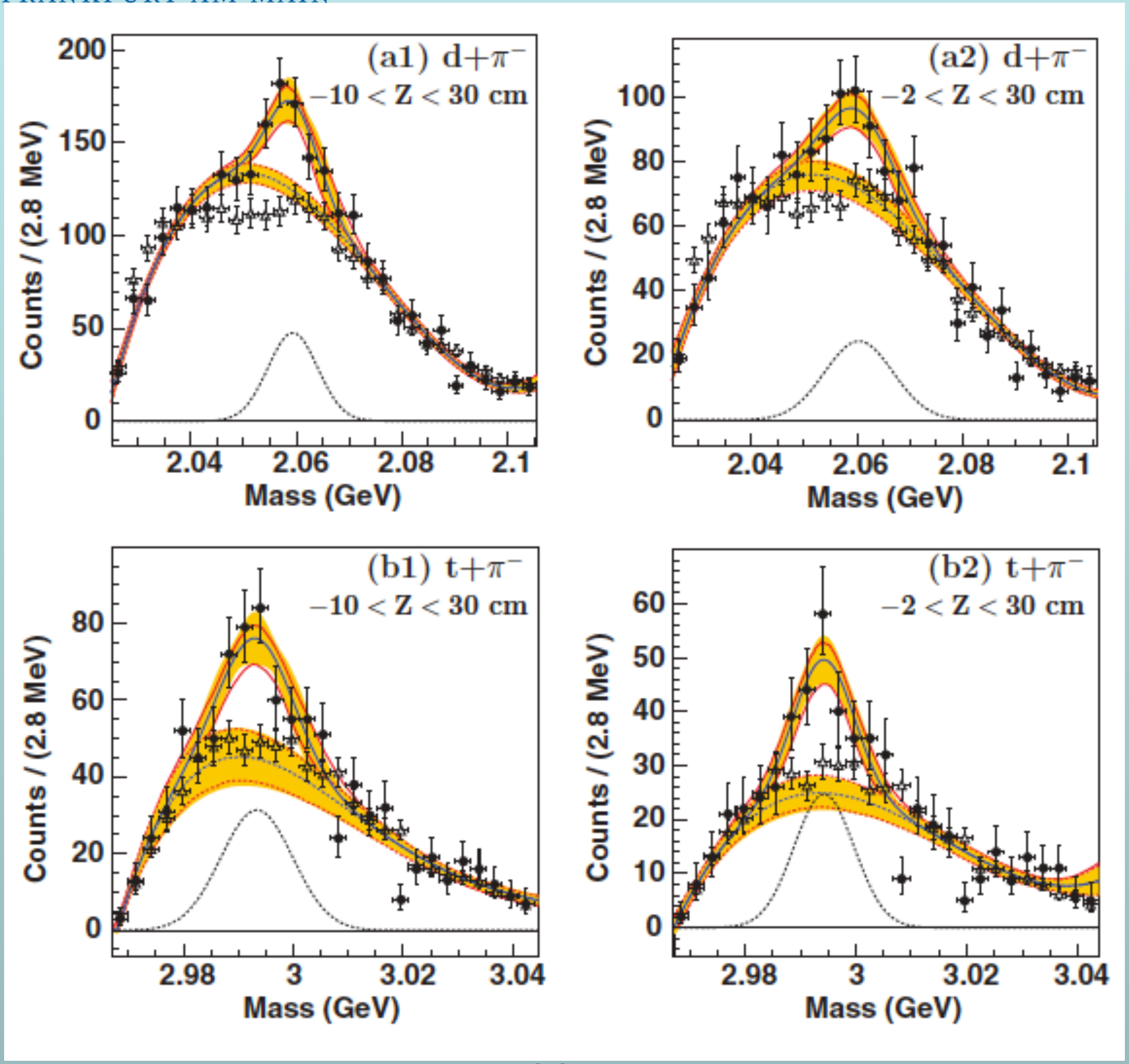
Hypertriton „puzzle"

- Recently extracted lifetimes significantly below the free Λ lifetime
  - Not expected from theory!
  - Data before 2010 from emulsions
  - Currently most precise data coming from heavy-ion collisions
  - Better precision expected from larger data samples to be taken



As shown by Yifei Xu at HYP2015 conference

Exotica



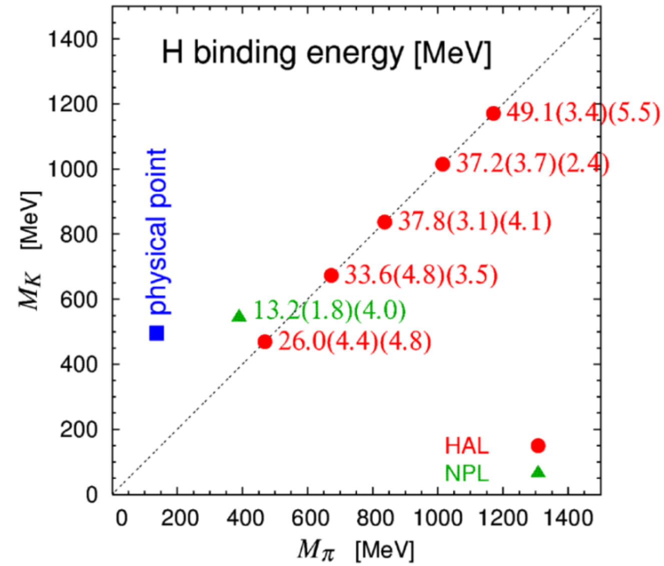
HypHI Collaboration observed signals in the t+π and d+π invariant mass distributions

C. Rappold et al., PRC 88, 041001 (2013)

H-Dibaryon

- Hypothetical bound state of *uuddss* (ΛΛ)
- First predicted by Jaffe in a bag model calculation (*PRL 195, 38 +617 (1977)*)
- Recent lattice calculations suggest *(Inoue et al., PRL 106, 162001 (2011) and Beane et al., PRL 106, 162002 (2011))* a bound state (20-50 MeV/c^2 or 13 MeV/c^2)
- *Shanahan et al., PRL 107, 092004 (2011) and Haidenbauer, Meißner, PLB 706, 100 (2011)* made chiral extrapolation to a physical pion mass and got as result:
  - the H is unbound by 13±14 MeV/c^2 or lies close to the Ξp threshold

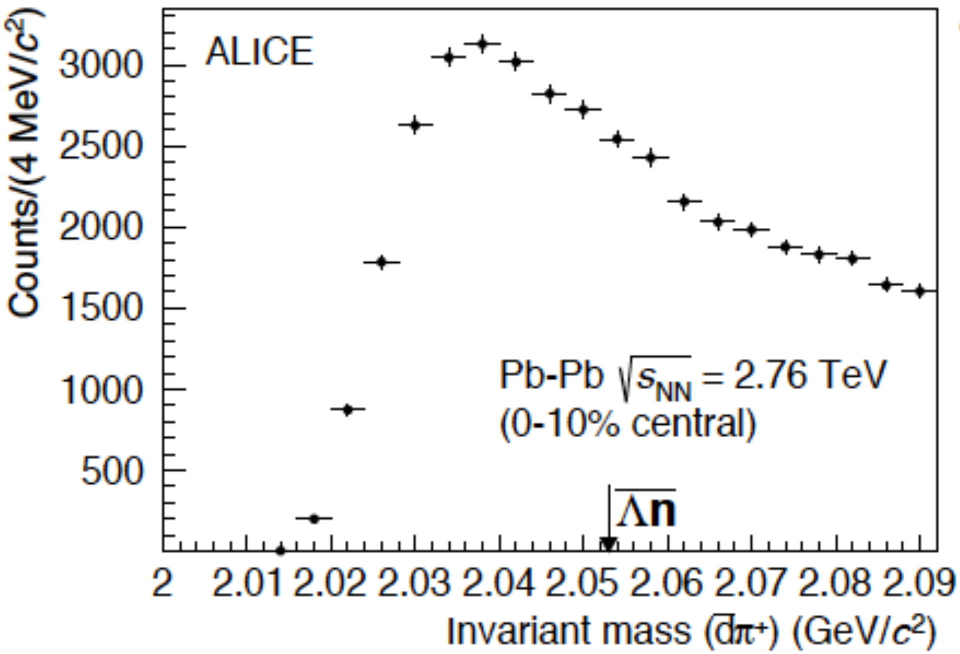
→ Renewed interest in experimental searches

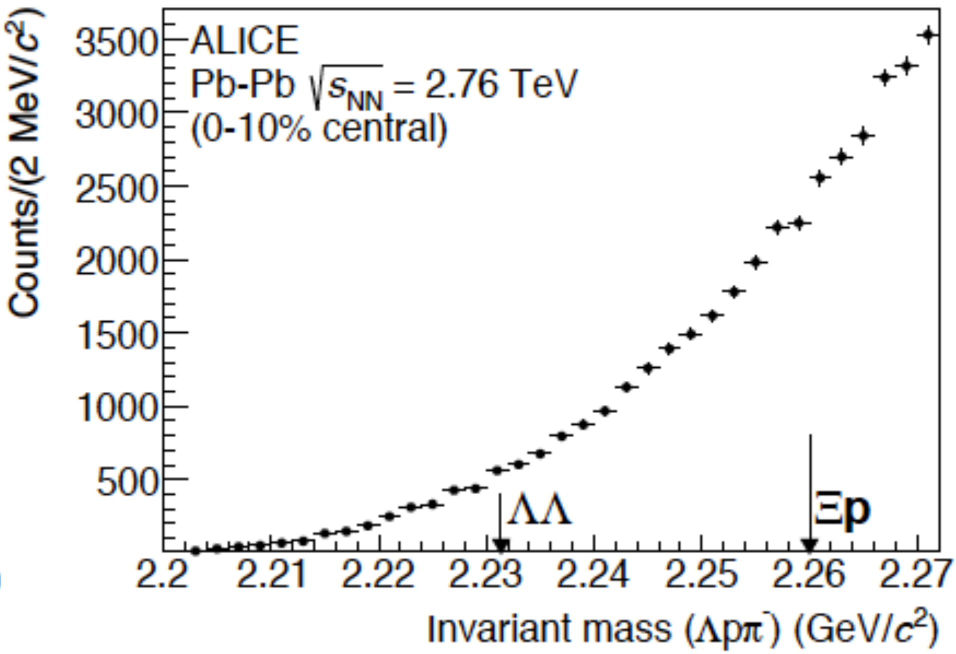


T. Inoue, private communication

Searches for bound states

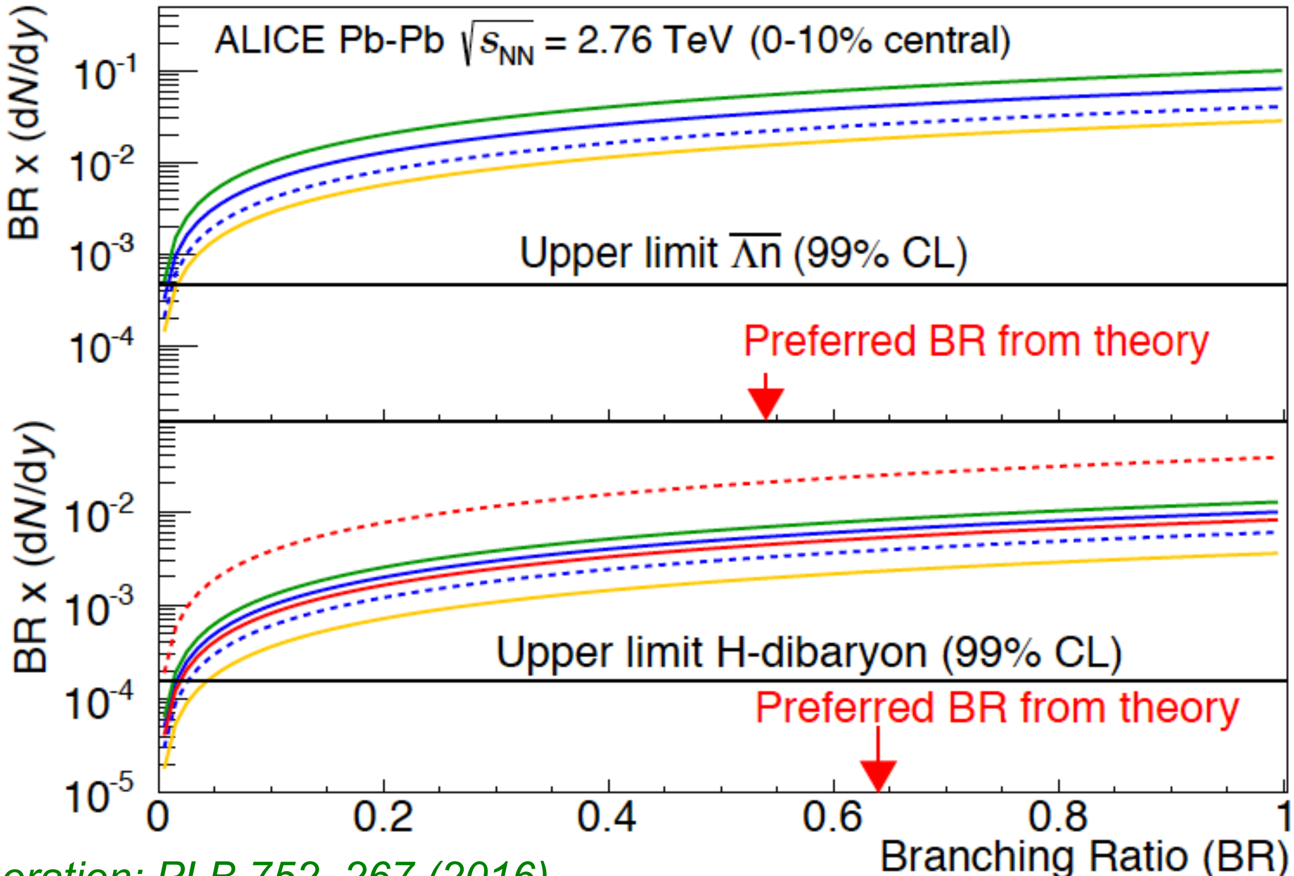
ALICE Collaboration: PLB 752, 267 (2016)





Invariant mass analyses of the two hypothetical particles lead to no visible signal → Upper limits set

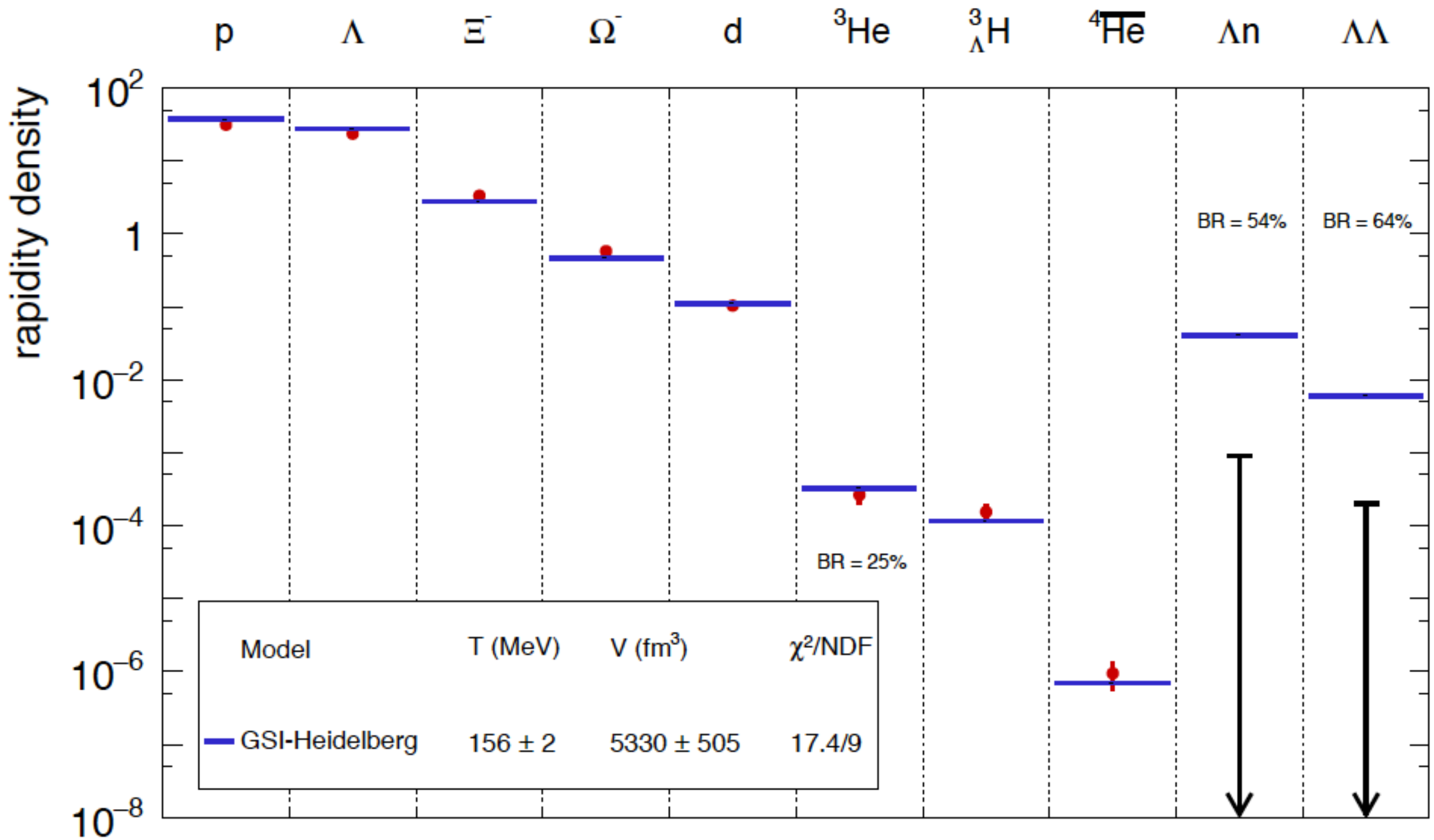
Dependence on BR



ALICE Collaboration: PLB 752, 267 (2016)

If the Λ lifetime is assumed, the upper limits are away from the expectations, as long as the branching ratio stays reasonable

Comparison with fit

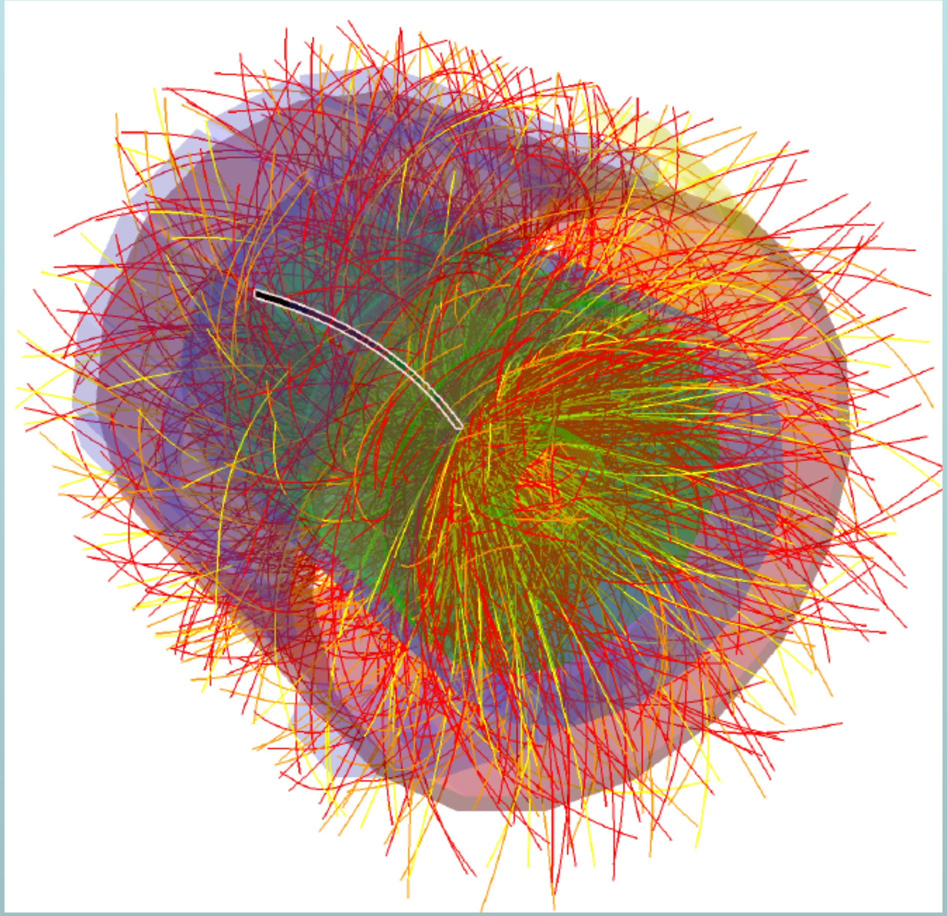


Simplified plot, from the CERN Courier (September 2015)

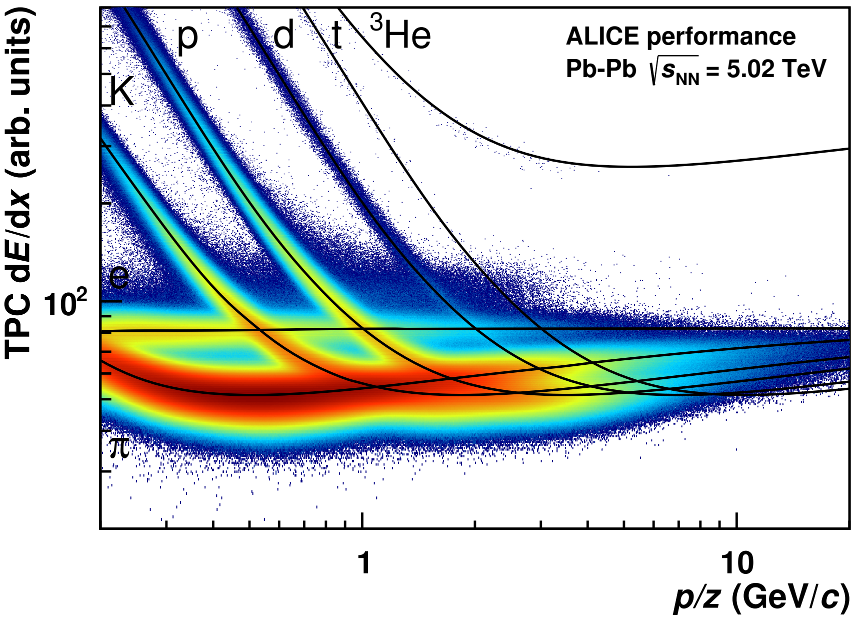
Hypertriton (B_Λ: 130 keV) and Anti-Alpha (B/A: 7MeV) yields fit well with the thermal model expectations

→ Upper limits of ΛΛ and Λn are factors of >25 away from the model

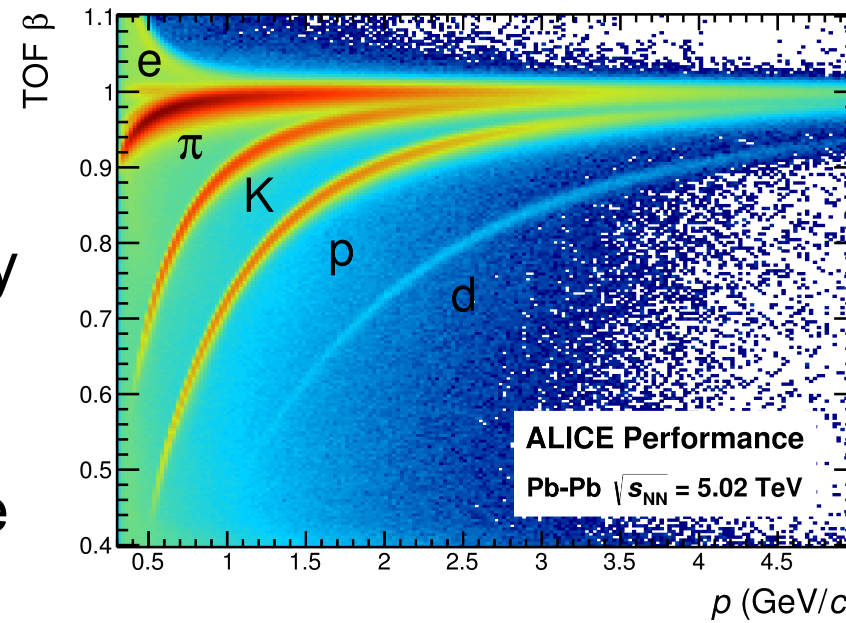
Outlook



Outlook: Run 2



- Run 2 of the LHC has started in 2015 and for Pb-Pb collisions ~ factor 10 increase expected in statistics



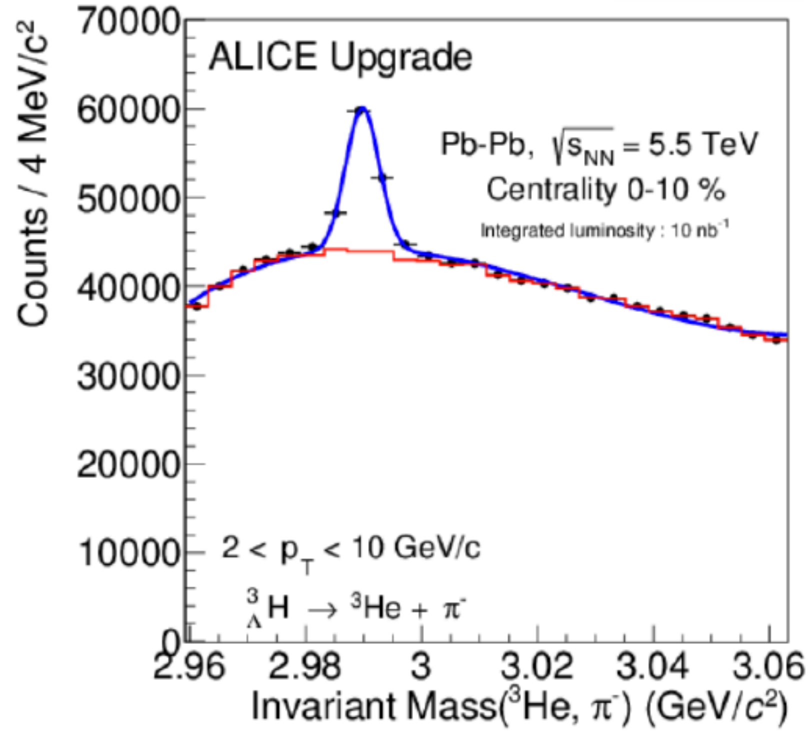
- Performance shown here only for a small fraction (~3M MB events)

→ Light nuclei are clearly visible

→ Interesting results ahead

Expectations

- Run 3 & Run 4 of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)
- Upgraded ALICE detector will be able to cope with the high luminosity
- TPC Upgrade: GEMs for continous readout
- ITS Upgrade: less material budget and more precise tracking for the identification of hyper-nuclei
- Physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4



ITS Upgrade TDR: J. Phys. G 41, 087002 (2014)

State	dN/dy	B.R.	$\langle Acc \times \epsilon \rangle$	Yield
${}^{3}_{\Lambda}H$	1×10^{-4}	25%	11 %	44000
${}^{4}_{\Lambda}H$	2×10^{-7}	50%	7 %	110
${}^{4}_{\Lambda}He$	2×10^{-7}	32%	8 %	130

Conclusion

- ALICE@LHC is well suited to study light (anti-)(hyper-)nuclei and perform searches for exotic bound states (A<5)
- Copious production of loosely bound objects measured by ALICE as predicted by the thermal model
- Thermal and coalescence models describe the (anti-)(hyper-)nuclei data rather well
- Hypertriton lifetime measurements show a significant deviation from the free Λ lifetime
- Upper limits for searched exotica are 25 times below the thermal model expectation
- New data can be expected from the LHC on the presented topics in the next years

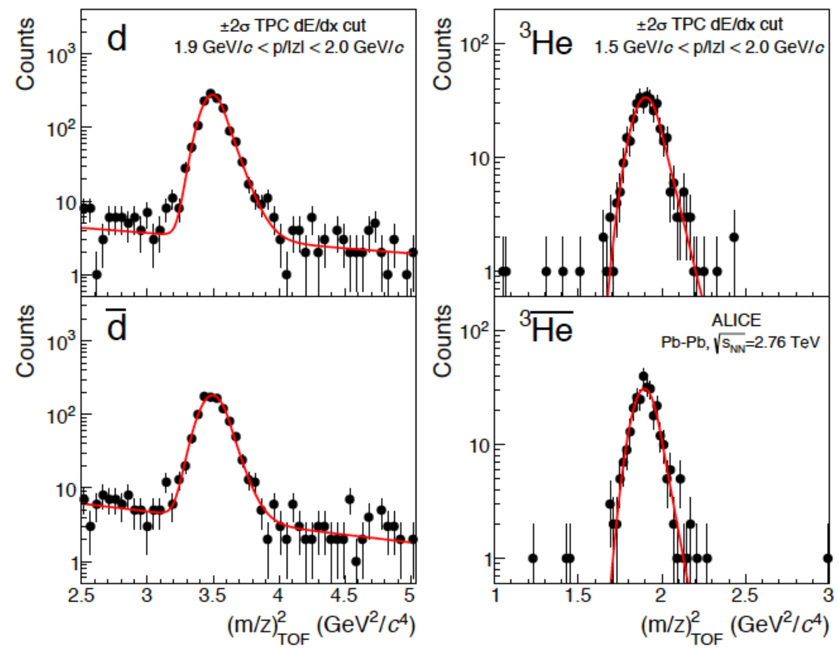
Backup

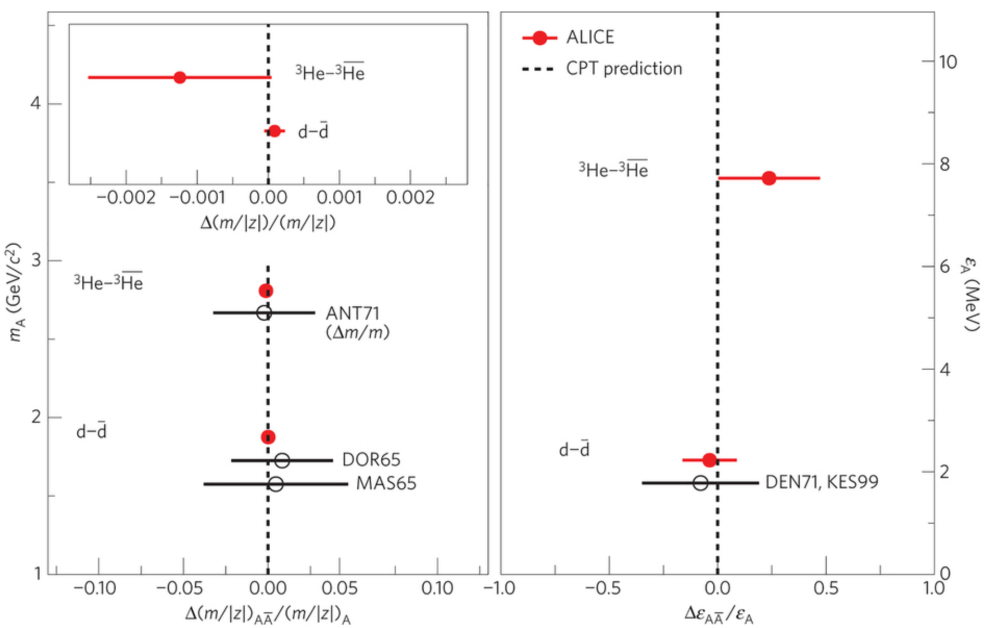
Precision mass measurement

ALICE Collaboration: Nature Phys. 11, 811 (2015)

- 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

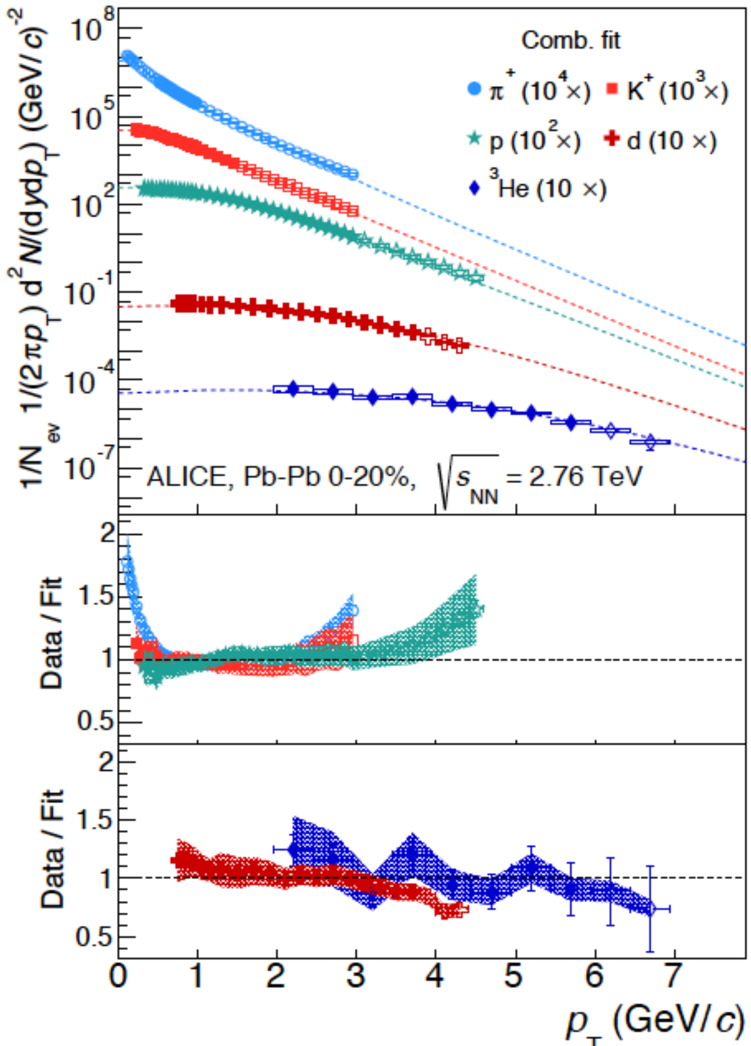
➜ Measurement confirms the CPT invariance for light nuclei.

Combined Blast-Wave fit

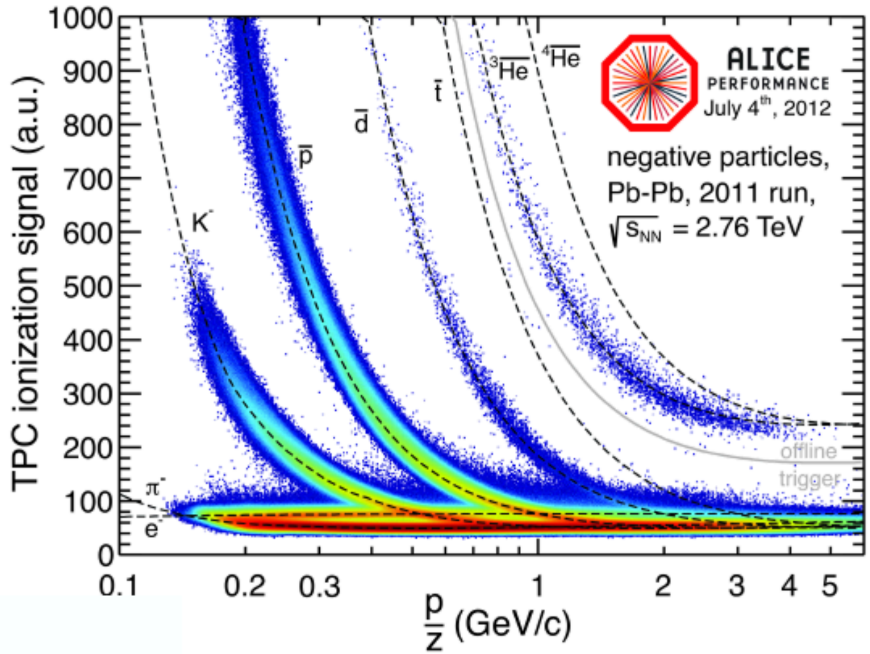
ALICE Collaboration: J. Adam et al., PRC 93, 024917 (2016)

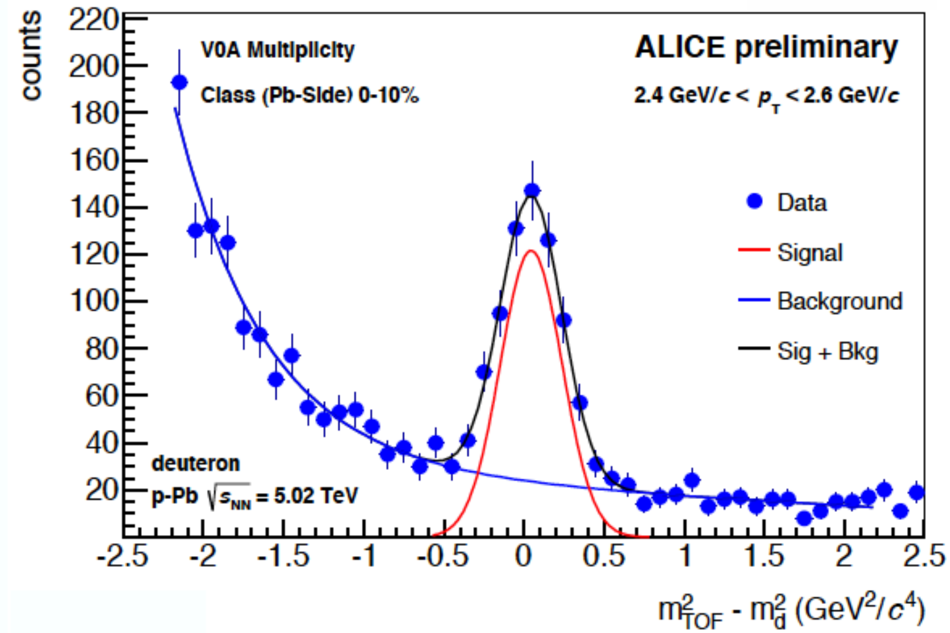
Simultaneous Blast-Wave fit of π^+, K^+, p, d and ^{3}He spectra for central Pb-Pb collisions leads to values for $<\beta>$ and T_{kin} close to those obtained when only π,K,p are used

All particles are described rather well with this simultaneous fit



Particle Identification





Low momenta:

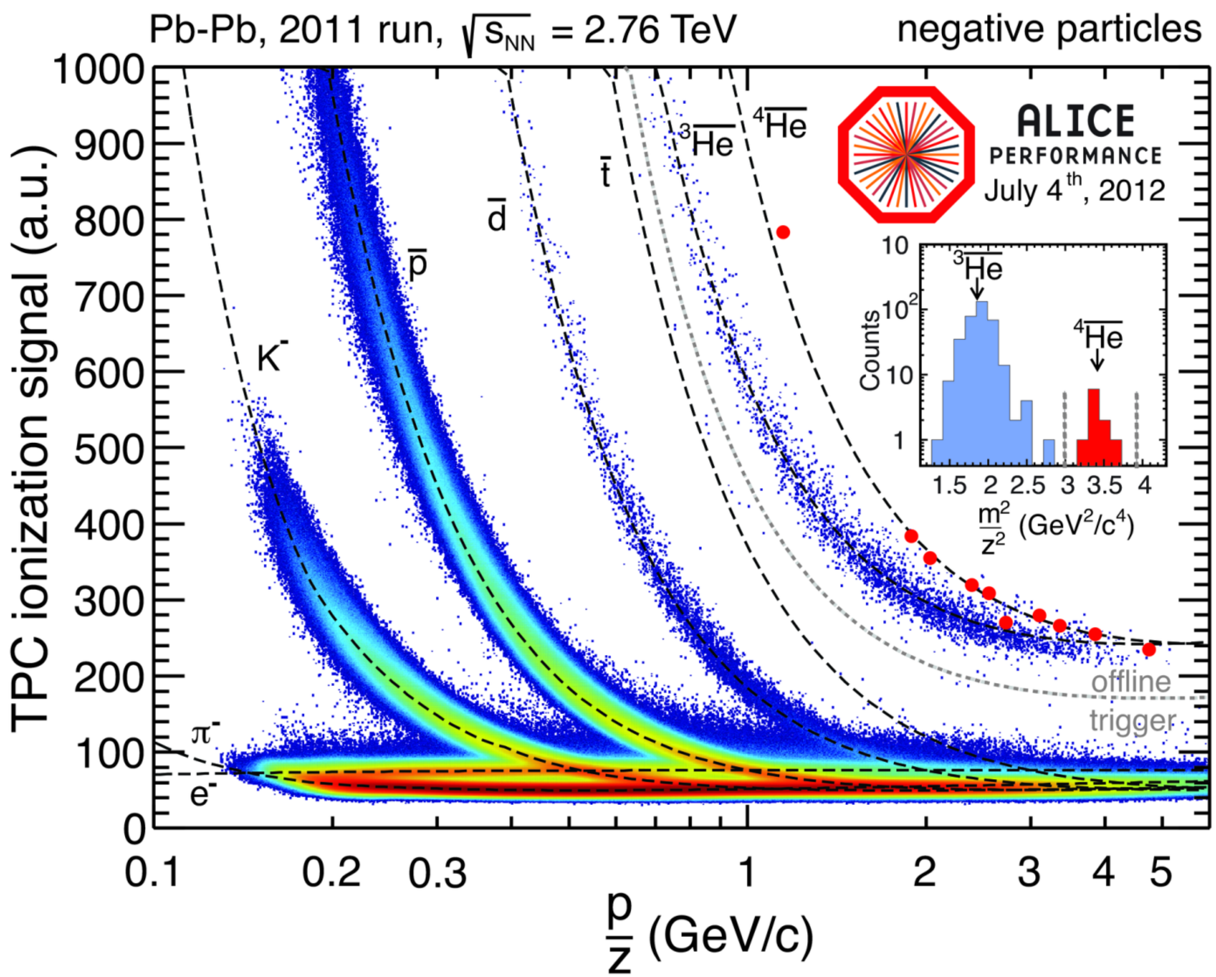
Nuclei are identified using the d*E*/d*x* measurement in the Time Projection Chamber (TPC)

Higher momenta:

Velocity measurement with the Time-of-Flight (TOF) detector is used to calculate the m^2 distribution

Anti-Alpha

For the full statistics of 2011 ALICE identified 10 Anti-Alphas using TPC and TOF



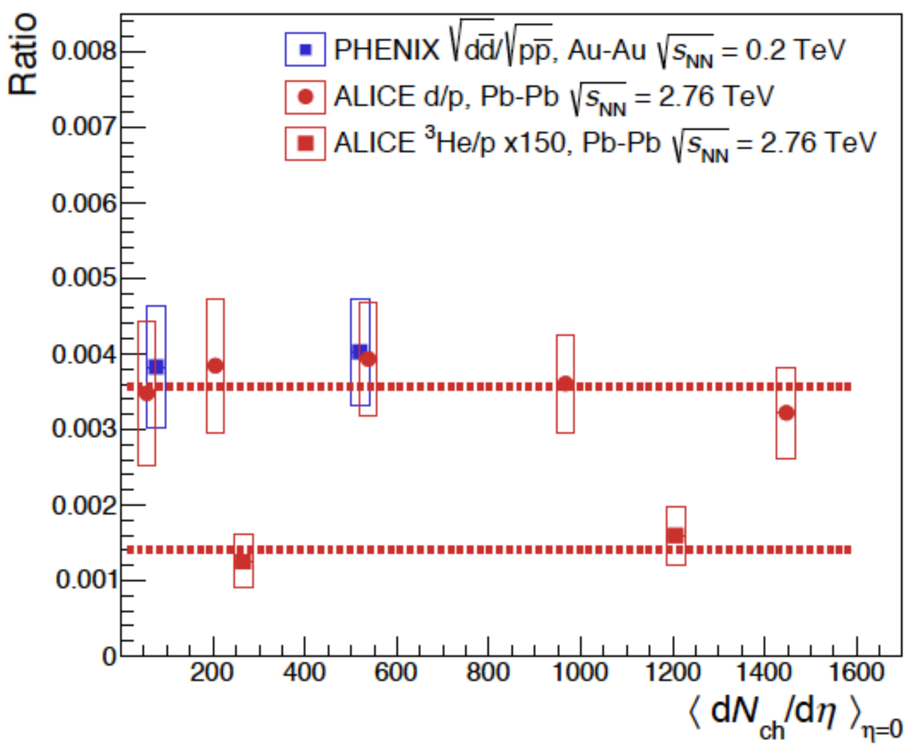
STAR observed the Anti-Alpha in 2010:

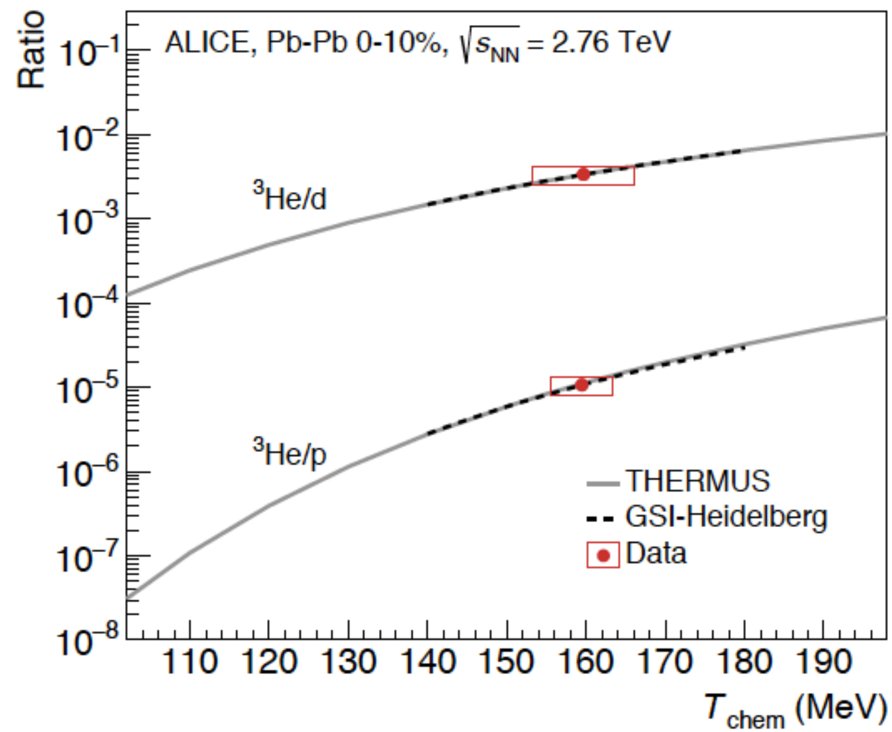
Nature 473, 353 (2011)

Ratios between species

ALICE Collaboration: J. Adam et al., PRC 93, 024917 (2016)

Extracted ratios agree with the thermal model values





d/p ratio agrees well with the „averaged" measurement at RHIC

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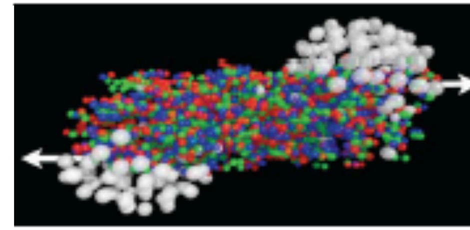
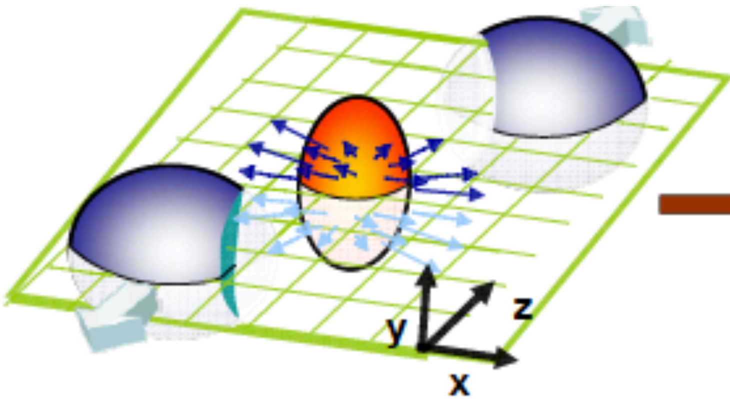
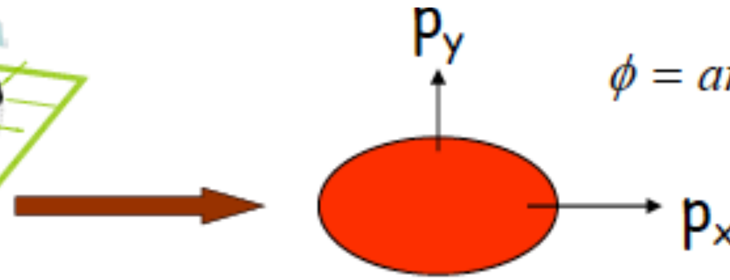
Elliptic flow







$$\phi = arc\ \tan \frac{p_y}{p_x}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial coordinate-space anisotropy

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

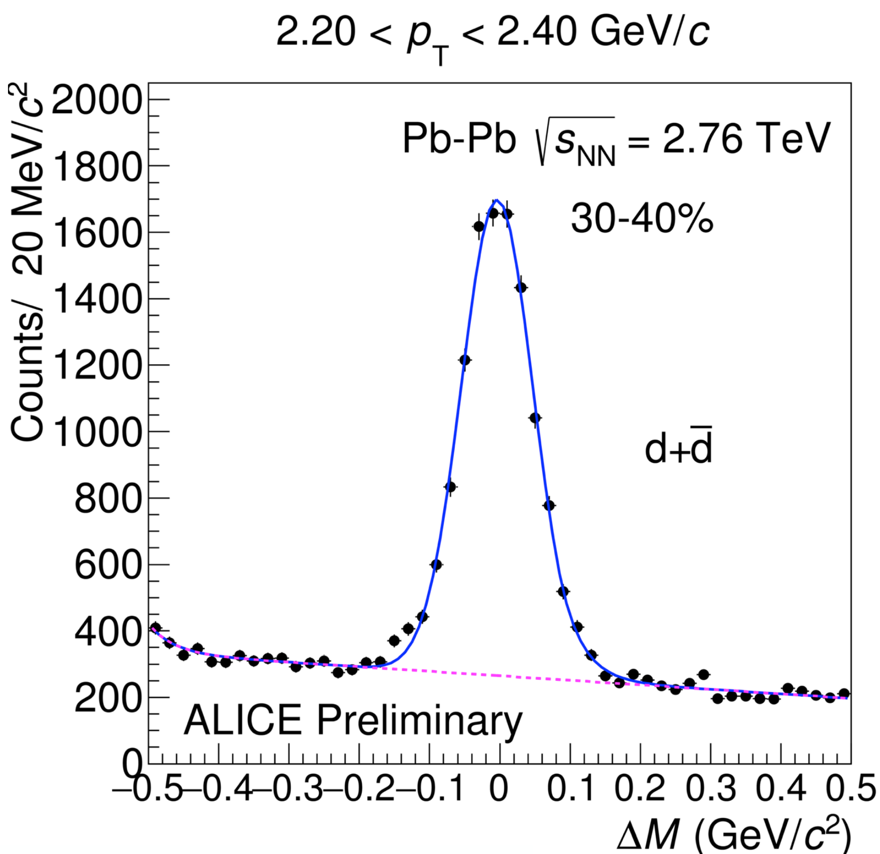
Final momentum-space anisotropy

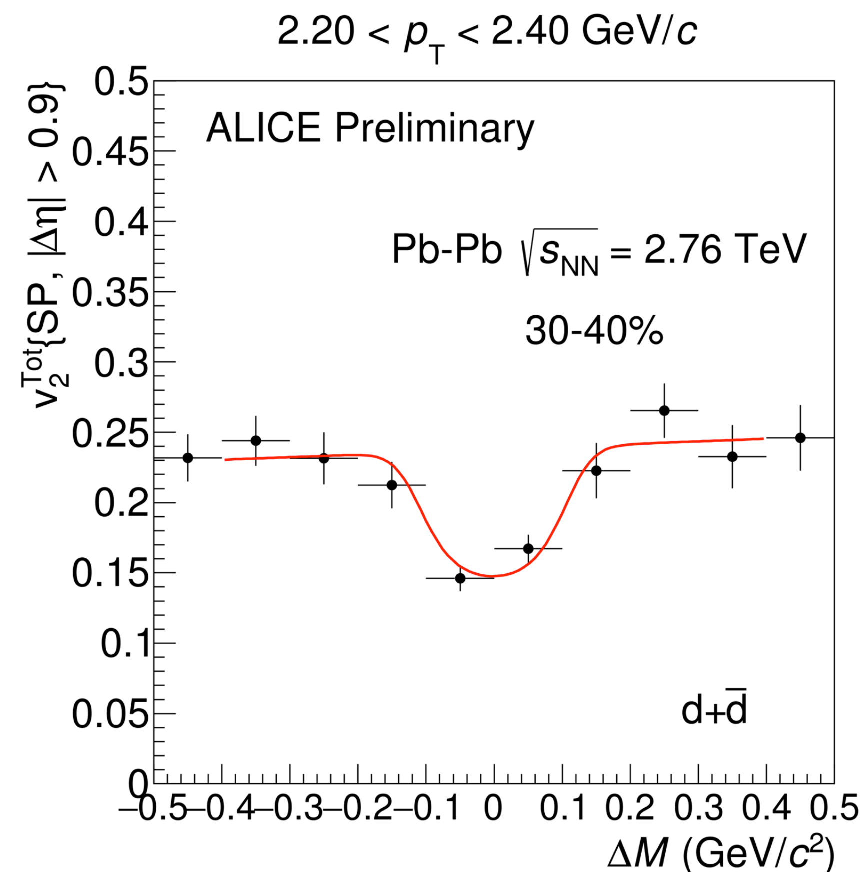
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_R)] + 2v_4 \cos[4(\phi - \Psi_R)] + \ldots$$

Elliptic term

Anisotropy self-quenches, so v_2 is sensitive to early times

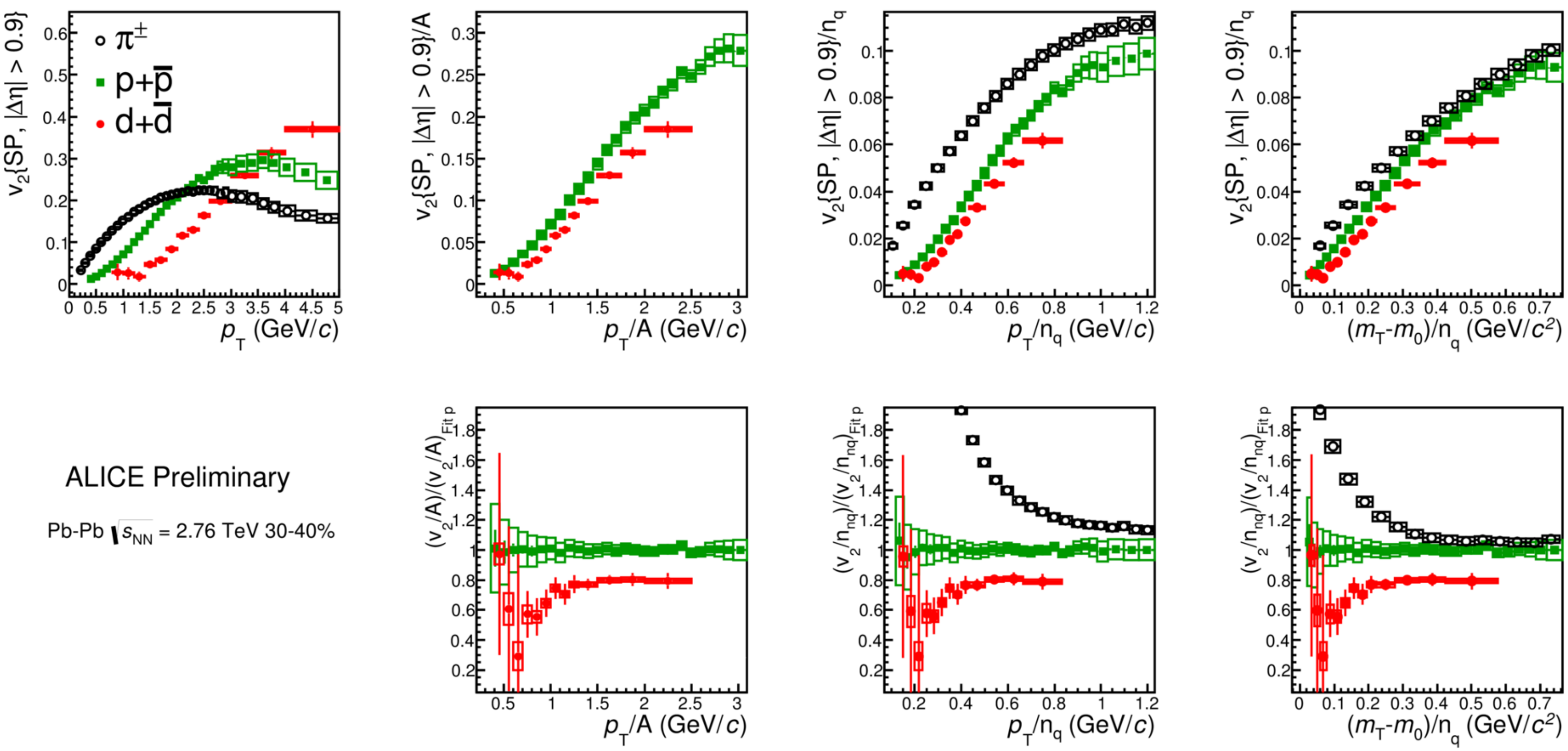
Elliptic flow



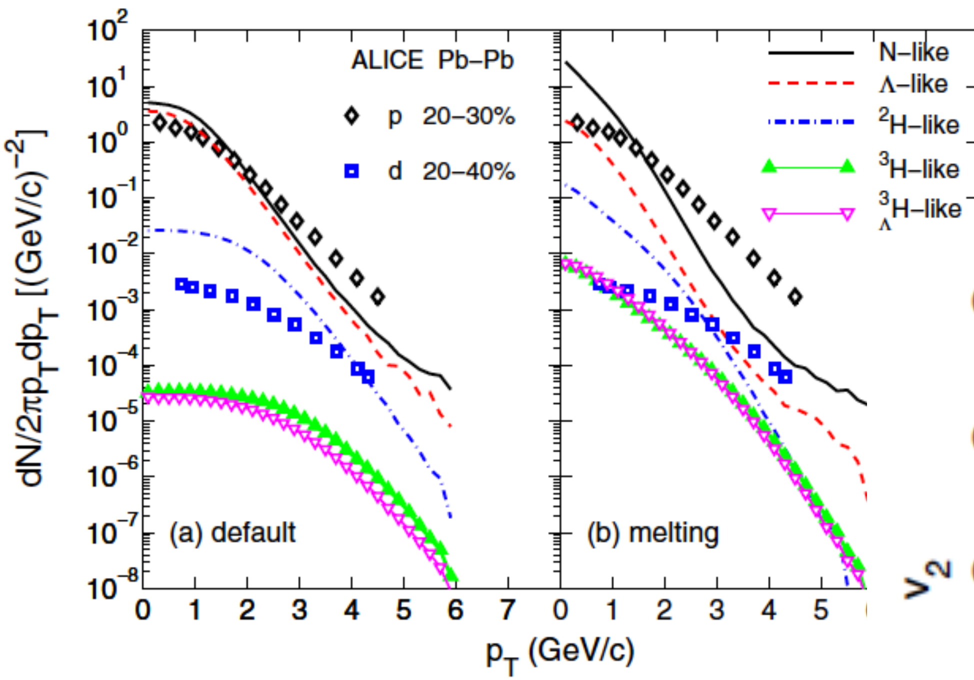


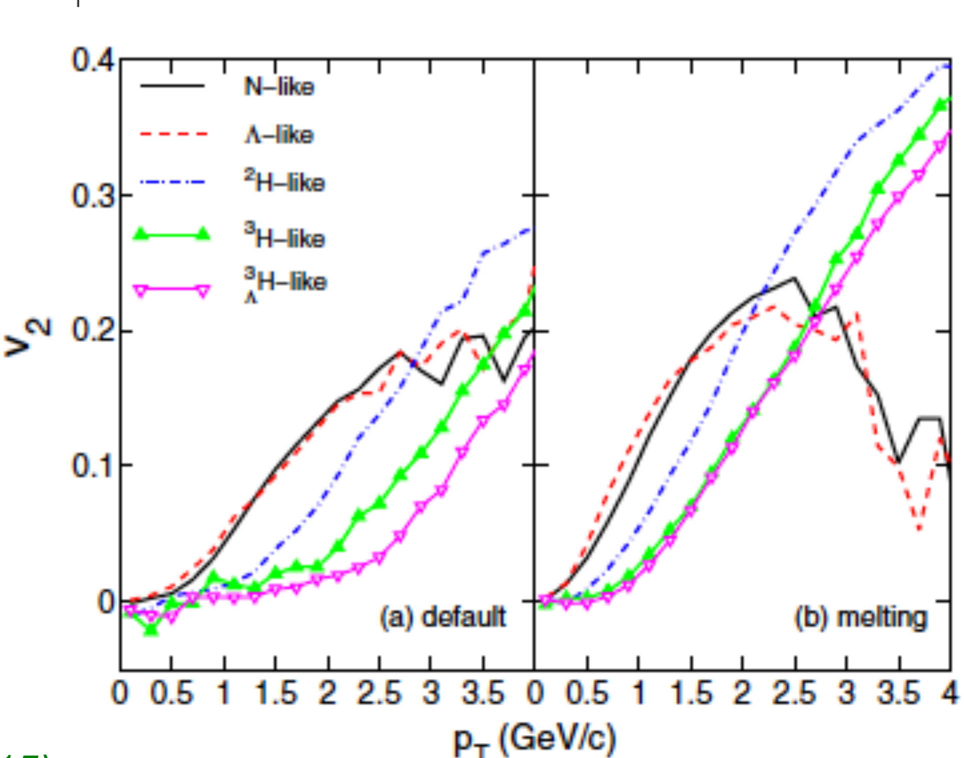
$$v_n\{SP\} = \frac{\langle u_{n,i}(p_T,\eta) \cdot \frac{Q_n^*}{M} \rangle}{\sqrt{\langle \frac{Q^*_{n,A}}{M_A} \cdot \frac{Q^*_{n,B}}{M_B} \rangle}}$$

Elliptic flow



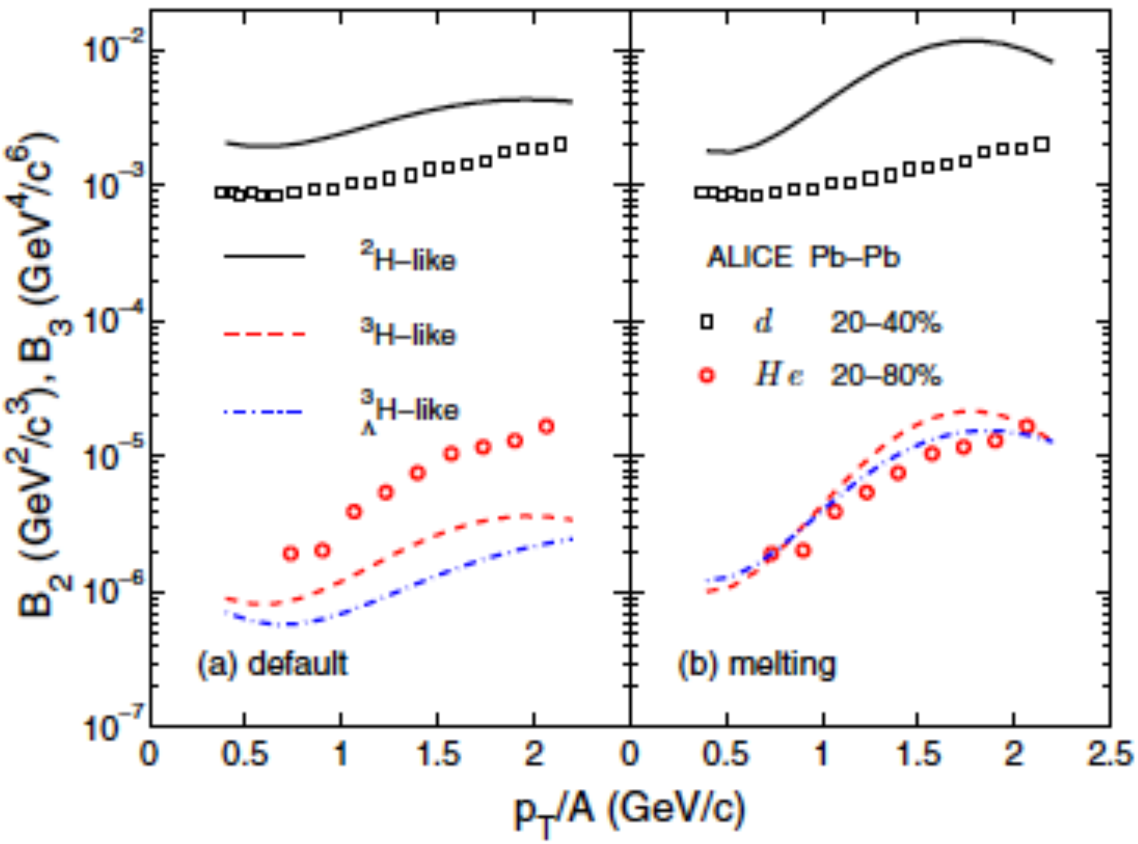
Elliptic flow





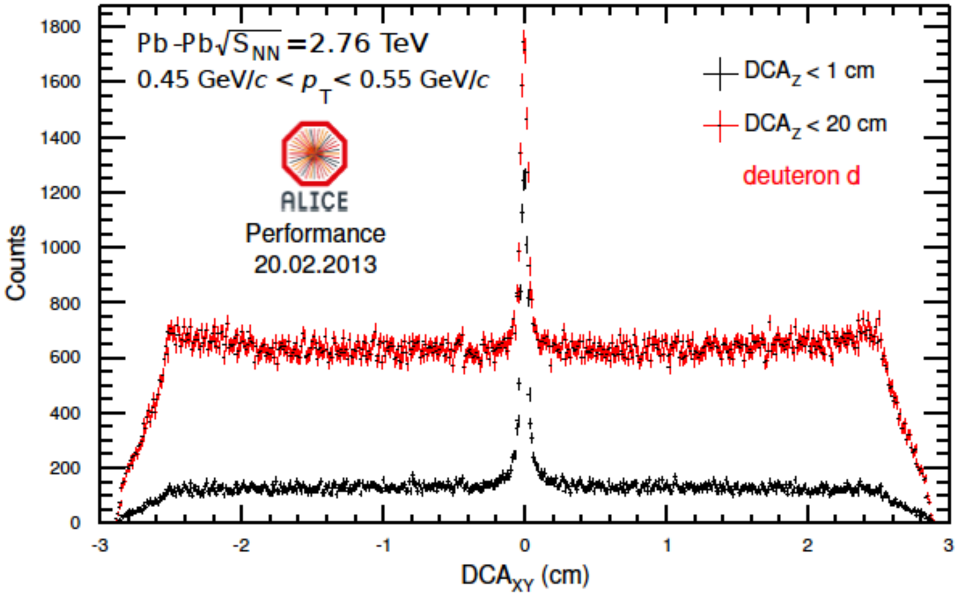
L. Zhu, C.M. Ko, X. Yin: PRC 92, 064911 (2015)

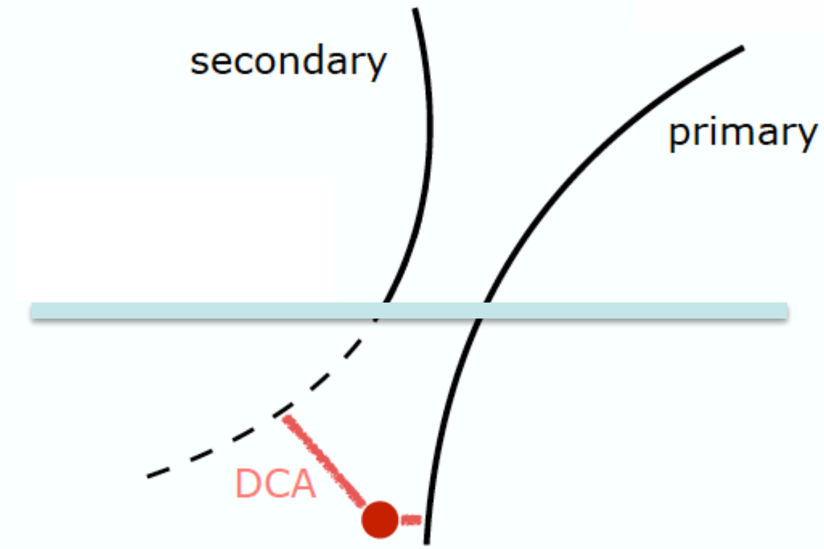
Elliptic flow



L. Zhu, C.M. Ko, X. Yin: PRC 92, 064911 (2015)

Secondary contamination





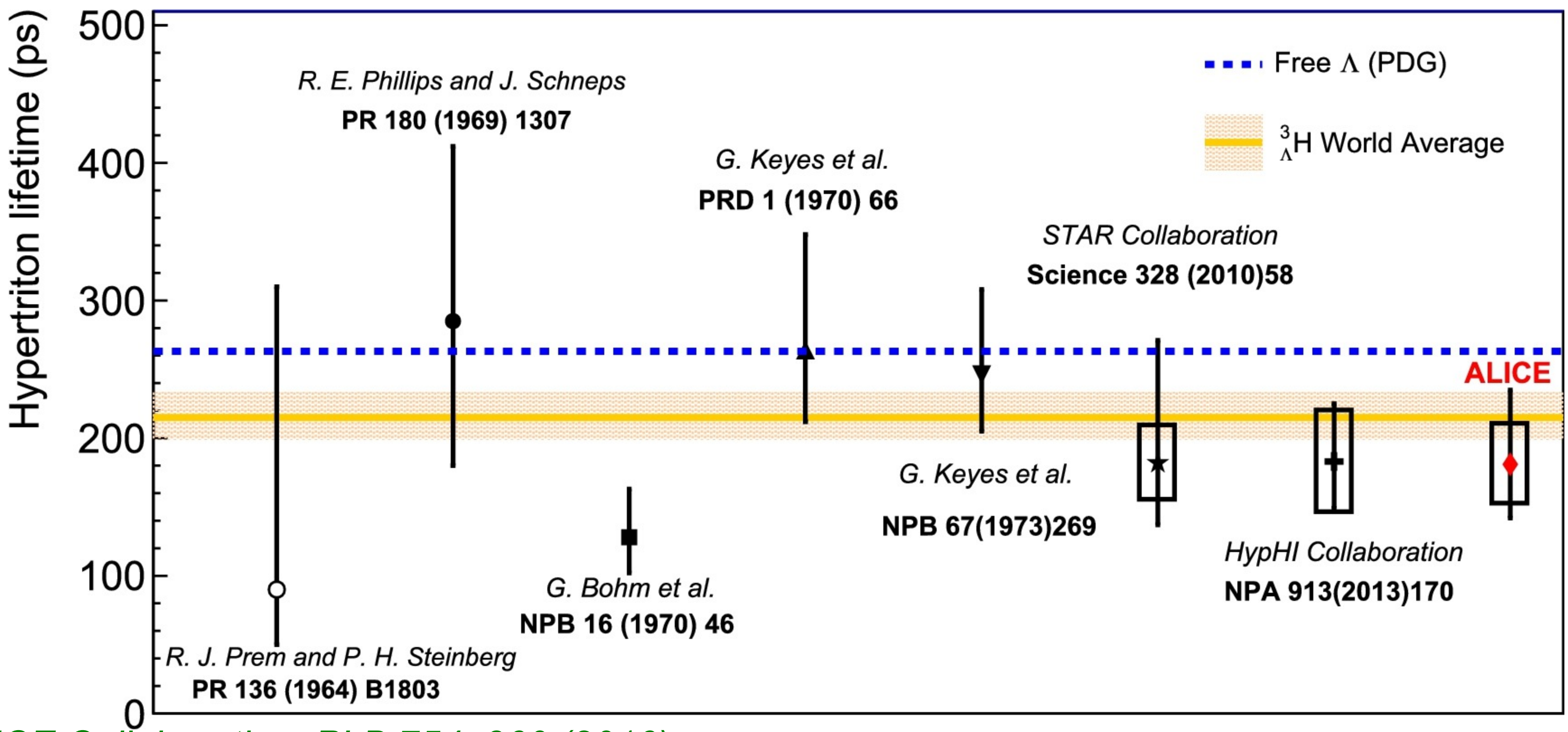
➜ Distance-of-Closest-Approach (DCA) distributions can be used to separate primary particles (produced in the collision) from secondary particles (from knock-out of the material, e.g. beam pipe)

➜ Knock-out is a significant problem at low p_T, but only for nuclei not for anti-nuclei

Hypertriton lifetime

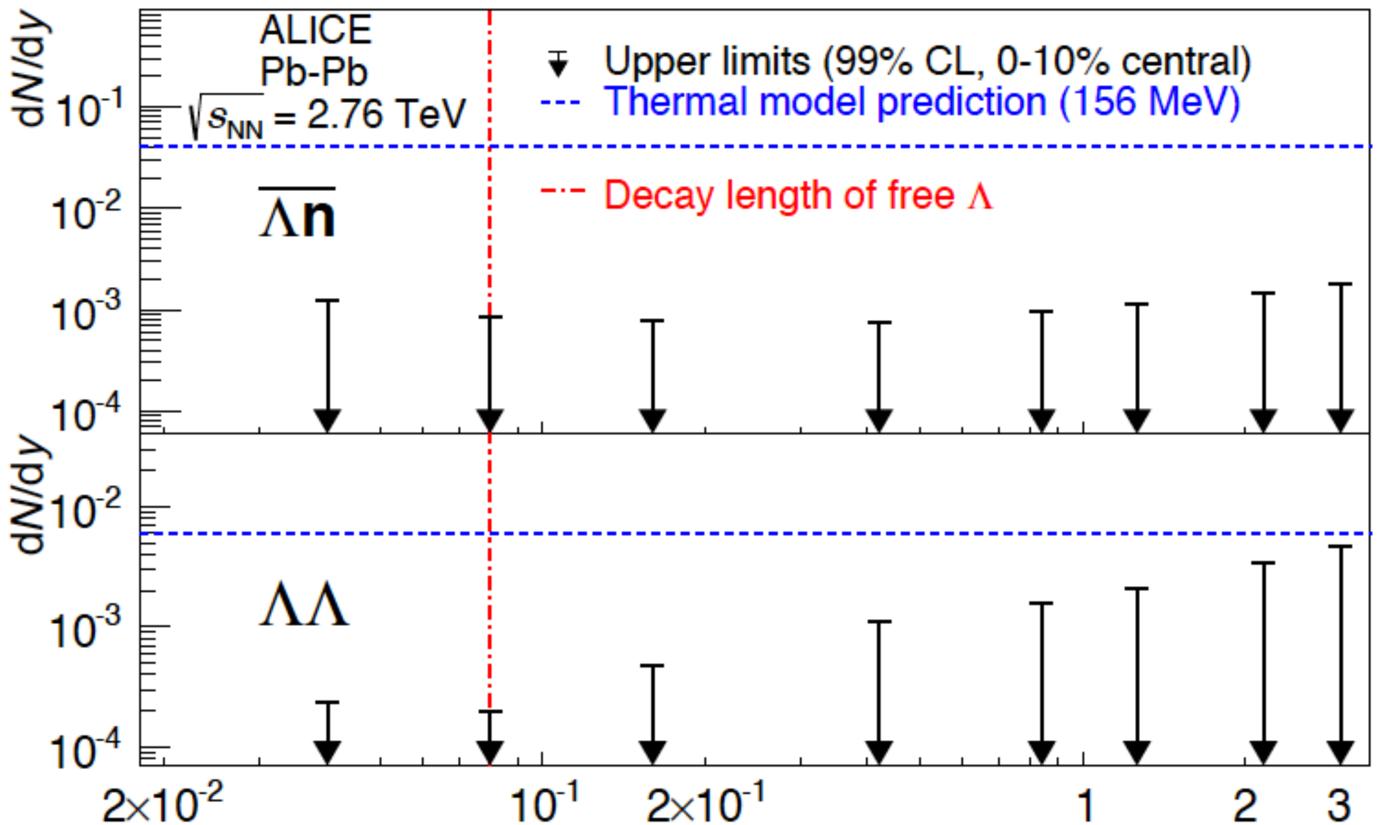
Extracted lifetime below the free Λ lifetime

– Not expected by theory



ALICE Collaboration: PLB 754, 360 (2016)

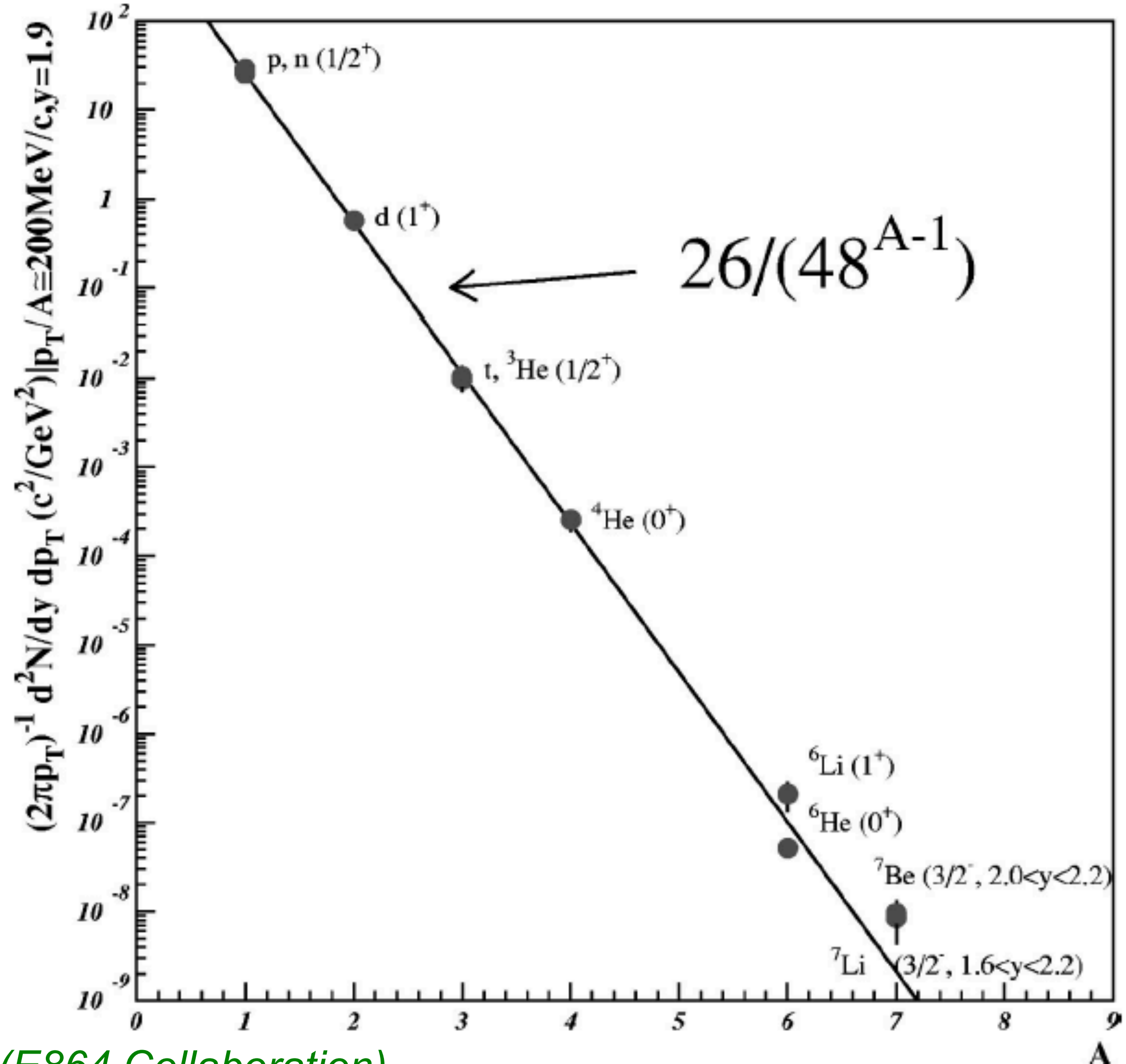
Decay length dependence



ALICE Collaboration: PLB 752, 267 (2016)

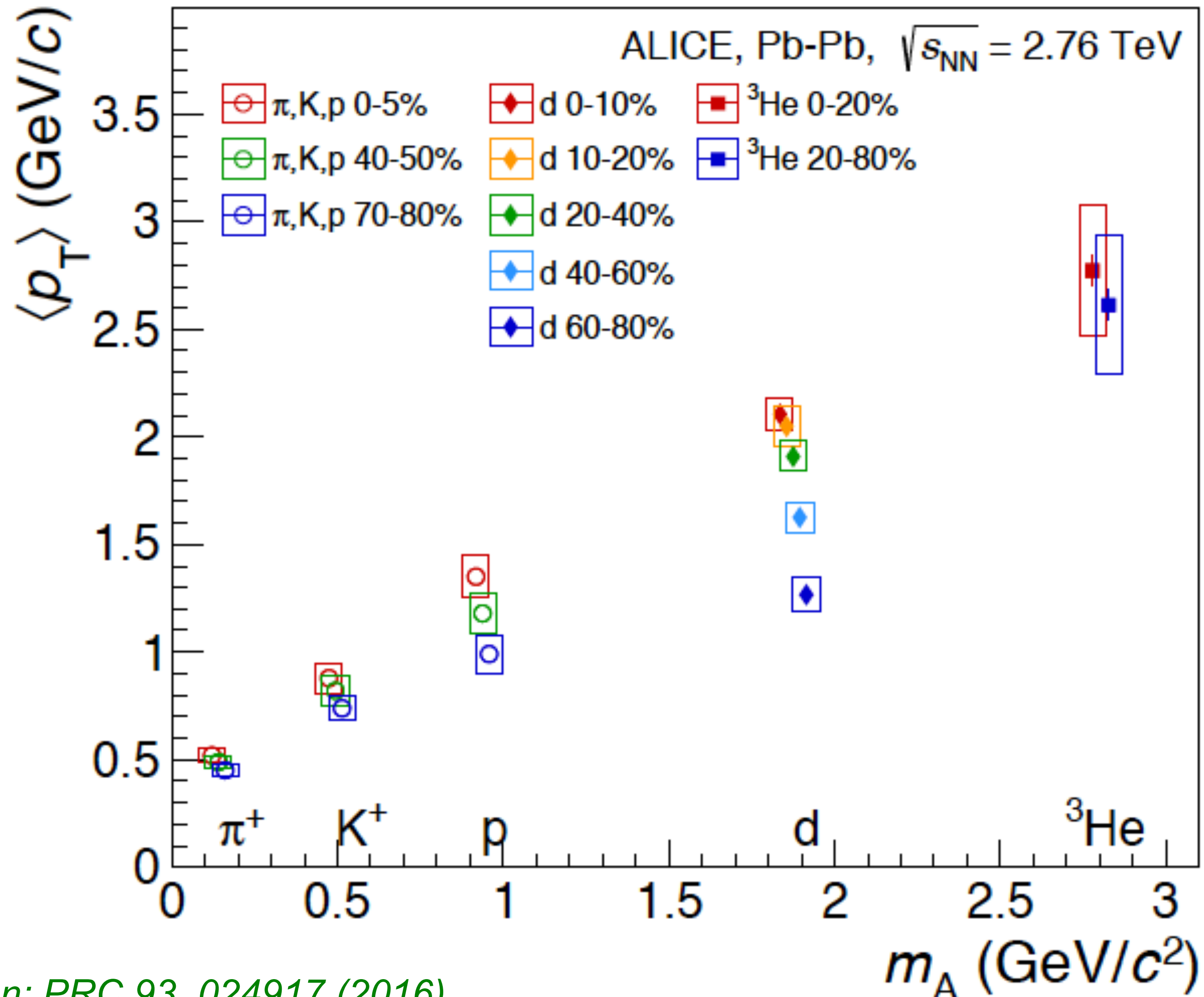
Search for a bound state of Λn and ΛΛ, shows no hint of signal
→ upper limits set (for different lifetimes assumed for the bound states)

E864 nuclei result



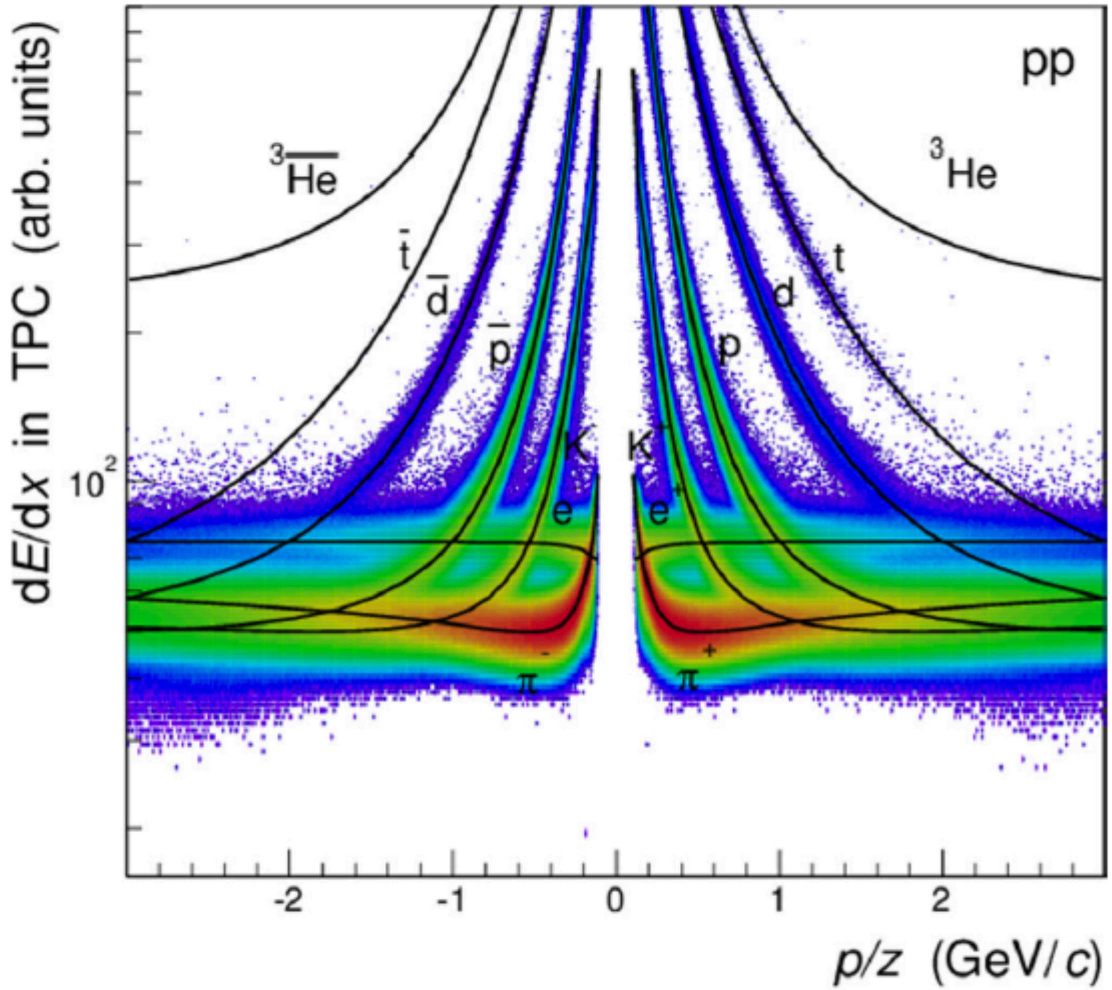
T.A. Armstrong et al. (E864 Collaboration), Phys. Rev. C 61 (2000) 064908

Mean p_T



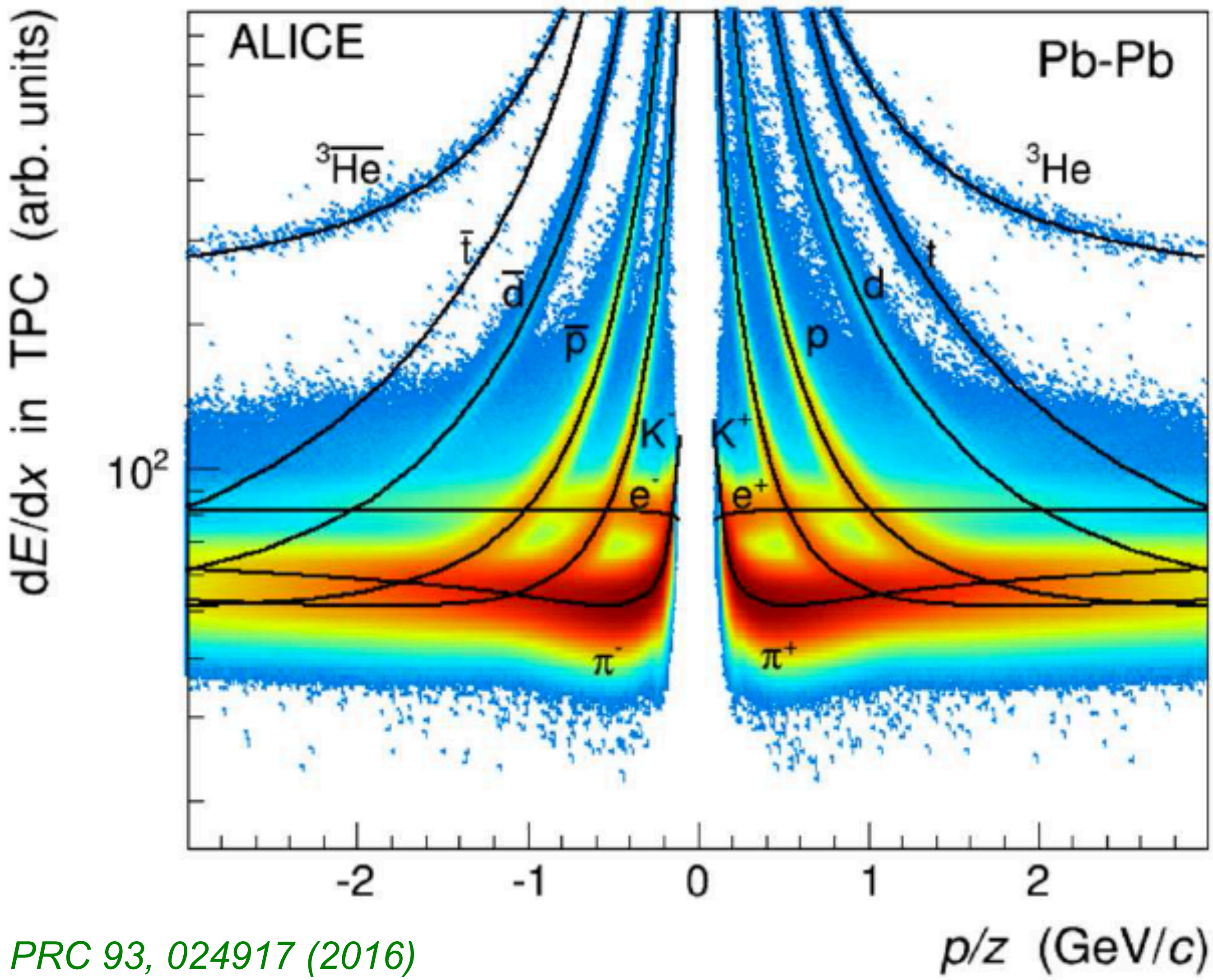
ALICE Collaboration: PRC 93, 024917 (2016)

TPC PID in pp



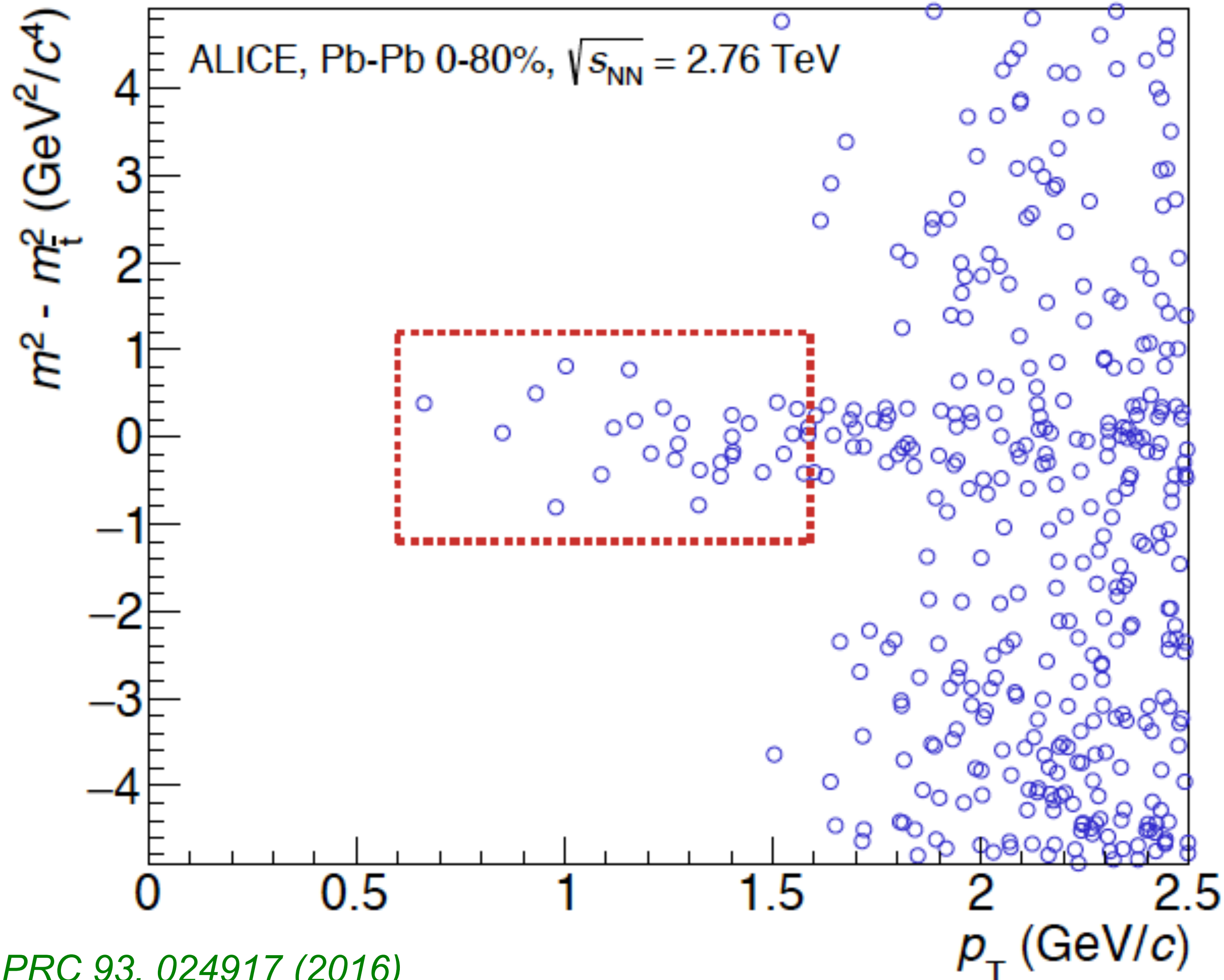
ALICE Collaboration: PRC 93, 024917 (2016)

TPC PID in Pb-Pb



ALICE Collaboration: PRC 93, 024917 (2016)

Anti-tritons



ALICE Collaboration: PRC 93, 024917 (2016)